ADBI Series on Asian and Pacific Sustainable Development

CLIMATE CHANGE MITIGATION

Policies and Lessons for Asia

Edited by

Dina Azhgaliyeva and Dil B. Rahut

ADBInstitute

ASIAN DEVELOPMENT BANK INSTITUTE

ADBI Series on Asian and Pacific Sustainable Development

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Economic growth, poverty reduction, and living standards in Asia and the Pacific have improved dramatically in recent decades, but the region now faces a diverse range of new and ongoing challenges. The *ADBI Series on Asian and Pacific Sustainable Development* highlights innovative research and policy guidance for enabling greater socioeconomic progress amid fast-changing conditions. The series aims to be a forward-looking and impactful source of knowledge for policy makers and scholars interested in building a prosperous, inclusive, resilient, and sustainable Asia and the Pacific.

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Contents

PART I Energy Sector: Transition toward High Renewable Energy Penetration

PART II Buildings: Promoting and Financing Demand-Side Energy Efficiency

PART III Transport Sector: Promoting Cleaner Transportation

PART IV Decarbonizing through the Agriculture Sector

PART V Carbon Pricing

Tables, Figures, and Boxes

Tables

Figures

Boxes

Abbreviations

4Rs	reduce, reuse, recycle, and replace
ADB	Asian Development Bank
ADBI	Asian Development Bank Institute
AFOLU	agriculture, forestry, and other land use
BAU	business as usual
BEMS	building energy management system
BEV	battery electric vehicle
CAGR	compound annual growth rate
CH_4	methane
CNG	compressed natural gas
CO_2	carbon dioxide
COP	Conference of the Parties
CT	carbon tax
EPA	Environmental Protection Agency
EPC	energy performance contract
ESCO	energy service company
ETS	emissions trading scheme
EU	European Union
EV	electric vehicle
FAO	Food and Agriculture Organization of the United Nations
GBL	Green Building Labelling
GDP	gross domestic product
Gg	gigagram
GHG	greenhouse gas
Gt	gigaton
GW	gigawatt
HCFC	hydrochlorofluorocarbon
HCV	heavy commercial vehicle
HEV	hybrid electric vehicle
HFC	hydrofluorocarbon
ICE	internal combustion engine
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
km	kilometer
LCOE	levelized cost of energy
LED	light-emitting diode
LEED	leadership in energy and environmental design
LNG	liquefied natural gas

LUC	land use change
m^2	square meter
mha	million hectares
$MtCO_2$	million tons of CO_2
$MtCO_2e$	million tons of carbon dioxide equivalent
Mtoe	million tons of oil equivalent
MW	megawatt
MWh	megawatt-hour
N_2O	nitrous oxide
NAMA	nationally appropriate mitigation action
OECD	Organisation for Economic Co-operation and Development
PHEV	plug-in hybrid electric vehicle
PPA	power purchase agreement
PRC	People’s Republic of China
R&D	research and development
REC	renewable energy certificate
RER	renewable energy resource
SDGs	Sustainable Development Goals
SFPFC	Standardized Fixed-Price Forward Contract
SGBMP	Singapore Green Building Masterplan
TFP	total factor productivity
Tg	teragram
TWh	terawatt-hour
UK	United Kingdom
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
xEV	electrified vehicle

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Foreword

Asia and the Pacific is one of the most vulnerable regions to the destructive effects of climate change. The region is also the source of more than 50% of annual global greenhouse gas (GHG) emissions. It is clear that bold and urgent action is needed to combat the enormous climate challenge while offering pathways for low-carbon development that can support robust, sustainable, and inclusive economic growth.

Climate Change Mitigation: Policies and Lessons for Asia serves as a much-needed resource for researchers, policy makers, and development practitioners as they develop effective climate change solutions for Asia and the Pacific. The book is the result of the Asian Development Bank Institute Annual Conference held on 1–3 December 2021.

The authors and discussants offer innovative policy recommendations and lessons for climate change mitigation that can be applied across the transport, building, and agriculture sectors. Each of these sectors is a significant source of carbon emissions. At the same time, they are vital to the region's development as well as to achieving climate action targets. In addition, this book addresses carbon pricing, a potential solution for reducing GHG emissions that can be applied to many sectors. Together, these efforts can benefit Asia and the Pacific in a number of ways, including better energy access, higher energy security, more livable cities, and other social and economic gains.

This book will inform climate change mitigation research and policy making, complementing the work of the Asian Development Bank. The Asian Development Bank's support to Asia and the Pacific as the region's climate bank includes its ambition to provide $100 billion in climate finance between 2019 and 2030, game-changing carbon reduction models, including the Energy Transition Mechanism, and an updated energy policy that commits to formally withdraw from financing new coal-fired plants.

We are grateful to the authors for their contributions to this timely publication. We are confident that it will have a far-reaching impact on the global effort to achieve net zero carbon emissions.

M. A

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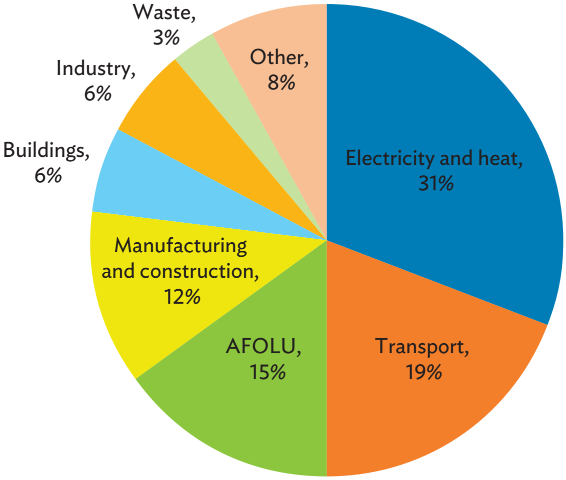
Executive Summary

Dina Azhgaliyeva and Dil B. Rahut

This book titled *Climate Change Mitigation: Policies and Lessons for Asia* is a result of the Asian Development Bank Institute's Annual Conference held on 1–3 December 2021 and focuses on climate change mitigation solutions across four sectors—energy; building; transport; and agriculture—as well as solutions from carbon pricing. These sectors were selected because of their large share of greenhouse gas (GHG) emissions and because efforts in reducing GHG emissions across these sectors could lead to noticeable GHG emissions reduction. This book also includes carbon pricing, which can reduce GHG emissions across various sectors.

Figure: Global Greenhouse Gas Emissions by Sector, 2019
(%)



AFOLU = agriculture, forestry, and other land use.

Source: Authors' elaboration using data from H. Ritchie, M. Roser, and P. Rosado. 2020. CO_2 and Greenhouse Gas Emissions. OurWorldInData.org. https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions

This book is organized in five parts: the energy sector (chapter 1), the building sector (chapters 2–3), the transport sector (chapters 4–5), the agriculture sector (chapters 6–7), and carbon pricing (chapters 8–9). A brief description of each chapter is given below. We also highlight some of the key findings and recommendations from this book.

Part I. Energy Sector: Transition toward High Renewable Energy Penetration provides solutions for electricity markets with a high penetration of renewable energy. Electricity and heat contribute 31% of GHG emissions. This part contains one chapter.

Chapter 1, "Financing the Energy Transition in a Low-Cost Intermittent Renewable Energy Environment," proposes that short-term market design and a long-term resource adequacy mechanism are crucial for achieving a given renewable energy goal with minimal above-market costs. Declines in the up-front costs of wind and solar generation units have considerably reduced the gap between the levelized cost of energy (LCOE) for these resources and the LCOE of natural gas and coal-fired generation. Such changes have the potential to reduce the cost of increasing the share of intermittent renewable resources in Asia, which currently accounts for almost half of global energy demand and is the world largest greenhouse gas-emitting region. This chapter proposes a multi-settlement locational marginal pricing short-term market design, a standardized fixed-price forward contract approach to long-term resource adequacy, and a renewable energy certificate market as the major market design elements to achieve this goal.

Part II. Buildings: Promoting Demand-Side Energy Efficiency provides solutions for decarbonizing the building sector (including building construction), which accounts for 37% of total GHG emissions and 36% of total energy consumption (in 2020). This part contains two chapters.

Chapter 2, "Future-Proofing Sustainable Cooling Demand," explains that sustainable solutions for meeting the fast-growing demand for cooling are not just about renewable energy but also include thermal energy storage, passive cooling, and behaviorl changes. This chapter presents a system-level approach to cooling provision in buildings and urban environments, also highlighting the need for a holistic consideration of cooling demand across other sectors (e.g., transport), to ensure sustainability and resilience throughout the life cycle of buildings and infrastructure more broadly. It aims to drive new system-level thinking in key areas—how we mitigate, make, store, move, manage, finance, and regulate cold—to meet current and future cooling needs efficiently, sustainably, and affordably, in line with the ambitions of the Paris Agreement, the Kigali Amendment to the Montreal Protocol, and the United Nations Sustainable Development Goals.

Chapter 3, "Promoting Green Buildings: Barriers, Solutions, and Policies," provides an overview of policies supporting green buildings. Building and construction account for 36% of total GHG emissions and 37% of total energy use, which is expected to increase immensely in the future due to increased demand for housing given rising population and income. Green buildings could significantly mitigate GHG emissions from the building sector. The concept of green building, includes using environmentally friendly materials and decreasing the use of resources such as energy, water, etc. This chapter offers a systematic review of the barriers to scaling green buildings. It shows that access to construction materials and skilled labor for green buildings, followed by the high cost of construction, lack of standards, policies, and government support, are major hurdles for policy makers.

Part III. Transport Sector: Promoting Cleaner Transportation provides solutions for decarbonizing the transport sector, which accounts for over 10% of global GHG emissions. This part contains two chapters.

Chapter 4, "Transport CO_2 Mitigation and the Production of Low Traffic Neighborhoods: Lessons from London," assesses the Low Traffic Neighborhood 21 (LTN21) in suburban West London and draws implications for wider contexts, such as in Asian cities, including that wide-ranging sustainable mobility strategies need to consider carbon dioxide and social equity impacts. Further, it recommends a strengthened participatory and deliberative transport planning process to improve the process of project delivery.

Chapter 5, "Decarbonizing the Transport Sector through Electrification and Biofuel Use in Emerging Economies of Asia," examines the carbon emissions reduction potentials of using biofuel in road vehicles as a complementary strategy to increasing electrified vehicles in India, Indonesia, and Thailand. The findings display that a stand-alone moderate electrification strategy is insufficient to reduce carbon emissions in the transport sector to the level required by 2030. The complementary use of conventional and next-generation biofuels will have total net positive carbon reduction and economic benefits as a substitute for transport fuel demand.

Part IV. Decarbonizing through the Agriculture Sector discusses solutions for the agriculture sector, which is one of the most vulnerable sectors to climate change due to its dependence on weather and climatic conditions. This part contains two chapters.

Chapter 6, "Contribution of Agriculture to Climate Change and Low-Emissions Agricultural Development in Asia and the Pacific," recommends that appropriate integration of policies at multiple levels and the application of multiple measures simultaneously can increase the mitigation potential as desired by the Paris Agreement and help achieve several of the United Nations Sustainable Development Goals. Against the backdrop of the agriculture sector's significant contribution to GHG emissions due to methane-producing rice production, increases in food production to feed the growing population, changes in dietary patterns, and massive use of synthetic fertilizer and energy in agricultural production in the Asia and Pacific region for the last few decades, this chapter conducts a systematic review of strategies that can reduce emissions from the agriculture sector using a multidimensional approach—supply-side measures, demand-side measures, and cross cutting measures.

Chapter 7, "Best Bets for Achieving a Carbon-Neutral Global Food System," suggests that the highest priority for policy makers should be limiting emissions from land use change, as this drives the biggest share of emissions, presents the most cost-effective mitigation potential, and is easily verified. Reducing GHG emissions from food systems is a key element of strategies to slow climate change. A second priority should be enhancing on-farm carbon storage, which currently provides significant low-cost mitigation potential and often has substantial co-benefits. A third priority should be reducing methane emissions from rice and industrial animal systems, where solutions are more cost-effective and more easily verified than in less-intensive animal systems. A fourth priority should be investing in technologies to limit methane and nitrous oxide emissions, for which current solutions are often too expensive. Finally, demand-side solutions, including fostering the alternative protein industry, could play an important role in achieving carbon neutrality.

Part V. Carbon Pricing discusses the impact of different carbon pricing instruments on GHG emissions reduction.

Chapter 8, "Exploiting Complementarity of Carbon Pricing Instruments for Low-Carbon Development in the People's Republic of China," explores whether a single cost-effective instrument is adequate for developing a low-carbon economy in the PRC or whether a policy portfolio would be more effective. The PRC has planned energy and climate policy targets to contribute to its efforts to meet the goal enshrined in the Paris Agreement. Results show that a nationwide emissions trading scheme (ETS) has advantages over a carbon tax regarding gross domestic product losses. It also performs better in promoting the transfer of labor and capital from the eastern regions to the central and western regions. However, a single ETS is less effective in regard to industrial structure adjustments and emissions reduction in sectors that are not included in the ETS, such as the transport sector. The results also show that a policy portfolio could achieve the same emissions reduction target with more moderate impacts. Therefore, it is suggested that the implementation of a carbon tax for sectors that are excluded from the ETS or a subsidy for energy-efficient vehicles could be considered as supplementary policies for the ETS in the PRC.

Chapter 9, "What Role for Carbon Taxes and Emissions Trading in a Portfolio of Policies to Reduce Greenhouse Gas Emissions," explores how overlaps and interactions of policies affect policy design and how governments can use policy packages to deal with practical constraints as well as to achieve multiple policy objectives. The chapter also reviews ways in which emissions trading and carbon taxes have been designed to better meet policy objectives or requirements, based on the experience made in existing emissions trading schemes that have evolved incrementally. Economic theory suggests a central role for carbon pricing, and more governments are implementing emissions trading schemes or carbon taxes. However, carbon pricing is never the only instrument aimed to reduce emissions and often not the dominant one, with various types of regulatory policies as well as fiscal policies also playing important roles.

Solutions explored in this book for climate change mitigation across sectors include electricity market design for achieving a given renewable energy goal with minimal above-market costs, (agriculture and food, phase-out the sale of new internal combustion engine vehicles, sustainable cooling and green buildings, as well as carbon pricing. Such solutions can help in climate change mitigation efforts and can also have a number of benefits in developing Asia apart from limiting global temperature rise and preventing catastrophic climate change. Such solutions can help to reduce high pollution levels in large cities in the region and provide better energy security. Solving these problems will improve quality of life and increase life expectancy, while reducing health-care expenses. There is no single solution for meeting impactful climate goals in developing Asia. Appropriate policy measures will need to account for variations in geography, climate, and electricity market characteristics. They will also require long-term planning, learning from other countries, and learning by doing, especially when preparing the electricity market for a highly renewable world. This book, by spotlighting new research on climate imperatives across key sectors and carbon pricing, explores the next steps for climate change mitigation in Asia and the Pacific. With breakthroughs in these areas, the region could help lead the way toward achieving measurable progress in the fight against climate change.

Introduction: Climate Change Mitigation for a Sustainable Future

Dil B. Rahut and Dina Azhgaliyeva

Climate Change

Climate change is a severe threat to the sustainable future of humanity (Hoegh-Guldberg et al. 2019; Aryal et al. 2020b; Tollefson 2018). Greenhouse gas (GHG) emissions from human activities such as carbon dioxide (CO_2), methane, water vapor, nitrous oxides, and ozone, are the leading cause of global warming and hence changes in the climatic condition (WMO 2021).[1] The adverse effects of climate change, such as rising temperatures, erratic rainfall, water stress, heat waves, drought, desertification, land degradation, glacial meltdown, rising sea levels, seawater inundation, salination, and flooding, are becoming more visible. As a result of these manifestations of climate change, different stakeholders—even the skeptics—have recognized that climate change is real and investment in climate change mitigation strategy is crucial. If climate change continues at the current rate, it could severely threaten livelihoods, human health, biodiversity, food security, and the economy, and reverse the progress made by humanity so far (Rahut et al. 2022; Hertel and Rosch 2010). Further, it could increase poverty, as well as food and nutritional insecurity, thereby making it challenging to achieve sustainable goals in the short and medium term (Hallegatte and Rozenberg 2017; Fankhauser and Stern 2019).

The Paris Agreement was adopted by 196 countries at the Conference of the Parties (COP21) on 12 December 2015, to limit global warming to below 2°C and, if possible, to 1.5°C compared to preindustrial levels (United Nations 2022). An increase in temperature

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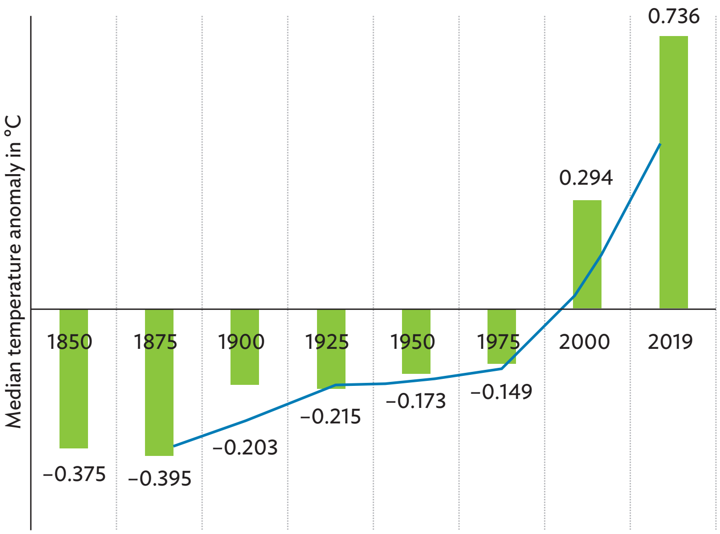
[1] According to Our World in Data (https://ourworldindata.org/greenhouse-gas-emissions), CO_2 accounts for 74.4%, methane 17.3%, nitrous oxide 6.2%, and other emissions (hydrofluorocarbons, chlorofluorocarbons, sulfur hexafluoride) 2.1%.

beyond 1.5°C could severely damage human civilization and the entire ecosystem (Tollefson 2018; Azhgaliyeva et al. 2021). The global community must act immediately and swiftly to reduce GHG emissions. Reductions in emissions of CO_2 and other GHGs must be achieved in the coming decades to avoid catastrophic global temperature rises. Limiting global warming to within 1.5°C will require rapid, far-reaching, and unprecedented changes in all sectors.

Figure 1 shows that the global median temperature has been rising gradually: in 1850 it was −0.373, in 1900 it was −0.203, in 1950 it was −0.173, in 2000 it was 0.294, and in 2019 it was 0.736. The most recent heat wave of 2022 in India and Pakistan, leading to health issues and deaths (Arnold 2022; Kishore et al. 2022; Patel et al. 2022), is also a signal that the rising temperature will lead to several challenges to human health and well-being.

Figure I.1: Median Temperature Anomaly in °C from 1961 to 1990

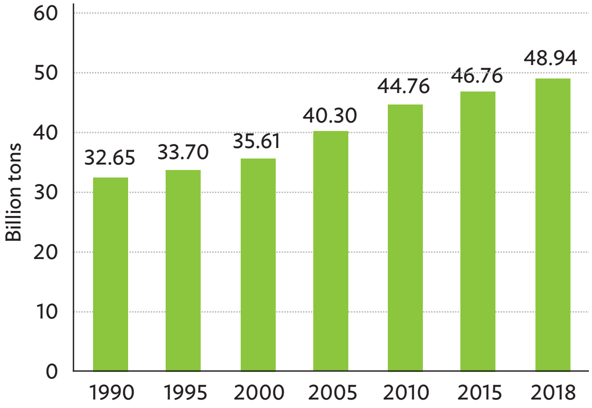


Source: Our World in Data. https://ourworldindata.org/grapher/temperature-anomaly (8 August 2022).

Trend of GHG Emissions

Figure I.2 shows the level of GHG emissions (CO_2 equivalent) in the last 3 decades. Between 1990 to 2018, GHG emissions increased by 50%, from 32.65 billion tons to 48.94 billion tons. Given the increase in the demand for goods and services, increasing population, and slow transformation to clean energy and technology, GHG emissions are expected to rise in the future under a business-as-usual scenario, which will have a detrimental effect on the economy and human life.

Figure I.2: Level of GHG Emissions, 1990–2018 (CO_2 equivalent)



GHG = greenhouse gas.

Source: Our World in Data.

Today, the People's Republic of China (PRC) is the largest contributor to GHG emissions, followed by the United States (US), India, and the European Union (EU). In the case of the PRC, GHG emissions (CO_2 equivalent) have increased dramatically from 2.87 billion tons in 1990 to 11.71 billion tons in 2018. During the same period, GHG emissions in India increased from 1.01 to 3.35 billion tons, while they declined in the EU 27 and the Russian Federation and increased marginally for the United States (Table I.1).

Table I.1: GHG Emissions by Country
(CO_2 equivalent)

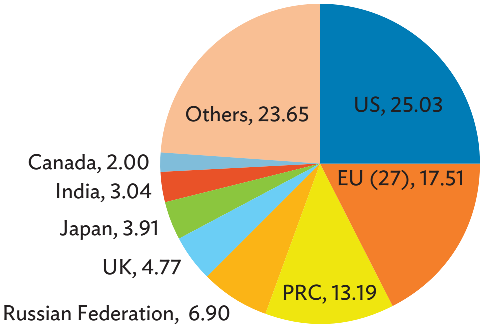
	2018			2010		2000		1990	
	(A)	(B)	(C)	(A)	(B)	(A)	(B)	(A)	(B)
PRC	11.71	23.9%	6.77	9.87	22.1%	4.25	11.9%	2.87	8.8%
United States	5.79	11.8%	14.52	6.04	13.5%	6.45	18.1%	5.54	17.0%
India	3.35	6.8%	1.77	2.58	5.8%	1.50	4.2%	1.01	3.1%
European Union 27	3.33	6.8%	5.93	3.65	8.1%	3.93	11.0%	4.28	13.1%
Russian Federation	1.99	4.1%	7.20	1.69	3.8%	1.83	5.1%	2.89	8.8%
Indonesia	1.70	3.5%	4.74	2.58	2.5%	1.19	3.3%	1.26	3.9%
Brazil	1.42	2.9%	3.88	2.10	4.7%	1.81	5.1%	1.64	5.0%
Japan	1.15	2.4%	8.44	1.13	2.5%	1.20	3.4%	1.11	3.4%
Others	18.49	37.8%	NA	15.12	37.0%	13.45	37.8%	12.05	36.9%
Total	48.9	100.0%	4.78	44.8	100.0%	35.6	100.0%	32.7	100.0%

GHG = greenhouse gas, NA = not applicable, PRC = People's Republic of China.
Notes:
A: GHG emissions (billion tons of CO_2 equivalent)
B: Share to total GHG emissions
C: Per capita GHG emissions (tons of CO_2 equivalent)
Source: Our World in Data.

Figure I.3 shows that the cumulative share of GHG emissions is highest for the US (25.03%), the EU (17.51%), the PRC (13.19%), the Russian Federation (6.9%), the United Kingdom (4.77%), and Japan (3.91%).

Figure I.4 shows that the energy sectors contribute 73% of GHG emissions, while agriculture, forestry, and land use contribute 18.4%. A further breakdown of the GHG emissions of the energy sectors by user of the sector shows that industry contributes 24.2% of energy-related GHG emissions, with buildings contributing to 17.5%, and transport contributing 16.2%.

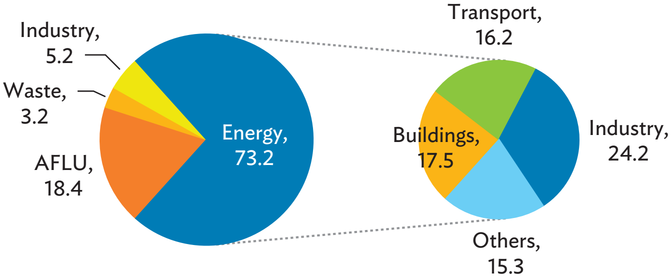
Figure I.3: Cumulative Share of GHG Emissions, 2018
(%)



EU = European Union, GHG = greenhouse gas, PRC = People's Republic of China, UK = United Kingdom, US = United States.

Source: Our World in Data.

Figure I.4: Share of GHG Emissions by Sector
(%)



AFLU = agriculture, forestry, and land use, GHG = greenhouse gas.

Source: Our World in Data.

Impact

Climate risk is a covariate shock, as it affects everyone. However, people living in developing countries and vulnerable areas are more susceptible to climate change due to their limited capacity to invest in climate change mitigation.

Agriculture, Forestry, and Livestock

Although all sectors are vulnerable to climate change, the agriculture sector is the most vulnerable as it is directly dependent on climatic factors such as rainfall and temperature (Aryal et al. 2020a; Ortiz-Bobea et al. 2021). Slight changes in the rainfall pattern and temperature could directly or indirectly damage crops through crop pests, disease, infection, and water stress (shortage and flooding). For instance, with the increase in temperature, the productivity of crops will decline, resulting in lower yields, food insecurity, and poverty. Furthermore, rising inequality due to food insecurity and poverty could result in conflicts and instability. Several studies have projected that under a business-as-usual scenario, production of several crops would decline in the future.

Natural Resources and Ecology

Global warming adversely affects natural resources and ecology (Kushawaha et al. 2021; Watson et al. 2005), thereby threatening livelihoods and life on earth. Water shortages are becoming more frequent, with changes in the precipitation pattern, glacial melting, and the rising sea level. With rising temperatures, erratic rainfall patterns, and water stress, soil quality deteriorates, further leading to desertification. Such changes in the temperature, precipitation, and deterioration in soil health disrupt ecology. Ultimately, it could severely affect the well-being of humanity.

Health

There is evidence that climate change has adversely affected human health (McMichael et al. 2006; Haines et al. 2006). For instance, dengue and malaria cases have surged in some places (Barclay 2008), while in Africa, the disease burden could shift from malaria to arboviruses (Mordecai et al. 2020). There is also discussion that climate change could result in the melting of glaciers and the release of pathogens that remain buried. Further extreme heat waves could affect sleep patterns and result in adverse effects on health or directly affect health leading to death (Arnold 2022; Kishore et al. 2022; Patel et al. 2022).

Economy

Finally, climate change could destroy economic progress, for instance, through the destruction of structures such as roads and buildings, or through the depletion and degradation of natural resources, which in turn affects farm productivity (Nordhaus 2007; Stern 2008). The direct impact could be the destruction of infrastructure and property from flooding, cyclones, and crop failure, while the indirect impact could be the impairment of soil health, and ecosystem services, among others.

Way Forward

Environmental Kuznets Curve Hypothesis

According to the Environmental Kuznets Curve hypothesis, economic growth leads to environmental degradation, and after a certain level of economic development, the marginal utilities of a better environment increase, and countries will start investing in clean technology (Selden and Song 1994; Zhu et al. 2016; Narayan and Narayan 2010). However, the literature differs in terms of the validity of the Environmental Kuznets Curve hypothesis (Sahoo et al. 2022).

Technology

The literature has also suggested that the increase in deployment of environmentally friendly technology leads to a decline in GHG emissions (Sahoo et al. 2022; Bhowmik et al. 2022). Therefore, investment and scaling of green technology could significantly contribute to the reduction of GHG emissions. However, the role of technology in climate change mitigation faces two key difficulties: (i) making these technologies accessible to developing countries, and (ii) measuring the future adverse effects of these technologies.

Environmental Regulations

Environmental regulations are important to reduce GHG emissions and prevent environmental degradation (Kolstad 1996; Ulucak et al. 2020).

Some studies have highlighted that environmental regulations reduce the performance of the industry on which the regulations are imposed, such as mining, making it less competitive.

Energy Transition

As energy contributes about 73% of GHG emissions, it is crucial to expedite the energy transition from fossil fuels to clean fuels such as solar, hydropower, wind power, and thermal power. However, the share of primary energy from renewable[2] sources is still low, which indicates the need to expedite the switch to renewable energy. For instance, according to the Our World in Data database (https://ourworldindata.org/), renewable energy as a percent of equivalent primary energy increased from 6.45% in 1965 to 7.75% in 1995, and 13.47% in 2021 (Figure I.5).

The energy sector in developing Asia depends heavily on fossil fuels, and energy prices are often subsidized or government-controlled. Therefore, substantial investments are required to increase the supply of clean and renewable energy to displace non-renewable sources of energy.

Yet, public expenditure in the region is constrained, and this has been especially compounded by high coronavirus disease (COVID-19)-related expenditures. The intermittency of variable renewable energy (due to clouds and wind speed changes) requires investment in renewable energy and in energy storage, electricity transmission lines, and other infrastructure. The power sector is undergoing a significant transition, and variable and/or intermittent renewable energy will be the main building block for low-carbon power systems. Flexibility is the key to electricity security, which requires timely investments in flexible resources such as dispatchable power plants, grids, demand side, and energy storage.

The following crucial policy solutions for the electricity market for achieving a given renewable energy goal at least cost to electricity consumers are proposed in this book:

- a well-designed short-term wholesale electricity market with efficient pricing, such as a multi-settlement locational marginal pricing short-term market design;
- a long-term resource adequacy mechanism for the wholesale electricity market, such as a standardized fixed-price forward contract approach to long-term resource adequacy; and
- a renewable energy support mechanism such as a renewable energy certificate market.

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[2] Includes hydropower, solar, wind, geothermal, wave, tidal, and modern biofuels.

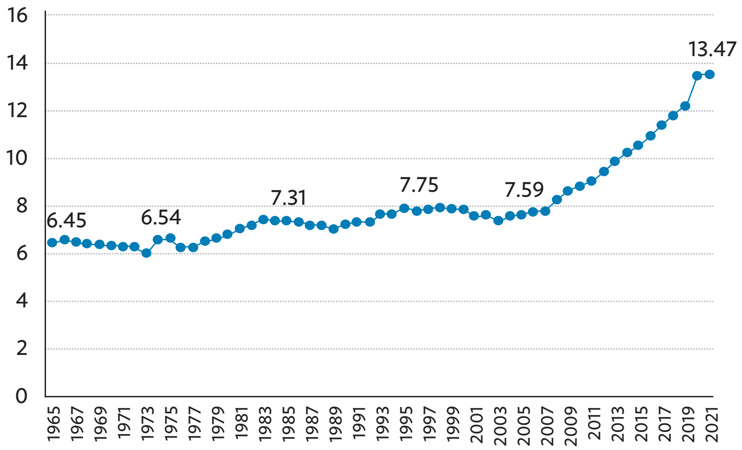

Figure I.5: Renewable Energy Share (% equivalent primary energy)

Source: Our World in Data. https://ourworldindata.org/

Transport

As energy use in the transport sector contributes to about 16.2%[3] of the total GHG emissions, there exists great potential to reduce GHG emissions from transport. Scaling up electric vehicles, switching to renewable energy transport systems, improving public transport systems, carpooling, using bicycles, and walking for short-distance travel are some strategies to reduce GHG emissions from the transport sector. Transitioning to new transport methods can take time because individuals make a choice, based on their individual utility maximization under their budget constraints.

Road transport accounts for over 10% of global GHG emissions, with emissions rising faster than in many other sectors. A declaration to sell only zero-emissions transport vehicles globally by 2040, and by no later than 2035 in leading markets, was signed at COP26 in Glasgow, Scotland, by many governments, local and regional authorities, and automotive companies and investors. These new targets aim to

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[3] GHG emissions from different transport sectors: road transport 11.9%, aviation 1.9%, shipping 1.7%, and rail 0.4%.

accelerate the transition to zero-emissions vehicles in a bid to achieve the Paris Agreement's goals.

Largely due to an increase in income, urbanization, and population, the demand for transport services will increase significantly. Robin Hickman, Professor of Transport and City Planning at University College London, highlighted projections by the International Transport Federation that the number of vehicles globally would increase to 2.4 billion by 2050 from 1 billion vehicles in 2015 (OECD 2017). Although battery electric vehicles could be a better alternative to fuel-based automobiles for mitigating air pollution, their higher cost and the lack of ubiquitous charging infrastructure networks are major bottlenecks.

For decarbonizing the transport sector and to achieve the 1.5°C target, this book provides the following recommendations:

- promote investments in clean energy technology in the transport sector,
- phase out the sale of new internal combustion engine vehicles by 2030,
- increase walking and cycling to 50% of trips,
- double public transport capacity by 2030, and
- electrify at least 70% of railways and prioritize electricity as a primary transport fuel.

Green Buildings

The building sector accounts for about 39% of GHG emissions, which includes 28% from building operations and 11% from building materials and construction. With an increasing population and an increasing demand for houses, the GHG emissions from the building and construction sectors will continue to rise under the business-as-usual scenario.

About 20% of all electricity used is in buildings, while cooling accounts for more than 7% of global GHG emissions and is the fastest-growing source of hydrofluorocarbon emissions. The manufacturing of steel and cement, which are widely used as construction materials in buildings, accounts for 14%–16% of global energy-related CO_2 emissions (S&P Global 2021). If the cement industry was a country, it would be the third-largest emitter (*The Economist* 2021). Five countries—the United Kingdom, India, Germany, Canada, and the United Arab Emirates—have pledged to support demand for low-carbon steel, cement, and concrete.

Therefore, green buildings will emerge to play an important role in achieving carbon neutrality by 2060. Green buildings include the design, construction, and operation of buildings to reduce adverse effects on the climate and environment. Green buildings are not merely energy efficient; building them also involves the use of environmentally friendly material, water use efficiency, waste material management, and a healthy environment.

Policy recommendations from this book include:

- Promote green buildings and low-carbon cooling in developing Asia, especially Southeast Asia, due to its climatic conditions.
- Meet the fast-growing demand for cooling, not only by investing in renewable energy but also in thermal energy storage, passive cooling, and incentivizing behavior changes.
- Promote the construction of new green buildings to provide demand for low-carbon construction materials, such as steel, cement, and concrete, as well as other measures for environmentally friendly construction (such as reduce, reuse, and recycle [3Rs]) in order to reduce emissions from the building construction sector.
- Provide subsidies for green (or energy efficient) buildings and energy-efficient cooling and heating, which can be used to support low-income and vulnerable groups.

Sustainable Farming Practices and Food Waste

The agriculture, forestry, and other land use (AFOLU) sector contributes about 18.4% of the total GHG emissions. Therefore, this sector could also contribute significantly to the global effort to reduce GHG emissions. Agriculture is both a major cause and a victim of climate change. Agriculture and land-use change contribute to about one-quarter of global GHG emissions. However, agriculture is dependent on weather and climatic conditions, making it the most vulnerable sector.

As a large portion of the food produced is lost in the supply chain and consumption stage, reducing food waste and loss would help reduce GHG emissions from the agriculture sector. Furthermore, consuming less emissions-intensive food could also help reduce GHG emissions. On the supply side, sustainable farming practices such as intercropping, crop rotation, agroforestry, and minimum tillage could also reduce GHG emissions.

It is estimated that GHG emissions from the AFOLU sector can be reduced by 80% by 2030 through supply and demand management (Smith et al. 2014).

The proposed solutions for the agriculture, forestry, and land use sector include:

- The agriculture sector requires investment to improve the resilience of smallholder farmers and ensure food security in the light of climate change, environmental degradation, and rising populations.

- There is a need to expand digital advisory services, access to insurance, finance, markets, and adaptive technologies for smallholder farmers.
- Policy makers should prioritize scalable, cost-effective, and feasible solutions to get the best out of investment in climate-smart agricultural technology. Forests, as an important component of nature-based climate solutions, present tangible opportunities to significantly reduce GHG emissions.
- Managing forests to sequester carbon has the combined advantage of producing goods and services, while conserving biodiversity and preventing environmental degradation.

References

Arnold, C. 2022. Death by Climate Change. *Nature Climate Change* 12: 607–609.

Aryal, J. P. et al. 2020a. Climate Change Mitigation Options Among Farmers in South Asia. *Environment, Development and Sustainability* 22: 3267–3289.

Aryal, J.P. et al. 2020b. Climate Change and Agriculture in South Asia: Adaptation Options in Smallholder Production Systems. *Environment, Development and Sustainability* 22: 5045–5075.

Azhgaliyeva, D., D. Rahut, and P. J. Morgan. 2021. The Next Steps for Meeting Nationally Determined Contributions after COP26. *Asia Pathways*. Tokyo: Asian Developement Bank Institute.

Barclay, E. 2008. Is Climate Change Affecting Dengue in the Americas? *The Lancet* 371: 973–974.

Bhowmik, R., D. B. Rahu, and Q. R. Syed. 2022. Investigating the Impact of Climate Change Mitigation Technology on the Transport Sector CO_2 Emissions: Evidence From Panel Quantile Regression. *Frontiers in Environmental Science*.

The Economist. 2021. How Cement May Yet Help Slow Global Warming. 4 November.

Fankhauser, S., and N. Stern. 2019. Climate Change, Development, Poverty and Economics. In K. Basu, D. Rosenblatt, and C. Sepúlveda, eds. *The State of Economics, the State of the World*. Cambridge, MA, US: MIT Press, pp. 295–320.

Haines, A. et al. 2006. Climate Change and Human Health: Impacts, Vulnerability, and Mitigation. *The Lancet* 367: 2101–2109.

Hallegatte, S., and J. Rozenberg. 2017. Climate Change Through a Poverty Lens. *Nature Climate Change* 7: 250–256.

Hertel, T.W., and S. D. Rosch. 2010. Climate Change, Agriculture, and Poverty. *Applied Economic Perspectives and Policy* 32: 355–385.

Hoegh-Guldberg, O. et al. 2019. The Human Imperative of Stabilizing Global Climate Change at 1.5C. *Science* 365: eaaw6974.

Intergovernmental Panel on Climate Change (IPCC). 2007. *Climate Change 2007 Mitigation. Working Group III Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate.* Cambridge, UK and Geneva, Switzerland: Cambridge University Press and IPCC.

Kishore, P. 2022. Anthropogenic Influence on the Changing Risk of Heat Waves over India. *Scientific Reports* 12: 1–8.

Kolstad, C. D. 1996. Learning and Stock Effects in Environmental Regulation: The Case of Greenhouse Gas Emissions. *Journal of Environmental Economics and Management* 31: 1–18.

Kushawaha, J. et al. 2021. Climate Change and its Impact on Natural Resources. *Water Conservation in the Era of Global Climate Change*. Elsevier, pp. 333–346.

McMichael, A. J., R. E. Woodruff, and S. Hales. 2006 Climate Change and Human Health: Present and Future Risks. *The Lancet* 367: 859–869.

Mordecai, E. A. et al. 2020. Climate Change Could Shift Disease Burden from Malaria to Arboviruses in Africa. *The Lancet Planetary Health* 4: e416-e423.

Narayan, P. K., and S. Narayan. 2010. Carbon Dioxide Emissions and Economic Growth: Panel Data Evidence from Developing Countries. *Energy Policy* 38: 661–666.

Nordhaus, W. D. 2007. A Review of the Stern Review on the Economics of Climate Change. *Journal of Economic Literature* 45: 686–702.

Organisation for Economic Co-operation and Development (OECD) 2017. Transport Demand and CO2 Emissions to 2050. In *ITF Transport Outlook 2017.* Paris: OECD Publishing, chapter 2.

Ortiz-Bobea, A. et al. 2021. Anthropogenic Climate Change has Slowed Global Agricultural Productivity Growth. *Nature Climate Change* 11: 306–312.

Patel, L. et al. 2022. Climate Change and Extreme Heat Events: how Health Systems Should Prepare. *NEJM Catalyst Innovations in Care Delivery* 3(7). https://doi.org/10.1056/CAT.21.0454 CAT.21.0454

Rahut, D. B., J. P. Aryal, N. Manchanda, and T. Sonobe. 2022. Expectations for Household Food Security in the Coming Decades: A Global Scenario. In R. Bhat, ed. *Future Foods: Global Trends, Opportunities, and Sustainability Challenges.* Academic Press, 107–131.

S&P Global. 2021. COP26: Five Developed Nations to Commit to Support Low Carbon Steel, Cement Sectors. 9 November.

Sahoo, B., D. K. Behera, and D. Rahut. 2022. Decarbonization: Examining the Role of Environmental Innovation Versus Renewable Energy Use. *Environmental Science and Pollution Research*: 29(32): 1–16.

Selden, T. M., and D. Song. 1994. Environmental Quality and Development: Is There a Kuznets Curve for Air Pollution Emissions? *Journal of Environmental Economics and management* 27: 147–162.

Smith, P. et al. 2014: Agriculture, Forestry and Other Land Use (AFOLU). In O. Edenhofer, et al. eds. *Climate Change 2014: Mitigation of Climate Change. Contribution of Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK and New York, NY, US: Cambridge University Press, pp. 811–922.

Stern, N. 2008. The Economics of Climate Change. *American Economic Review* 98: 1–37.

Tollefson, J. 2018. IPCC says Limiting Global Warming to 1.5 [degrees] C Will Require Drastic Action. *Nature* 562: 172–174.

Ulucak, R. et al. 2020. Mitigation Pathways Toward Sustainable Development: Is There Any Trade-off between Environmental Regulation and Carbon Emissions Reduction? *Sustainable Development* 28: 813–822.

United Nations (UN). 2022. Why the UN General Assembly Must Back the Right to a Healthy Environment, UN News, 22 July. https://news.un.org/en/story/2022/07/1123142

Watson, R.T. 2005. Environmental Health Implications of Global Climate Change. *Journal of Environmental Monitoring* 7: 834–843.

World Meteorological Organization (WMO). 2021. The State of Greenhouse Gases in the Atmosphere Based on Global Observations through 2020. Geneva, Switzerland: WMO.

Zhu, H. et al. 2016. The Effects of FDI, Economic Growth and Energy Consumption on Carbon Emissions in ASEAN-5: Evidence from Panel Quantile Regression. *Economic Modelling* 58: 237–248.

PART I

Energy Sector: Transition toward High Renewable Energy Penetration

1

Financing the Energy Transition in a Low-Cost Intermittent Renewable Energy Environment[1]

Frank A. Wolak

1.1 Introduction

Until recently, transitioning from a fossil fuel-dominated electricity supply industry to an intermittent-renewables-dominated low-carbon electricity supply industry has required significant above-market financial support for investments in wind and solar generation resources because the levelized cost of energy (LCOE) from these resources was greater than the average market price at which the electricity they produced could be sold. Declines in the cost of both wind and solar generation capacity over the past decade has significantly closed the gap between the LCOE for these resources and the LCOE of natural gas and coal-fired generation.

Figure 1.1 plots the annual global quantity-weighted average LCOE for grid scale wind and solar photovoltaic generation units that began operation during each year from 2010 to 2020 (IRENA 2021). Figure 1.1 also plots the annual quantity-weighted average LCOE for residential and commercial solar photovoltaic generation units that began operation during the year (IRENA 2021). This graph demonstrates that in 2020, the LCOE of grid scale wind and solar was one-third to one-quarter of the LCOE of distributed solar energy.

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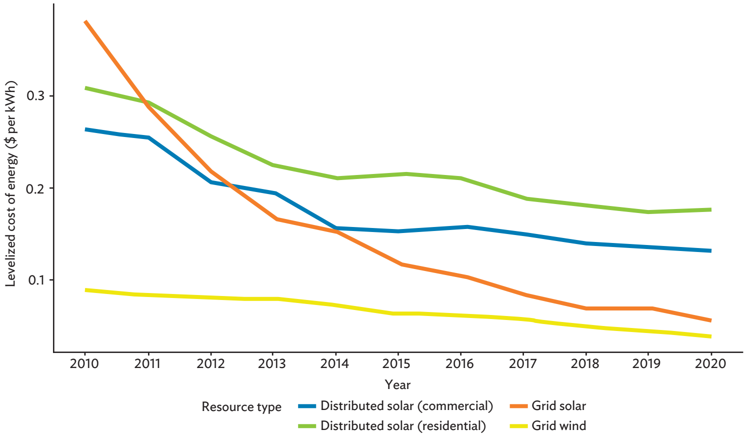
[1] This chapter is an updated version of chapter 4 that originally appeared in Glachant, Joskow, and M. G. Pollitt, eds. (2021).

Figure 1.1: Levelized Cost of Energy from Grid Scale Wind and Solar and Distributed Solar Generation, 2010–2020



kWh = kilowatt-hour.

Source: IRENA (2021).

The United States Energy Information Administration (EIA) estimates that the LCOE for a new combined cycle natural gas generation unit entering service in 2023 is $33.21 per megawatt-hour (MWh) versus $30.44/MWh and $30.63/MWh for grid scale wind and solar resources (EIA 2021, Table A1a). These LCOE differences signal a new regime for investments in wind and solar resources. However, because of the intermittency of wind and solar resources, there is still the need for a significant amount of dispatchable generation capacity to supply energy when the wind is not blowing, or the sun is not shining. This low-cost intermittent renewable energy regime and the desire of policy makers to significantly increase the share of their jurisdiction's energy consumption produced by intermittent renewables argues for a paradigm shift in electricity market design.

The purpose of this chapter is to explain why this paradigm shift is necessary and outline a short-term electricity market design, long-term resource adequacy mechanism, and renewables support mechanism for this low-cost intermittent renewable energy regime. A multi-settlement locational marginal pricing (LMP) market design with the co-optimized procurement of ancillary services rewards quick response dispatchable resources and appropriately prices the intermittency of wind and solar resources. This market design easily accommodates the additional reliability constraints on system operation required by a larger share of intermittent renewables into the energy and ancillary services markets. Finally, this short-term market design prices electricity across both space and time to provide financial incentives to locate storage and load flexibility investments where they can provide the greatest benefits to system reliability. Energy efficiency investments that reduce electricity consumption at high-priced locations in the transmission network provide greater wholesale energy cost savings and grid reliability benefits than the same investment at low-priced locations.

A fixed-price forward contract for energy approach to long-term resource adequacy is the most important change necessary to support large renewable energy shares under a low-cost intermittent renewable energy regime. A significant amount of dispatchable generation capacity will still be required to produce energy when the underlying renewable resources are unavailable. However, these generation resources will start up and shut down more frequently and operate at increasingly smaller annual capacity factors as the share of intermittent renewables increases. Consequently, the long-term resource adequacy mechanism must encourage cross-hedging between intermittent renewables and dispatchable generation units. The intermittent renewable resource owners must have an economic incentive to purchase price spike insurance from dispatchable thermal resources for the times when these renewables are unlikely to produce energy. As explained in section 1.5, these price spike insurance payments provide a revenue stream to dispatchable resources that contributes to their financial viability even though they have significantly lower annual capacity factors in a region with a large share of intermittent renewable generation.

The ultimate success of this approach to long-term resource adequacy requires phasing out a common approach to financing investments in intermittent renewables—paid-as-delivered power purchase agreements. These long-term contracts pay the intermittent renewable generation unit owner according to a fixed price schedule for all energy produced by the generation unit, regardless of when this energy is produced. These contracts provide an implicit subsidy to intermittent renewable resources because similar contract terms are not offered to dispatchable generation units. Moreover, paid-as-delivered contracts dull the financial incentive for intermittent renewable resource owners to pair their investments with storage capacity to manage the uncertainty in energy production from their units. As explained in section 1.4, requiring all resources to sell standardized fixed-price and fixed-quantity forward contracts provides strong incentives for market mechanisms to find the least-cost solution to meeting a given renewable energy target.

To provide the least-cost amount of above-market revenues to intermittent renewables resources to meet a given renewable energy share goal, a renewables portfolio standard mechanism is necessary. This mechanism prices the renewable attribute separate from the energy the intermittent renewable resource produces. This renewables support mechanism and a multi-settlement LMP market design with 5-minute settlement in the real-time market provide strong incentives for investments in the storage facilities necessary to achieve renewable energy shares in excess of 50%.

The remainder of the chapter proceeds as follows. Section 1.2 discusses the essential features of the short-term market design to support the least-cost deployment of large share intermittent renewables. Section 1.3 discusses the necessity of a long-term resource adequacy mechanism for all wholesale electricity markets with a finite offer cap on the short-term market and why the traditional capacity-based approach to long-term resource adequacy is poorly suited to regions with significant intermittent renewable energy goals. Section 1.4 introduces our proposed standardized fixed-price forward contract approach to long-term resource adequacy and explains why it is a more efficient solution to the long-term resource adequacy challenge for an intermittent renewable energy dominated electricity supply industry. Section 1.5 explains why a renewable energy certificate market is necessary to achieve renewable energy shares above 50%. This section also explains why paid-as-delivered forward contracts for intermittent renewable energy do not support achieving a large share of renewable energy at least cost to electricity consumers. This section proposes financial products that allow intermittent renewable resource owners to transition from paid-as-delivered forward contracts to fixed-price and fixed-quantity forward contracts. Section 1.6 concludes and proposes directions for future research.

1.2 Short-Term Market Design

An important lesson from electricity market design processes around the world is the extent to which the market mechanism used to dispatch and operate generation units is consistent with how the grid operates in real time. In the early stages of wholesale market designs in the United States (US), all the regions attempted to operate wholesale markets that used simplified transmission network models. These single zone or multiple zone markets assume infinite transmission capacity between locations in the transmission grid or only recognize transmission constraints across large geographic regions. These simplifications of the transmission network configuration and other relevant operating constraints create opportunities for market participants to increase their profits by taking advantage of the fact that in real time the actual configuration of the transmission network and other operating constraints must be respected.

Zonal markets set a single market-clearing price for a half hour or an hour for an entire country or large geographic region, even though there are generation units with offer prices below the market-clearing price not producing electricity and units with offer prices above the market-clearing price producing electricity. This outcome occurs because of the location of demand and available generation units within the region, and the configuration of the transmission network prevents some of these low-offer-price units from producing electricity and requires some of the high-offer-price units to supply electricity. The former units are typically called "constrained-off" units, and the latter are called "constrained-on" or "must-run" units.

A market design challenge arises because how generation units are compensated for being constrained-on or constrained-off impacts the offer prices they submit into the wholesale energy market. For example, if a generation unit is paid its offer price for electricity when it is constrained-on and the owner knows the unit will be constrained-on, a profit-maximizing owner will submit an offer price significantly higher than the average variable cost of the unit and be paid that price for the incremental energy, which ultimately raises the total cost of electricity supplied to final consumers.

A similar set of circumstances arises for a constrained-off generation unit. These units are typically paid the difference between the market-clearing price and the unit's offer price for not supplying electricity that the unit would have produced if not for the configuration of the transmission network. This market rule creates an incentive for a profit-maximizing supplier that knows its unit will be constrained-off to submit the lowest possible offer price in order to receive the highest possible payment for being constrained-off, which raises the total cost of electricity supplied to final consumers.

This problem occurred so frequently in the early US zonal markets that it acquired the name "the DEC game," because it involves a supplier selling energy in the day-ahead market that it knows is highly likely to be infeasible to inject into the transmission grid in real time. The supplier then agrees to buy decremental (DEC) energy at a price below the day-ahead market price and earns the difference between these two prices times the amount of decremental energy purchased for producing little or no energy in real time. Wolak, Bushnell, and Hobbs

(2008) discuss this problem and its market efficiency consequences in the context of the initial zonal market in California. Graf, Quaglia, and Wolak (2020) document the incentives for generation unit owner offer behavior created by the divergence between the day-ahead zonal market model and full network model used to operate the Italian market in real time. The DEC game is not unique to markets in industrialized countries. Wolak (2009) discusses these same issues in the context of the Colombian single-price market with its negative and positive reconciliation payment mechanism.

1.2.1 Locational Marginal Pricing (LMP)

As described in the previous subsection, almost any difference between the market model used to set dispatch levels and market prices and the actual operation of the generation units needed to serve demand creates an opportunity for market participants to take actions that raise their profits at the expense of overall market efficiency. Wholesale electricity markets that use LMP, also referred to as nodal pricing, largely avoid these constrained-on and constrained-off problems, because all transmission constraints and other relevant operating constraints are respected in the process of determining dispatch levels and locational marginal prices. Consequently, different from single-zone or zonal market designs, LMP markets can allow multiple settlements without creating opportunities for suppliers to degrade the efficiency of the short-term market by taking advantage of the constrained-on and constrained-off process discussed in the previous section.

All LMP markets in the US co-optimize the procurement of energy and operating reserves. This means that all suppliers submit to the wholesale market operator their generation unit-specific willingness-to-supply schedules for energy and any operating reserve the generation unit can provide. Likewise, large loads and load-serving entities submit their willingness-to-purchase-energy schedules. Locational prices for energy and ancillary services and dispatch levels and ancillary services commitments for generation units at each location in the transmission network are determined by minimizing the as-offered costs of meeting the demand for energy and operating reserves at all locations in the transmission network, subject to all transmission network and other relevant generation unit operating constraints. No generation unit will be accepted to supply energy or an operating reserve if doing so would violate a transmission or other operating constraint.

An important distinction between an LMP market design and virtually all zonal markets is the centralized commitment of generation units to provide energy and ancillary services. The zonal markets throughout Europe do not typically require generation units to submit energy offer curves into the day-ahead market and instead allow individual producers to make commitment decisions for their generation units using simplified single-zone or multiple-zone models of the transmission network. A self-commitment market can result in higher cost generation units operating because of differences between producers in their assessment of the likely market price.

Self-commitment energy markets also do not allow the simultaneous procurement of energy and operating reserves and instead rely on sequential procurement of operating reserves before or after day-ahead energy schedules have been determined. As Oren (2001) demonstrates, sequential clearing of energy and operating reserves markets increases the opportunities for generation unit owners to exercise unilateral market power in the energy or operating reserves markets. Suppliers know that capacity sold in an earlier market cannot compete with suppliers in subsequent markets, which limits competition in the markets that clear later in the sequence.

A centralized LMP market that co-optimizes the procurement of energy and operating reserves ensures that each generation unit is used in the most cost-effective manner based on the energy and operating reserves offers of all generation units, not just those owned by a single market participant. Specifically, the opportunity cost of supplying any operating reserve a unit can provide will be explicitly considered in deciding whether to use the unit for that ancillary service. For example, if the price of energy at a generation unit's location is $40/MWh, the unit's offer price for energy is $30/MWh, the unit's offer price for the only operating reserve the unit can supply is $0/MWh, and the market-clearing price of that reserve is $5/MWh, then the unit will be accepted to supply energy rather than that operating reserve. This outcome occurs because the opportunity cost of supplying energy, $10/MWh = $40/MWh − $30/MWh, is less than the price paid for that operating reserve. At this price of energy, the unit will be accepted to supply the operating reserve only if its price is greater than or equal to the $10/MWh opportunity cost of energy for that unit.

In contrast, self-commitment markets or sequential operating reserves markets such as those that exist in Europe and other industrialized countries must rely on individual market participants to make the least-cost choice between supplying energy or an ancillary service from each generation unit in the market. This is possible for a supplier to do within its portfolio of generation units, but it is unlikely to be the case across all suppliers in the market. Consequently, there are likely to be many instances when a resource is taken to supply an operating reserve at a dollar per megawatt-hour price that turns out to be less than the unit's opportunity of providing energy. There are also likely to be instances when a resource is providing energy at price that has smaller opportunity cost of energy than the prevailing price of an operating reserve the unit can provide with that same generation capacity.

The nodal price at each location is the increase in the minimized value of the "as-offered costs" objective function because of a one unit increase in the amount of energy withdrawn at that location in the transmission network. In a co-optimized energy and operating reserves locational marginal pricing market, the price of each operating reserve is defined as the increase in the optimized value of the as-offered costs objective function due to a one-unit increase in the demand for that operating reserve. In most LMP markets, operating reserves are procured at a coarser level of spatial granularity than energy. For example, energy is typically priced at the nodal level and operating reserves are priced over larger geographic regions. Bohn, Caramanis, and Schweppe (1984) provide an accessible discussion of the properties of the LMP market mechanism.

Another strength of the LMP market design is the fact that other constraints that the system operator considers in operating the transmission network can also be accounted for in setting dispatch levels and locational prices. For example, suppose that reliability studies have shown that a minimum amount of energy must be produced by a group of generation units located in a small region of the grid. This operating constraint can be built into the market-clearing mechanism and reflected in the resulting locational marginal prices. This property of LMP markets is particularly relevant to the cost-effective integration of a significant amount of intermittent renewable generation capacity because additional reliability constraints may need to be formulated and incorporated into an LMP market mechanism to account for the fact that this energy can quickly disappear and reappear.

An important lesson from the US experience with LMP markets is that explicitly accounting for the configuration of the transmission network in determining dispatch levels both within and across regions can significantly increase the amount of trade that takes place between the regions. Mansur and White (2012) dramatically demonstrate this point by comparing the volume of trade between two regions of the eastern US, what the authors call the Midwest and the East of PJM (the original PJM Interconnection footprint), before and after these regions were integrated into a single LMP market that accounts for the configuration of the transmission network throughout the entire expanded PJM region. Average daily energy flows from the Midwest to the East of PJM almost tripled immediately following the integration of the two regions into a single LMP market. There was no change in the physical configuration of the transmission network for the two regions. This increase in energy flows was purely the result of incorporating the two regions into a single LMP market that recognizes the configuration of the transmission network for the two regions in dispatching generation units.

1.2.2 Multi-Settlement Markets

Multi-settlement nodal-pricing markets have been adopted by all US jurisdictions with a formal short-term wholesale electricity market. A multi-settlement market has a day-ahead forward market that is run in advance of real-time system operation. Generation unit owners submit generation unit-specific offer curves for each hour of the following day for energy and operating reserves, as well as the technical characteristics of their generation units, such as ramp rates, minimum and maximum safe operating levels, and other operating characteristics required by the system operator. Large consumers and electricity retailers submit demand curves for energy for each hour of the following day. The system operator sets the demands for each operating reserve and then minimizes the as-offered cost to meet the demand for energy and each operating reserve simultaneously for all 24 hours of the following day subject to the anticipated configuration of the transmission network and other relevant operating constraints. This gives rise to LMPs and firm financial commitments to buy and sell energy and each operating reserve each hour of the following day for all generation unit and load locations.

The day-ahead market typically allows generation unit owners to submit their start-up and minimum load cost offers as well as energy offer curves, and both of these costs enter the objective function used to compute hourly generation schedules and LMPs for all 24 hours of the following day. This logic implies that a generation unit will not be dispatched in the day-ahead market unless the combination of its start-up and no-load costs and energy costs are part of the least-cost solution to serving hourly demands for all 24 hours of the following day.

To the extent that generation unit owners do not receive sufficient revenues from energy and operating reserves sales to recover their as-offered start-up, minimum load and energy operating costs to provide these products throughout the day, they are provided with a make-whole payment to recover the remaining costs. For example, if a generation unit owner with a start-up cost of \$5,000 and a variable cost of energy offer of \$40/MWh sells 100 MWh at a price of \$82/MWh, the unit's make-whole payment would be \$5,000 – \$4,200 = \$800. Total make-whole payments are recovered from all loads through a dollar per megawatt-hour charge. For example, if system demand was 4,000 MWh and this was the only make-whole payment made, then the per unit charge to demand would be $0.20/MWh.

The energy schedules that arise from the day-ahead market do not require a generation unit to supply the amount sold or a load to consume the amount purchased in the day-ahead market. The only requirement is that any shortfall in a day-ahead commitment to supply energy must be purchased from the real-time market at that same location or any production greater than the day-ahead commitment is sold at the real-time price at that same location. For loads, the same logic applies. Additional consumption beyond the load's day-ahead purchase is paid for at the real-time price at that location, and the surplus of a day-ahead purchase relative to actual consumption is sold at the real-time price at that location. Both buyers and sellers of energy in the day-ahead market bear the full financial consequences of failing to meet their day-ahead sales and purchase obligations.

In all US wholesale markets, real-time LMPs are determined from the real-time offer curves of all available generation units and dispatchable loads by minimizing the as-offered cost to meet real-time demands (rather than bid-in demands) at all locations considering the current configuration of the transmission network and other relevant operating constraints. This process gives rise to LMPs at all locations in the transmission network and the actual hourly operating levels for all generation units. Real-time imbalances relative to day-ahead schedules are cleared at these real-time prices. Wolak (2021b) discusses mechanics of a two-settlement (day-ahead and real-time) market and why it provides strong incentives for generation unit owners and loads to schedule accurately in the day-ahead market and limit the magnitude of their real-time deviations from these day-ahead schedules.

Wolak (2011) quantifies the magnitude of the economic benefits associated with the transition to a two-settlement nodal pricing market from a two-settlement zonal-pricing market that is very similar to the standard market design currently in Europe and other industrialized countries. Wolak (2011) finds that for the same amount of hourly system-wide thermal generation, the total hourly British thermal units of fossil fuel energy consumed to produce that electricity is 2.5% lower, the total hourly variable cost of production for fossil fuels units is 2.1% lower, and the total number of hourly starts is 0.17% higher after the implementation of nodal pricing. This 2.1% cost reduction implies a roughly $105 million reduction in the total annual variable cost of producing electricity from fossil fuels in California associated with the introduction of nodal pricing. Triolo and Wolak (2022) study the transition from a European-style zonal market design with self-scheduling and self-commitment to a multi-settlement nodal market design in the Electricity Reliability Council of Texas (ERCOT) on 1 December 2010. They find a 3.9% reduction in the total variable cost of fossil fuel generation for the first year of operation of this market, yielding annual cost savings of $323 million.

1.2.3 Multi-Settlement LMP Market with Significant Intermittent Renewables

A multi-settlement LMP market design is well suited to managing a generation mix with a significant share of intermittent renewable resources. The additional operating constraints necessary for reliable system operation with an increased number of renewable resources can easily be incorporated into the day-ahead and real-time market models. Therefore, the economic benefits from implementing a multi-settlement LMP market relative to zonal market designs that do not model transmission and other operating constraints are likely to be greater the larger the share of intermittent renewable resources. Bjørndal et al. (2018) shows that in a region with significant wind resources even embedding a nodal market design within a larger zonal market design outperforms a full zonal market design. The authors also demonstrate that a nodal design for the entire region yields even greater savings relative to a zonal design. Consequently, any region with significant renewable energy goals is likely to realize significant economic benefits from implementing a multi-settlement LMP market.

This short-term market design values the dispatchability and flexibility of generation units even though it pays all resources at the same location in the grid the same price in the day-ahead and real-time markets. Wolak (2021b) provides several examples that demonstrate that despite paying the same price for all energy at the same location in the day-ahead and real-time markets, a multi-settlement market pays a higher average price for the energy ultimately produced in real time to the dispatchable generation unit relative to the intermittent wind or solar generation unit. This is because intermittent resources typically sell more than their day-ahead schedule when real-time prices are lower than average and sell less than their day-ahead schedule when real-time prices are higher than average. In contrast, dispatchable resources can produce more than their day-ahead schedules when real-time prices are higher than average and produce less than their day-ahead schedules when real-time prices are lower than average.

An additional way to reward flexibility in a multi-settlement LMP market is to clear the real-time market as frequently as possible within the hour. For example, all US wholesale markets set real-time prices and dispatch levels every 5 minutes. This means that real-time prices can increase rapidly across 5-minute intervals when net system demand—the difference between system demand and intermittent renewable generation—rapidly increases. This rewards generation units that can quickly increase their output with substantially higher prices for the output they supply within that 5-minute interval. Units that can rapidly reduce their output in response to a decrease in net demand during a 5-minute interval can sell back energy scheduled in the day-ahead market at substantially lower prices.

Shorter settlement intervals can also reduce the demand for frequency response operating reserves, because more fast-response units are moving up and down according to 5-minute dispatch instructions within the hour, so that less secondary frequency up and less secondary frequency down are needed to maintain system balance within the hour. More frequent settlement of the real-time market rewards dispatchable resources for the quick response and flexibility that they provide, particularly if the share of intermittent renewable generation increases significantly.

1.2.4 A Cost-Based Multi-Settlement LMP Market

The transition to formal market mechanisms in a number of Asian countries has been slow. These regions frequently face significant challenges because of limited transmission capacity between and within their member countries. Consequently, any attempt to operate an offer-based market for most of these countries is likely to run into severe local and system-wide market power problems. In addition, the almost complete absence of hourly meters in these regions limits the opportunities for active demand-side participation, which makes implementing an offer-based wholesale market even more challenging.

Building on the experience of the Latin American countries discussed in Wolak (2014), a viable market design for these regions is a cost-based short-term market that uses LMP. This market design is straightforward to implement because it simply involves solving for the optimal dispatch of generation units in the region based on the market operator's estimate of each unit's variable cost, including start-up and minimum load costs, subject to the operating constraints implied by the actual regional transmission network and other reliability constraints.[2]

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[2] Galetovic, Muñoz, and Wolak (2015) describe the Chilean cost-based market, which has been in operation since the 1980s.

All generation unit owners submit the technical characteristics of their generation units to the market operator, including the heat rate curve, the amount of fuel required to start up the unit and operate at the unit's minimum safe operating level, the unit's ramp rate, and minimum uptime and downtime. The system operator would then determine the start-up cost and variable cost of operating for each generation unit using a publicly available price index for the unit's fossil fuel. For example, for a coal-fired generation unit, the market operator could use a globally traded price for coal and a benchmark delivery cost to the generation unit to determine the fuel cost of the unit. This would be multiplied by the unit's heat rate to compute its variable fuel cost. An estimate of the variable operating and maintenance cost for the unit could be added to this variable fuel cost to arrive at the total variable cost of the unit.

The variable cost computed by the market operator along with the configuration of the transmission network would be used to set day-ahead schedules and prices for each location in a multi-settlement version of this market design. In real time, the dispatch and LMP process would be completed using the actual system demand and actual configuration of the transmission network with these same generation unit-level variable cost figures.

It is important to emphasize that this short-term market is only for settling imbalances relative to long-term contracts for energy. Joskow (1997) argues that the majority of the economic benefits from electricity industry restructuring are likely to come from more efficient investment decisions in new generation capacity. The combination of a cost-based multi-settlement LMP market and fixed-price forward contract mandates on electricity retailers as discussed in section 1.4 is a low-cost and low-regulatory burden approach to realizing significant increases in new generation capacity. This market design can be implemented in any Asian country with limited regulatory burden and provide strong incentives for least-cost operation of existing generation resources and least-cost investment in new generation resources to serve load growth and unit retirements.

This market design also has the advantage that it can easily transition to an offer-based market once the transmission network in the region is expanded, hourly meters are deployed, and the regulator is able to design an effective local market power mitigation mechanism. Graf et. al (2021) summarize the structure and performance of the local market power mitigation mechanisms in place in US markets. If a cost-based LMP market is in already place, the generation unit owners' costs as computed by the market operator can easily be replaced by the offer prices of these producers. Starting from a cost-based market and transitioning to an offer-based market is a low-risk approach to introducing an offer-based market. PJM Interconnection in the eastern

US followed this strategy during the early stages of its development. It operated as a cost-based market before transitioning to an offer-based market.

1.3 The Reliability Externality and Long-Term Resource Adequacy

Why do wholesale electricity markets require a regulatory mandate to ensure long-term resource adequacy? Electricity is essential to modern life, but so are many other goods and services. Consumers want cars, but there is no regulatory mandate that ensures enough automobile assembly plants to produce these cars. They want point-to-point air travel, but there is no regulatory mandate to ensure enough airplanes to accomplish this. Many goods are produced using high fixed cost, lowmarginal cost technologies similar to electricity supply. Nevertheless, these firms recover their production costs, including a return on the capital invested, by selling their output at a market-determined price.

What is different about electricity that requires a long-term resource adequacy mechanism? The regulatory history of the electricity supply industry and the legacy technology for metering electricity consumption results in what Wolak (2013) calls a *reliability externality.*

1.3.1 The Reliability Externality

Different from the case of wholesale electricity, the markets for automobiles and air travel do not have a regulatory limit on the level of the short-term price. Airlines adjust the prices for seats on a flight over time in an attempt to ensure that the number of customers traveling on that flight equals the number of seats flying. This ability to use price to allocate the available seats is also what allows the airline to recover its total production costs and can result in as many different prices paid for the same flight as there are customers on the flight.

Using the short-term price to manage the real-time supply and demand balance in a wholesale electricity market is limited by a finite upper bound on a supplier's offer price and/or a price cap set by the regulator that limits the maximum market-clearing price. Although offer caps and price caps can limit the ability of suppliers to exercise unilateral market power in the short-term energy market, they also reduce the revenues suppliers can receive during scarcity conditions. This is often referred to as the *missing money* problem for generation unit owners. However, this missing money problem is only a symptom of and not the cause of the *reliability externality*.

This externality exists because offer caps limit the cost to electricity retailers of failing to hedge their expected purchases from the short-term market. Specifically, if a retailer or large consumer knows the price cap on the short-term market is $250/MWh, then it is unlikely to be willing to pay more than that for electricity in any earlier forward market. This creates the possibility that real-time system conditions can occur where the amount of electricity demanded at the offer cap is more than the amount suppliers are willing to offer at this offer cap.

This outcome implies that the system operator must be forced to either abandon the market mechanism or curtail firm load until the available supply offered at or below the offer cap equals this level of demand, as occurred several times in California between January 2001 and April 2001, and most recently on 14 and 15 August 2020. A similar, but far more extreme set of circumstances arose from 14 to 18 February 2021 in Texas, and this required significant demand curtailments from 15 to 18 February.[3]

Because random curtailments of supply to different distribution grids served by the transmission network—also known as rolling blackouts—are used to make demand equal to the available supply at under these system conditions, this mechanism creates a *reliability externality* because no retailer bears the full cost of failing to procure adequate energy to meet their demand in advance of delivery. A retailer that has purchased sufficient supply in the forward market to meet its real-time demand is equally likely to be randomly curtailed as any other retailer of the same size that has not procured adequate energy in the forward market. The technology to curtail specific customers when there is a system-wide shortfall of energy does not currently exist in any electricity delivery network.

For this reason, all retailers have an incentive to under procure their expected energy needs in the forward market. However, when short-term prices rise, retailers that have not hedged the wholesale energy necessary to serve the demand of their fixed-price retail customers are likely to go bankrupt. If these retailers attempt to pass these short-term wholesale prices on to their retail customers, many will be likely to be unable to pay their electricity bills. As discussed in section 4.4.2 of Wolak (2022), both outcomes occurred in Texas following the events of 14 to 18 February 2021.

The lower the offer cap, the greater is the likelihood that a retailer will delay its electricity purchases to the short-term market. Delaying more purchases to the short-term market increases the likelihood of

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[3] https://www.ercot.com/files/docs/2021/02/24/2.2_REVISED_ERCOT_Presentation.pdf

insufficient supply in the short-term market at or below the offer cap. Because retailers do not bear the full cost of failing to procure sufficient energy in the forward market, there is a missing market for long-term contracts for energy with long enough delivery horizons into the future to allow new generation units to be financed and constructed to serve demand under all possible future conditions in the short-term market. Therefore, a regulator-mandated long-term resource adequacy mechanism is necessary to replace this missing market.

Regulatory intervention is necessary to internalize the resulting *reliability externality* unless the regulator is willing to eliminate the offer cap and commit to allowing the short-term price to clear the real-time market under all possible system conditions. There are no short-term wholesale electricity markets in the world that make such a commitment. All of them have either explicit or implicit caps on the offer prices suppliers can submit to the short-term market. ERCOT had a $9,000/MWh offer cap, which was highest in the US in February of 2021. Australia's National Electricity Market currently has a A$15,500 MWh offer cap.

As the experience of 14 to 18 February 2021 in Texas demonstrated, an extremely high offer cap on the short-term market does not eliminate the *reliability externality*. It just shrinks the size of the set of system conditions when random curtailments are required to balance real-time supply and demand.

1.3.2 Conventional Solution to Reliability Externality with Intermittent Renewables

Currently, the most popular approach to addressing the *reliability externality* is a capacity procurement mechanism that assigns a firm capacity value to each generation unit based on the amount of energy it can provide under stressed system conditions. Retailers are then required to demonstrate that they have purchased sufficient firm capacity to meet their monthly or annual demand peaks. Having sufficient firm capacity typically means that the retailer has purchased firm capacity equal to between 1.10 and 1.20 times its annual demand peak. The exact multiple of peak demand chosen by a region depends on the mix of generation resources and the reliability requirements of the system operator.

Under the current long-term resource adequacy mechanism in California, firm-level capacity procurement obligations are assigned to retailers by the California Public Utilities Commission to ensure that monthly and annual system demand peaks can be met. Electricity retailers are free to negotiate bilateral capacity contracts with individual generation unit owners to purchase firm capacity to meet these obligations. The eastern US wholesale electricity markets in the PJM Interconnection, independent system operator (ISO) of New England, New York ISO, and Midcontinental ISO markets all have a centralized market for firm capacity. These involve periodic capacity auctions run by the wholesale market operator where all retailers purchase their capacity requirements at a market-clearing price. ERCOT does not currently have formal long-term resource adequacy mechanism besides its $9,000/MWh offer cap and an ancillary services scarcity pricing mechanism.

All capacity-based approaches to long-term resource adequacy rely on the credibility of the firm capacity measure assigned to each generation unit. This is a relatively straightforward process for dispatchable thermal units. The nameplate capacity of the generation unit times its annual availability factor (the fraction of hours of the year a unit is expected to be available to produce electricity) is the typical starting point for estimating the amount of energy the unit can provide under stressed system conditions. As discussed below, if all retailers have met their firm capacity requirements in a sizable market with only dispatchable thermal generation, there is a very high probability that the demand for energy will met during peak demand periods.

A simple example helps to illustrate the logic behind this claim. Suppose that the peak demand for the market is 1,000 MW, the market is composed of equal size generation units, and each unit has a 90% annual availability factor, meaning that it is available to produce electricity any hour of the year with 0.90 probability. Suppose that the event that one generation unit fails to operate is independent of the event that any other generation unit fails to operate. This independence assumption is reasonable for dispatchable thermal generation units because unavailability is typically due to an event specific to that generation unit. If each generation unit has a nameplate capacity of 100 MW, each has a firm capacity of 90 MW (= 0.90 x 100 MW). If there are 13 generation units, then with 0.96 probability peak demand will be met.[4] Thus, a firm capacity requirement of 1.17 times the demand peak would ensure that system demand is met with 0.96 probability. Assuming that each generation unit is one-tenth of the system demand peak is unrealistic for most electricity supply industries, but it does illustrate the important point that smaller markets require

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[4] The number of generation units available is a binomial random variable with probability p = 0.9 and with number of trials N = the number of generation units. The probability of meeting the demand peak is the probability the available capacity is greater than or equal to the peak demand.

firm capacity equal to a larger multiple of peak demand to achieve the desired level of reliability of supply.

Suppose that each generation unit is now 50 MW and each still has the same availability factor, so the firm capacity of each unit is now 45 MW. In this case, the same firm capacity requirement of 1.17 times the demand peak, or 26 generation units, would ensure system demand is met with 0.988 probability. If each generation unit had a nameplate capacity of 20 MW with the same availability factor, each unit would have a firm capacity of 18 MW. This 1.17 times peak demand firm capacity requirement, or 65 generation units, would ensure that system demand is met with 0.999 probability. This example illustrates that an electricity supply industry based on dispatchable thermal generation units, where each unit has an independent 10% probability of being unavailable, the system demand peak will be met with a very high probability with a firm capacity requirement of 1.17 times peak demand if all the generation units are small relative to the system demand peak.

Introducing renewables into a capacity-based long-term resource adequacy mechanism considerably complicates the problem of computing the probability of meeting peak system demand for two major reasons. First, the ability to produce electricity depends on the availability of the underlying renewable resource. A hydroelectric resource requires water behind the turbine, a wind resource requires wind to spin the turbine, and a solar facility requires sunlight to hit the solar panels. Second, and perhaps most importantly, the availability of water, wind, or sunshine to renewable generation resources is highly positively correlated across locations for a given technology within a given geographic region. This fact invalidates the assumption of independence of energy availability across locations that allows a firm capacity mechanism to ensure system demand peaks can be met with a very high probability. For example, if the correlation across locations in the availability of generation units is sufficiently high, then a 0.9 availability factor at one location would imply only a slightly higher than a 0.9 availability factor for meeting system demand, almost regardless of the amount intermittent renewable capacity that is installed.

Hydroelectric facilities have been integrated into firm capacity regimes by using percentiles of the distribution of past hydrological conditions for that generation unit to determine its firm capacity value. However, this approach only partially addresses the problem of accounting for the high degree of contemporaneous correlation across locations in water availability in hydroelectric-dominated systems. There is typically a significant amount of data available on the marginal distribution of water availability at individual hydroelectric generation units. However, the joint distribution of water availability across all hydro locations is likely to be more difficult to obtain. The weather-dependent intermittency in energy availability for hydroelectric resources is typically on an annual frequency. There are low-water years and high-water years depending on global weather patterns such as the El Niño and La Niña weather events as discussed in McRae and Wolak (2016).

Incorporating wind or solar generation units into a firm capacity mechanism is even more challenging, and increasingly so as the share of energy produced in a region from these resources increases. The intermittency in energy supply is much more frequent than it is for hydroelectric energy. There can be substantial differences across and within days in the output of wind and solar generation units. Moreover, if stressed system conditions occur when it is dark, the firm capacity of a solar resource is zero. Similarly, if stressed system conditions occur when the wind is not blowing, a likely outcome on extremely hot days, the firm capacity of a wind resource is zero.

The contemporaneous correlation across locations in the output of solar or wind generation resources for a given geographic area is typically extremely high. There is even a high degree of correlation across locations in the output of wind and solar resources. Wolak (2016) demonstrates the extremely high degree of contemporaneous correlation between the energy produced each hour of the year by solar and wind facilities in California. Again, information on marginal distribution of wind or solar energy availability at a location is much more readily available than the joint distribution of wind and solar energy availability for all wind and solar locations in a region. For these reasons, calculating a defensible estimate of the firm capacity of a wind or solar resource that is equivalent to the firm capacity of a dispatchable thermal generation resource is extremely difficult, if not impossible.

The high degree of contemporaneous correlation across locations in hourly capacity factors requires a methodology for computing firm capacity that accounts for the joint distribution of hourly capacity factors across locations throughout the year. Not only does this methodology need to account for the contemporaneous correlation in capacity factors across locations, but also the high degree of correlation of capacity factors over time for the same location and other locations. California currently uses an effective load carrying capacity (ELCC) methodology for computing the firm capacity values of wind and solar generation units. The ELCC methodology was introduced by Garver (1966), and it measures the additional load that the system can supply from a specified increase in the megawatts of that generation technology with no net change in reliability. The loss of load probability, which is the probability that system demand will exceed the available supply, is the measure of reliability used in the ELCC calculation. Consistent with the results of Wolak (2016), the ELCC values for solar generation resources in California have declined significantly as the amount of solar generation capacity in the state has increased.

For example, a recent study prepared for California's three investor-owned utilities (Carden, Dombrowsky, and Winkler 2020), Southern California Edison, Pacific Gas and Electric, and San Diego Gas and Electric, recommended ELCC values for 1 MW of fixed-mount solar photovoltaic capacity for 2022 of approximately 5% of the nameplate capacity. Their estimates for 2026 are less than half that amount, and those for 2030 are less than one-fourth that amount. These declines in the ELCC values are due to the forecast increase in the amount of solar generation capacity in California.

An additional problem with computing the firm capacity of solar or wind generation resource using the ELCC methodology is that the same megawatt investment in wind or solar capacity is likely to be able to serve different increments to system demand depending on the location of the investment, the location of the increment to demand, and the size and location of other renewable resources in the region. This leaves the system operator with two difficult choices for setting the value of firm capacity for solar and wind resources. The first would be to set different values of firm capacity for resources based on their location in the transmission network. This would likely be a very politically contentious process because of the many assumptions that go into computing the ELCC of a resource. The second approach would set the same firm capacity value for all resources employing the same generation technology. This means that two resources with very different ELCC values could sell the same product to the potential detriment of overall system reliability.

Wolak (2022) evaluates the performance of California's capacity-based long-term resource adequacy mechanism based on the experience of 14 to 18 August 2020. Except for May for wind and July for solar, the monthly values of firm capacity computed using the ELCC methodology are slightly below the average capacity factors for the month. However, it is important to bear in mind that the firm capacity of a generation unit is supposed to measure what the facility can reliably produce under extreme system conditions, not what it produces on average. Consequently, a monthly average capacity factor less than the firm capacity value assigned to wind or solar generation resources provides further evidence against the viability of a capacity-based long-term resource adequacy mechanism with a large share of intermittent renewables. This outcome implies there are many hours in the month when the intermittent wind or solar resource is producing less than its firm capacity. Given the unpredictable intermittent nature of these resources, there is a non-zero probability this outcome will occur during a time with stressed system conditions, similar to those that occurred in August 2020 in California and February 2021 in Texas.

These facts, and the fact that what are predicted to be the major sources of renewable electricity in the future have been estimated to have a little firm capacity value in a high intermittent renewable energy future, imply that it would be prudent for Asian countries with ambitious renewable energy goals to consider alternatives to a capacity-based long-term resource mechanism if they intend to meet these goals in a least-cost manner.

1.4 Standardized Fixed-Price Forward Contract Approach to Long-Term Resource Adequacy

The primary reliability challenge in regions with significant intermittent renewable energy goals is not adequate generation capacity to serve demand peaks but adequate energy available to serve realized demand during all hours of the year. As the examples of California in August 2020 and Texas in February 2021 demonstrate, supply shortfalls do not necessarily occur during system demand peaks, but during net demand peaks.

Because of the substantial contemporaneous correlation in hourly output across locations and across renewable energy technologies, ensuring sufficient supply to meet demand throughout the year will require taking full advantage of the mix of available generation resources. Intermittent renewable resources must reinsure the energy they sell in the forward market with dispatchable generation resources and storage devices. The long-term resource adequacy mechanism must also recognize the increasing weather dependence of electricity demand with more customers heating and cooling their homes with electricity.

The Standardized Fixed Price Forward Contract (SFPFC) mechanism introduced in Wolak (2021a) results in the realized system demand each hour of the compliance period being covered by a fixed-price forward contract. The SFPFC approach to long-term resource adequacy recognizes that a supplier with the ability to serve demand at a reasonable price must also have the incentive to do so if it has the ability to exercise unilateral market power in the short-term energy market. As Wolak (2000) demonstrates, an expected profit-maximizing supplier with the ability to exercise unilateral market power that has a fixed-price forward contract obligation would like to minimize the cost of supplying the quantity of energy sold in the forward contract.

The SFPFC long-term resource adequacy mechanism takes advantage of this incentive by requiring retailers to hold hourly fixed-price forward contract obligations for energy that sum to the hourly value of system demand. This mechanism also implies that all expected profit-maximizing suppliers would like to minimize the cost of meeting their hourly fixed-price forward contract obligations, the sum of which equals the hourly system demand for all hours of the year.

To understand the logic behind the SFPFC mechanism, consider the example of a supplier that owns 150 MWh of generation capacity that has sold 100 MWh in a fixed-forward contract at a price of $25/MWh for a certain hour of the day. This supplier has two options for fulfilling this forward contract: (i) produce the 100 MWh energy from its own units at their marginal cost of $20/MWh or (ii) buy this energy from the short-term market at the prevailing market-clearing price. The supplier will receive $2,500 from the buyer of the contract for the 100 MWh sold, regardless of how it is supplied. This means that the supplier maximizes the profits it earns from this fixed-price forward contract sale by minimizing the cost of supplying the 100 MWh of energy.

To ensure that the least-cost “make versus buy” decision for the 100 MWh is made, the supplier should offer 100 MWh in the short-term market at its marginal cost of $20/MWh. This offer price for 100 MWh ensures that if it is cheaper to produce the energy from its generation units—the market price is at or above $20/MWh—the supplier’s offer to produce the energy will be accepted in the short-term market. If it is cheaper to purchase the energy from the short-term market—the market price is below $20/MWh—the supplier’s offer will not be accepted, and the supplier will purchase the 100 MWh from the short-term market at a price below $20/MWh.

This example demonstrates that the SFPFC approach to long-term resource adequacy makes it expected profit-maximizing for each seller to minimize the cost of supplying the quantity of energy sold in this forward contract each hour of the delivery period. By the logic of the above example, each supplier will find it in its unilateral interest to submit an offer price into the short-term market equal to its marginal cost for its hourly SFPFC quantity of energy, in order to make the efficient make-versus-buy decision for fulfilling this obligation.

The incentives for supplier offer behavior in a short-term wholesale electricity market created by a fixed-price forward contract obligation are analyzed in Wolak (2000). McRae and Wolak (2014) provide empirical support for these incentives for the four largest suppliers in the New Zealand electricity market. Under the SFPFC mechanism, each supplier knows that the sum of the values of the hourly SFPFC obligations across all suppliers is equal the system demand. This means that each supplier of SFPFCs knows that its competitors have substantial fixed-price forward contract obligations for that hour. This implies that all suppliers know that they have limited opportunities to raise the price they receive for short-term market sales beyond their hourly SFPFC quantity.

As discussed below, a supplier's fixed-price forward quantity for an hour under the SFPFC mechanism increases with the value of hourly system demand. Therefore, the supplier that owns 150 MWh of capacity in the above example has a strong incentive to submit an offer price close to its marginal cost for the capacity of its generation unit to ensure that its hourly production is higher than the realized value of its SFPFC energy for that hour. Therefore, the SFPFC mechanism not only ensures that system demand is met every hour of the year, but it also provides strong incentives for this to occur at the lowest possible short-term price. Wolak (2022) provide a number of examples that illustrate the details of the SFPFC mechanism and why it ensures that system demand will be met at least cost with a high probability.

1.4.1 Mechanics of the Standardized Forward Contract Procurement Process

The SFPFCs would be purchased through auctions several years in advance of delivery in order to allow new entrants to compete to supply this energy. Because the aggregate hourly values of these SFPFC obligations are allocated to retailers based on their actual share of system demand during the month, this mechanism can easily accommodate retail competition. If one retailer loses load and another gains it during the month, the share of the aggregate hourly value of SFPFCs allocated to the first retailer falls and the share allocated to the second retailer rises.

The wholesale market operator would run the SFPFC auctions with oversight by the regulator. One advantage of the design of the SFPFC products is that a simple auction mechanism can be used to purchase each annual product. A multi-round auction could be run where suppliers submit the total amount of annual SFPFC energy they would like to sell for a given delivery period at the price for the current round. With each round of the auction, the price would decrease until the amount suppliers are willing to sell at that price is less than or equal to the aggregate amount of SFPFC energy demanded.

The wholesale market operator would also run a clearinghouse to manage the counterparty risk associated with these contracts. All US wholesale market operators currently do this for all participants in their energy and ancillary services markets. In several US markets, the market operator also provides counterparty risk management services for long-term financial transmission rights, which is not significantly different from performing this function for SFPFCs. Both buyers and sellers would be required to post collateral with the wholesale market operator to ensure that each market participant finds it unilaterally profit-maximizing to meet its financial commitments for the SFPFC energy that it has purchased or sold.

SFPFC auctions would be run on an annual basis for deliveries starting 2, 3, and 4 years in the future. In steady state, auctions for incremental amounts of each annual contract would also be needed so that the aggregate share of demand covered by each annual SFPFC could increase over time. The eventual 100% coverage of demand occurs through a final true-up auction that takes place after the realized values for hourly demand for the delivery period are known. The mechanics of the true-up auctions are described in Wolak (2022).

1.4.2 Incentives for Behavior by Intermittent Renewable and Controllable Resources

Under the SFPFC approach to long-term resource adequacy, all suppliers know that all energy consumed every hour of the year is covered by SFPFC energy purchased at a fixed price. This creates a strong incentive for suppliers to find the least-cost mix of intermittent and controllable resources to serve these hourly demands. To the extent that there is concern that the generation resources available or likely to be available in the future to meet demand are insufficient, features of the existing capacity-based resource adequacy mechanism can be retained until system operators have sufficient confidence in this mechanism leading to a reliable supply of energy. The firm capacity values from the existing capacity-based long-term resource adequacy approach can be used to limit the amount of SFPFC energy a supplier can sell.

The firm capacity value multiplied by number of hours in the year would be the maximum amount of SFPFC energy that a unit owner could sell in any given year. Therefore, a controllable thermal generation unit owner could sell significantly more SFPFC energy than it expects to produce annually, and an intermittent renewable resource owner could sell significantly less SFPFC energy than it expects to produce annually. This upper bound on the amount of SFPFC energy any generation unit could sell enforces an incentive for cross-hedging between controllable generation units and intermittent renewable resources. This mechanism uses the firm capacity construct to limit forward market sales of energy by individual resource owners to ensure that it is physically feasible to serve demand during all hours of the year.

Cross-hedging between a controllable resource and an intermittent resource implies that in most years, the controllable resource owner would be producing energy in a small number of hours of the year but earning the difference between the price at which it sold the energy in the SFPFC auction and the hourly short-term market price times the hourly value of its SFPFC energy obligation for all the hours that it does not produce energy. Intermittent renewables resource owners would typically produce more than their SFPFC obligation in energy and sell any energy produced beyond this quantity at the short-term price. In years with low renewable output near their SFPRC obligations, controllable resource owners would produce close to the hourly value of their SFPFC energy obligation, thus making average short-term prices significantly higher. However, aggregate retail demand would largely be shielded from these high short-term prices because of their SFPFC holdings.

1.4.3 Empirical Evidence on the Performance of the Standardized Forward Contract Mechanism

Although the SFPFC mechanism in the form described above does not exist in any currently operating electricity supply industry, the long-term resource adequacy mechanisms in Chile and Peru create the same set of incentives for supplier behavior as the SFPFC mechanism by assigning system-wide short-term price and quantity risk during all hours of the year to suppliers. Both Chile and Peru operate a supplier-only, cost-based short-term wholesale electricity market. The system operator employs regulated variable cost estimates for each generation unit and an opportunity cost of water for hydroelectric generation units to dispatch all generation units to meet locational demands throughout each country. All consumers or their retailers are required to purchase full requirements contracts from suppliers to meet their retail load obligations. Suppliers financially settle imbalances between the amount of energy they produce and the amount of energy their customers consume under these full requirements contracts. Suppliers that produce more energy than their customers consume receive payments from the suppliers that produce less energy than their customers consume.[5]

To see the equivalence of the incentives created for supplier behavior under the market designs in Chile and Peru and the SFPFC mechanism, let QR_i equal the consumption of customers served by the supplier i and PR_i the quantity-weighted average price paid for full requirements

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[5] See section 3.2 of Wolak (2021c) for more details on this settlement mechanism.

contracts by customers served by supplier i. Let system demand equal QD, which is also equal to $\sum_{i=1}^{N} QR_i$, the sum of the consumption of all customers served by the N suppliers. The short-term price is PS, amount of energy sold in the short-term market is QS and cost of producing this energy is C(QS). The variable profit of supplier i is equal to

$$\begin{aligned}\pi_i &= PS \times QS - C(QS) - (PS - PR_i) \times QR_i \\ &= PS \times (QS - QR_i) + PR_i \times QR_i - C(QS), \qquad (1)\end{aligned}$$

which is identical to the case of supplier having fixed-price forward contract equal to QC and at price of PC by setting QR_i equal to QC and PR_i equal to PC. Moreover, because QD = $\sum_{i=1}^{N} QR_i$, all short-term price and quantity risk is borne jointly by the N suppliers that have sold full requirements contracts to electricity retailers and large loads.

The long-term resource adequacy mechanisms in Chile and Peru have delivered a reliable supply of electricity for at least the past 15 years in each country in the face of significant hydroelectric energy supply uncertainty and an increasing share of the energy consumed coming from intermittent wind and solar generation units. This outcome has been achieved through a cost-based short-term market in two countries with typical growth rates in annual electricity demand that are three to four times that in regions in the US with formal wholesale electricity markets. Consequently, the experience of Chile and Peru provides a strong argument in favor of the SFPFC mechanism for Asian countries with significant intermittent renewable energy goals.

1.5 Mechanisms That Support Large Renewable Energy Shares

This section describes two mechanisms that support large renewable energy shares at least cost to electricity consumers. The first mechanism is a renewable energy certificate market for a region to meet its renewable energy goals. This is followed by a discussion of the need to integrate intermittent renewable resources into the standardized long-term contract approach to long-term resource adequacy as the share of intermittent renewables increases. Finally, this section discusses how a cost-based market can foster the development of renewable resources.

1.5.1 Renewable Energy Certificate Market

A renewable energy certificate (REC) market is a significantly lower-cost approach to achieving a given renewable energy goal than other available mechanisms because it creates a competitive market for the renewable energy attribute. Under this mechanism, the relevant regulatory authority would set up a registry of qualified renewable energy resources (RERs) for the region. The set of generation resources that are qualified to sell RECs would be established and overseen by this regulatory authority. Once a resource is qualified to sell RECs, its energy production would be compiled in the registry established by the regulatory authority and each of these resources would be issued a quantity of RECs equal to the megawatt-hours of energy the resource produced during the compliance period.

Assuming an annual compliance period for the renewables mandate, retailers would be required to purchase the required percentage of their annual consumption of energy in RECs. For example, if the renewables mandate was 30% for 2024, free consumers and distributors would have to surrender RECs produced during 2024 equal to 30% of their annual consumption in 2024. A retailer with an annual consumption of 20,000 MWh would be required to surrender 6,000 RECs or pay a $1/MWh penalty set by the regulatory authority for any shortfall relative to this magnitude. For instance, if the retailer only held 5,900 RECs for the 2024 compliance period, it would be liable for a penalty of 100 RECs times this penalty price. The penalty price should be set sufficiently high so that all free consumers and distributors find it expected profit-maximizing to meet their renewable energy requirement.

Renewable resource owners would be allowed to sell RECs that their units have not yet produced, but they would be subject to the financial penalty for any shortfall between the quantity of RECs they have sold for the compliance period and the amount of RECs their units produced during the compliance period. For example, if a renewable resource owner sold 1,000 RECs and only produced 900 MWh of energy during the compliance year, the resource owner to be assessed a penalty for the 100 REC shortfall times the per REC penalty. This resource owner could also purchase these 100 RECs from qualified renewable generation unit owners with surplus RECs.

Unused RECs from the previous compliance year could be used in the following compliance year, but not in any subsequent year. For example, an RER unit that produced 100 RECs in 2024 and only sold 90 of these RECs for compliance in 2024 could sell the remaining 10 RECs for the 2025 compliance period. Similarly, if a free consumer or distributor only needed 95 RECs for compliance in 2024, but it held 105 RECs for the 2024 compliance period, the unused 10 RECs could be used for compliance in 2025. This ability to carry over RECs would only be possible for consecutive compliance years, so a REC produced in 2024 could not be used in the 2026 compliance year or subsequent years.

Unless a jurisdiction establishes a legal commitment to renewable energy targets into the distant future, there is no reason to establish a REC market. Moreover, a longer regulatory commitment would increase the likelihood that a forward market for RECs would develop to support investments in RERs to meet this goal. A centralized forward market procurement mechanism similar to the SFPFC mechanism for long-term resource adequacy could be implemented to ensure retailers purchase sufficient RECs into the distant future to provide the revenue stream necessary to meet the region's renewable energy goals. For example, centralized auctions for RECs could be run at similar time horizons to delivery compared to the SFPFC auctions. A guaranteed 4-year future revenue stream from future REC sales would provide the above-market revenues to the quantity of RERs necessary to achieve the long-term RER goal.

It is important to emphasize that without a legally mandated commitment by the relevant jurisdiction to meet a specific renewable energy target, such as 20% of electricity consumption from these resources by 2030, establishing a RPS is unnecessary. Intermittent renewable resources are free to compete with conventional generation resources in the long-term resource adequacy mechanism selling SFPFCs.

Procurement processes for specific renewable technologies should be avoided. Procurement mechanisms that specify shares of renewable energy for specific technologies simply reduce the extent of competition suppliers of these products face, which increases costs to consumers, with no accompanying economic or environmental benefit that could not be achieved at lower cost through an RPS. As noted in Wolak (2021c), an RPS creates a competitive market for the renewable attribute that all qualified sources of renewable energy can compete to provide. Different from a regulatory mandate that requires, say, 40% of renewable energy to come from wind and 60% to come from solar, an RPS provides strong incentives for suppliers to find the least-cost mix of renewable resources to achieve a given renewable energy goal. Technology-specific feed-in tariffs that specify a fixed price schedule paid for energy from each renewable technology not only fail to find the least-cost mix of renewable energy technologies but may not even find the least-cost mix renewable generation units for the same technology. That is because as long as a feed-in tariff provides a revenue stream greater than the cost of the renewable energy, the project developer has an economic incentive to build the project, whether or not it is the cheapest source of the energy from that renewable generation technology.

1.5.2 Transitioning Renewables to Standardized Forward Contracts

As the share of intermittent RERs increases, it is increasing costly to place the burden of managing their intermittency on buyers of the renewable power purchase agreement (PPA). A contract that pays a renewable resource owner a fixed price for all megawatt-hours regardless of when this energy is produced provides an implicit subsidy to the RER owner in a multi-settlement LMP market. The period-level variable profit of the RER unit owner under a paid-as-delivered PPA is (PC − C) QC, because the short-term market output of the resource QS is equal to the forward contract quantity QC for all periods under the terms of a paid-as-delivered contract that pays the RER owner PC for every megawatt-hour produced regardless of when it is produced. This PPA completely insulates the RER unit from the short-term market price, which means it has no financial incentive to manage its intermittency.

This contract form is not offered to conventional dispatchable resources for precisely this reason. Clearly, a thermal or hydroelectric resource owner would prefer a contract that transfers all of its outage or energy shortfall risk to the buyer of the contract. For this reason, all fixed-price and actual production PPA contracts must eventually be eliminated for all RERs, because a paid-as-delivered contract leaves the buyer of this energy with a volatile net demand position that must be purchased from the short-term energy market. Every hour the buyer of this renewable contract must purchase or sell the difference between its real-time demand and the output of the renewable resource. Moreover, the hours when short-term prices are high (because of little renewable energy production) the net demand of the retailer is likely to be positive and large, and the hours when short-term prices are low the net demand of the retailer is likely to be negative and large in absolute value.

Under the proposed multi-settlement LMP market without these PPA contracts, RERs that schedule energy in the day-ahead market must be responsible for the cost or revenues associated with any deviation between their day-ahead schedule and real-time output level. If the RER unit does not schedule any energy in the day-ahead market, then the energy the unit produces would be paid the real-time price. Because of the high degree of contemporaneous correlation between wind and solar generation resources documented in Wolak (2014), selling in the real-time market only implies selling low output relative to capacity at a high price and high output relative to capacity at a low price.

Facing intermittent renewable resources with the full cost of their intermittency will foster the development of cross-hedging arrangements between intermittent renewable resources and dispatchable resources. For example, a solar resource owner might purchase price spike insurance against high short-term prices during hours of the day when the resource cannot or is unlikely to produce energy. In this case, the solar resource owner would make an up-front payment to the dispatchable resource owner in exchange for the hourly payment stream of max(0,(P(spot,h)-P(strike))) times the number of megawatt-hours sold during the term of this "cap contract." P(spot,h) is the spot price during hour h, P(strike) is the negotiated strike price of the cap contract, and max(x,y) is a function that chooses the maximum of x and y. The solar resource owner would earn (P(spot,h) – P(strike)) per megawatt-hour purchased from this cap contract when P(spot,h) > P(strike) and zero otherwise. The dispatchable resource that sold this contract is liable for this payment stream. For this reason, the dispatchable resource has a strong incentive to produce as much output as possible during periods when P(spot,h) is likely to exceed P(strike) to avoid making this payment.

Under a fixed-price and fixed-quantity forward contract, the renewable resource owner's variable profit is $\pi = PS(QS - QC) + PC^*QC$, where both PS and QS are random variables not known to the resource owner until after the hour. The variable cost of producing QS is assumed to be zero. The expected value E(.) of the resource owner's variable profit is:

$$E(\pi) = Cov(PS,QS) + E(PS)E(QS) - E(PS)QC + PC^*QC \qquad (2)$$

As noted earlier, Cov(PS,QS), the covariance between the PS and QS, is likely to be negative. Under the paid-as-delivered forward contract the resource owner's variable profit is $\pi = PC^*QC$, because $QS = QC$ each hour. Consequently, transitioning from paid-as-delivered contracts to fixed-price and fixed-quantity forward contracts implies a significant increase in variable profit risk for intermittent renewable resource owners.

Cross-hedging between dispatchable resources and intermittent renewable resources selling fixed-price forward contracts accomplishes two goals. First, it provides up-front revenues to dispatchable generation resources to cover their annual fixed costs in a world in which they operate fewer hours of the year because of the increasing amount intermittent RERs. Second, it ensures that intermittent RERs account for the full cost of their intermittency in the prices they offer for SFPFC energy and RECs. If intermittent renewable resource owners are unable to recover these costs from selling SFPFC energy or energy in the short-term market, these above-market costs must then be recovered from sales of RECs, assuming that the government has set a legally binding target for energy production.

1.5.3 Cost-Based LMP Market and Renewables Integration

The strength of a cost-based LMP market design for RER integration is that all resources in the control area, including intermittent renewable resources, will be dispatched in a least-cost manner using the variable costs determined by the market operator. How these resources are compensated for the energy they sold in the SFPFC auctions will not impact how the resource is ultimately used to produce energy. As noted earlier, all suppliers have a strong financial incentive to supply their hourly allocation of SFPFC energy at the lowest possible cost, either by producing it or purchasing it from the short-term market.

A cost-based short-term LMP market provides RER owners with a transparent short-term market to purchase energy from when their intermittent renewable units do not produce sufficient energy to meet their hourly SFPFC obligation and sell excess energy beyond this forward market obligation when their units produce more than this quantity of energy. This logic emphasizes the importance of a publicly disclosed process for clearing the day-ahead and real-time cost-based markets. The renewable resource owner can factor in how these imbalances will be settled in making offers to supply SFPFC energy.

Shifting renewable resource owners to fixed-price and fixed-quantity forward contracts from fixed-price and quantity-produced contracts will also provide financial incentives for renewable resource owners to manage the intermittency of their production through storage investments and financial contracts that support investments in fast-ramping dispatchable generation resources to provide insurance against renewable energy shortfalls. Transitioning forward contracts for renewable energy to require the seller to manage the quantity risk associated with the energy it provides is a crucial step in increasing the amount of intermittent renewable energy produced while maintaining a high level of grid reliability.

In all LMP markets operating around the world, there is an ongoing process of updating the set of constraints incorporated into the market mechanism to ensure that the match between how the market sets prices and dispatch levels agrees as closely as possible with how the grid is operated. This logic implies that as the share of intermittent renewable resources increases an LMP market can be easily adapted to deal with the new reliability challenges this creates.

For example, California has added several new operating reserves to account for the fact that the large share of solar RERs has created the need to manage a large daily ramp-up of dispatchable resources at the end of the daylight hours and a slightly smaller ramp-down in the early morning hours. The introduction of these new operating reserves required additional constraints in the day-ahead market-clearing mechanism and adding the offer prices times the offer quantities for these products into the objective function.

A multi-settlement LMP market can efficiently manage the sudden generation unit starts and stops that arise with a significant amount of intermittent renewable generation units and the need to configure combined cycle natural gas units to operate as either individual combustion turbines or as an integrated pair of combustion turbines with an associated steam turbine. A formal day-ahead market allows these generation units to obtain day-ahead schedules that are consistent with their physical operating constraints. The real-time market can then be used to account for unexpected changes in these day-ahead schedules because of changes in the operating characteristics of generation units such as a forced outage or limitations in the amount of available input fossil fuel, as well as changes in demand between the day-ahead and real-time markets.

1.6 Concluding Comments

Achieving the large shares of intermittent renewable energy necessary to reduce substantially the carbon content of a region's electricity supply is likely to be significantly less costly because of the recent reduction in the LCOE of wind and solar resources. However, ensuring that this transition occurs in a least-cost manner requires efficient pricing in the short-term energy market and a long-term resource adequacy mechanism designed for an industry with a large share of intermittent renewables. Zonal pricing markets that do not account for all relevant operating constraints on dispatchable and intermittent renewable generation units in day-ahead and real-time markets unnecessarily increase the cost of making this energy transition.

The major system reliability challenge with a significant amount intermittent renewable resources changes from having sufficient generation capacity to meet annual system demand peaks to the ability to meet the hourly net demands (system demand less intermittent renewable output) for energy throughout the year. Particularly in an electricity supply industry with a summer annual peak demand and significant installed solar generation capacity, meeting daily system demand peaks is relatively straightforward because demand peaks occur when there is significant solar energy production. The new focus on meeting net demand peaks implies a system-wide focus on energy adequacy where intermittent renewable resources have a financial incentive to hedge their short-term and production quantity risk with dispatchable generation resources to cover these net demand peaks.

A multi-settlement LMP market design efficiently prices the system-wide and local reliability benefits provided by dispatchable resources relative to intermittent renewable resources. By co-optimizing the procurement of energy and ancillary services, this market design ensures that the demand for energy and ancillary services at all locations in the transmission network are met at least cost. The standardized energy contracting approach to long-term resource adequacy described in this chapter addresses the primary long-term resource adequacy challenge in regions with significant intermittent renewables. It provides strong incentives for intermittent resources to cross-hedge their quantity and price risk associated with selling these standardized long-term contracts with dispatchable resources to provide the revenue necessary to keep enough of this generation capacity available to meet hourly net demands throughout the year. The experience of Chile and Peru over the past 15 years, each of which has a market design that creates the same set of incentives for supplier behavior as the SFPFC mechanism, provides encouraging empirical evidence in favor of its adoption in regions with significant intermittent renewable energy goals.

Finally, if a region has a legal mandate to achieve a prespecified renewable energy goal by a given date, such as 60% of energy consumed by 2040, then a renewable energy certificate market is the least-cost approach to achieving this goal. If a region does not have a mandated renewable energy goal, then such a market is no longer necessary. The recent declines in the LCOE of wind and solar resources currently make them a lower LCOE solution than natural gas and coal generation units in many regions.

References

Bjørndal, E., M. Bjørndal, H. Cai, and E. Panos. 2018. Hybrid Pricing in a Coupled European Power Market with More Wind Power. *European Journal of Operational Research* 264(3): 919–931.

Bohn, R. E., M. C. Caramanis, and F. C. Schweppe. 1984. Optimal Pricing in Electrical Networks over Space and Time. *RAND Journal of Economics* 15(5): 360–376.

Carden, K., A. K. Dombrowsky, and C. Winkler. 2020. 2020 Joint IOU ELCC Study, Report 1. https://www.astrape.com/2020-joint-ca-iou-elcc-study-report-1/

Energy Information Administration (EIA). 2021. Levelized Costs of New Generation Resources in the *Annual Review Outlook 2021*. United States Energy Information Administration. https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf

Galetovic, A., C. M. Muñoz, and F. A. Wolak. 2015. Capacity Payments in a Cost-Based Wholesale Electricity Market: The Case of Chile. *The Electricity Journal* 28(10): 80–96.

Garver, L. L. 1966. Effective Load Carrying Capability of Generating Units. *IEEE Transactions on Power Apparatus and Systems* PAS-85(8): 910–919.

Graf, C., F. Quaglia, and F. A. Wolak. 2020. Simplified Electricity Market Models with Significant Intermittent Renewable Capacity: Evidence from Italy. http://web.stanford.edu/group/fwolak/cgi-bin/sites/default/files/GrafQuagliaWolak_SimplifiedElectricityMarketModelsRenewables.pdf

Graf, C., E. La Pera, F. Quaglia, and F. A. Wolak. 2021. Market Power Mitigation Mechanisms for Wholesale Electricity Markets: Status Quo and Challenges. http://web.stanford.edu/group/fwolak/cgi-bin/sites/default/files/MPM_Review_GPQW.pdf

International Renewable Energy Agency (IRENA). 2021. *Power Generation Costs in 2020*. Abu Dhabi: IRENA.

Joskow, P. L. 1997. Restructuring, Competition and Regulatory Reform in the U.S. Electricity Sector. *The Journal of Economic Perspectives* 11(3): 119–138.

Mansur, E. T., and M. W. White. 2012. Market Organization and Efficiency in Electricity Markets. http://www.dartmouth.edu/~mansur/papers/mansur_white_pjmaep.pdf

McRae, S. D., and F. A. Wolak. 2014. How Do Firms Exercise Unilateral Market Power? Evidence from a Bid-Based Wholesale Electricity Market. In J.-M. Glachant and E. Brousseau, eds. *Manufacturing*

Markets: Legal, Political and Economic Dynamics. Cambridge University Press, pp. 390–420.

McRae, S. D., and F. A. Wolak. 2016. Diagnosing the Causes of the Recent El Nino Event and Recommendations for Reform. http://web.stanford.edu/group/fwolak/cgi-bin/sites/default/files/diagnosing-el-nino_mcrae_wolak.pdf

Oren, S. S. 2001. Design of Ancillary Service Markets. In *Proceedings of the 34th Hawaii International Conference on System Sciences*, pp. 1–9.

Triolo, R. C., and F. A. Wolak. 2022. Quantifying the Benefits of a Nodal Market Design in the Texas Electricity Market. *Energy Economics* 112: 106154.

Wolak, F. A. 2000. An Empirical Analysis of the Impact of Hedge Contracts on Bidding Behavior in a Competitive Electricity Market. *International Economic Journal* 14(2): 1–39.

____. 2009. Report on Market Performance and Market Monitoring in the Colombian Electricity Supply Industry. http://web.stanford.edu/group/fwolak/cgi-bin/sites/default/files/files/sspd_report_wolak_july_30.pdf

____. 2011. Measuring the Benefits of Greater Spatial Granularity in Short-Term Pricing in Wholesale Electricity Markets. *American Economic Review* 93(2): 247–252.

____. 2013. Economic and Political Constraints on the Demand-Side of Electricity Industry Re-structuring Processes. *Review of Economics and Institutions* 4(1): 42.

____. 2014. Regulating Competition in Wholesale Electricity Supply. In N. L. Rose, ed. *Economic Regulation and Its Reform: What Have We Learned*? University of Chicago Press, pp. 195–289.

____. 2016. Level versus Variability Trade-offs in Wind and Solar Generation Investments: The Case of California. *The Energy Journal* 37(Special Issue 2): 185–220.

____. 2021a. Market Design in an Intermittent Renewable Future: Cost Recovery with Zero-Marginal-Cost Resources. *IEEE Power and Energy Magazine* 19(1): 29–40.

____. 2021b. Wholesale Electricity Market Design. In J.-M. Glachant, P. L. Joskow, and M. G. Pollitt, eds. *Handbook on Electricity Markets*. Cheltenham, UK and Northampton, MA, US: Edward Elgar Publishing, pp. 73–110. https://www.e-elgar.com/shop/gbp/handbook-on-electricity-markets-9781788979948.html

____. 2021c. Final Report on Thematic Line 2: Transformation of the Peruvian Wholesale Electricity Market. Prepared for the Ministry of Mines and Energy of Peru.

———. 2022. Long-Term Resource Adequacy in Wholesale Electricity Markets with Significant Intermittent Renewables. *Environmental and Energy Policy and the Economy* 3(1): 155–220.

Wolak F.A., J. Bushnell, and B.F. Hobbs. 2008. Opinion on "The DEC Bidding Activity Rule under MRTU". https://www.caiso.com/Documents/MSCFinalOpiniononDECBiddingActivityRuleunderMRTU.pdf

PART II

Buildings: Promoting and Financing Demand-Side Energy Efficiency

2

Future-Proofing Sustainable Cooling Demand

Toby Peters and Leyla Sayin

2.1 Introduction

Our planet is warming at an alarming rate. The global mean temperature by 2100 could be 3.4°C–3.9°C higher than before the Industrial Revolution began. Around 74% of the world's population could be exposed to deadly climatic conditions, and direct heat-related deaths could reach more than 255,000 per year by 2050, with impacts expected to be greatest in the South, East, and Southeast Asian regions (UNEP 2019; Mora et al. 2017; WHO 2014). In response, the cooling demand is set to grow substantially with the emerging need to adapt to higher temperatures and to survive in a world with more intense and frequent heatwaves and widespread droughts. This growth in demand is also exacerbated by multiple demographic and development changes such as rising populations, urbanization, increasing incomes, and improved access to electricity in developing nations that are often located in the parts of the world that are most vulnerable to climate change. The irony is, however, that conventional active cooling devices already account for more than 10% of global fossil carbon dioxide (CO_2) emissions, or 7% of all global greenhouse gas (GHG) emissions, further warming the planet (Kigali Cooling Efficiency Programme 2018). In the absence of any intervention, these GHG emissions from cooling may double by 2030, and triple by 2100 (World Bank 2019). Hydrofluorocarbons are in fact the fastest-growing source of GHG emissions today, mainly due to the increasing global demand for cooling (North American Sustainable Refrigeration Council n.d.). Yet, cooling demand remains a critical blind spot in sustainability and climate debates.

The energy demand for space cooling more than tripled between 1990 and 2016, and it is the fastest-growing energy service in buildings worldwide. In 2016, space cooling accounted for more than

2,020 terawatt-hours (TWh) of electricity, which was nearly 10% of the world's total electricity consumption, and almost 20% of all electricity used in buildings (IEA 2018). Without any intervention, the electricity demand for space cooling could increase by 300%, reaching 6,200 TWh in 2050—consuming as much electricity as the whole of the People's Republic of China (PRC) and India today (IEA 2018). In some hotter regions of the world, the share of space cooling in electricity consumption already reaches staggering numbers. For example, 70% of Saudi Arabia's electricity is used for air conditioning (Schlanger 2018). In India, the share of air conditioning in the peak electricity load is projected to reach 45% in 2050 from 10% today in the absence of any intervention (IEA 2018).

While today only less than one-third of households around the world own an air conditioner,[1] two in every three households around the world are expected to have one by 2050, with the PRC, India, and Indonesia accounting for half of this demand. Due to rising temperatures, along with other drivers, many cities in the developing world that currently have a low number of air conditioners will see a big increase in air-conditioning purchases. This surging and highly variable space cooling demand will add massive additional electricity loads to the energy systems. As a result, these cities may struggle to deploy larger-capacity electricity infrastructure into existing urban areas due to limited space (UNEP 2021a).

In order to achieve the 1.5°C target of the United Nations Framework Convention on Climate Change Paris Agreement, the International Energy Agency (IEA) estimates that direct building CO_2 emissions (refrigerants) need to be reduced by 50% and indirect building emissions (energy) by 60% by 2030 (UNEP 2021b). In this regard, how we deliver cooling in buildings will play a significant role given the increasing demand for energy consumption. However, cooling provision will not only be needed for thermal comfort in the built environment. Additional capacity will also be sought to address cooling needs across health, agriculture, and transport sectors. Projections suggest that the number of cooling devices—air conditioners, fans, and refrigerators—could increase to 9.5 billion globally by 2050 from today's 3.6 billion. Despite this anticipated increase, providing cooling for all who need it, and not just those who can afford it, will require 14 billion devices by 2050—which is 3.8 times as many devices as are in use today (Peters 2018a). This is an important issue as providing access to cooling for all is critical

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[1] In 2018, air-conditioner ownership was 90% among households in Japan and the United States; however, among the 2.8 billion people living in the hottest parts of the world, ownership was only 8% (IEA 2018).

to achieving many of the United Nations (UN) Sustainable Development Goals (SDGs). In parallel with failing to make sufficient progress toward meeting the Paris Agreement targets, the international community is not on track to deliver the SDGs by 2030. Access to cooling can reduce food loss, protect the quality and safety of food produced, and prevent productivity loss due to extreme heat, thereby contributing toward major global issues such as eradicating poverty, hunger, and malnutrition, especially in developing countries. It can prevent heat-related illnesses and deaths, and is often essential to maintain the quality, safety, and efficacy of vaccines, blood, and other temperature-sensitive medicines. These benefits not only provide strategic and social gains, but also often have a financial value.

How we meet this surging cooling demand across a variety of sectors will have important implications for our future climate and energy systems globally. The increasing need to adapt to higher ambient temperatures may result in rushed responses that are highly polluting and energy intensive, resulting in technological lock-in. The multi-level, multi-sector, and multi-actor challenge that is faced by policy makers, financiers, business leaders, entrepreneurs, technology developers, and engineers today is how to meet surging cooling needs in a warming world sustainably, while also building resilience. Sustainability and resilience are two different concepts. While sustainability refers to meeting the needs of current generations without compromising the ability of future generations to meet their own needs, resilience denotes the ability of systems to bounce back and recover from disruptions quickly and adapt to inevitable changes. To deliver cooling in line with climate and developmental targets, we need to hit the sweet spot at the intersection of sustainability and resilience. As different countries face different needs and climate risks, and have varying levels of vulnerability, sustainability solutions that are effective in some locations may not be feasible in others. To manage the complexity and deliver cooling in the most cost-efficient way with minimum environmental impact, countries should focus on actions that play to their strengths (e.g., local energy resources and assets) and carefully define their strategies and priority actions—which is the key to building resilience. Furthermore, it is important to design solutions for the changing climate conditions. For example, under high ambient temperatures induced by climate change, current systems would fail or struggle to operate efficiently. Hence, in the short term, solutions will be needed to keep existing systems operating effectively, and in the long run, new system designs will be required.

The scope of energy provision today typically focuses on electricity and batteries, even though a large slice of our energy consumption comes in the form of thermal demands. In the transition to renewables, cooling demands may often be better served by thermal-to-thermal solutions and thermal energy storage. Achieving this requires taking a needs-driven, integrated, system-level approach to cooling provision and driving a new thinking in key areas: How do we mitigate, make, store, move, manage, and finance and/or regulate cold? The holistic systems approach aims to minimize the demand for active cooling via integration of passive cooling techniques and approaches as well as behavior changes (which is particularly important in regions where there is demand for cooling throughout the entire year), helps make sure individual cooling technologies are supported by the broader infrastructural landscape (e.g., energy and transport) in which they are embedded and interdependencies between energy services are understood and managed, and ensures the whole system is supported by appropriate skills, policies, regulations, and finance and business models. In this regard, it is important to take a future-oriented approach by understanding not only the current but also the future cooling energy service needs, by anticipating social, economic, environmental, technological, and regulatory changes over the long term, and by planning for unexpected and/or uncontrollable events and circumstances, such as disasters and pandemics, that could disrupt the cooling service or alter the demand profile.

Future-proofed design is critical to ensure future capability and capacity in a long life cycle. Buildings constructed today will still be in use for at least the next 50 years. For example, if new buildings are designed without considering the risk of overheating, the higher ambient temperatures and intense heatwaves that are expected to occur more often in coming decades will increase the reliance on air-conditioning systems, which are typically highly energy intensive and polluting. Furthermore, the need to comply with increasingly stringent building codes and standards will lead to unnecessary retrofitting costs. Similarly, electric vehicle charging points will likely need to be integrated into buildings, consequently impacting the grid energy demand and peak loads, and this requires careful planning.[2]

With 80% of the buildings that will exist in 2050 in developing countries yet to be built (Juquois 2017), there is now a window of opportunity in these countries to significantly reduce space cooling energy demand and emissions in buildings, improve thermal comfort in outdoor urban environments, and maximize their life cycle value through

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[2] From a systems-level perspective, electric vehicles will play a critical role in reducing the transport refrigeration and mobile space cooling emissions. For example, 40% of a bus's energy consumption in Asia can be air-conditioning load, while a transport refrigeration unit consumes up to 20% of a refrigerated vehicle's diesel.

future-oriented, needs-driven, and resource-smart design approaches. At the same time, we must recognize that addressing the cooling needs across other sectors requires equal attention. To this end, taking an extensive and comprehensive whole system-of-systems approach to cooling provision by identifying and leveraging interdependencies across cooling sectors and wider energy systems is key to ensuring current and future cooling needs are met for all efficiently, sustainably, and affordably, while building resilience.

2.2 The Drivers of Cooling Demand Growth

Climate change. According to the Intergovernmental Panel on Climate Change Sixth Assessment Report, "each of the last four decades has been successively warmer than any decade that preceded it since 1850." Since 1950, while hot extremes have become more frequent and more intense, cold extremes have become less frequent and less severe, and projections suggest future increases in the intensity and frequency of hot extremes, including heatwaves (IPCC 2021). For example, in the tropical region, the temperatures increased by 0.7°C–0.8°C over the last century, with climate models predicting an increase of 1°C–2°C by 2050 and 1°C–4°C by 2100 (Corlett 2014). Without any intervention, the average number of cooling degree days, the number of degrees that a day's average temperature is above 18°C, during which a building must be cooled to achieve a comfortable indoor temperature, could increase globally by nearly 25% between 2016 and 2050, with the highest increases expected to occur in developing countries located in the hottest parts of the world (IEA 2018). For example, in India, the number of cooling degree days is already high with more than 3,000 per year, and this figure is expected to increase by 13% by 2050 (IEA 2018). Without any intervention, by 2070, up to 3.5 billion people around the world could be exposed to annual mean temperatures of 29°C, which are higher than nearly anywhere today (Xu et al. 2020). Another research led by the United Kingdom's Met Office suggests that 1 billion people could suffer from extreme heat stress if global temperatures were to increase by 2°C (Madge 2021).

Increasing population. The world's population is expected to increase by 2 billion by 2050, from 7.7 billion in 2019 to 9.7 billion, and may reach 10.9 billion in 2100. Much of this growth is expected to come primarily from developing nations in hotter parts of the world that are more vulnerable to climate change. For example, in 2019, 43% of the world's population, almost 3.8 billion people, were living in the tropical region, and this is expected to increase to 50% by 2050 (UN 2019).

Urbanization. Over half of the world's population currently lives in urban areas, and this figure is expected to reach as much as 70% by

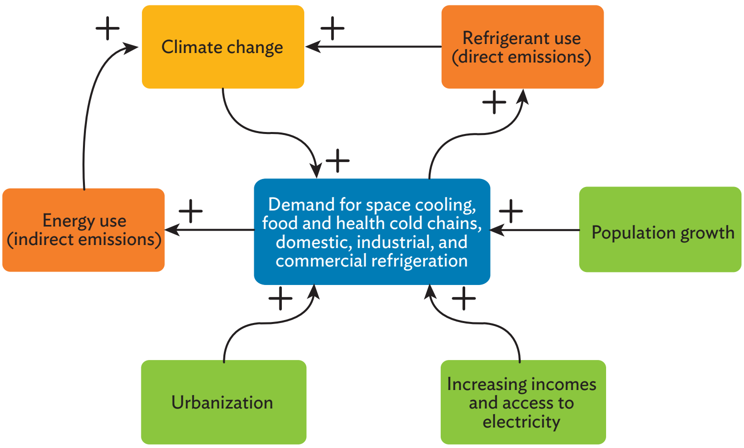
2050 (UN-Habitat 2020). A substantial proportion of this growth in human urbanization is projected to occur in the developing economies of the world and in locations that will experience significantly increased ambient temperatures and more frequent and intense extreme heat events. The impacts of these trends will be exacerbated by urban heat island effects that raise local temperatures in the centers of cities and urban conurbations to levels several degrees higher than simultaneously experienced in the surrounding suburbs or rural hinterland (Li et al. 2019). According to the United States Environmental Protection Agency, the annual mean air temperature of a city can be 1°C–3°C warmer on average—and as much as 12°C warmer in the evening than the surrounding areas (US EPA 2014). Recent projections suggest that cities across the world could warm by more than 4°C on average by the end of the century (Krayenhoff et al. 2021). The urban heat island effect is a complex phenomenon that depends on a multitude of factors. Buildings and other structures reflect less solar energy and absorb and emit more heat than natural surfaces. Displacing natural surfaces reduces the natural cooling effects of shading and evaporation of water from soil and leaves. Furthermore, the dimensions and spacing of buildings impact wind flow and the ability of urban surfaces to absorb and release heat. For example, narrow spaces between tall buildings (i.e., urban canyons) can block wind flow and trap heat. Moreover, waste heat from vehicles, factories, and air conditioners further exacerbates the heat island effect. For example, research suggests that heat released from active cooling technologies alone can increase nighttime temperatures in cities by 1°C or 2°C (heat island effect) (Salamanca et al. 2014).

Increasing incomes and access to electricity in developing countries. In the last decade, air-conditioner ownership has been rapidly increasing in emerging and developing economies, such as India with 16%, Indonesia with 13%, and the PRC with 8% (UNEP 2021b). While current air-conditioner ownership globally is mostly concentrated in the developed world, it is anticipated that 80% of the refrigeration and air-conditioning market will be located in developing countries by 2030, mainly due to increasing incomes and improved access to electricity (GIZ 2018). Although 759 million people globally still lacked access to electricity as of 2019, significant progress has been made, and this number has decreased from 1.2 billion in 2010 and is expected to further decrease (World Bank 2021). Estimations suggest that 2.2 billion lower-middle-income people in developing countries newly entering the world's "middle classes" will soon be able to purchase the most affordable air conditioners (Sustainable Energy for All 2019). However, these devices will likely be too inefficient and energy intensive in the absence of finance and business models to encourage best-in-class purchasing.

In addition to increasing demand for air conditioners in buildings, which is the largest energy consumer among the cooling sectors, accounting for 41% of global cooling energy consumption (Peters 2018a), the combination of these factors will drive the demand for cooling in other sectors. For example, rising temperatures will consequently increase the demand for space cooling in the transport environment; higher income levels will potentially result in higher food consumption levels, which will increase the demand for cooling in the food sector, both in the food production and cold chain; urbanization will increase demand for refrigeration at urban retail and hospitality outlets to meet the urban food demand; and food producers will be pushed further from the demand due to urban expansion, resulting in greater demand for cold chain logistics. The nature and size of the cooling demand across sectors will be impacted by other parameters specific to local circumstances, in addition to the ones mentioned, ranging from changing shopping preferences to increasing health, safety, and environmental concerns, as well as production patterns, among others.

This demand will likely contribute to its own growth, as conventional active cooling devices are energy intensive and highly polluting due to the emissions from energy use (indirect emissions), especially if generated

Figure 2.1: Linkages between Demand Growth for Active Cooling, Climate Change, and Other Drivers



Source: Authors.

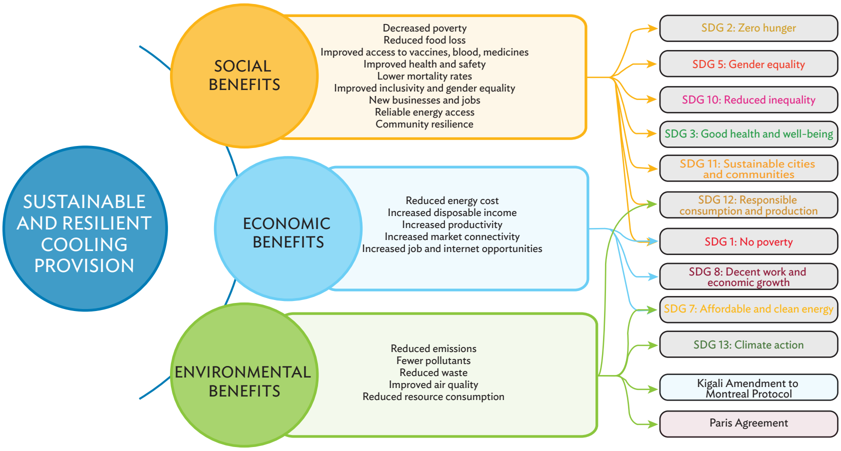
from carbon-intensive sources, and from refrigerant leakages during use and servicing as well as when the equipment is discarded at the end of life (direct emissions) (Figure 2.1). These devices contribute more than 7% of GHG emissions today, and left unchecked, these emissions may double by 2030 and triple by 2100.

The critical importance of cooling in delivering climate and development targets has been recognized in recent years globally. In response, many countries have been developing and implementing national cooling plans with support from the cooling community. These plans involve road maps and timetables for achieving a sustainable cooling economy, involving short- and long-term considerations on refrigerant transitions (phasing out hydrochlorofluorocarbons and phasing down hydrofluorocarbons [HFC]), reducing the cooling demand, enhanced minimum energy performance standards ,building codes, and universal access to sustainable cooling. Currently 55 countries have committed to reducing their cooling emissions, either in their enhanced Nationally Determined Contributions (NDCs) or long-term climate plans (Clean Cooling Cooperative 2021). Of these 55 countries, only six included cooling in their NDCs in 2015 (Cool Coalition 2021). In this regard, for example, Cambodia included space cooling of buildings as a priority GHG mitigation in 2020 in its revised NDC. The NDC includes passive cooling strategies to reduce energy consumption in buildings and to reduce the urban heat island effect in cities. To this end, through the Kigali Cooling Efficiency Program NDC Support Facility, the Ministry of the Environment of Cambodia, the UN Economic and Social Commission for Asia and the Pacific (ESCAP), and the UN Environment Programme (UNEP) are planning to implement a technical assistance program on "passive cooling strategies implementation in Cambodia" by the end of 2021 (UNEP 2021b).

2.3 Understanding the Real Value

In a warming world, cooling access is increasingly becoming a necessity for maintaining adequate human living standards. In countries with hotter climates, surging cooling demand is often coupled with the need for economic growth and development. Sustainable and resilient cooling access can provide many socioeconomic, societal, and political benefits that are inherently aligned to, and critical for, achieving many of our SDG targets (Figure 2.2). This is particularly relevant in the context of inequalities. The social and economic costs of a lack of cooling access fall disproportionately on poor, disadvantaged, and often marginalized individuals and communities, as well as on women and girls, exacerbating inequalities and creating additional barriers to achieving the SDGs. More than 1 billion people face immediate risk from a lack of access to cooling, which includes 680 million slum dwellers living in hotter-climate urban environments (Sustainable Energy for All 2019). These people are often not included in the climate planning processes, and some adaptation efforts may even exacerbate existing inequalities if not planned carefully (Guardaro et al. 2020). For example, rapid urbanization and growth of large cities in developing countries have been accompanied by the rapid growth of highly vulnerable urban communities living in informal settlements. These communities are often located on land at high risk from extreme weather (Revi et al. 2014).

Figure 2.2: Multiple Benefits of Sustainable and Resilient Cooling Provision and Its Linkages to SDGs



SDG = Sustainable Development Goal.

Source: Authors.

Despite the surging demand and central importance of cooling to a functioning modern society and the plethora of benefits it delivers, approaches to cooling provision today tend to be narrowly focused on simply measuring energy efficiency alone, quantifying savings on energy bills, and using these as the basis for the return-on-investment calculations. The broader societal benefits of access to cooling are typically treated as a "soft win," rather than the core driver for provision. Realizing a truly sustainable and resilient cooling system demands understanding, quantifying, and valuing the broader and potentially strategic impacts of cooling with their linkages to climate and development goals, targets, and commitments.

The key is to recognize that social and environmental benefits do have financial value—which often translates to reductions in other costs or lower economic losses—and the necessary data for their assessment are likely to be available once a requirement has been identified. For example:

- Higher ambient and extreme temperatures in a warmer world will negatively impact labor productivity by as much as 12% in South Asia and West Africa by 2050, which may potentially result in an annual gross domestic product (GDP) loss of up to 6% (Monsalve and Watsa 2020). Increased heat stress is projected by the International Labour Organization to reduce total working hours worldwide by 2.2% and global GDP by $2.4 trillion in 2030, affecting agricultural and construction workers particularly severely (Kjellstrom et al. 2019). A recent study estimates that the labor productivity loss for low-income and lower-middle-income countries due to high temperatures is approximately 9 times more than that of high-income countries and that economic losses may already be as much as 2% of global GDP as a result (Chavaillaz et al. 2019). In terms of strategic value, the provision of sustainable and resilient cooling is directly linked to SDG 8: Decent Work and Economic Growth.
- Women and girls are disproportionately affected by a lack of cooling, as they typically spend more time at home engaging in domestic activities than men and boys,[3] especially in developing countries (Lundgren-Kownacki et al. 2018). Ensuring equitable access to sustainable cooling can contribute to SDG 5: Gender Equality and SDG 10: Reduced Inequalities.
- Climate change is estimated to be currently responsible for over 150,000 deaths annually, and between 2030 and 2050 it is expected to cause approximately 250,000 additional deaths per year, from malnutrition, malaria, diarrhea, and heat stress (WHO 2021). For example, the estimated economic costs from the increase in heat-related mortality in the United Kingdom is estimated to have been £2.5 billion per year in 2020, and it is expected to rise to a staggering £9.9 billion per year by 2050

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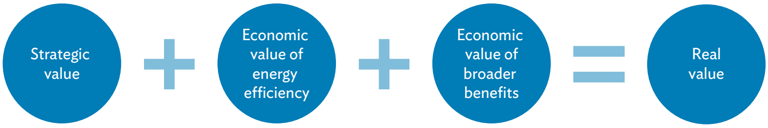
[3] According to UNICEF, girls spend 160 million more hours a day than boys doing unpaid household chores (UNICEF 2016).

(Climate Change Committee 2019). In terms of strategic value, this is directly linked to SDG 3: Good Health and Well-being.

- Increasing temperatures lead to high levels of discomfort and heat stress not only for humans but also for animals, which can result in increased morbidity and mortality levels. For example, more than 17 million chickens died in India during the 2015 heatwave (Jadhav 2015). Increasing temperatures can also result in productivity loss and reduced reproduction rates (Dash et al. 2016; Sejian et al. 2018). For example, multiple studies conducted in India suggest that heat stress can reduce milk production by between 5% and 50% (Belsare and Pandey 2008; National Dairy Development Board 2017). These are directly linked to SDG 1: No Poverty and SDG 2: Zero Hunger.

Figure 2.3: Real Value of Sustainable and Resilient Cooling Provision



Source: Authors.

To summarize, the process for assessing the real value of delivering clean cooling involves the following steps (Figure 2.3):

(1) Identify the social and environmental benefits and their impacts.
(2) Create strategic value by linking benefits to a strategic direction, such as goals, targets, or commitments.
(3) Quantify the economic value of social and environmental benefits.
(4) Determine the energy cost savings through energy efficiency measures.
(5) Aggregate all these values to establish the real value of delivering sustainable and resilient cooling.

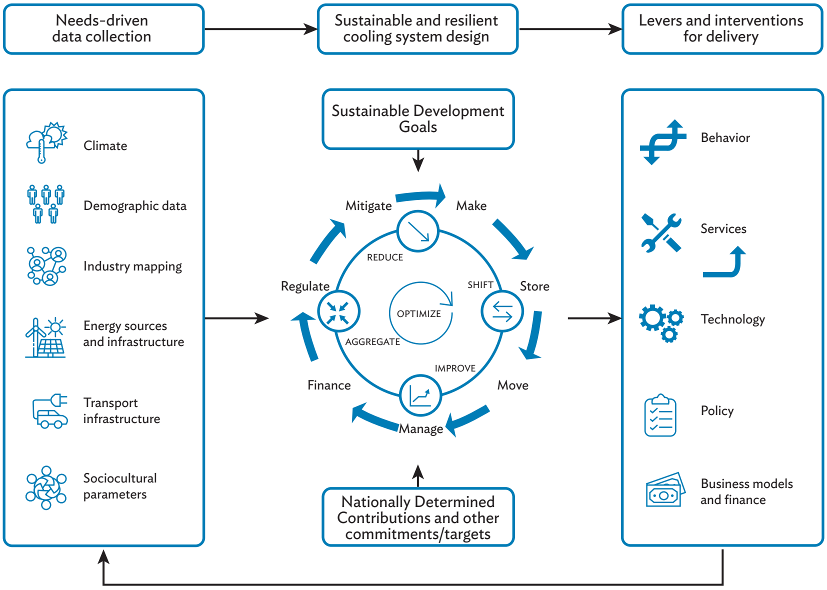
2.4 The Systems Approach

Governments' efforts to decarbonize economies today focus mainly on "greening the electricity supply" by replacing fossil fuels with renewable and low-carbon sources, such as solar, wind, hydro, and nuclear. In the cooling sectors, while these efforts will help with GHG emissions associated with energy use, they are falling short in the face of surging demand. For example, over 100 gigawatts (GW) of building space cooling capacity was added in 2017, outpacing the record 94 GW of solar power generation added to the world's renewable energy infrastructure that year (Campbell, Kalanki, and Sachar 2018). Similarly, 2018 was again a record year for global deployment of solar power with 104 GW of installed capacity added, while simultaneously the energy demand resulting from new sales of room air conditioner units was 115 GW (Garry 2019). This excludes all existing cooling as well as new cooling equipment and appliances installed for other purposes. Even if the electricity grid is fully decarbonized, refrigerant emissions still need to be reduced. Note that achieving the 1.5°C target also requires deep reductions in non-CO_2 emissions such as HFCs from refrigerant leakage and/or spillage (Masson-Delmotte et al. 2018). Emissions from refrigerants represent around one-third of the total GHG cooling emissions, and HFCs are the fastest-growing source of GHG emissions globally due to the surging demand for cooling (North American Sustainable Refrigeration Council n.d.; Green Cooling Initiative n.d.).

Similarly, we cannot rely on energy efficiency improvements in cooling technologies alone to meet the cooling needs sustainably in line with our emission targets. For example, after flattening between 2013 and 2016, emissions from energy use in buildings have increased in recent years as the increased demand for energy services, especially electricity for cooling appliances and connected devices, has outpaced energy efficiency and decarbonization efforts (IEA 2020). Within this, there needs to be a paradigm shift to a different way of thinking that goes beyond simply taking a business-as-usual approach focused on energy efficiency and greening electricity.

Design and technical development approaches to cooling provision today typically focus on improving individual technologies viewed from a siloed perspective. While optimizing the components of the whole system is important, this reductionist approach neglects the interdependencies that exist between economic decisions, available energy resources, technology choices, climate change mitigation and adaptation strategies, and social, cultural, and political systems—and results in a suboptimal outcome. Solving the global cooling challenge and meeting the thermal comfort needs in buildings and urban

Figure 2.4: Systems Approach to Cooling Provision



Source: Authors.

environments while simultaneously delivering the targets of the Paris Agreement, the Kigali Amendment, and the SDGs simultaneously require taking a systems approach to cooling provision. This requires assessing the current and future cooling needs in urban environments, and understanding the wide range of drivers and barriers that will shape the cooling system along with climatic, demographic, and socioeconomic statistics, energy and transport infrastructure, and existing and emerging technologies, as well as policies, goals, targets, commitments, and initiatives, and a new thinking in the key areas of mitigating, making, storing, managing, financing, and regulating cold to meet the current and future demand sustainably while building resilience. The optimum mix of fit-for-market solutions across behavior change, technology, services and/or skills, policy, business models, and finance solutions can be delivered through a “reduce-shift-improve” approach, adding in the intervention of “aggregate,” supporting both early wins and the deep systemic changes that are essential to achieve a sustainable and resilient cooling system in urban environments (Figure 2.4). Within this, the ultimate goal is to create an economically, environmentally, and socially sustainable integrated cooling system that:

- optimizes the sustainable use of all available natural, renewable, and waste resources;
- harnesses and leverages synergies between sectors and systems, to create symbiotic yet resilient relationships that account for unintended consequences and potential system vulnerabilities from integration and coupling;
- minimizes the need for energy-intensive active cooling devices through the use of passive approaches and techniques, behavior change, demand reduction, and aggregation strategies;
- is regularly monitored, optimized, and adequately maintained;
- is supported by policy, regulation, and appropriately structured finance; and
- enables safe decommissioning of component systems for reuse, remanufacture, and recycling in a circular economy model, with no unanticipated impacts on the overall sustainability of the system.

Mitigate

Mitigate refers to reducing the demand for active cooling in buildings and improving thermal comfort in residential and commercial buildings but also in outdoor urban environments through urban planning and infrastructure. Nature-based solutions (such as trees and plants), passive cooling techniques and approaches, and behavior changes can be a partial or, in some cases, full substitute for energy-consuming mechanical cooling processes with chemical refrigerants (i.e., active cooling) in buildings and can improve thermal comfort in outdoor urban environments significantly by reducing the heat island effect. Integrating cooling demand mitigation through design and other means is especially important in countries and regions with high ambient temperatures and humidity levels all year, such as tropical climates where monthly average temperatures are 18°C or higher all year round and there is no demand for heating.

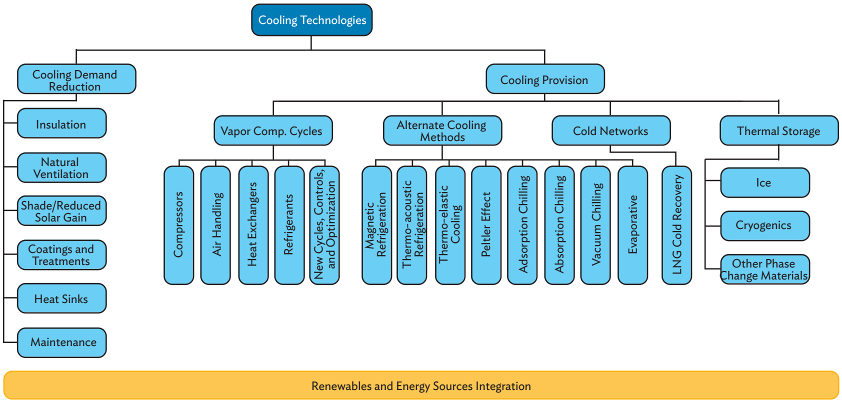
Passive cooling techniques and approaches reduce the cooling energy consumption either by removing heat from buildings to a natural heat sink, such as ground, air, or water, or by preventing heat from entering buildings from external heat sources, such as through shading and thermal insulation or white roofs. At the city level, smart urban design and construction can significantly reduce the need for indoor and outdoor cooling by minimizing the heat island effect. Examples include building wind flow corridors and water bodies into city designs, and replacing or coating heat-absorbing materials like asphalt and concrete with more reflective alternatives. Similarly, trees (and other plants) reduce urban air temperatures by providing shade and by releasing water vapor into the atmosphere from their leaves (i.e., transpiration). In the building sector, cool roofs are used to reduce solar radiation absorption, which can cut active cooling use by up to 20% (Carbon Trust et al. 2020). Similarly, green roofs reduce the solar heat gain and provide added insulation. Orientation is often used in building design to manage solar gain through the alignment of surfaces, windows, and inner courtyards with areas of shading or lower solar gain. Natural ventilation is a method of supplying fresh air to buildings by means of passive forces, typically achieved through alignment of openings to predominant wind or breeze directions or through utilizing differences in air pressure internally and externally. A study conducted in southern Europe revealed that natural ventilation can provide a 13% annual saving in air-conditioning energy use (Gonzalez-Lezcano and Hormigos-Jimenez 2016). The solution or combination of solutions should be carefully evaluated on a case-by-case basis taking into consideration parameters such as climatic conditions, occupancy levels, building function, and time of use to decide which are most appropriate and effective.

User behavior has a significant influence on energy consumption. Behavior changes that can reduce the need for active cooling include, among other things, increasing space cooling temperature set points, reducing the amount of cooled space, reducing lighting levels, switching to light-emitting diode (LED) bulbs (which emit less heat than conventional bulbs), optimizing thermostat settings, cooling only occupied rooms, and keeping windows and doors of the cooled space closed.

Make

Vapor compression-based air-conditioning systems are the most widely applied space cooling approach in buildings today and are expected to remain so in the foreseeable future due to their ease of use, scalability, and reliability (UNEP 2021a). Alternate cooling methods have been developed but remain for use in niche applications because they have not reached the scale needed to lower costs, such as magnetic refrigeration, thermo-acoustic cooling, and thermo-elastic cooling (Figure 2.5).

Figure 2.5: Cooling Technologies



LNG = liquefied natural gas.

Source: Peters (2018b).

While supporting the uptake of energy-efficient air conditioners is important, the key is to take a resource-focused approach and explore opportunities to harness free and waste energy resources. Space cooling needs can be effectively and efficiently met by making use of waste cooling resources that are localized, but also by harnessing and aggregating more remote waste cooling opportunities via a district cooling-type network infrastructure. For example, cold water from local rivers, lakes, or ocean sources can be circulated into a building to provide cooling. Similarly, industrial waste cold (e.g., waste cold from liquefied natural gas [LNG] regasification)[4] can be utilized to meet demands in an aggregated manner. In 2020, the global demand for LNG was estimated to be 360 million tons, which is expected to double to 700 million tons by 2040, with Asia set to drive approximately 75% of the new demand for LNG (Shell 2021). Globally, cold energy utilization from LNG regasification represents less than 1% of the total potential (Agarwal et al. 2017). Given the expected increase in demand for LNG,

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[4] LNG is obtained by cooling natural gas down to the point of condensation, –162°C, under atmospheric pressure. The cooling process reduces the volume of the gas 600 times, which not only makes it easier and safer to store and transport but also expands its scope of application. LNG is regasified before supplying it to end users, such as industry clusters, electrical power plants, and buildings. The LNG regasification process releases a large amount of cold energy, around 240 kilowatt-hours per ton of LNG.

the recovery of “coolth” from LNG regasification is an opportunity that merits further investigation.

District cooling networks that exploit economies of scale to offer space cooling in industrial, commercial, and residential buildings as a service are in use in some countries. Aside from the economy of scale advantage, these networks offer the possibility of sharing the benefit of waste resources across multiple users. Research suggests that district cooling is five to ten times more energy efficient than conventional active air-conditioning systems, and it can provide savings on cooling energy consumption by up to 50% (Danfoss n.d.). At the same time, rather than solely focusing on thermal comfort, the key is to assess how multiple cooling services could be integrated into a community-based thermal energy system using thermal networks for cooling.

Store

Space cooling represents almost 20% of all the electricity used in buildings and is projected to increase in the years ahead. Thermal energy storage can increase energy efficiency in buildings by reducing energy demand or peak loads for thermal energy needs (i.e., cooling and heating), and supports the wider energy system decarbonization by reducing the investment need for increased power grid and generation capacity, freeing up limited renewables capacity for other uses, reducing peak energy demand, and creating more room for intermittent renewable and waste thermal energy sources.

The variation in temperatures throughout the day can be exploited to provide cooling through the storage of cold energy at times when temperatures are low (typically during the night) and its subsequent use for absorbing heat when temperatures are high. Furthermore, for example, heat rejected from refrigeration systems can be used synergistically for heating, providing significant energy and emission savings, and leading to overall emissions reductions. With the integration of thermal energy storage, heat can be stored when refrigeration loads and heating requirements are mismatched, and the stored heat can be made available for use later. One study of refrigeration system heat recovery for space heating provision in supermarkets found that through such an approach, thermal storage increases the potential of heat recovery by 11%–12% (Maouris et al. 2020).

Manage

Under the Montreal Protocol, the Technology and Economic Assessment Panel recognized that “the impact of proper installation, maintenance, and servicing on the efficiency of equipment and systems is considerable over the lifetime of these systems while the additional cost is minimal. The benefit of proper maintenance is considerable. Appropriate maintenance and servicing practice can curtail up to 50% reduction in performance and maintain the related performance over the lifetime" (UNEP 2018, p. 4). Directly related to this, effective optimization, monitoring, and maintenance can, in fact, reduce total cooling GHG emissions by 13% and deliver substantial energy savings of up to 20% over the equipment life span (Kigali Cooling Efficiency Programme 2018). Additionally, the lifetime of equipment can be improved, and the risk of breakdown can be reduced through better design, installation, maintenance, and servicing practices, thereby preventing downtime and early replacement of equipment. For example, the Indoor Air Quality Association estimates that regular maintenance of air conditioners can reduce the risk of breakdowns by as much as 95% (IAQA n.d.) To this end, it is important to develop a cooling workforce with the right skill sets for the proper installation and maintenance of existing equipment and innovative technologies, taking into consideration the digitalization of the sector and the rapid pace of advancements, requiring dynamic and continuous training.

Digitalization of cooling systems with smart controls and sensors can also improve the energy performance of buildings by eliminating the unnecessary use of cooling equipment. These systems can be as simple as a programmable thermostat, or they may be complex systems that can control various processes throughout a group of buildings (UNEP 2021a). According to the IEA, between 2017 and 2040, digitalization could reduce total energy use in residential and commercial buildings by up to 10%, and provide a cumulative energy saving of 65 petawatt-hours, which is equal to the total final energy consumed in non-Organisation for Economic Co-operation and Development countries in 2015 (IEA 2017).

Finance and Regulate

According to the IEA, most consumers purchase air conditioners that are two to three times less efficient than the ones available on the market, the major reason being the high up-front costs associated with sustainable cooling technologies that can deliver cooling with a significantly lower environmental impact (IEA 2021). Air-conditioner manufacturers have been reluctant to risk large investments in research and development or commercialization of innovative technologies. Innovation prizes are effective tools to address this issue. For example, the Global Cooling Prize has recently shown what can be achieved with room air conditioners, and there are many emerging technologies that show promise. In April 2021, Gree Electric Appliances, Inc. of Zhuhai with partner Tsinghua University, and Daikin with partner Nikken Sekkei Ltd. emerged as the two winners among eight finalists of the Global Cooling Prize by producing prototypes that exceed the prize's five times lower climate impact criteria (Global Cooling Prize 2021). However, to bring these technologies to market, regulations and standards need to be aligned to the technological progress. Most of the performance standards today are not ambitious enough to encourage the adoption of best-in-class technologies (World Bank 2021). As a best-practice example, Japan's Top Runner Program, introduced in 1999, was designed to stimulate continuous improvement by setting energy efficiency targets for appliances based on the most efficient model available on the market (FuturePolicy.org 2014). Financial incentives such as subsidies for sustainable equipment and passive design solutions—e.g., cool roofs—that reduce the up-front cost of sustainable solutions can also be effective in increasing uptake. Equally, financial barriers and risk of investment could be addressed through business models such as pay-as-you-go, cooling-as-a-service, energy efficiency as a service, and energy savings insurance, as well as bulk procurement programs. For example, 100,000 room air conditioners have been procured in India under the Energy Efficiency Services Limited Super-Efficient Air Conditioning Programme, providing highly efficient equipment to consumers at a discounted price (EESL Mart; Singh and Gurumurthy 2019). Equally importantly, we need to develop the skills required to properly install, maintain, and operate these new technologies, especially in developing countries where significant skill shortages exist. At the building level, building energy codes and standards are effective in bringing about energy efficiency gains and can address the issues around split incentives in the building sector arising from the fact that those responsible for paying energy bills are often not those making investment decisions. For example, in India, a 20% reduction in cooling loads can be achieved by 2037–38 in upcoming commercial buildings through robust implementation of the building energy codes and climate-appropriate building envelopes (Ministry of Environment, Forest and Climate Change 2019). Furthermore, incentives can be provided to building developers, such as approving fast-track permits, waiving permit or planning fees, or allowing more buildable space, in exchange for integrating cooling load mitigation solutions in their projects (World Bank 2020). For example, in Hong Kong, China, the government grants gross floor area concession offers up to a 10% increase in allowable gross floor to developers that pursue certification under BEAM Plus (World Bank 2020; Buildings Department). However, the unintended consequences of such incentives should be carefully planned for. Research suggests that an excessive gross floor area concession can increase the building bulk and height, leading to negative impacts, especially in dense cities, such as a lack of daylight and views, and air ventilation problems (Qian, Fan, and Chan 2016).

2.5 Discussion

Energy use for space cooling has more than tripled since 1990, and rising temperatures, more frequent and extreme heatwaves, increasing incomes and access to electricity, population growth, and urbanization are expected to lead to an unprecedented demand for cooling in buildings in the next decade. Furthermore, often not captured by projections, providing access to cooling for all that need it to adapt to rising temperatures will require significantly more investment in cooling provision than anticipated to ensure equitable access to cooling.

How the cooling demand is met in buildings and outdoor urban environments and integrated into the wider energy systems will have implications for our climate and environment globally, but also for our broader aspirations for a sustainable human future. To deliver cooling in a sustainable and resilient way, we need more than efficient air conditioners. What is required is a needs-driven, system-level approach, first to mitigate demand through passive approaches and behavior changes; second to understand and identify multiple cooling needs, the thermal, waste, and wrong-time energy resources; and finally to define the right portfolio of solutions to integrate those resources with service needs optimally. This necessitates the integrated development of skills and capacity, the right policies and regulations, and finance and business models that are fit for purpose. It is important to recognize that the benefits of sustainable cooling provision go beyond reduced energy demand and costs, and emissions. Sustainable, resilient, and equitable access to cooling provides multiple benefits from productivity gains to health improvements, all of which have financial value and should be quantified where possible to underpin and facilitate investments.

2.6 Conclusions and Policy Recommendations

With the emerging need to adapt to climate change, the demand for cooling is set to grow substantially. Indeed, predictions suggest that energy demand for space cooling globally could overtake that for heating by 2060 (Isaac and van Vuuren 2009). Today, more than 1 billion people already face immediate risk from a lack of access to cooling, including 680 million slum dwellers living in hot-climate urban areas. Moreover, from a gender perspective, women and girls face significant challenges in accessing cooling services and the benefits they provide. Delivering sustainable and resilient cooling for all would provide a multitude of economic, social, and environmental benefits, and is key to achieving many of our SDG targets. Understanding, quantifying, and valuing the broader and potentially strategic impacts of sustainable and resilient cooling with their linkages to climate and development goals, targets, and commitments is key to attracting the necessary prioritization and investment by governments.

Business-as-usual approaches to cooling provision that primarily focus on piecemeal energy efficiency improvements and greening electricity will not be able to meet the surging cooling demand in buildings as well as other sectors. Achieving a truly sustainable and resilient cooling economy requires integrated system-level approaches to cooling provision, such as minimizing the demand for air conditioners in buildings through passive design techniques, looking for ways within the energy system to harness untapped thermal resources and make use of thermal energy storage to unlock otherwise redundant resources of renewable or waste energy, and aggregating demand through district cooling. It also requires integration and system management between the built environment and mobile cooling and energy demands.

As immediate wins, governments should (i) encourage the commercialization and uptake of ultra-high-efficiency sustainable air conditioners through more ambitious labeling and minimum energy performance standards supported by innovative finance and business models for consumers to overcome first-cost barriers, and (ii) strengthen building codes and standards through the integration of passive cooling and energy efficiency requirements.

In parallel, there is a need to develop the skills and training required to deliver current sustainable technologies in the market, but also to scan the horizon by engaging with industry and technology developers to understand the potential future skill requirements to meet the technologies in development and manufacturing.

To summarize, while meeting the surging cooling demand for everyone poses a massive environmental challenge, it also represents an opportunity for governments to strategically meet targets of the Paris Agreement, the Kigali Amendment, and the SDGs simultaneously. We are seeing the development of more energy-efficient and less polluting cooling equipment. But these alone will not be sufficient to deliver cooling for all sustainably. Achieving this will require rethinking the way we deliver cooling: minimizing the need for active cooling in the first place, making best use of renewable, thermal, and waste resources available and the novel energy vectors, thermal stores, and sustainable cooling technologies appropriate for the societal, cultural, climate, and infrastructure context, and developing the appropriate skills, capacity, business and finance models, and policy frameworks to support them. In other words, it will require a transition from thinking at the technology level to the system level.

References

Agarwal, R., T. J. Rainey, S. M. A. Rahman, T. Steinberg, R. K. Perrons, and R. J. Brown. 2017. LNG Regasification Terminals: The Role of Geography and Meteorology on Technology Choices. *Energies* 10(12): 2152. doi: 10.3390/en10122152

Belsare V., and V. Pandey. 2008. Management of Heat Stress in Dairy Cattle and Buffaloes for Optimum Productivity. *Journal of Agrometeorology* 10: 365–368.

Buildings Department. n.d. Summary of Gross Floor Area (GFA) and Related Information of Private Developments. https://www.bd.gov.hk/en/resources/codes-and-references/notices-and-reports/GFA.html (accessed 12 November 2021).

Campbell, I., A. Kalanki, and S. Sachar. 2018. *Solving the Global Cooling Challenge. How to Counter the Climate Threat from Room Air Conditioners*. Rocky Mountain Institute.

Carbon Trust, Cool Coalition, High-Level Champions, Kigali Cooling Efficiency Program, and Oxford Martin School at the University of Oxford. *2020. Climate Action Pathway: Net-Zero Cooling – Executive Summary.* https://coolcoalition.org/climate-action-pathway-net-zero-cooling-executive-summary/ (accessed 15 February 2021).

Chavaillaz, Y. P. Roy, A.-I. Partanen, L. Da Silva, É. Bresson, N.Mengis, D. Chaumont, and H.D. Matthews. 2019. Exposure to Excessive Heat and Impacts on Labour Productivity Linked to Cumulative CO2 Emissions. *Scientific Reports* 9(1): Article 13711. doi: 10.1038/s41598-019-50047-w

Clean Cooling Cooperative. 2021. How Countries Can Enhance Nationally Determined Contributions in 2021 with Climate-Friendly Cooling. https://www.cleancoolingcollaborative.org/report/how-countries-can-enhance-nationally-determined-contributions-in-2021-with-climate-friendly-cooling/ (accessed 2 September 2021).

Climate Change Committee. 2019. *Impacts of Climate Change on Meeting Government Outcomes in England*. https://www.theccc.org.uk/publication/impacts-of-climate-change-on-meeting-government-outcomes-in-england-paul-watkiss-associates/ (accessed 3 November 2021).

Cool Coalition. 2021. Boosting Climate Ambition: Enhancing NDCs with Climate-Friendly Cooling. 12 May. https://coolcoalition.org/boosting-climate-ambition-enhancing-ndcs-with-climate-friendly-cooling/ (accessed 2 September 2021).

Corlett, R. T. 2014. Essay 2: The Impacts of Climate Change in the Tropics. https://www.jcu.edu.au/state-of-the-tropics/publications/2014-state-of-the-tropics-report/2014-essay-pdfs/Essay-2-Corlett.pdf

Danfoss. n.d. District Cooling. https://www.danfoss.com/en-gb/markets/district-energy/dhs/district-cooling/ (accessed 12 November 2021).

Dash, S., A. K. Chakravarty, A. Singh, A. Upadhyay, M. Singh, and S. Yousuf. 2016. Effect of Heat Stress on Reproductive Performances of Dairy Cattle and Buffaloes: A Review. *Vet World* 9(3): 235–244. doi: 10.14202/vetworld.2016.235-244.

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ). 2018. *Coordinating Finance for Sustainable Refrigeration and Air Conditioning*. Eschborn, Germany: GIZ.

EESL Mart. https://eeslmart.in/ (accessed 8 November 2021).

FuturePolicy.org. 2014. Japan's Top Runner Programme, 15 December. https://www.futurepolicy.org/climate-stability/japans-top-runner-programme/ (accessed 4 November 2021).

Garry, M. 2019. Professor Peters at ATMO Europe. We Need to Reinvent the Cold Chain. 18 October. *hydrocarbons21.com* (accessed 28 April 2021).

Global Cooling Prize. 2021. Breakthrough, Climate-Friendly https://globalcoolingprize.org/grand-winners-press-release/ (accessed12 May 2021).

Gonzalez-Lezcano R., and S. Hormigos-Jimenez. 2016. Energy Saving Due to Natural Ventilation in Housing Blocks in Madrid. *IOP Conference Series Materials Science and Engineering*, 138: 012002. doi: 10.1088/1757-899X/138/1/012002

Green Cooling Initiative. Country Data. https://www.green-cooling-initiative.org/country-data/#!total-emissions/all-sectors/absolute (accessed 14 February 2021).

Guardaro, M., M. Messerschmidt, D. M. Hondula, N. B. Grimm, and C. L. Redman. 2020. Building Community Heat Action Plans Story by Story: A Three Neighborhood Case Study. *Cities*. 107: 102886. doi: 10.1016/j.cities.2020.102886

Indoor Air Quality Association (IAQA). n.d. HVAC Preventive Maintenance is Essential (6 Reasons Why). https://iaqa.org/consumer-resources/hvac-preventive-maintenance-is-essential/ (accessed 7 July 2021).

Intergovernmental Panel on Climate Change (IPCC). 2021. Summary for Policymakers. In V. Masson-Delmotte et al. eds. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK and New York, NY, US: Cambridge University Press.

International Energy Agency (IEA). 2017. *Digitalization and Energy*. Paris: IEA.IEA. https://www.iea.org/reports/digitalisation-and-energy (accessed 12 November 2021).

———. 2018. *The Future of Cooling: Opportunities for Energy-Efficient Air Conditioning*. Paris: IEA. https://www.iea.org/reports/the-future-of-cooling (accessed 24 March 2021).

———. 2020. *Tracking Buildings 2020 – Analysis*. Paris: IEA. https://www.iea.org/reports/tracking-buildings-2020 (accessed 25 March 2021).

———. 2021. *Cooling – Analysis*. Paris: IEA. https://www.iea.org/reports/cooling (accessed 17 February 2021).

Isaac, M., and D. P. van Vuuren. 2009. Modeling Global Residential Sector Energy Demand for Heating and Air Conditioning in the Context of Climate Change. *Energy Policy* 37(2): 507–521. doi: 10.1016/j.enpol.2008.09.051

Jadhav, R. 2015. Indian Chicken Prices Surge to Record as Heat Wave Kills Millions of Birds. *Reuters,* 1 June. https://www.reuters.com/article/india-heatwave-chicken-idUSL3N0YM0B920150601 (accessed 2 June 2021).

Juquois, F. 2017. Climate: The Importance of the More Energy-efficient Buildings. *ID4D*, 7 February. https://ideas4development.org/en/buildings-climate-change/ (accessed 11 March 2022).

Kigali Cooling Efficiency Programme. 2018. Optimization, Monitoring, and Maintenance of Cooling Technology. https://k-cep.org/wp-content/uploads/2018/03/Optimization-Monitoring-Maintenance-of-Cooling-Technology-v2-subhead….pdf

Kjellstrom, T., N. Maitre, C. Saget, M. Otto, and T. Karimova. 2019. *Working on a Warmer Planet: The Effect of Heat Stress on Productivity and Decent Work*. Geneva: International Labour Organization. http://www.ilo.org/global/publications/books/WCMS_711919/lang--en/index.htm (accessed 25 March 2021).

Krayenhoff, E. S. et al. 2021. Cooling Hot Cities: A Systematic and Critical Review of the Numerical Modelling Literature. *Environ. Res. Lett.* 16(5): 053007. doi: 10.1088/1748-9326/abdcf1

Li, D. et al. 2019. Urban Heat Island: Aerodynamics or Imperviousness? *Science Advances* 5(4): eaau4299. doi: 10.1126/sciadv.aau4299

Lundgren-Kownacki, K., E. D. Hornyanszky, T. A. Chu, J. A. Olsson, and P. Becker. 2018. Challenges of Using Air Conditioning in an Increasingly Hot Climate. *International Journal of Biometeorology* 62(3): 401–412. doi: 10.1007/s00484-017-1493-z

Madge, G. 2021. One Billion Face Heat-stress Risk from 2°C Rise. UK Met Office, 9 November. https://www.metoffice.gov.uk/about-us/press-office/news/weather-and-climate/2021/2c-rise-to-put-one-in-eight-of-global-population-at-heat-stress-risk (accessed 9 November 2021).

Masson-Delmotte, V., et al., eds. 2018: *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above*

Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty. Intergovernmental Panel on Climate Change.

Maouris, G., E. J. Sarabia Escriva, S. Acha, N. Shah, and C. N. Markides. 2020. CO2 Refrigeration system Heat Recovery and thermal Storage Modelling for Space Heating Provision in Supermarkets: An Integrated Approach. *Applied Energy* 264: 114722. doi: 10.1016/j.apenergy.2020.114722

Ministry of Environment, Forest and Climate Change. 2019. India Cooling Action Plan.

Monsalve, C., and K. Watsa. 2020. Human Capital and Climate Action: Outcomes that Deliver for People and Planet. World Bank Blog, 12 May. https://blogs.worldbank.org/climatechange/human-capital-and-climate-action-outcomes-deliver-people-and-planet (accessed 24 March 2021).

Mora, C. et al. 2017. Global Risk of Deadly Heat. *Nature Climate Change* 7(July). doi: 10.1038/nclimate3322

National Dairy Development Board. 2017.Indian Dairy Association – 45th Dairy Industry Conference. https://www.nddb.coop/about/speech/dic (accessed 2 June 2021).

North American Sustainable Refrigeration Council. n.d. The HFC Problem. https://nasrc.org/the-hfc-problem (accessed 27 April 2021).

Peters, T. 2018a. A Cool World: Defining the Energy Conundrum of Cooling for All. University of Birmingham.

____. 2018b. *Clean Cooling Landscape Assessment*. https://www.clean-cooling.ac.uk/resources/CleanCoolingLandscapeAssessment%2012-18.pdf

Qian, Q. K., K. Fan, and E. H. W. Chan. 2016. Regulatory Incentives for Green Buildings: Gross Floor Area Concessions. *Building Research & Information* 44(5–6): 675–693. doi: 10.1080/09613218.2016.1181874

Revi, A. et al. 2014. Urban Areas in Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. In *Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,* pp. 535–612.

Salamanca, F., M. Georgescu, A. Mahalov, M. Moustaoui, and M. Wang. 2014. Anthropogenic Heating of the Urban Environment Due to Air Conditioning. *Journal of Geophysical Research: Atmospheres* 119(10): 5949–5965. doi: 10.1002/2013JD021225.

Schlanger, Z. 2018. 70% of Saudi Arabia's Electricity is used for Air Conditioning. *Quartz,* 22 May. https://qz.com/1284239/70-of

-saudi-arabias-electricity-is-used-for-air-conditioning/ (accessed 2 November 2021).

Sejian, V., R. Bhatta, J. B. Gaughan, F. R. Dunshea, and N. Lacetera. 2018. Review: Adaptation of Animals to Heat Stress. *Animal* 12: s431–s444. doi: 10.1017/S1751731118001945

Shell Plc. 2021. Shell LNG Outlook 2021. https://www.shell.com/energy-and-innovation/natural-gas/liquefied-natural-gas-lng/lng-outlook-2021.html (accessed 6 May 2021).

Singh, M., and G. Gurumurthy. 2019. Bulk Procurement in Room Air Conditioning: A Critical Analysis of the EESL Programme. TERI Policy Brief 2009. New Delhi: The Energy and Resources Institute.

Sustainable Energy for All. 2019. *Chilling Prospects: Tracking Sustainable Cooling for All 2019.* https://www.seforall.org/publications/chilling-prospects-2019 Vienna: Sustainable Energy for All (accessed 24 March 2021).

United Nations (UN). 2019. *World Population Prospects 2019*. https://population.un.org/wpp/ (accessed 17 May 2021).

UN Environment Programme (UNEP). 2018. *UNEP Report of the Technology and Economic Assessment Panel. Volume 5: Decision XXIX/10 Task Force Report on Issues Related to Energy Efficiency While Phasing Down Hydrofluorocarbons*. September (updated final report).

———. 2019. *Emissions Gap Report 2019*. Nairobi: UNEP. http://www.unep.org/resources/emissions-gap-report-2019 (accessed 24 March 2021).

———. 2021a. *Beating the Heat: A Sustainable Cooling Handbook for Cities*. Nairobi: UNEP. http://www.unep.org/resources/report/beating-heat-sustainable-cooling-handbook-cities (accessed 3 November 2021).

———. 2021b. *2021 Global Status Report for Buildings and Construction*. Nairobi: UNEP. https://globalabc.org/resources/publications/2021-global-status-report-buildings-and-construction (accessed 3 November 2021).

UN Human Settlement Programme (UN-Habitat). 2020. World Cities Report. 2020. *The Value of Sustainable Urbanization*. Nairobi: UN-Habitat. https://unhabitat.org/World%20Cities%20Report%202020 (accessed 25 March 2021).

United Nations Children's Fund (UNICEF). 2016. Girls Spend 160 Million More Hours than Boys Doing Household Chores Everyday. Press Release, 7 October. https://www.unicef.org/press-releases/girls-spend-160-million-more-hours-boys-doing-household-chores-everyday (accessed 4 June 2021).

United States Environmental Protection Agency (US EPA). 2014. Heat Island Effect. https://www.epa.gov/heatislands (accessed 3 November 2021).

World Bank. 2019. Four Things You Should Know About Sustainable Cooling. 23 May. World Bank. https://www.worldbank.org/en/news/feature/2019/05/23/four-things-you-should-know-about-sustainable-cooling (accessed 24 March 2021).

____. 2020. *Primer for Cool Cities: Reducing Excessive Urban Heat – With a Focus on Passive Measures*. Washington, DC: World Bank. doi: 10.1596/34218

____. 2021a. *The Cold Road to Paris: Mapping Pathways Toward Sustainable Cooling for Resilient People and Economies by 2050*. Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/36439 (accessed 4 November 2021).

____. 2021b. Universal Access to Sustainable Energy Will Remain Elusive Without Addressing Inequalities. World Bank Press Release 7 June. https://www.worldbank.org/en/news/press-release/2021/06/07/report-universal-access-to-sustainable-energy-will-remain-elusive-without-addressing-inequalities (accessed 3 November 2021).

World Health Organization (WHO). 2014. *Quantitative Risk Assessment of the Effects of Climate Change on Selected Causes of Death, 2030s and 2050s*. Geneva: WHO.

____. 2021. Climate Change and Health. https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health (accessed 28 April 2021).

____. n.d. Climate Change. https://www.who.int/heli/risks/climate/climatechange/en/ (accessed 28 April 2021).

Xu, C., T. A. Kohler, T. M. Lenton, J.-C. Svenning, and M. Scheffer. 2020. Future of the Human Climate Niche. *PNAS* 117(21): 11350–11355. doi: 0.1073/pnas.1910114117

3

Promoting Green Buildings: Barriers, Solutions, and Policies

Dina Azhgaliyeva and Dil B. Rahut

3.1 Introduction

Several countries from developing Asia, including Thailand, Kazakhstan, and Viet Nam, announced net-zero carbon emission targets by around 2050–2060 at the 26th United Nations Climate Change Conference of the Parties (COP26) in Glasgow from 31 October to 13 November 2021. Along with the energy sector, other sectors such as construction, heavy industries, and transport will all need to decarbonize to reach these targets. This chapter reviews the existing policy support for decarbonizing the building and construction sector, particularly those policies promoting green buildings.

3.1.1 Greenhouse Gas Emissions

Greenhouse gas (GHG) emissions due to human consumption have been increasing over time, which is leading to major climatic changes (Strandsbjerg et al. 2021). Climate change is manifesting in the form of an increase in temperature, prolonged drought, variation in the rainfall pattern, glacial melting, flood, and salination, resulting in the loss of life, assets, and livelihoods (Aryal et al. 2020b). Compared to 1961, the global average temperature has increased by about 0.7°C in 2019, and during the same period, annual carbon dioxide (CO_2) emissions have increased from 9.36 billion tons to 36.45 billion tons (Ritchie, Roser, and Rosado 2020). However, the increase in temperature has varied across the regions. The adverse effect of GHG emissions and climate change is manifesting through prolonged drought (Le Houérou 1996; Easterling et al. 2000; Dai 2011; Leng, Tang, and Rayburg 2015), flooding and erratic rainfall (Aryal et al. 2020a), salination (Reid et al. 2009; Muir 2010; Colombani et al. 2016; Slama, Gargouri-Ellouze, and Bouhlila

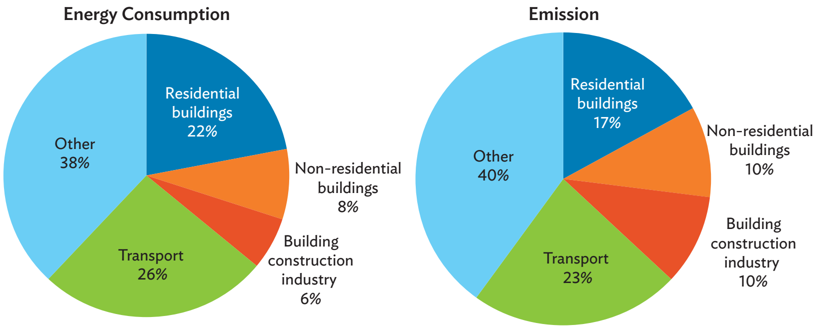
2020), desertification (Le Houérou 1996; Sivakumar 2007; Shukla et al. 2019), water stress (Gandure, Walker, and Botha 2013; Hejazi et al. 2015; Gosling and Arnell 2016), glacial lake outburst flooding (Bajracharya, Mool, and Shrestha 2007; Kaushik et al. 2020), and sinking of coastal land (Fuchs 2010; Erkens et al. 2015). Unchecked increase in GHG emissions could threaten the progress made thus far (Aaheim et al. 2012; Victor 2012; Estrada, Tol, and Gay-Garcia 2015; Albert 2020) and would pose challenges to achieving the global Sustainable Development Goals. It is thus of paramount importance for the global community to invest in technology and promote policies that will contribute to reducing GHG emissions.

3.1.2 GHG Emissions in the Building Sector

The Asia and Pacific region is currently responsible for over 50% of global GHG emissions (Asakawa 2021). Decarbonizing the building sector is important not only for reaching nationally determined contributions (NDCs) and net-zero emissions targets, but also for making cities more livable. Many large cities in developing Asia (not only in India and the People's Republic of China [PRC]) suffer from high levels of air pollution, especially in winter, which has a negative impact on life expectancy, health, and quality of life. Buildings account for about 36% of the total energy consumption (22% from residential buildings, 8% from non-residential buildings, and 6% from manufacturing of construction material) and contribute to about 37% of GHG emissions (17% from residential buildings, 10% from non-residential buildings, and 10% from manufacturing of construction material) (UNEP 2021). The building construction industry (manufacturing construction material such as steel, cement, and glass) consumes 5% of energy and contributes 10% of GHG emissions (Figure 3.1).

Concrete and steel are the top contributors to GHG emissions (two-thirds) among construction materials, followed by bricks (18%) and aluminum (8%) Asia, particularly the PRC, is the largest contributor of GHG emissions from construction materials, and it is projected that India will overtake the PRC by 2053. It is alarming that building material–related emissions alone are projected to rise by 3.5 to 4.6 gigatons of CO_2 equivalent per year from 2020 to 2060, mostly coming from developing countries (Zhong et al. 2021).

Figure 3.1: Global Shares of Energy Consumption and Emissions, 2019



Source: UNEP (2021).

3.1.3 Prospects

Energy use in residential and non-residential buildings relates to cooking, lighting, heating (in cold countries), and cooling (in hot countries).[1] Given growing populations, increasing income, and urbanization, the demand for energy in residential and non-residential buildings will continue to rise. Reducing the energy consumption in such buildings could thus contribute to reducing GHG emissions and mitigate climate change. Improving energy efficiency through controlling leakages and waste and using gadgets that require less energy could help to minimize energy consumption. Numerous private and public benefits are also associated with the adoption of green building, such as a low life-cycle cost (Arif et al. 2009; Abidin and Powmya 2014; Windapo 2014); energy savings (Manoliadis, Tsolas, and Nakou 2006; Mulligan et al. 2014); water savings (Ahn et al. 2013; Devine and Kok 2015); comfort, satisfaction, and health benefits (Arif et al. 2009; Gou, Lau, and Prasad 2013); reduction in the environmental impact of buildings (Manoliadis, Tsolas, and Nakou 2006; Ahn et al. 2013); better indoor environmental quality (Bond 2010; Aktas and Ozorhon 2015); and good company image and/or reputation or marketing strategy (Zhang, Shen, and Wu 2011).

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[1] For more information about cooling demand, see Chapter 2 in this book: Future-Proofing Sustainable Cooling Demand.

The demand for energy-efficient buildings is growing, but it has yet to gain momentum in developing countries. Governments around the world have recognized the importance of the building sector in decarbonization, as is evident from the fact that from the countries who submitted NDCs, 136 countries stated *buildings*, 53 stated *energy-efficient buildings*, and 38 stated *building energy code* (UNEP 2020). Recognizing the importance of green building in reducing environmental degradation (Yoon and Lee 2003), governments in developing countries such as Viet Nam have initiated actions to promote green buildings, but the implementation has been slow and lacking in policy support (Nguyen and Gray 2016). Although the investment in energy-efficient buildings has been increasing, it is small compared to the total investment in the building and construction sector. For example, in 2019, the investment in energy-efficient buildings was $152 billion, compared to $5.8 trillion investment in the building and construction sector. Currently, the ratio between investment in energy-efficient buildings to conventional construction is 1:37 (UNEP 2020).

In light of climate change and the increasing need to reduce GHG emissions to conserve scarce resources, the concept of green buildings is increasingly being recognized as an important way to reduce humanity's carbon footprint and provide a high quality, environmentally friendly future. Green buildings are complex and multifaceted and encompass several features, such as energy, water, and other resource efficiency; use of renewable energy; pollution and waste reduction measures; good indoor air quality; use of non-toxic material; environmentally friendly; and adaptable to changing environments.

This chapter explores the opportunities and challenges associated with the adoption of green buildings, particularly in developing Asia. It reviews recent policies promoting the development in green buildings and provides recommendations to policy makers. The literature studying the effectiveness of policies promoting energy efficiency in buildings is more abundant than on policies promoting green buildings. A systematic review of the definition of green buildings, their environmental benefits, and the associated technological, life cycle assessment, managerial, and behavioral and/or cultural factors are provided in Zuo and Zhao (2014). Franco, Pawar, and Wu (2021) provide a comparative assessment of green building policies. However, a review of green building policies is scarce. Therefore, this chapter aims to fill this gap.

The remainder of this chapter is structured as follows. Section 3.2 provides a definition of green buildings. Sections 3.3 and 3.4 explain the need for policy support for green buildings by reviewing the barriers to green buildings, as well as the opportunities and solutions that green buildings provide. Section 3.5 reviews the most popular existing policies to promote green buildings. Section 3.6 concludes and provides policy recommendations.

3.2 Definition of Green Buildings

Green buildings usually refer to the use of environmentally friendly construction materials, processes, operation, and maintenance. The concept of a green building is driven by incentives to reduce the cost of energy and waste management in light of global warming and environmental degradation. It is a common approach among public buildings where energy use is high. Green buildings also have a higher social and environmental value, which cannot be quantified in monetary terms (Esa et al. 2011). Given the high energy consumption by the construction sector, green and sustainable building practices have been implemented for years (Lorenzen 2012), and there is increasing demand to reduce energy consumption as well as to reduce environmental degradation (Azhar et al. 2011; Jalaei and Jrade 2015).

The green building concept has evolved over time. Initially, a green building was defined only in terms of environmental performance (Kua and Lee 2002; Yoshida and Sugiura 2010), but it has evolved to include sustainable and environmentally friendly construction methods and products (Hoffman and Henn 2008; Allwood et al. 2011; Hertwich et al. 2020), and further sustainable and environmentally friendly construction methods and products were added. In recent years, the efficient use of resources, the improvement of air quality, and the reduction of pollution have been added to the characteristics of a green or sustainable building (Haapio and Viitaniemi 2008; Kibert 2016; Li et al. 2016).

Unlike energy-efficient buildings, green buildings include environmental aspects other than energy efficiency, such as water efficiency, waste management, and the use of green materials in construction (Figure 3.2). Green buildings should not be confused with net-zero carbon buildings, which have achieved net-zero carbon emissions by reducing energy consumption and are powered from onsite and/or offsite renewable energy sources (UKGBC 2019). Unlike green buildings, net-zero carbon buildings need to generate renewable energy and are usually low-rise buildings to produce enough renewable energy to satisfy building demand. Net-zero carbon buildings are less common than green and energy-efficient buildings.

Figure 3.2: Energy Efficient, Green, and Net-Zero Carbon Buildings

GHG = greenhouse gas.

Source: Authors.

3.3 Barriers

Although green buildings are attractive and environmentally friendly, and have a major role to play in reducing GHG emissions and protecting the environment, there are several challenges to increasing the adoption of green buildings. Barriers to financing green buildings include (i) split incentives in the building market; (ii) developer hesitance to absorb the additional up-front costs of green building design, when the cost savings will only accrue for future owners; (iii) mismatch between building longevity and the relatively short holding periods for real estate assets in investment portfolios; (iv) minimal landlord incentives to invest in energy-efficient equipment because the tenant is paying the utility bill; and (v) subsidized or government-controlled energy prices (Kapoor et al. 2021).

The cost of implementing green buildings is the most important challenge in scaling their adoption. The high cost also leads to higher rental costs and makes it difficult to find both investors and tenants, thus making green building less attractive to individuals with limited capital. There are also three other challenges: (i) lack of awareness, information, and education about the benefits of green buildings (both private and public benefit); (ii) limited access to design, construction materials, and skilled workers; and (iii) the lack of guidelines and policies promoting green buildings.

A study in Malaysia highlighted that lack of awareness is the major challenge for green building implementation in the country (Esa et al. 2011), and this is also true in many developing countries around the world. Similarly, in Ghana, Chan et al. (2018) found higher costs, lack of financing, lack of skilled labor and market for green building (demand and supply), and lack of green building codes, regulation, promotion, leadership, and government incentives. Green certificates could be a vital tool to enhance sustainability by encompassing design, construction, operation, maintenance, and demolition, or building information modeling (Muller et al. 2019). Leadership in energy and environmental design (LEED) is one of the most widely used certifications based on several encompassing features (Nguyen and Altan 2011; Dong, O'Neill, and Li 2014; Suzer 2015). Critical impediments to the adoption of green buildings in developing countries include high cost, lack of incentives (grants, tax reliefs), and lack of information; trained labor, material, and technology; and absence of lead organizations (DuBose, Bosch, and Pearce 2007; Potbhare, Syal, and Korkmaz 2009). Developing countries should therefore invest in removing these barriers. As the rapidly growing population and increases in income, particularly in developing countries, will increase the need for buildings and associated housing timbers that could act as carbon sink and reduce the production of construction materials that emit carbon (Churkina et al. 2020).

3.4 Opportunities and Solutions

As the climate is changing rapidly and causing distress and destruction, there is an increasing need to reduce GHG emissions from buildings, including in those associated with the material and construction methods that contribute significantly to emissions (Li et al. 2017). It is of paramount importance to promote the concept of green and sustainable building at all levels—commercial, public, and residential. Failure to act now could pose a great threat to humanity in the coming decades. Green or sustainable buildings could contribute to decarbonization by reducing energy consumption in building use, as well as material and construction (Li et al. 2017; Zhong et al. 2021). Increases in population and income are resulting in an increase in demand for housing (Samir and Lutz 2017; GlobalABC, IEA, and UNEP 2019), which in turn increases demand for construction materials. There are thus opportunities to use materials that are environmentally friendly to build structures that are energy efficient (IEA 2019; Hertwich et al. 2019).

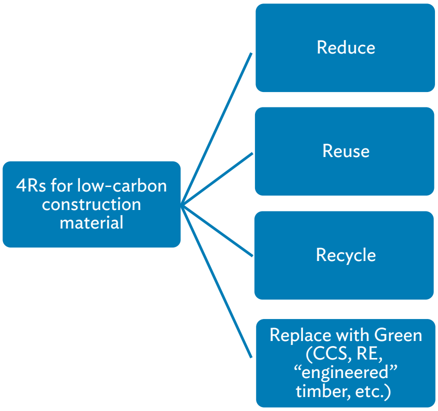
The construction industry is responsible for 11% of the world's human-made CO_2 emissions (*The Economist* 2022). Steel and cement are among the most carbon-intensive industrial materials on the planet, and their production accounts for 14%–16% of global energy-related CO_2 emissions (S&P Global 2021). If the cement industry was a country, it would be the third-largest emitter of GHGs (*The Economist* 2021). To meet a 2°C scenario, the cement industry needs to reduce its emissions by 24% by 2050, while meeting a demand forecast for an increase by 23% (BNEF 2021). GHG emissions from construction materials can be reduced via the 4Rs: reduce, reuse, recycle, and replace with low-carbon construction materials (Figure 3.3). Reducing the use of or greening construction materials such as concrete, steel, bricks, and aluminum would play an important role in reducing GHG emissions in the construction sector (Hertwich et al. 2020; Hansemann et al. 2021; Zhong et al. 2021). Replacing construction material with low-carbon materials such as engineered timber or other lightweight material could support decarbonization (Churkina et al. 2020; Arehart et al. 2021). Cement can also be replaced with industrial waste (*The Economist* 2022). Further, recycling and reuse of building reconstruction materials, such as recycled concrete, would also contribute to emissions reduction (Dodoo, Gustavsson, and Sathre 2009; Liu, Bangs, and Müller 2013; Oh et al. 2014).

Non-green buildings consume a huge amount of energy for light, cooling, heating, and cooking purposes, so green buildings using equipment that is energy efficient could dramatically reduce energy consumption, particularly with the assistance of other technologies, such as artificial intelligence for automatically controlling lights, heating, and cooling systems.

The construction industry uses natural resources and consumes massive amounts of energy; it is responsible for large carbon emissions, environmental degradation, and global warming (Stadel et al. 2011; Wong et al. 2013; Wang 2014; Wong and Kuan 2014; Wong and Zhou 2015). There is a need to invest, within the construction industry, in reducing GHG emissions and environmental degradation, which could provide opportunities to producers of environmentally friendly materials and products. Given that the major challenges for green buildings are the cost, awareness, construction materials, and skills, there is a strong need for government policies such as tax subsidies, credits, and interest rates to encourage the expansion of green building and awareness of its benefits. There are tremendous opportunities for the construction industry to supply green building materials and for financial intermediates to finance costs. For the consumer, green buildings are expected to reduce the cost of maintenance and energy, although they may be subject to higher rental fees as construction costs are high (Esa et al. 2011).

Policy support for green buildings can incentivize demand for low-carbon construction materials, and investment in green construction could provide huge opportunities to producers of such construction materials. The United Kingdom, India, Germany, Canada, and the United Arab Emirates have committed to support new markets for low-carbon steel, cement, and concrete (S&P Global 2021).

Figure 3.3: Greening Construction



4Rs = reduce, reuse, recycle, and replace, CCS = carbon capture and storage, RE = renewable energy.

Source: Authors.

3.5 Policies

Because of the existing barriers for financing green buildings (as mentioned in section 3.3) and their positive externalities for the environment and energy security (as mentioned in section 3.4), policy support is provided for green buildings in many countries. The policy instruments to support green buildings can be structured as shown in Figure 3.4. Policy makers need to consider the differentiation of policy support for green buildings to ensure such policies are more cost-effective (Table 3.1). Policies are usually differentiated by or limited to the following building types: commercial, industrial, residential, and public sector buildings. Policy incentives could be provided for energy efficiency improvements in general, green, and zero-carbon buildings; renewable energy installations in buildings; research, development, and demonstration; manufacturing of energy-efficient technologies; and building energy audits. Policy incentives could be funded from the general public budget for a specified period or from a specified, limited fund. Such incentives would end after the specified period or when the fund is exhausted. Policy support could be provided at different stages: for the construction of new green buildings or for retrofitting existing buildings to meet green building standards. The advantage of supporting new green building construction is that such a policy would also support demand for low-carbon construction materials such as steel, cement, and concrete, which would help to reduce emissions and waste at the construction stage and not only at the operation stage.

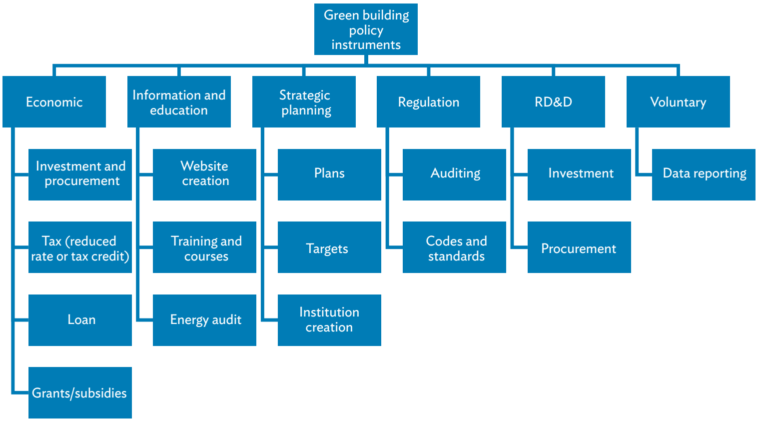
Mandatory green building regulations may be a more effective tool to promote energy efficiency improvements than voluntary instruments (Kim and Lim 2018). A review of green building standards and certifications has been provided by Franco, Pawar, and Wu (2021), and only policies with mandatory requirements to obtain green building certification are effective in promoting green buildings (Fuerst, Kotokosta, and McAllister 2014). For example, a mandatory energy disclosure program contributed to the reduction in energy usage and carbon emissions from the affected building stocks in Australia (Kim and Lim 2018). Studies on developing Asia include evaluations of the effectiveness of green building policies in the PRC (Shi et al. 2014; Shen and Faure 2021), the determinants of green building adaptation in the PRC (Wang et al. 2018), and barriers to green building development in Malaysia (Samari et al. 2013).

Green building policies not only promote energy efficiency, but also benefit corporations, households, and governments by reducing energy bills. Green building policies could thus be considered a sustainable alternative to energy subsidies. A database of building policies has been provided by the International Energy Agency (IEA) (2021) Policies and Measures database. Figure 3.5 illustrates the implementation of new (not accumulated) policies supporting energy efficiency in buildings. In addition to green building policies, other environmental policies, such as green subsidies, environmental taxes, and carbon emissions trading, can also promote green buildings. A combination of environmental taxes, green subsidies, and a carbon trading scheme is even better at promoting green buildings (Yang et al. 2021).

Any policy instrument can be cost-effective if selected, designed, implemented, and enforced in a tailored way to local resources, capacities, and cultures (Boza-Kiss, Moles-Grueso, and Urge-Vorsatz 2013): “No single policy instrument in itself is optimal to promote green building” (Shen and Faure 2021, p. 183), but rather an effective mix of policies need to be designed to promote green buildings (Rosenow et al. 2016). Many studies have therefore focused on an efficient mix of policies (Lee and Yik 2004; Rosenow, Kern, and Rogge 2017) rather than on individual policies. Theoretical and empirical contributions from the literature on energy efficiency policy mixes are provided in Rosenow et al. (2016). A comprehensive literature review of regulatory and voluntary policy instruments on building energy efficiency is provided in Lee and Yik (2004), but there is a lack of systematic reviews on literature studying the effectiveness of policies promoting green buildings.

The evaluation of effectiveness of energy efficiency policies is more abundant (e.g., Rosenow, Kern, and Rogge 2017) than that of green building policies. Most studies have focused on building energy efficiency, and even papers on green buildings tend to refer to the benefits of green buildings in terms of improved energy efficiency and reduction of GHG emissions and waste. The use of green construction materials and the recycling, reuse, and reduction of construction materials have been overlooked.

Figure 3.4: Green Building Policies



R&D = research, development, and demonstration.

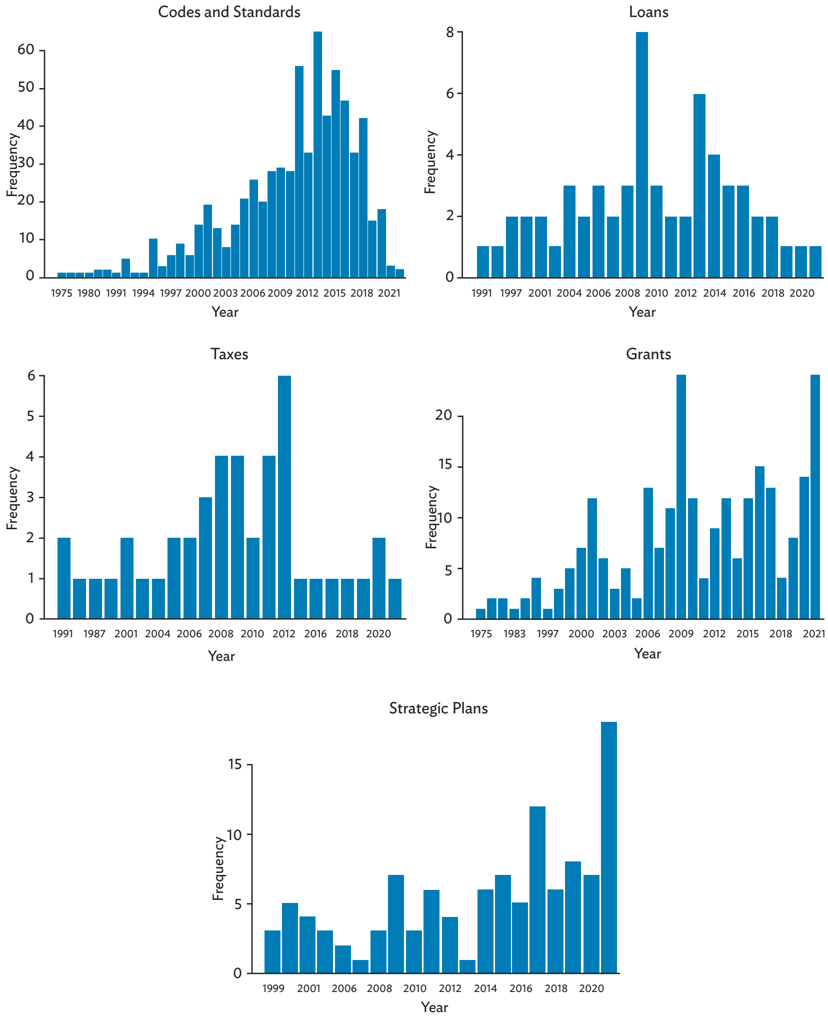
Source: Authors' elaboration using data from IEA (2021).

Table 3.1: Considerations for Policies Supporting Green Buildings

Policy Target	Options
Building types	Public sector, commercial, industrial, residential
Change	Green buildings or other (energy efficient, net-zero carbon, renewable energy installations in buildings, research and development, manufacturing of energy-efficient technologies, energy audits)
Stage	New/existing buildings
Measure of results	Meeting specified building standards, technology installations, etc.
Policy instrument	As noted in Figure 3.4
Strictness	Voluntary or mandatory

Source: Authors.

Figure 3.5: Policies Supporting Energy Efficiency in Buildings


Codes and Standards

Loans

Taxes

Grants

Strategic Plans

Source: Authors' elaboration using data from IEA (2021).

Box 3.1: Green Building Policies in the People's Republic of China

This box is written by Nicolas Dei Castelli, senior transport specialist, Asian Development Bank (ADB); Yixin Yao, senior research fellow, Asian Development Bank Institute; and Ellen May Reynes, climate change and technical project management consultant, ADB.

The People's Republic of China (PRC) has experienced unprecedented urbanization and socioeconomic growth, which has driven the massive expansion of its building stock. The total building floor area increased from 35 billion square meters (m^2) in 2000 to 64 billion m^2 in 2017. Residential buildings in urban areas increased by 188% from 2000 to 2017, while public, commercial, and office buildings increased by 161%. With 70% of the total population expected to live in cities by 2030, up from 56% in 2020a, the building stock is expected to further increase in the coming decade.

Growth in the building sector has been associated with significant resource and energy consumption, carbon emissions, and air pollution. In the PRC, buildings account for nearly one-third of total carbon emissions. There is a huge potential for energy saving and greenhouse gas emissions reduction if the energy performance of buildings is enhanced significantly, including the scaling up of green buildings. The government has promoted green buildings since 2006 and has developed measures to promote their development, ranging from information and capacity building to an overarching strategy with binding targets, technical standards and guidelines, demonstrations, financial incentives, and rewards. Table B3.1 lists the key policies for promoting green buildings in the PRC.

Table B3.1: Key Policies of Green Buildings in the People's Republic of China

Year	Policies	Key Content
2006	”Green building standard (1st version)	Defining green buildings, with six categories of criteria
2007	Measures for green building labeling	Defining different levels of green buildings, i.e., 1-, 2-, and 3-star (low to high)
2012	Implementation advice for accelerating green building development	A first-of-its-kind green building policy issued by the central government (rather than a ministry policy document): accelerating green building development and establishing the overall policy framework of green building development especially, specifying financial incentives to promote green buildings.
2013	National action plan for green building development	Issued by the central government: defining national targets of green building development, key tasks, and support mechanisms. The green building development target became an evaluation criterion for local government performance.

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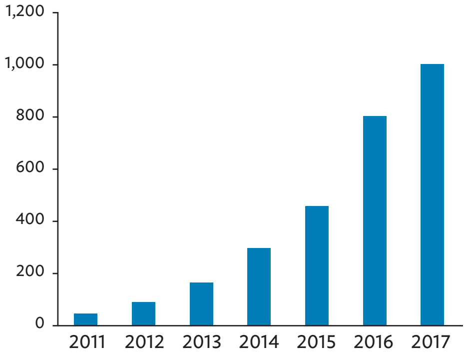
Box 3.1 *continued*

Year	Policies	Key Content
2014	Green building standard (2nd version)	Creating two types of labels for design and operation. The former is certified if the design of a specific building fulfills green building criteria, while the latter is certified after a building has been in use for a year. In addition, the standard introduced detailed scores for different "green" categories.
2019	Green building standard (3rd version)	Redefining the key principles of green buildings: "human-centered and high quality of life" instead of an exclusive focus on environmental sustainability; creating new criteria based on this new principle; green buildings certified only after construction is complete; including a basic level as another level of green building label (four levels).

The PRC's national certification program to promote green buildings, the China Green Building Labelling (GBL), has the following criteria for evaluation: safety, durability, convenience, environment and livability, resource efficiency, health and comfort, and innovation. In its current design, GBL certification cannot be directly translated into carbon emissions reduction and other quantitative resource savings. Green buildings in the PRC have been scaled up from single pilot projects to new green building districts. Figure B3.1 shows the rapid growth of green buildings since 2011. However, most buildings only have designer instead of operational labels, which implies that buildings may only have been designed as green buildings but may not necessarily been constructed accordingly.

Figure B3.1: Growth in Number of Green Buildings, 2011–2017 in the People's Republic of China



Source: World Bank database.

Box 3.2: Low-Carbon City: Xiangtan (People's Republic of China)

This box is written by Nicolas Dei Castelli, senior transport specialist, Asian Development Bank (ADB); Yixin Yao, senior research fellow, Asian Development Bank Institute; and Ellen May Reynes, climate change and technical project management consultant, ADB.

While all eyes are on the decarbonization policy of the People's Republic of China (PRC), one climate-vulnerable and rapidly urbanizing city is paving the way toward the low-carbon cities of the future. Xiangtan, located in the south-central province of Hunan, has a semitropical climate and is prone to extreme precipitation events and floods from the surrounding rivers. Home to almost 3 million people, with an urbanization rate of 62%, it is an old industrial city undergoing rapid urbanization and industrial transformation. In 2018, Xiangtan became a low-carbon city under the Low Carbon City Initiative (LCCI) and has been striving to achieve carbon peaking by 2028 to contribute to the PRC's Nationally Determined Contribution target under the Paris Agreement. This target calls for great efforts to substantially reduce greenhouse gas (GHG) emissions in a very limited time frame without hindering economic growth.

Between 2005 and 2016, the GHG emissions from the building sector in Xiangtan grew by 330%, reflecting the massive growth and urbanization the city has experienced. As the total floor area of urban buildings is expected to grow further, substantial growth in GHG emissions is expected if green building interventions are not in place. Traditional construction practices have little focus on efficiency or low-carbon design. To reduce emissions from the built environment, Xiangtan is starting to retrofit existing buildings and implement measures for new buildings, adopting construction techniques and designs that require fewer natural resources and emit less GHGs. Residents are expected to benefit from the energy and cost savings of buildings with better insulation and a more sustainable design.

As part of the effort to reduce GHG emissions in the building sector, the Xiangtan Municipal Government (XMG) is taking a two-pronged approach in the Xiangtan Low Carbon Transformation Sector Development Program[a]: through policies and certified green building projects showcasing green and low-carbon building techniques. The XMG has established the following policies to enhance low-carbon energy and buildings systems to bolster its vision for transformation:

- Xiangtan's 13th five-year plan and comprehensive work program for energy conservation and emissions reduction identified objectives and priority projects to promote clean and renewable energy technologies, specifically energy performance contracts (EPC), energy service companies (ESCs), and green buildings.
- Management rules on industrial zone autonomy will be set up in 2022 regarding the use of energy and resources to support each

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Box 3.2 *continued*

industrial zone in creating its own management schemes and rules, including mandatory connection to a smart energy/utility management system, if available in the area, to promote energy efficiency.

- An addendum in implementing regulations regarding green buildings has been approved to promote the use of EPCs to enhance the energy efficiency of buildings for public institutions, support local banks in developing financing products for green buildings, and pilot building energy management systems for public buildings.
- Green building management rules have been passed to promote quantifiable green buildings certification, EPCs, and ESCOs for energy efficiency, energy audits, and a more comprehensive statistics system for new and existing buildings.

At the same time, the XMG is set to demonstrate building transformation by integrating advanced technologies and resilience measures in both new construction and building retrofits. First, the XMG plans to construct a new hospital with integrated solutions, including a passive building design, water-saving features, and a trigeneration energy system to generate power, heating, and cooling, which will be connected to an intelligent building energy (and utility) management system (BEMS) that will cover 200 public buildings in Xiangtan. BEMS is a smart platform for energy management in buildings that will automatically regulate heating, cooling, and lighting, using weather predictions and sensors that will detect buildings' usage patterns, temperature, and air quality. BEMS will facilitate operational efficiency, informed decision-making, and behavior changes, thus lowering energy consumption in public buildings.

Because Xiangtan's new hospital is being built in a flood-prone area, extensive climate resilience and nature-based measures such as rain gardens, rainwater detention ponds, green roofs with drainage delay, permeable pavement, and infiltration trenches will enhance the site's flood resilience compared to the PRC's sponge city technical standards.[b] These ecosystem-based measures will also improve the quality of green spaces for the patients and visitors while storing rainwater for water green spaces throughout the hospital campus during severe droughts. The plans also include establishing an off-grid energy system and critical infrastructure for the hospital above the ground floor to keep the hospital functional and ensure the continuation of operations during city-wide power outages and severe flooding events.

Second, the XMG will retrofit a currently unused government building to house the Asia Low-Carbon Training Center, showcasing green and low-carbon building techniques. The retrofit will include upgrading the 6,000-square-meter building by installing external wall and roof insulation, triple/quadruple-glazed windows, water-saving faucets and toilets, an

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Box 3.2 *continued*

Xiangtan's new flood-resistant hospital, which will follow green building principles and have a trigeneration system for heating, cooling, and power. It will be able to withstand severe weather and flooding through ecosystem-based adaptation measures with large run-off areas and underground storage tanks (photo by Xiangtan PMO/design institute).

intelligent building energy monitoring system, and a combined heat pump and rooftop photovoltaic solar energy system. With support from the Hunan Provincial Government and the LCCI, the XMG plans to run the Asia Pacific Low-Carbon Training Center to share its experience on low-carbon transformation with the goal of replicating the city's low-carbon models in other cities in the PRC and other developing countries in Asia and the Pacific that share similar challenges.[c]

Third, Xiangtan aims to mainstream green buildings using a cost-efficient and quantifiable certification called the Excellence in Design for Greater Efficiencies (EDGE) certification that focuses on cutting energy consumption and carbon emissions from the building sector. Both buildings mentioned, the hospital and the Asia Pacific Low-Carbon Training Center, will obtain EDGE certification, achieving more than 20% savings each in energy, water, and the energy embedded in the building design and materials compared to the relevant PRC standards.[d] EDGE requires a reduction in emissions and resource use during construction as well as during operation.

The XMG is also carrying out a holistic approach to becoming a low-carbon city by not only constructing greening buildings but also maintaining and upgrading older buildings. The XMG is set to transform 20 aging urban communities into modern, livable, and sustainable places using low-carbon

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Box 3.2 *continued*

solutions such as light-emitting diode (LED) street lighting, photovoltaic solar panels, e-bicycle sharing, ecosystem-based adaptation measures at parking lots, drainage improvement, safer streets for walking and cycling, and installation of natural gas for cooking to show how any neighborhood can live with minimal environmental impact.

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[a] Asian Development Bank. People's Republic of China: Xiangtan Low-Carbon Transformation Sector Development Program. https://www.adb.org/projects/52230-001/main#project-pds-collapse

[b] Ecosystem-based adaptation measures with green and blue assets are effective for flood control, drought mitigation, heat stress reduction, and carbon sinks, with co-benefits such as aesthetic quality, recreational capacity, better air quality, and improved health quality.

[c] Xiangtan is part of a network of cities participating in the LCCI that aims to decarbonize cities with historically high rates of carbon intensity and growth.

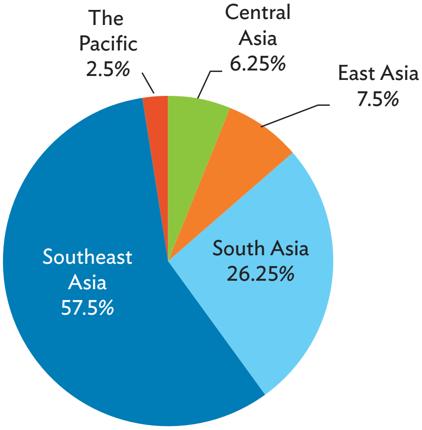
[d] The EDGE green buildings platform, which includes a green building standard, a software application, and a certification program for homes, hospitality, retail, offices, hospitals, and education buildings, helps users determine the most cost-effective options for designing green buildings within a local climate context to reduce operational expenses and environmental impact.

3.5.1 Codes and Standards

Codes and standards are the most popular policy instruments for supporting green buildings. This policy is particularly popular in Southeast Asia (Figure 3.6). Buildings can be certified as green buildings based on regional, national, and internationally recognized standards, which can also provide a certification level for building greenness, such as platinum, gold, silver, and bronze; number of stars; or score. A review of green building standards is provided in Franco, Pawar, and Wu (2021). Such standards are important for financing. For example, green bond proceeds could be used for green buildings that meet regional, national, or internationally recognized standards or certifications for environmental performance (ICMA 2021). Although some green building standards are internationally recognized and used around the world (e.g., LEED and BREEAM), national green building standards have adapted them to reflect specific national or regional needs and circumstances (IRENA 2021). Green building standards are usually voluntary, but they could be compulsory for new buildings. For example, the United Kingdom government announced that all new homes and businesses will have to meet rigorous new energy efficiency standards to lower energy consumption to achieve net-zero emissions by 2050 (Waterman 2021).

Most green building certification schemes are point-based rating systems. Points are given for each green building feature, which then determines the certification level. A building code could also be a voluntary or compulsory set of regulations for the construction, renovation, and repair of buildings, including energy use and efficiency targets for new buildings, specification of insulation standards, and stated building design choices to increase building energy efficiency (IRENA 2021). Building codes and standards are also important as a taxonomic and measurement tool for other policies promoting energy efficiency. Codes and standards can go beyond the whole building to include the appliances used in buildings, such as light bulbs and cooling and heating technologies. Examples of green building codes and standards are provided in Franco, Pawar, and Wu (2021).

Figure 3.6: Building Codes and Standards across Asia (2010–2020)



Source: Authors' elaboration using data from IEA (2021).

Box 3.3: Singapore's Green Building Standard

Buildings account for over 20% of Singapore's emissions.[a] Hence, greening buildings is a key strategy for meeting Singapore's Nationally Derermined Contributions.

The Building and Construction Authority (BCA) launched the voluntary Green Mark Scheme in 2005 to promote sustainable and environmentally friendly buildings in Singapore.

In 2006, Singapore launched its first Green Building Masterplan, which encouraged, enabled, and engaged industry stakeholders in adopting new green buildings.[b] Since then, the masterplan has been continuously updated over the years. Updates have included targeting new building owners to encourage sustainable design from the onset. This was later expanded to existing buildings, with the BCA engaging building occupants to change their energy consumption behaviors.

The latest iteration of the Singapore Green Building Masterplan (SGBMP) was launched in 2021, capturing the collective commitment by the built environment to pursue even more ambitious sustainability targets. It aims to deliver three key targets of "80-80-80 in 2030":

i. 80% of buildings by gross floor area to be greenified by 2030,
ii. 80% of new developments by gross floor area to be super low energy[c] from 2030, and
iii. 80% energy efficiency improvement (from 2005 levels) for best-in-class green buildings[d] by 2030.

During the development of the SGBMP, more than 80 industry stakeholders (architects, consultants, developers, engineers, contractors, suppliers, researchers, and others) and 5,000 individuals from the community were engaged.[e]

Survey on green buildings noted that 91% of respondents agreed that Singapore needs to do more to green its buildings to tackle the impact of climate change.[e]

The survey also noted the top three challenges faced by industry practitioners for super low energy buildings today were: "lack of capital/funds/financial incentives," "lack of leadership buy-in," and "lack of consumer demand."[e] Since 2018, has been working closely with firms through the Super Low Energy Building Programme to encourage them to venture into the super low energy building space. To spur adoption of super low energy buildings, the government took the lead to drive demand by implementing the new GreenGov.SG requirements for public sector buildings in July 2021. All new and retrofitted public sector buildings will need to achieve Green Mark Platinum (Super Low Energy) standards or equivalent, where feasible. Other initiatives to encourage private building owners and developers to strive toward super low energy buildings include the Built Environment Transformation Gross Floor Area Incentive scheme launched in November 2021, and the enhanced Green Mark Incentive Scheme for Existing Buildings 2.0 scheme announced in March 2022 and launched in June 2022.

Other survey results can be viewed in BCA and SGBC (2021)'s Singapore Green Building Masterplan Public Engagement Report and infographic.[f]

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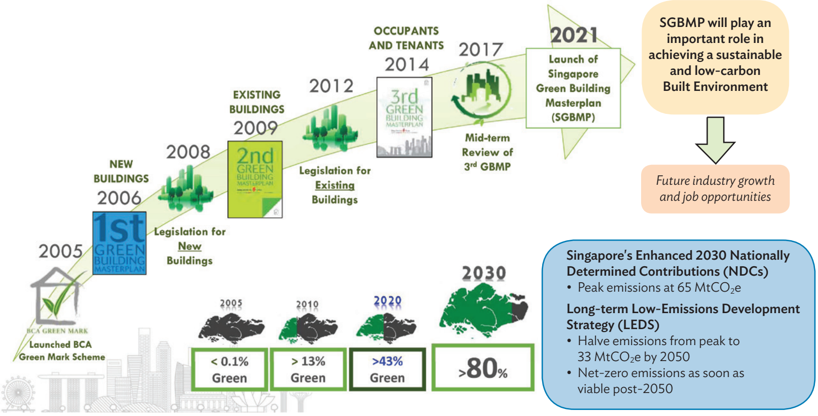
Box 3.3 *continued*

Figure B3.3: Singapore's Green Building Journey



Source: Excerpt from presentation of Noel Chin, Principal Manager, Green Building Technology, Building and Construction Authority of Singapore at IEA training program to promote low carbon buildings on 27 July and 28 July 2021. https://build4people.org/build4people-team-members-invited-as-speakers-at-iea-training-programme-to-promote-low-carbon-buildings/

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[a] National Climate Change Secretariat Singapore. Singapore's Emissions Profile. https://www.nccs.gov.sg/singapores-climate-action/singapore-emissions-profile/

[b] Building and Construction Authority (BCA). Green Building Masterplans. https://www1.bca.gov.sg/buildsg/sustainability/green-building-masterplans

[c] The best-in-class performing Green Mark Building that achieves at least 60% energy savings above 2005 building codes. https://www1.bca.gov.sg/buildsg/sustainability/super-low-energy-programme

[d] As of March 2022, best-in-class buildings were able to achieve 65%–70% improvement in energy efficiency over 2005 levels.

[e] BCA and Singapore Green Building Council. 2021. Infographics. https://www1.bca.gov.sg/docs/default-source/docs-corp-buildsg/sustainability/report-infographics.pdf?sfvrsn=c891f6d2_0

[f] BCA. 2022. What Are People in Singapore Saying About the Future of Green Buildings? https://www1.bca.gov.sg/docs/default-source/docs-corp-buildsg/sustainability/report-infographics.pdf?sfvrsn=c891f6d2_0

Box 3.4: Mainstreaming Green Building Development and Retrofitting with EDGE Certification

This box is written by Nicolas Dei Castelli, senior transport specialist, Asian Development Bank (ADB); Yixin Yao, senior research fellow, Asian Development Bank Institute; and Ellen May Reynes, climate change and technical project management consultant, ADB.

To ease the calculation of carbon emissions reduction, Xiangtan in the People's Republic of China (PRC) is promoting the new user-friendly Excellence in Design for Greater Efficiencies (EDGE) certification system. The EDGE green buildings platform includes a green building standard, a software application, and a certification program for homes, hospitality, retail, offices, hospitals, and education buildings in more than 140 countries to help users determine the most cost-effective options for designing green buildings within a local climate context to reduce operational expenses and environmental impact. EDGE empowers emerging markets to scale up resource-efficient buildings in a fast, easy, and affordable way. EDGE certification can be achieved when a building uses at least 20% less energy, water, and carbon-intensive building materials compared to relevant PRC building standards. EDGE certifications can be granted to both new and old buildings with adequate retrofitting of sustainability technologies. The EDGE program also requires certification during both the design phase and post-construction to evaluate if the expected efficiencies were realized and if they resulted in actual reductions in GHG emissions.

Xiangtan's newest hospital is striving to become the first hospital in the PRC to achieve the EDGE certificate, which entails being energy and resource efficient right from the start. In addition to the efficiency gains through passive building design, water, and energy-saving features, the building will also rely on its own energy source—a combined cooling, heating, and power generation unit fueled by natural gas. This means that the unit can cool the building during the summer, heat the building during the winter, and supply energy throughout the year. Compared to other hospitals in Xiangtan, which rely on locally generated electricity that is 96% coal-based, the new hospital's energy source is more efficient and responsible for lower emissions.

An old, abandoned government building is also being transformed into a new sustainability training center, the Asia Pacific Low-Carbon Training Center, as outlined in Box 3.2. The building will become a place to train officials and other stakeholders from the PRC and other cities in Asia and the Pacific on low-carbon transformation in cities by showcasing the low-carbon initiatives implemented in Xiangtan that they can use in their own projects.

Compared to building energy efficiency standards in the PRC, the new hospital has 28% energy savings, 48% water savings, and 50% less embodied energy in materials. The retrofitted government building will have 20.6% energy savings, almost 25% water savings, and more than 31% savings on embodied energy. Xiangtan hopes to make green buildings mainstream

continued on next page

Box 3.4 *continued*

using this cost-efficient and quantifiable certification that focuses on cutting energy consumption and carbon emissions in the building sector.

Co-benefits

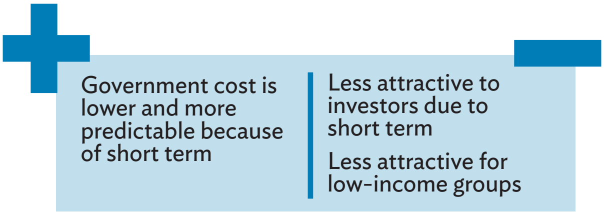
- Economic: EDGE certification requires lower resource use during construction and operation, which enables the allocation of more resources elsewhere.
- Environmental: EDGE certification has helped buildings reduce water consumption and waste production during construction and operation.

3.5.2 Tax Incentives

Tax incentives for promoting energy efficiency improvements in buildings can be provided in the form of reduced tax rates, such as customs tariffs on energy efficient technologies, deductions for expenses, or a lump-sum tax credit (per square meter/foot) on energy efficiency improvements in buildings from the taxable base (e.g., income) of individuals and corporates (also called a tax credit) for income, production, or investment taxes. Tax credits and deduction of eligible expenses need not necessarily be 100%; they could be below, as in the United States, where 30% of qualified expenses are deductible, or they could be above, as in Italy, where 110% of qualified expenses are deductible.

Tax incentives can be also provided for renewable energy installations. This policy is particularly attractive in countries with a high income tax rate. The main drawback of this policy is that it is less attractive for low income groups, as their tax rate is usually low, or in countries with a low-income tax rate (Figure 3.7). The cost of this policy for the government is lower and more predictable due to its short-term nature, as tax incentives do not require long-term commitment from the government and could be ended at any time. If the tax credit exceeds the tax liability, the excess amount can be carried forward to the succeeding fiscal period. Examples of tax incentives for low-carbon buildings are provided in Table 3.2.

Figure 3.7: Pros and Cons of Tax Incentives



Source: Authors.

Table 3.2: Examples of Tax Incentives to Promote Energy Efficiency Improvements in Buildings

Country	Policy	Tax	Year
Italy	Energy efficiency and renewable energy refurbishment tax reduction	Tax deduction, specified at 110% for thermal insulation refurbishments, as well as other energy efficiency measures	2020
Indonesia	Ministerial Regulation No. 2 on Green Building	Reduced land and building taxes	2015
Japan	Financial measures for houses	Tax scheme for businesses that acquire specified energy conservation equipment, which provides special depreciation rate applied for 30% of the acquisition cost	2002
Australia	Financial incentives for investment in residential renewable generation and residential efficiency	Expenses excluded from taxable income	2001
United States	Tax incentives for energy-efficiency upgrades in commercial buildings	A tax deduction of up to $1.80 per square foot available for buildings that save at least 50% of the heating and cooling energy of a system or building; partial deductions of up to $.60 per square foot can be taken for measures affecting: the building envelope, lighting, or heating and cooling systems	
France	Tax credit for energy transition		2005

Source: Authors using various sources.

3.5.3 Grants and Subsidies

Grants and subsidies are usually provided for investments in energy efficiency technologies to reduce the up-front costs of introducing energy-efficient technologies in buildings, making buildings energy-efficient, green, or net-zero carbon (Table 3.3). Grants and subsidies could be provided as a lump sum or as a proportion of the cost, with a ceiling cap. Like taxes, grants and subsidies have a lower cost and are more predictable for governments. They could be closed at the end of a specified period, when the specified funds are exhausted, or at any time.

Box 3.5: Energy Efficiency Services Limited India

The government-owned Energy Efficiency Services Limited (EESL)[a] was created by India's Ministry of Power to facilitate energy efficiency investments, including designing, implementing, monitoring, and investing in energy-efficient projects. EESL has implemented projects in India by providing non-subsidized energy efficient appliances to the residential sector, businesses, and municipalities. The procurement of efficient bulbs has led to substantial cost reductions due to the large scale of this project, which may be the world's largest light-emitting diode (LED) distribution project and include street lighting as well as building lighting. EESL plans to apply the same method to air-conditioning appliances due to a fast-growing demand for cooling in India. Projects have been executed in collaboration with financing organizations such as the Asian Development Bank (ADB), the World Bank, the United Nations Environment Programme, and the United States Agency for International Development. ADB[b] provided a loan to EESL, guaranteed by the Government of India, to support demand-side energy efficiency investments in several Indian states. ADB's loan covered high-priority areas under EESL's energy service company business with (i) more efficient LED municipal street lighting equipped with remote operating technology; (ii) more efficient domestic lighting through the replacement of incandescent lights with LEDs; and (iii) more energy-efficient agricultural water pumps. EESL estimates that energy savings of 80% can be achieved through domestic lighting programs and 30% can be achieved with more efficient pumps.

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[a] See https://eeslindia.org/en/home/

[b] See https://www.adb.org/projects/48224-002/main

Table 3.3: Example Grants for Energy Efficiency Improvements in Buildings

Jurisdiction	Policy	Grant	Year
Japan	Subsidies for commercial and residential building energy efficiency investments	i. Replacement of existing equipment with energy-efficient equipment at factories or other facilities: between one-half and one third of the project cost. ii. Introduction of net-zero energy houses (ZEH): fixed amount per house. iii. Demonstration of net-zero energy buildings (ZEB): up to two-thirds of the project cost. iv. Retrofit of insulation in existing houses using energy-efficient building materials: up to one-third of the project cost.	2016
	Promotion of home/building energy management systems (HEMS/BEMS)	Management systems for managing the energy consumption of appliances by using information technology.	2001
	Promotion of zero energy building/houses (ZEB/ZEH)		
Haryana, India	Scheme on promotion of energy audit in buildings	50% of the energy audit cost with the maximum limit of ₹50,000	2001
Denmark	Subsidy scheme to replace oil burners with heat pumps in buildings outside the district heating and gas grids	Heat pumps	2020
Estonia	Renovation of apartment buildings	30%–50% of total cost	2019
United Kingdom	Green Homes Grant	The voucher covers up to two-thirds of the cost with a cap of £5,000.	2020

Source: Authors using various sources.

3.5.4 Public Investment and Procurement

Energy efficiency in buildings could be incentivized for public buildings using grants, subsidies loans, public procurement, or public investments (Table 3.4). Examples of public buildings include schools, administrative buildings, and hospitals. This policy allows not only the promotion of energy efficiency in buildings, but also the reduction in public expenditure on energy bills. Public procurement of energy-efficient technologies allows purchasing at competitive cost due to large-scale negotiations between the government and manufacturers, which allows companies, households, and the public sector to purchase these technologies at a predetermined price.

Table 3.4: Example Policies Promoting Energy Efficiency in Public Buildings

Jurisdiction	Policy	Buildings	Year
Canada	Community buildings retrofit initiative	Local governments and not-for-profit organizations to retrofit public buildings to improve energy performance, lower operating and maintenance costs, and transition to cleaner energy solutions.	2021
Denmark	Subsidy scheme for energy savings in public buildings	Energy renovations in regional and municipal buildings with the lowest energy performance certificate standards (D-G) as well as buildings heated by oil burners and gas furnaces.	2021
Portugal	Solar thermal incentive scheme	Purchase of a solar thermal kit, comprising panels and ancillary equipment, installation, yearly maintenance for 6 years, and a 6-year guarantee. The kit is acquired at a competitive cost, firstly due to large-scale negotiations between the government and manufacturers. The government also provides an immediate rebate of €1,641.70 for the purchase of a solar thermal kit, and four banks (Caixa Geral de Depósitos, BES, Millennium bcp, and BPI) have special preferential rate fixing programs for those wishing to take a credit to cover the remaining cost of the solar thermal system. In addition, the incentive scheme can be combined with existing tax credit provisions for the installation of such systems.	2009
Italy	Kyoto fund for energy efficiency of public buildings	Projects should guarantee an improvement for the building of at least two energy efficiency classes in public buildings.	2021
Denmark	Subsidy scheme for energy savings in public buildings	Energy renovations in regional and municipal buildings with the lowest energy performance certificate standards (D-G) as well as buildings that are heated by oil burners and gas furnaces.	2021
Portugal	Resource efficiency program in public administration 2030	Sets energy efficiency targets by 2030 for public administration buildings.	2021

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Table 3.4 *continued*

Jurisdiction	Policy	Buildings	Year
Spain	Modernization of public administration	Energy efficiency and renewable energy installations in public administration buildings; forbids the purchase of boilers using fossil fuels.	2021
Greece	ELECTRA	To improve the energy efficiency of public buildings to be classified at energy efficiency level B.	2020–2026

Source: Authors.

Box 3.6: Green Public Buildings in India and Indonesia

This box is written by Ranjeeta Mishra, consulting economist, Reserve Bank of India and Mahesti Okitasari, consultant, United Nations University Institute for the Advanced Study of Sustainability.

India and Indonesia are burdened with low-quality housing, slums, and increasing demand for affordable housing for low-income households. As the main target of urbanization, big cities such as Mumbai and Surabaya have experienced high external and inner-city migration, leading to high demand for housing. The lack of available government land has led to a higher preference for developing multi-story public housing, including for lower-income groups. Efforts to improve sustainable public housing practices have been made in India and Indonesia. Green infrastructure features are present in recent housing projects, whether through built-in and/or add-on features. Common built-in features to reduce the energy required for servicing the building include passive cooling design and the building envelope. Popular add-on features include waste management and rainwater harvesting. As not all cities are equipped with a mandatory green building code, the features vary across cities and housing projects.

Many cities have created programs to provide affordable green public housing and improve living conditions with support from the national and local government. In Indonesia, low-income public housing is financed through the state (Ministry of Public Works and Housing) and local government budgets. Financing through the Housing Finance Liquidity Facility program, a government-owned structure that funds 70% of the total mortgage at a 7.25% interest rate, has not been fully utilized. The government recently introduced a financing scheme for housing built through public–private partnerships with a payment mechanism. This scheme was previously used to finance infrastructure in Indonesia. For both public and private housing, there are tax exemptions and easier credit or bank loan provisions for sustainable housing that complies with the green rating standardization.

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Box 3.6 *continued*

Sustainability outcomes in low-income public housing are rarely measured, leading to a lack of understanding of the factors affecting social acceptance of green infrastructure features among low-income households. To address this gap, our study analyzed public housing that accommodated relocation from the slums and squatter settlements in Mumbai and Surabaya. Social acceptance was measured as household-level acceptance of sustainable housing through residential satisfaction or quality of life. Variables to measure acceptance of green public housing were developed from sustainable housing indicators (Nair et al. 2005; Habitat for Humanity 2012), a model of housing quality determinants for affordable housing (Chohan et al. 2015; Wallbaum et al. 2012), and green building assessment tools (BREEAM; International Initiative for a Sustainable Built Environment; United States Green Building Council). To identify the distribution of economic and social gains, the attributes of well-being, employment, affordability, and accessibility were included.

In Surabaya, three low-income housing complexes of two to five buildings were selected: Rusun Penjaringan Sari, Urip Sumoharjo, and Grudo. Each tower consists of four to five floors with a total of 60 to 80 units. Each housing unit measures 21 to 24 square meters. Resource efficiency measures for energy and water conservation were installed in the units, including renovation in some of the towers built before 2000. According to local regulations, waste management incorporating the tenets of reduce, reuse, and recycle and community management should be present as part of the community green and clean program. The survey was conducted between May and June 2018 with a target of 300 respondents.

In Mumbai, three low-income housing complexes were selected in Shivneri, Santacruz, and Bhoiwada. Like other more recent housing projects, eco-housing criteria were applied during the project implementation, including biodiversity conservation methods during the site planning process; environmental architecture adopting climate responsive design practices to achieve thermal comfort, cross-ventilation, and reduce glare; energy conservation and management with the use of fluorescent lamps; efficient building materials for finishing materials; water conservation; and waste segregation facilities. The survey was conducted between April and July 2019 with a target of 300 respondents (Figure B3.6.1).

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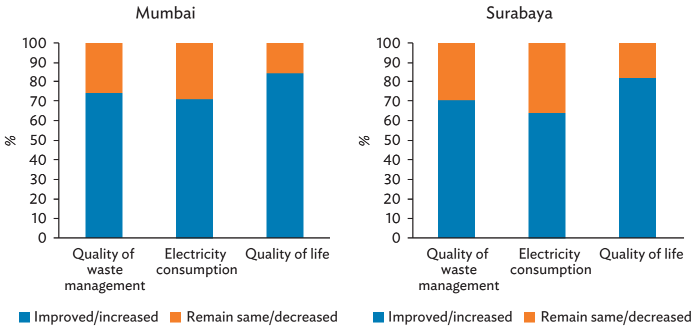
Box 3.6 *continued*

Figure B3.6.1: Perception of Housing Quality and Quality of Life in Green Low-Income Public Housing



Box 3.7: Green Buildings for Hospitals

This box is written by Nicolas Dei Castelli, senior transport specialist, Asian Development Bank (ADB); Yixin Yao, senior research fellow, Asian Development Bank Institute; and Ellen May Reynes, climate change and technical project management consultant, ADB.

Independent All-in-One Heating, Cooling, and Power System in Xiangtan's New Hospital

Apart from passive building design and water-saving features, Xiangtan's newest hospital will install a new natural gas-powered combined cooling, heating, and power generation system alongside a solar photovoltaic power system. The system will be built according to the best international practices and will be able to provide the entire hospital with heating, cooling, and electricity—even during blackouts. The system consists of several unit types: one natural gas-powered electricity generation unit capable of powering the entire hospital, one heat recovery unit connected to the electricity generation unit that will provide heat (or power and an absorption unit for cooling), two chillers for warm summers, and two natural gas boilers for the winter. In the future, natural gas could be replaced by biogas produced from organic waste.

A "DeNOx" system will also be installed on the natural gas-powered unit to ensure nitrogen oxide emissions live up to the highest international clean emissions standards. In addition, the heat recovery unit will maximize the energy use of the natural gas-powered unit by recovering the waste heat

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Box 3.7 *continued*

and providing more than 15% of the total heating required. When cooling is needed, the recovery unit will power the absorption machine, which will provide upwards of 13% of the entire cooling capacity needed for the hospital. A building energy management system will forecast the demand for energy during operations and intelligently manage the energy systems.

Co-benefits

- Economic: The trigeneration unit capable of providing cooling, heating, and power will be able to provide the hospital with cheaper energy.
- Climate: The natural gas-powered trigeneration unit will emit fewer greenhouse gases than the largely coal-fired power main grid.
- Key numbers:
  - 16.6 megawatts (MW) of cooling capacity can be provided by the two mechanical chillers included in the trigeneration unit.
  - 12.8 MW of heating capacity is the peak power that the two natural gas boilers in the trigeneration unit can provide.

Creating a climate-resilient low-carbon hospital

Hospitals need to be able to operate year-round without interruptions, so preventing interruptions due to flooding is critical. Climatic modeling and risk assessments showed that the new hospital in Xiangtan was being built in a flood-prone area with higher-than-expected risks. To combat this, the hospital will make use of nature-based adaptation measures to increase the resilience against future flooding events. While the original design followed national sponge city standards, enhanced measures had to be implemented due to the increased risk. The sponge city standard, developed in 2014, mandated that the hospital have 740 cubic meters (m^3) of water storage capacity. However new assessments showed a total of 7,840 m^3 water storage capacity is needed to withstand once-in-30-years flooding events.

The increase in capacity will be added through enhanced nature-based adaptation measures such as rain gardens, rainwater detention ponds, green roofs with drainage delay, permeable pavement, and infiltration trenches. While the rainwater ponds will primarily be used for flood drainage, they will also improve the quality of the green spaces for patients and visitors. The ponds will be used to grow medical plants and herbs while also providing water for green spaces throughout the hospital campus during severe droughts.

With the new flood prevention measures and an off-grid trigeneration energy system generator located on an upper ground floor to avoid flooding accidents, the hospital will be able to operate even during city-wide power outages and severe flooding events. The ground floor will also be lifted 0.5 to 1 meters to limit damage to the equipment during floods, while an emergency plan on actions to take if the building is flooded will provide guidelines for personnel.

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Box 3.7 *continued*

Co-benefits

- Social: The patients at the new hospital in Xiangtan will be able to enjoy enhanced green spaces providing medical plants and herbs while also securing the area in case of flooding events.
- Health: The hospital will be able to continuously provide healthcare regardless of blackout or flooding events.

The newest Xiangtan hospital will be able to withstand severe flooding due to the presence of large run-off areas, underground storage tanks, and backup generators in case the grid experiences a blackout (photo by Xiangtan PMO/design institute).

3.5.5 Strategic Plans

Strategic plans include policy signals demonstrating national plans for reaching energy efficiency, including national targets (such as NDCs and net-zero emissions), national strategic plans, and creation of institutions. Some countries have announced targets relevant to green buildings, such as net-zero targets, NDCs, and emissions intensity, while some countries have targets related specifically to green buildings or energy efficiency (Table 3.5). The advantages of targets, as a policy instrument, are that they are clear and measurable and can be used for long-term planning of other policies for meeting these targets.

Table 3.5: Green Building and Other Relevant Targets

Country	Target	Target Year	Document	Organization
	Net zero carbon target	Mid-21st century		
	GHG emissions reduction		National Determined Contributions	
	Energy intensity			
Netherlands	Energy label targets Voluntary agreement to bring building stock to an average of energy label B. Mandatory for all office buildings to have an energy label C. Energy label A will be the standard.	2020 From 2023 From 2030	Dutch national government	
India	(i) Reduce cooling demand across sectors by 20% to 25% by 2037–2038 (ii) Reduce refrigerant demand by 25% to 30% by 2037–2038 (iii) Reduce cooling energy requirements by 25% to 40% by 2037–2038 (iv) Recognize “cooling and related areas” as a key area of research under national Science and Technology Program (v) Training and certification of 100,000 servicing sector technicians by 2022–2023		Cooling Action Plan	

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Box 3.5 *continued*

Country	Target	Target Year	Document	Organization
People's Republic of China	Green buildings should account for over 50% of all newly constructed buildings in urban areas by 2020, and more than 60% of existing residential buildings in urban areas across the country should be retrofitted as energy-efficient buildings		13th Five Year Plan for the Development of Building Energy Efficiency and Green Building	
Singapore	80% of green buildings	2030	Singapore Green Building Masterplan	Building and Construction Authority and Singapore Green Building Council
	80% of new developments (by gross floor area) to be super low energy (SLE) buildings	From 2030		
	80% improvement in energy efficient for best-in-class green buildings	2030		
International	To reduce (and compensate where necessary) all operational and embodied carbon emissions within their portfolios	2030	Net Zero Carbon Buildings Commitment	World Green Building Council
	All buildings to be net-zero whole-life carbon	2050		
Australia	Zero energy and carbon-ready commercial and residential buildings		Trajectory for Low Energy Buildings	
United Kingdom	600,000 heat pump installations per year by 2028		Ten Point Plan for a Green Industrial Revolution – Point 7: Greener Buildings	

Source: Compiled by authors.

3.5.6 Energy Audits

Although policies incentivizing building energy audits do not directly promote improvements to energy efficiency, audits can help to realize potential energy efficiency improvements and provide justification for investment. Energy audits include the inspection, verification, technical and economic analysis, and evaluation of energy use systems, equipment operation, management, and energy consumption, as well as recommendations for improvements. They are usually voluntary and incentivized using grants, subsidies, or tax incentives. Regular energy audits (usually every 4–5 years) could be compulsory for certain building categories, such as large energy consumers in Morocco, public organizations in the PRC, or large companies in Germany and Austria. Buildings with certified energy efficiency may be excluded from obligatory energy audits. Such policies require the availability of certified energy auditors, which also creates employment opportunities.

Box 3.8: Conserving Energy and Water with 200 Smart Buildings in Xiangtan (People's Republic of China)

This box is written by Nicolas Dei Castelli, senior transport specialist, Asian Development Bank (ADB); Yixin Yao, senior research fellow, Asian Development Bank Institute; and Ellen May Reynes, climate change and technical project management consultant, ADB.

To reduce energy consumption and water use in public buildings, Xiangtan is installing a new intelligent building energy management system (BEMS). Data from sensors in more than 200 public government buildings will be sent to a central database. The resource management software will then be able to tap into that data to regulate lighting, temperature, humidity, and water consumption to optimize resource consumption.

One of the buildings that will be connected to the city-wide BEMS is the new Xiangtan hospital. Data collected from throughout the building using onsite sensors and meters, including cooling demand, heating demand, electricity demand, hot water demand, outside temperature, humidity, weather information, number of patients, and behavioral characteristics, will be consolidated and analyzed for trends and to prepare demand forecasts to allow for efficient and effective facility-wide insight and control. The insights from the BEMS can then be used to further optimize energy management strategies, which will also reduce operational costs. Smart controls in the BEMS will be able to adjust temperature and lighting in individual rooms

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Box 3.8 *continued*

according to real-time usage, as well as incorporating behavioral and weather forecasts. The BEMS can integrate actual efficiency performance and measure it against performance targets.

Connecting 900,000 square meters in 200 public buildings to the city-wide BEMS will enable monitoring of building energy statistics, city-wide building energy saving efforts, and the resulting reduction in greenhouse gas (GHG) emissions. As part of the Xiangtan government's commitment to reducing GHG emissions from the building sector, the local government issued the Implementation Rules for Green Buildings. The new rules are meant to incentivize new and existing buildings to become smarter using an intelligent BEMS, which in most cases enables energy performance contraction to accelerate effective energy conservation measures and reduce emissions from buildings.

Services from the Xiangtan Health Commission and Xiangtan Housing and Urban–Rural Construction Bureau will be improved with the data and demand-management capability of the BEMS at the hospital and in other government buildings.

Co-benefits

- Economic: The new monitoring systems are expected to improve energy efficiency in buildings by 10%, which translates to cost savings that can be invested elsewhere.
- Climate: The project will result in energy savings of almost 24,000 megawatt-hours per year, reducing the amount of coal needed to produce energy for the power grid.

3.6 Conclusions and Policy Implications

Rapid changes in climatic conditions, with an increase in the frequency of extreme weather events such as prolonged heat and drought, flooding, glacial lake outburst flooding, erratic rainfall, salination, and sea inundation have raised concern for the future of humanity. Global efforts encompassing all sectors are needed to check climate change through the reduction in GHG emissions. As the building and construction sectors account for one-third of total energy consumption and contribute one-third of GHG emissions, they have the potential to contribute significantly to the reduction in GHG emissions and reversing the trend of climate change. The rapidly growing population, which is expected to reach 9.7 billion by 2050, and increasing income will increase the demand for housing, so it is critical to bring about significant innovation in the sector to reduce GHG emissions, and green buildings could play a crucial role. Green construction involves greening the entire process from the manufacturing of building materials to design, construction, maintenance, and demolition. Green buildings that are environmentally friendly involve the use of processes and materials that cause minimal damage to the environment and are energy and resource efficient, as well as providing attractive amenities such as better indoor air.

There are challenges to the implementation of green buildings, particularly in developing countries, where the necessary construction materials and skilled laborers are not readily available. The cost of constructing green buildings is also high. The lack of standards, policies, and support from the government also act as a barrier to green buildings in developing countries, so policies should be developed to support skilled labor through training and increase access to green building materials. Popular policies that can help to promote green buildings include codes and standards, tax incentives, grants and subsidies, loans, and public investment and procurement, as well as strategic plans. Most policies are interlinked, so a combination of policies is required for better efficiency. This chapter provides the following key messages for policy makers:

- Green buildings can help to meet NDCs, energy security, and reduce GHG emissions from the sectors of manufacturing building materials, building construction, and building operation.
- Popular policies to promote green buildings include codes and standards, tax incentives, grants and subsidies, loans, public investment and procurement, and strategic plans.
- Mixed policy instruments are recommended.
- Most existing policies are provided for energy efficiency, not green buildings.
- Promoting energy efficiency in buildings is not an equal substitute for green building policies, as they do not promote manufacturing of low-carbon construction materials and low-carbon building construction.

Policies develop over time, and long-term planning of support is recommended, starting from more voluntary and rewarding policies and then moving toward compulsory and punitive policies.

References

Aaheim, A., H. Amundsen, T. Dokken, and T. Wei. 2012. Impacts and Adaptation to Climate Change in European Economies. *Global Environmental Change* 22 (4): 959–968.

Abidin, N. Z., and A. Powmya. 2014. Perceptions on Motivating Factors and Future Prospects of Green Construction in Oman. *Journal of Sustainable Development* 7: 231–239.

Ahn, Y. H., A. R. Pearce, Y. Wang, and G. Wang. 2013. Drivers and Barriers of Sustainable Design and Construction: The Perception of Green Building Experience. *International Journal of Sustainable Building Technology and Urban Development* 4: 35–45.

Aktas, B., and B. Ozorhon. 2015. Green Building Certification Process of Existing Buildings in Developing Countries: Cases from Turkey. *Journal of Management in Engineering* 31: 05015002.

Albert, M. J. 2020. Beyond Continuationism: Climate Change, Economic Growth, and the Future of World (Dis)order. *Cambridge Review of International Affairs*: 1–20.

Allwood, J. M., M. F. Ashby, T. G. Gutowski, and E. Worrell. 2011. Material Efficiency: A White Paper. *Resources, Conservation and Recycling* 55: 362–381.

Arehart, J. H., J. Hart, F. Pomponi, and B. D'Amico. 2021. Carbon Sequestration and Storage in the Built Environment. *Sustainable Production and Consumption* 27: 1047–1063.

Arif, M., C. Egbu, A. Haleem, and D. Kulonda. 2009. State of Green Construction in India: Drivers and Challenges. *Journal of Engineering, Design and Technology* 7: 223–234.

Aryal, J. P., D. B. Rahut, T. B. Sapkota, R. Khurana, and A. Khatri-Chhetri. 2020a. Climate Change Mitigation Options Among Farmers in South Asia. *Environment, Development and Sustainability* 22: 3267–3289.

Aryal, J. P., T. B. Sapkota, R. Khurana, and A. Khatri-Chhetri. 2020b. Climate Change and Agriculture in South Asia: Adaptation Options in Smallholder Production Systems. *Environment, Development and Sustainability* 22: 5045–5075.

Asakawa, M. 2021. 2021 International Climate Change Conference: A Just and Affordable Transition toward Net Zero. Speech, 22 July. https://www.adb.org/news/speeches/2021-international-climate-change-conference-just-affordable-transition-net-zero-masatsugu-asakawa

Azhar, S., W. A. Carlton, D. Olsen, and I. Ahmad. 2011. Building Information Modeling for Sustainable Design and LEED® Rating Analysis. *Automation in Construction* 20: 217–224.

Bajracharya, S. R., P. K. Mool, and B. R. Shrestha. 2007. *Impact of Climate Change on Himalayan Glaciers and Glacial Lakes: Case Studies on GLOF and Associated Hazards in Nepal and Bhutan*. Patan, Nepal: International Centre for Integrated Mountain Development.

Bloomberg New Energy Outlook (BNEF). 2021. BNEF Theme: Decarbonizing Cement and Concrete. https://www.bnef.com/core/themes/283

Bond, S. 2010. Lessons from the Leaders of Green Designed Commercial Buildings in Australia. *Pacific Rim Property Research Journal* 16: 314–338.

Boza-Kiss, B., S. Moles-Grueso, and D. Urge-Vorsatz. 2013. Evaluating Policy Instruments to Foster Energy Efficiency for the Sustainable Transformation of Buildings. *Current Opinion in Environmental Sustainability* 5(2): 163–176.

Chan, A. P. C., A. Darko, A. O. Olanipekun, and E. E. Ameyaw. 2018. Critical Barriers to Green Building Technologies Adoption in Developing Countries: The Case of Ghana. *Journal of Cleaner Production* 172: 1067–1079.

Chohan, A. H. et al. 2015. A Model of Housing Quality Determinants (HQD) for Affordable Housing. *Journal of Construction in Developing Countries* 20(1): 117–136.

Churkina, G. et al. 2020. Buildings as a Global Carbon Sink. *Nature Sustainability* 3: 269–276.

Colombani, N., A. Osti, G. Volta, and M. Mastrocicco. 2016. Impact of Climate Change on Salinization of Coastal Water Resources. *Water Resources Management* 30: 2483–2496.

Dai, A. 2011. Drought under Global Warming: A Review. *Wiley Interdisciplinary Reviews: Climate Change* 2: 45–65.

Devine, A. and N. Kok. 2015. Green Certification and Building Performance: Implications for Tangibles and Intangibles. *The Journal of Portfolio Management* 41: 151–163.

Dodoo, A., L. Gustavsson, and R. Sathre. 2009. Carbon Implications of End-of-Life Management of Building Materials. *Resources, Conservation and Recycling* 53: 276–286.

Dong, B., Z. O'Neill, and Z. Li. 2014. A BIM-Enabled Information Infrastructure for Building Energy Fault Detection and Diagnostics. *Automation in Construction* 44: 197–211.

DuBose, J. R., S. J. Bosch, and A. R. Pearce. 2007. Analysis of State-Wide Green Building Policies. *Journal of Green Building* 2: 161–177.

Easterling, D. R., G. A. Meehl, C. Parmesan, S. A, Chagnon, T. R. Karl, and L. O. Mearns. 2000. Climate Extremes: Observations, Modeling, and Impacts. *Science* 289: 2068–2074.

The Economist. 2021. How Cement May Yet Help Slow Global Warming. 4 November. https://www.economist.com/science-and-technology/how-cement-may-yet-help-slow-global-warming/21806083

———. 2022. How to Build Sustainably for a Growing Population. 22 May. https://www.economist.com/films/2022/03/22/how-to-build-sustainably-for-a-growing-population

Erkens, G., T. Bucx, R. Dam, G. de Lange, and J. Lambert. 2015. Sinking Coastal Cities. *Proceedings of the International Association of Hydrological Sciences* 372: 189–198.

Esa, M. R., M. A. Mahani. R. Yaman, and A. A. Hassan. 2011. Obstacles in Implementing Green Building Projects in Malaysia. *Australian Journal of Basic and Applied Sciences* 5: 1806–1812.

Estrada, F., R. S. Tol, and C. Gay-Garcia. 2015. The Persistence of Shocks in GDP and the Estimation of the Potential Economic Costs of Climate Change. *Environmental Modelling & Software* 69: 155–165.

Franco, M.A.J.Q., P. Pawar, and X. Wu. 2021. Green Building Policies in Cities: A Comparative Assessment and Analysis. *Energy and Buildings* 231: 110561.

Fuchs, R. J. 2010. Cities at Risk: Asia's Coastal Cities in an Age of Climate Change. *Asia Pacific Issues* 96: 1–12.

Fuerst, F., C. Kontokosta, and P. McAllister. 2014. Determinants of Green Building Adoption. *Environment and Planning B: Planning and Design* 41(3): 551–570.

Global Alliance for Building and Construction (GlobalABC), International Energy Agency (IEA), and United Nations Environment Programme (UNEP). 2019. *Global Status Report for Buildings and Construction: Towards a Zero-Emissions, Efficient and Resilient Buildings and Construction Sector*. IEA and UNEP. https://www.worldgbc.org/sites/default/files/2019%20Global%20Status%20Report%20for%20Buildings%20and%20Construction.pdf

Gandure, S., S. Walker, and J. Botha. 2013. Farmers' Perceptions of Adaptation to Climate Change and Water Stress in a South African Rural Community. *Environmental Development* 5: 39–53.

Gosling, S. N., and N. W. Arnell. 2016. A Global Assessment of the Impact of Climate Change on Water Scarcity. *Climatic Change* 134: 371–385.

Gou, Z., S.-Y. Lau, and D. Prasad. 2013. Market Readiness and Policy Implications for Green Buildings: Case Study from [Hong Kong, China]. *Journal of Green Building* 8: 162–173.

Haapio, A., and P. Viitaniemi. 2008. A Critical Review of Building Environmental Assessment Tools. *Environmental Impact Assessment Review* 28: 469–482.

Habitat for Humanity International. 2012. *Global Housing Indicators: Evidence for Action*. Americus, GA, US: Habitat for Humanity International.

Hansemann, G., C. Holzinger, R. Schmid, J. P. Tapley, S. Peters, and A. Trummer. 2021. Lightweight Reinforced Concrete Slab: 130 Different 3D Printed Voids. *CPT Worldwide-Construction Printing Technology* 2021: 68.

Hejazi, M. I. et al. 2015. 21st Century United States Emissions Mitigation Could Increase Water Stress More than the Climate Change it Is Mitigating. *Proceedings of the National Academy of Sciences* 112: 10635–10640.

Hertwich, E. G. et al. 2019. Material Efficiency Strategies to Reducing Greenhouse Gas Emissions Associated with Buildings, Vehicles, and Electronics—A Review. *Environmental Research Letters* 14: 043004.

Hertwich, E., R. Lifset, S. Pauliuk, and N. A. Heeren. 2020. *Resource Efficiency and Climate Change: Material Efficiency Strategies for a Low-Carbon Future-Summary for Policymakers*. Report of the International Resource Panel. Nairobi: United Nations Environment Programme.

Hoffman, A. J., and R. Henn. 2008. Overcoming the Social and Psychological Barriers to Green Building. *Organization & Environment* 21: 390–419.

ICMA. 2021. The Green Bond Principles (GBP). https://www.icmagroup.org/sustainable-finance/the-principles-guidelines-and-handbooks/green-bond-principles-gbp/

International Energy Agency. IEA. Policies Database. https://www.iea.org/policies/about

____. 2019. *Material Efficiency in Clean Energy Transitions*. Vienna: IEA.

International Renewable Energy Agency (IRENA). 2021. Renewable Energy Policies for Cities: Buildings. Abu Dhabi: IRENA. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/May/IRENA_Policies_for_Cities_Buildings_2021.pdf

Jalaei, F., and A. Jrade. 2015. Integrating Building Information Modeling (BIM) and LEED System at the Conceptual Design Stage of Sustainable Buildings. *Sustainable Cities and Society* 18: 95–107.

Kapoor, A., E.-Q. Teo, D. Azhgaliyeva, and Y. Liu. 2021. The Viability of Green Bonds as a Financing Mechanism for Energy-Efficient Green Buildings in ASEAN: Lessons from Malaysia and Singapore. In Y. Liu, F. Taghizadeh-Hesary, and N. Yoshino, eds. *Energy Efficiency Financing and Market-Based Instruments*. Berlin: Springer, pp. 263–286.

Kaushik, S., M. Rafiq, P. Joshi, and T. Singh. 2020. Examining the Glacial Lake Dynamics in a Warming Climate and GLOF Modelling in Parts of Chandra Basin, Himachal Pradesh, India. *Science of the Total Environment* 714: 136455.

Kibert, C. J. 2016. *Sustainable Construction: Green Building Design and Delivery*. New York: John Wiley & Sons.

Kim, S., and B. T. H. Lim. 2018. How Effective is Mandatory Building Energy Disclosure Program in Australia? In *IOP Conference Series: Earth and Environmental Science* 140 (1): 012106. IOP Publishing.

Kua, H. W. and S. E. Lee. 2002. Demonstration Intelligent Building—A Methodology for the Promotion of Total Sustainability in the Built Environment. *Building and Environment* 37: 231–240.

Le Houérou, H. N. 1996. Climate Change, Drought and Desertification. *Journal of Arid Environments* 34: 133–185.

Lee, W. L. and F. W. H. Yik. 2004. Regulatory and Voluntary Approaches for Enhancing Building Energy Efficiency. *Progress in Energy and Combustion Science* 30(5): 477–499.

Leng, G., Q. Tang, and S. Rayburg. 2015. Climate Change Impacts on Meteorological, Agricultural and Hydrological Droughts in China. *Global and Planetary Change* 126: 23–34.

Li, Y., X. Chen, W. Wang, Y. Xu, and P.-H. Chen. 2017. A Review of Studies on Green Building Assessment Methods by Comparative Analysis. *Energy and Buildings* 146: 152–159.

Li, Y., W. Yu, B. Li, and R. Yao. 2016. A Multidimensional Model for Green Building Assessment: A Case Study of a Highest-Rated Project in Chongqing. *Energy and Buildings* 125: 231–243.

Liu, G., C. E. Bangs, and D. B. Müller. 2013. Stock Dynamics and Emission Pathways of the Global Aluminium Cycle. *Nature Climate Change* 3: 338–342.

Lorenzen, J. A. 2012. Going Green: The Process of Lifestyle Change. *Sociological Forum* 27(1): 94–116.

Manoliadis, O., I. Tsolas, and A. Nakou. 2006. Sustainable Construction and Drivers of Change in Greece: A Delphi Study. *Construction Management and Economics* 24: 113–120.

Muir, M. A. 2010. Managing Transboundary Aquifers for Climate Change: Challenges and Opportunities. UNESCO-IAH-UNEP Conference, Paris, 6–8 December 2010.

Muller, M. F., F. Esmanioto, N. Huber, E. R. Loures, and O. Canciglieri. 2019. A Systematic Literature Review of Interoperability in the Green Building Information Modeling Lifecycle. *Journal of Cleaner Production* 223: 397–412.

Mulligan, T. D., S. Mollaoğlu-Korkmaz, R. Cotner, and A. D. Goldsberry. 2014. Public Policy and Impacts on Adoption of Sustainable Built Environments: Learning from the Construction Industry Playmakers. *Journal of Green Building* 9: 182–202.

Nair, D. G., B. Enserink, G. Gopikuttan, P. Vergragt, A. Fraaij, and R. Dalmeijer. 2005. A Conceptual Framework for Sustainable-Affordable Housing for the Rural Poor in Less Developed Economies. Proceedings of the 2005 World Sustainable Building Conference, 27–29 September 2005, Tokyo, Japan.

Nguyen, B. K. and H. Altan. 2011. Comparative Review of Five Sustainable Rating Systems. *Procedia Engineering* 21: 376–386.

Nguyen, H.-T. and M. Gray. 2016. A Review on Green Building in Vietnam. *Procedia Engineering* 142: 314–321.

Oh, D. Y., T. Noguchi, R. Kitagaki, and W. J. Park. 2014. CO2 Emission Reduction by Reuse of Building Material Waste in the Japanese Cement Industry. *Renewable and Sustainable Energy Reviews* 38: 796–810. https://doi.org/10.1016/j.rser.2014.07.036

Potbhare, V., M. Syal, and S. Korkmaz. 2009. Adoption of Green Building Guidelines in Developing Countries Based on US and India Experiences. *Journal of Green Building* 4: 158–174.

Reid, H., M. Alam, R. Berger, T. Cannon, S. Huq, and A. Milligan. 2009. Community-Based Adaptation to Climate Change: An Overview. *Participatory Learning and Action* 60: 11–33.

Ritchie, H., M. Roser, and P. Rosado. 2020. CO_2 and Greenhouse Gas Emissions. https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions

Rosenow, J., T. Fawcett, N. Eyre, and V. Oikonomou. 2016. Energy Efficiency and the Policy Mix. *Building Research & Information* 44 (5–6): 562–574.

Rosenow, J., F. Kern, and K. Rogge. 2017. The Need for Comprehensive and Well Targeted Instrument Mixes to Stimulate Energy Transitions: The Case of Energy Efficiency Policy. *Energy Research & Social Science* 33: 95–104.

S&P Global. 2021. COP26: Five Developed Nations Commit to Support Low Carbon Steel, Cement Sectors. https://www.spglobal.com/platts/en/market-insights/latest-news/energy-transition/110921-cop26-five-developed-nations-commit-to-support-low-carbon-steel-cement-sectors

Samari, M., N. Godrati, R. Esmaeilifar, P. Olfat, and M. W. M. Shafiei. 2013. The Investigation of the Barriers in Developing Green Building in Malaysia. *Modern Applied Science* 7(2): 1.

Samir, K. C., and W. Lutz. 2017. The Human Core of the Shared Socioeconomic Pathways: Population Scenarios by Age, Sex and Level of Education for All Countries to 2100. *Global Environmental Change* 42: 181–192.

Shen, Y., and M. Faure. 2021. Green Building in China. *International Environmental Agreements: Politics, Law and Economics* 21(2): 183–199.

Shi, Q., X. Lai, X. Xie, and J. Zuo. 2014. Assessment of Green Building Policies–A Fuzzy Impact Matrix Approach. *Renewable and Sustainable Energy Reviews* 36: 203–211.

Shukla, P. et al. 2019. Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable

Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems. Geneva, Switzerland: Intergovernmental Panel on Climate Change.

Sivakumar, M. V. K. 2007. Interactions Between Climate and Desertification. *Agricultural and Forest Meteorology* 142: 143–155.

Slama, F., E. Gargouri-Ellouze, and R. Bouhlila. 2020. Impact of Rainfall Structure and Climate Change on Soil and Groundwater Salinization. *Climatic Change* 163: 395–413.

Stadel, A., J. Eboli, A. Ryberg, J. Mitchell, and S. Spatari. 2011. Intelligent Sustainable Design: Integration of Carbon Accounting and Building Information Modeling. *Journal of Professional Issues in Engineering Education and Practice* 137: 51–54.

Strandsbjerg, T. P. J. et al. 2021. An Assessment of the Performance of Scenarios Against Historical Global Emissions for IPCC Reports. *Global Environmental Change* 66: 102199.

Suzer, O. 2015. A Comparative Review of Environmental Concern Prioritization: LEED vs Other Major Certification Systems. *Journal of Environmental Management* 154: 266–283.

United Kingdom Green Building Council (UKGBC). 2019. Net Zero Carbon Buildings: A Framework Definition. https://www.worldgbc.org/sites/default/files/Net-Zero-Carbon-Buildings-A-framework-definition_0.pdf

United Nations Environment Programme (UNEP). 2020. Global Status Report for Buildings and Construction: Towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector. Nairobi, Kenya: UNEP.

———. 2021. 2021 Global Status Report for Buildings and Construction. Nairobi: UNEP. https://globalabc.org/resources/publications/2021-global-status-report-buildings-and-construction

Victor, P. A. 2012. Growth, Degrowth and Climate Change: A Scenario Analysis. *Ecological Economics* 84: 206–212.

Wallbaum, H., Y. Ostermeyer, C. Salzer, and E. Z. Escamilla. 2012. Indicator Based Sustainability Assessment Tool for Affordable Housing Construction Technologies. *Ecological Indicators* 18: 353–364.

Wang, N. 2014. The Role of the Construction Industry in China's Sustainable Urban Development. *Habitat International* 44: 442–450.

Wang, W., S. Zhang, Y. Su, and X. Deng. 2018. Key Factors to Green Building Technologies Adoption in Developing Countries: The Perspective of Chinese Designers. *Sustainability* 10 (11): 4135.

Waterman, G. 2021. UK Government Sets "Rigorous" New Targets for Green Building Revolution. *Climate Action*, 21 January. https://www

.climateaction.org/news/uk-government-sets-rigorous-new-targets-for-green-building-revolution?utm_source=ActiveCampaign&utm_medium=email&utm_content=UK+Government+sets++rigorous++new+targets+for+green+building+revolution+-+Climate+Action+News&utm_campaign=CA+%7C+2021+%7C+22+January+%7C+Newsletter&vgo_ee=LEHdapdrg7uvgcISMvlFjCo9UEipg8gmsF4AfoiW5NI%3D

Windapo, A. O. 2014. Examination of Green Building Drivers in the South African Construction Industry: Economics Versus Ecology. *Sustainability* 6: 6088–6106.

Wong, J. K. W., and K.-L. Kuan. 2014. Implementing "BEAM Plus" for BIM-Based Sustainability Analysis. *Automation in Construction* 44: 163–175.

Wong, J. K. W., and J. Zhou. 2015. Enhancing Environmental Sustainability over Building Life Cycles Through Green BIM: A Review. *Automation in Construction* 57: 156–165.

Wong, J. K. W., H. Li, H. Wang, T, Huang, E. Luo, and V. Li. 2013. Toward Low-Carbon Construction Processes: The Visualisation of Predicted Emission via Virtual Prototyping Technology. *Automation in Construction* 33: 72–78.

Yang, Z., H. Chen, L. Mi, P. Li, and K. Qi. 2021. Green Building Technologies Adoption Process in China: How Environmental Policies Are Reshaping the Decision-Making among Alliance-Based Construction Enterprises? *Sustainable Cities and Society* 73: 103122.

Yoon, S. W., and D. K. Lee. 2003. The Development of the Evaluation Model of Climate Changes and Air Pollution for Sustainability of Cities in Korea. *Landscape and Urban Planning* 63: 145–160.

Yoshida, J., and A. Sugiura. 2010. Which "Greenness" Is Valued? Evidence from Green Condominiums in Tokyo. Munich Personal RePEc Archive. https://mpra.ub.uni-muenchen.de/id/eprint/23124

Zhang, X., L. Shen, and Y. Wu. 2011. Green Strategy for Gaining Competitive Advantage in Housing Development: A China Study. *Journal of Cleaner Production* 19: 157–167.

Zhong, X., M. Hu, S. Deetman, and B. Stubing. 2021. Global Greenhouse Gas Emissions from Residential and Commercial Building Materials and Mitigation Strategies to 2060. *Nature Communications* 12: 6126.

Zuo, J., and Z. Y. Zhao. 2014. Green Building Research–Current Status and Future Agenda: A Review. *Renewable and Sustainable Energy Reviews* 30: 271–281.

PART III

Transport Sector: Promoting Cleaner Transportation

4

Transport Carbon Dioxide Mitigation and the Production of Low Traffic Neighborhoods: Lessons from London

Robin Hickman and Andrey Afonin

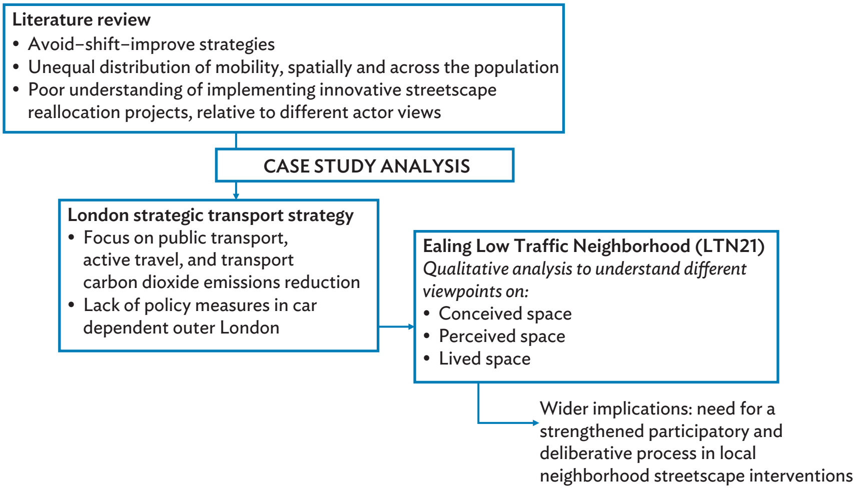
4.1 Introduction

Every society produces its own space and contemporary society has produced many car-dependent spaces, across multiple contexts internationally. Once people have become used to the shape and functioning of their local highways and streets, the restructuring of this becomes controversial. As Lefebvre (1974) suggests: space is produced, rather than simply existing—it is a product of contemporary social structures. The allocation of street space for walking, cycling, and public transport can be controversial, and the process of project implementation needs to include careful mediation of the different views on a project. The representation of space by a city authority can be different to that understood and used by different actors. Lefebvre's concept of the spatial triad hence can be useful here, including conceived space (i.e., how space is represented), perceived space (how space is understood), and lived space (how space is experienced).

Meeting the public policy challenges of climate change and social equity in the transport sector requires radically changed travel behaviors. This involves different transport systems and projects, across multiple cities and regions, in many varied political and cultural contexts, including different uses of streets and a significant allocation of street space to walking, cycling, and public transport. In many cases, this involves reallocating space away from the private car. The proposed changed use of street space may be highly contested, particularly where car ownership and use are high. This is likely to require a significant participatory effort, raising the level of debate on transport projects and urban planning, so that the key actors and local communities can support sustainable transport and urban development projects. The approaches to transport planning will need to change, including in project planning, appraisal, and implementation, so that sustainable transport projects can be more effectively delivered. There is a current "implementation gap" that means sufficient progress is not being made against climate change and social equity goals (Banister and Hickman 2013). This is the scale of the challenge ahead, if transport is to play its role in contributing to lower carbon dioxide (CO_2) emissions, while leading to more equitable travel and access to activities.

This chapter draws on these challenges, using London as the case study, examining the current strategic transport strategy and a local low traffic neighborhood (LTN) project aimed at reducing traffic levels in outer London (Figure 4.1).

Figure 4.1: Study Approach



Source: Authors.

It is the micro-level implementation of streetscape reallocation projects that is proving particularly problematic for reducing transport CO_2 emissions in an equitable manner in London. The contribution of the chapter is to critically examine the London-wide strategy and the aim to reduce transport CO_2 emissions, alongside the competing discourses concerning the local neighborhood streetscape project. The participatory approach used with this type of project is weak, and an approach to transport planning is put forward that includes a strengthened participatory and deliberative process. These types of problems are also seen in many wider contexts, including in Asian cities, where there is a need to develop wide-ranging environmentally sustainable mobility strategies, including streetscape reallocation projects, and consistent with social equitable objectives.

4.2 Literature Review

Following decades of research on sustainable transport planning, the broadly-accepted approach in practice is to implement an integrated Avoid–Shift–Improve strategy (Newman and Kenworthy 1999; Asian Development Bank 2009; Dalkmann and Brannigan 2007; Banister 2008; Hickman et al. 2011). The "Avoid" measures include urban planning to increase development densities and mixes of use around the public transport network, and potentially urban growth containment on the edge of cities to restrict sprawl. Traffic demand management can be used to restrict use of the private car, including pricing regimes, reallocation of road space, and traffic calming measures. The "Shift" measures include a range of investments in networks for walking, cycling, and public spaces, and in different public transport modes, including heavy rail, metro, light rail, bus rapid transit, and bus and paratransit. The "Improve" measures include low-emissions vehicles and electric vehicles, including in passenger, freight, and public and private fleets.

But, within this broad approach, there are many issues to resolve. Many of the measures that take away space for vehicle traffic can be difficult to implement (Hickman and Banister 2014) and, depending on the context, are sometimes not applied or discussed. Governments often prefer to rely on changes to the vehicle fleet and to maintain mobility growth, avoiding the need for shaping the built environment and managing traffic space, or investing in public transport, walking, and cycling. There are therefore many wider "policy taboos" in transport (Gössling and Cohen 2014), and the "more radical" policy measures remain unused in many contexts.

Further, the unequal distribution of mobility also remains overlooked. The social equity dimensions of transport are poorly understood, covering both access to transport and the activities reached beyond or even during the journey (Hickman et al. 2019). Low-carbon transport strategies may also be inequitable in impact, hence need careful definition and consideration. For example, if there is reliance on using low-emissions vehicles, this will exclude lower income groups.

At the neighborhood level, there are often difficulties in implementing streetscape reallocation projects. In the United Kingdom (UK) context, there is some monitoring of the use of local interventions, such as LTNs, which suggests that walking and cycling increases and car use falls (Aldred and Goodman 2021). There is wider consideration of spatial equity in implementation, relative to spatial deprivation and ethnicity, e.g., in terms of where projects are located (Aldred et al. 2021). But beyond, there is little understanding of how residents view or use the projects in particular neighborhoods.

The process for participation is an important element for implementing new transport projects, but again is often poorly developed. Transport is usually conceived and viewed in technocratic terms, assuming that if the right infrastructure can be built, then it will be used. But this has proved overly simplistic in practice, and frequently there are objections and controversy in project planning and delivery, resulting in many failed project implementation processes or poor use of projects. Public viewpoints are often different to the so-called "expert" views—hence, there is a need to understand subjectivity more in the transport planning process and how to best accommodate this.

Understanding discourse is helpful here; language is one of the means by which people construct their own reality (Berger and Luckman 1966), illustrating how they view a particular issue. Discourse is seen, in this context, as a group of statements or speech seen in relation to the beliefs, values and categories which it embodies (Mills 1997), or:

> "a shared way of apprehending the world. Embedded in language, it enables those who subscribe to it to interpret bits of information and put them into coherent stories or accounts [...] each discourse rests on assumptions, judgements, and contentions that provide the basic terms for analysis, debates, agreements and disagreements." (Dryzek 1997, p.9).

At any specific time, different views and discourses are evident on a particular controversial issue, directly affecting the way we think and perceive of the world. Discourses are not merely a representation of society, they actually help produce it (Keller 2013). Understanding discourse could be much more influential in transport planning, as the type and level of debate on a project influences what can be built and what public policy goals may be achieved. This can be related to the use of street space by considering that each society produces its own space according to its own social structures (Lefebvre 1974).

The development and implementation of an integrated Avoid–Shift–Improve framework requires an understanding of its likely progress toward public policy goals, such as climate change and social equity. It is here that many transport strategies fail—they do not lead to sufficient progress against key policy goals, as they are insufficiently ambitious and/or cannot be implemented. This chapter illustrates these issues in relation to the implementation of the LTN, relative to the development of the strategic transport strategy for London. The conceptual framework of the spatial triad, from Lefebvre, is used to structure the analysis of views on the LTN, to highlight that there are different views concerning the use of street space. The implications for mobility strategy development, for wider contexts such as in Asia, are also discussed.

4.3 London CO_2 Mitigation Strategies

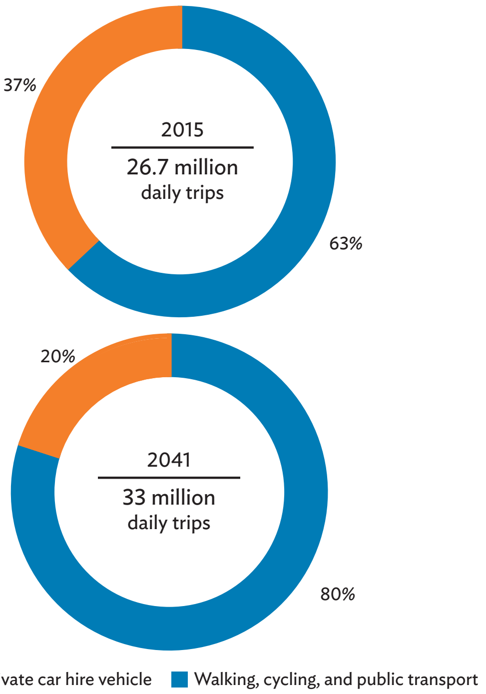
London is described as having a "world leading" transport strategy (Transport for London 2018), including its extensive public transport network and wider transport interventions. It is also seen as progressive in its strategies to reduce transport CO_2 emissions.

The population of London is 8.7 million (2015), with a projection to grow to 10.8 million by 2041. The Mayor's Transport Strategy (Transport for London 2018) suggests that: "London [should] become a city where walking, cycling, and public transport [are] the most appealing and practical choices" (p. 7) and that "the success of London's future transport strategy relies upon reducing London's dependency on cars." (p. 19).

The central target for transport is to increase the proportion of all trips in London by foot, cycle, or public transport from 63% in 2015 to 80% in 2041. The private vehicle mode share is already low at 37%, but will reduce further to 20%. A significant shift is hence envisaged from car use to public transport and the active modes, which are also perceived as being more space efficient, as the only way to move large volumes of people around a compact city. The growth in population will lead to more trips, from 26.7 million in 2015, rising to 33 million daily trips in 2041, but the mode share will change, hence allowing an increased volume of travel around the city (Figure 4.2).

There are many innovative transport projects being planned and implemented, usually led by Transport for London and the Greater London Authority. Major public transport projects include Crossrail, providing an east–west link across London and the region, opening in 2022 at a cost of £19 billion. Crossrail2 has been partially planned but is

Figure 4.2: Mode Share in London, 2015 and 2041

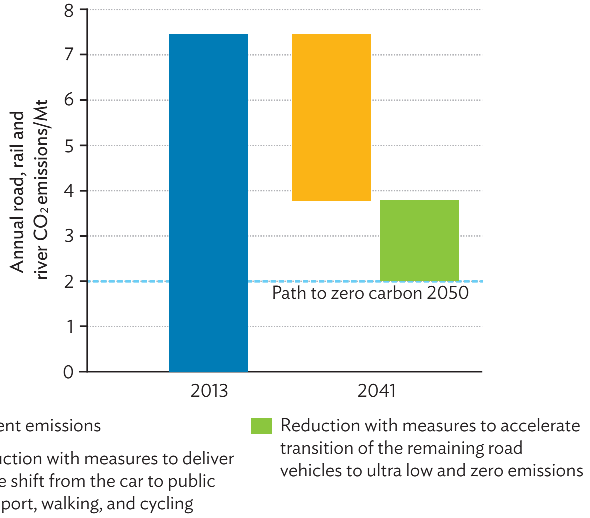


Source: Transport for London (2018).

indefinitely delayed, with an estimated cost of £31 billion. The project is yet to receive full funding from the central government, with earliest planned opening in the 2030s. The central area congestion zone was implemented in 2003, currently charging £15 for daily vehicle entry between 7 a.m. and 10 p.m., into the central cordon. The Ultra Low Emission Zone was implemented in 2021, covering the area within the North and South Circular Roads. Older, heavily polluting vehicles are charged, and a minimum Euro 4 petrol or Euro 6 diesel vehicle is required for free access. Vehicle charges are at £12.50 for most vehicle types, including cars, motorcycles, and vans (up to and including 3.5 tons) and £100 for heavier vehicles, including lorries (over 3.5 tons) and buses and coaches (over 5 tons). The clean vehicle threshold could be more stringent, but already this is a relatively progressive policy measure compared to many other cities.

In terms of CO_2 emissions, the aim of the transport strategy is to reduce transport CO_2 emissions by over 70%, from an annual 7 Mt in 2013 to 2 Mt by 2041 (Figure 4.3). Alongside the encouragement of public transport, walking, and cycling, the public vehicle fleet is to be moved to electric vehicles. The public vehicle fleet will be cleaned with all new taxis to be zero-emissions capable from 2018 and all new private hire vehicles from 2023, all new buses to be zero emissions from 2025, all new cars and vans from 2030, and all other vehicles from 2040. There is some fleet turnover; hence, all taxis and private hire vehicles should be zero-emissions capable by 2033, all buses should be zero emissions by 2037, and London's entire transport system should be zero emissions by 2050. The private vehicle fleet is much more difficult to tackle, as Transport for London has no significant influence on private purchasing, beyond initiatives such as the Ultra Low Emission Zone. Hence, despite many innovative projects, the CO_2 reduction targets will be difficult to achieve, particularly in the outer London areas where car dependency and an old vehicle fleet remain.

Figure 4.3: Reduction in Road, Rail, and River CO_2 Emissions, 2013–2041



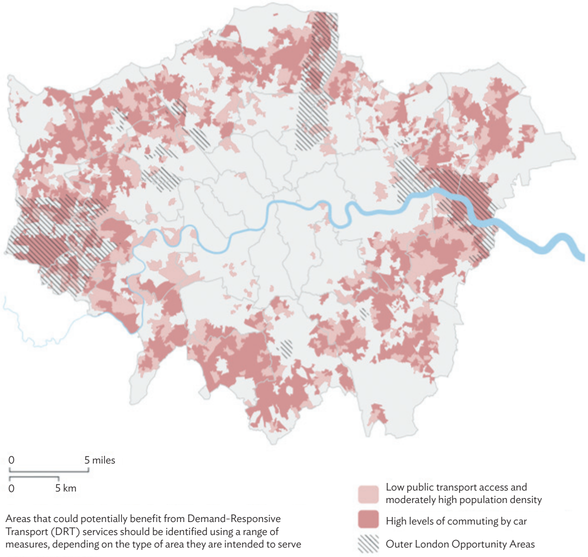
CO_2= carbon dioxide.

Source: Transport for London (2018).

There are some areas where policy making is less progressive. For example, there are few projects to significantly remove road space for private vehicles (Hickman and Huaylla Sallo 2022); and there are no tramway projects in outer London, with the exception of the Croydon tram. The cycle network is poor and consequently mode share for cycling is only at 2.5% in 2018 (Transport for London 2018), much lower than cities in the Netherlands or Denmark. The walking environment and public spaces in outer town centers are poor, and public transport access for people with disabilities is difficult.

Most trips into and within central London are carried out by public transport, walking, or cycling. But outer London is much more car dependent, with high levels of private car ownership and use, and this is where significant difficulties remain for sustainable transport. The introduction of Uber in London has led to much more use of private taxis, with a purported 45,000 drivers registered with Uber in London (CNBC 2021). Transport for London (2018) suggest that three-quarters of journeys currently made by car could reasonably be made by public transport, walking, or cycling—these are the short journeys under 5 kilometers (km) in length. But many parts of outer London have low public transport accessibility and high levels of car use (Figure 4.4), hence the solutions are not so obvious.

Figure 4.4: Car Dependency in Outer London



Areas that could potentially benefit from Demand-Responsive Transport (DRT) services should be identified using a range of measures, depending on the type of area they are intended to serve

Source: Transport for London (2018).

There is, therefore, much progress in central London to achieve greater sustainability in travel patterns, withstanding some difficulties in reallocating road space away from the car. But it is in outer London where there needs to be much greater consideration of options and project implementation. This is the strategic context for examining local streetscape interventions in outer London.

4.4 West Ealing South Low Traffic Neighborhood

4.4.1 LTN21 Context

The West Ealing South Low Traffic Neighborhood (LTN21) is examined to illustrate the often difficult implementation processes for traffic reduction measures in suburban areas. LTNs have been implemented in outer London as an attempt to reduce car travel in outer London. LTN21 was introduced in August 2020 in a mainly residential neighborhood, but with some retail and employment. The area is 2.5 kilometers (km) from Ealing Broadway town center (a 30-minute walk and 9-minute cycle ride). There are underground and overground rail stations immediately surrounding the LTN, Northfields and Boston Manor on the Piccadilly Line and West Ealing and Hanwell on the mainline into Paddington. The LTN covers a relatively large area, 2 km north to south (a 24-minute walk and 6-minute cycle ride) and 1 km east to west (a 12-minute walk and 3-minute cycle ride).

LTN21 was divided into cells giving access from the nearest perimeter road, and through traffic is restricted with so-called “modal filters” (Living Streets et al. 2020), such as planter boxes and bollards (Figures 4.5 and 4.6). Walking and cycling were given through access; hence, the area has “filtered permeability.” The stated objectives of the LTN were to reduce through traffic or “rat running” and to improve the environment for walking and cycling, allowing more people to choose these modes rather than private car or taxi (Ealing Council 2021a). The LTN was introduced with an Experimental Traffic Order that allowed a quick installation of measures during the coronavirus disease (COVID-19) lockdown. Residents were informed of the LTN only 1 week in advance of implementation and the project was subject to an experimental trial of 6 months, with residents and others responding to the statutory consultation at the end of this period. The project was subject to a legal challenge by local residents. Ealing Council issued new LTN orders in February 2021 and extended the consultation period to August 2021. Restrictions on emergency services and disabled residents were revised with the new LTN orders.

Figure 4.5: West Ealing South LTN21

LTN 21 West Ealing – South

ACCESS

🟦 Access from Broadway

🟨 🟥 Access from Northfield Avenue

🟪 🟪 🟧 Access from Boston Road

KEY

- ↳ Permitted direction of travel
- ● No access except for cyclists and pedestrians- Using Planters and Bollards
- ⃠ No right hand turn on to Broadway
- ★ No access except for cyclists and pedestrians - with number plate recognition camera
- ■ Existing Traffic Filter
- School street barrier locations - managed by school staff
  Hours of operation for Oaklands Primary: 8.15am to 9.15am and 2.45pm to 3.45pm
  Hours of operation for St Marks Primary: 8.15am to 9.15am and 2.30pm to 3.30pm
  - School street open to pedestrians and cyclists
- → One-way
- Cycle parking available at station

All local streets will have complete motor access for local uses, such as residents accessing their property, visitors, waste collection, emergency services and deliveries. Although in some cases a different route may need to be taken

Scan the QR code for more information

Ealing
www.ealing.gov.uk

CONTACT US

You can email us your support or objection to TrafficNotices@ealing.gov.uk, or post them to the Highways Service, Perceval House, 14-16 Uxbridge Road, W5 2HL.

Source: Ealing Council (2021b).

Figure 4.6: West Ealing South LTN21 – Modal Filters and Planter Boxes Aimed at Traffic Restriction

Source: www.thisislocallondon.co.uk

4.4.2 Method of Analysis

Qualitative analysis was used to provide a deeper understanding (Silverman 2013) of the differing perspectives related to the LTN implementation. Fifteen in-depth, semi-structured interviews were carried out with residents, resident groups, businesses, and other key actors in the neighborhood (from Afonin 2021). All the respondents lived in Ealing, with the majority living in LTN21. Convenience sampling was used to recruit respondents, aiming for an approximate balance of viewpoints relative to the implementation of the LTN. This was achieved with broadly pro-LTN (7) and anti-LTN (8) viewpoints within the survey responses. There is no attempt to claim representativeness of the wider population.

Each interview aimed to explore different viewpoints on the LTN. Interviews were primarily face-to-face, audio-recorded, and varied in length from 45 to 60 minutes. Each interview was audio-recorded and professionally transcribed. The interview content was analyzed using NVivo software and a coding scheme. The transcripts were coded to highlight the perceived important themes in the debate and then summarized into subthemes, describing the main arguments being used (Erlingsson and Brysiewicz 2017). The different viewpoints and experiences were recorded and the content analysis helps to uncover the underlying elements, alongside interpretations of meaning, in relation to the LTN project. Content analysis hence contributes to the identification of the non-obvious factors that might explain the success factors in project implementation

The discourses presented are assessed in terms of the spatial triad conceptual framework (Lefebvre 1974; Leary-Owhin 2016). This allows us to consider how space is related to and constructed by social relations, i.e., how space is a social product based on values and meanings, and how the use of the street means different things to different actors. The analysis is, therefore, primarily inductive, grounding the examination of the LTN and the inferences drawn in the interview data. But there is also use of a deductive approach in applying the spatial triad framework to the structure of the interviews and the analysis.

4.4.3 Differences in Language Used

There were protagonists and antagonists for the LTN scheme, including from the Ealing Borough Council, residents, employees, Ealing Cycling Campaign, and resident groups set up to oppose or support the LTN, such as One Ealing, Ealing Better Streets, and the Coldershaw and Midhurst Traffic Action Group.

The following views were given on the implementation of LTN21. Initially, we can see the language by the protagonists and antagonists is different (Table 4.1). The language used by each actor group involved or commenting on the projects differs quite significantly (Table 4.2). Interviewees who are pro-LTN talk about "people" (2.31% of interview content), "think" (2.2%), "road" (1.37%), "like" (0.98%), and "participant" (0.81%), hence are focused on the impact on pedestrians; while the anti-LTN interviewees are more focused on the impact on traffic, using "road" (2.31%), "traffic" (1.14%), "car" (1.03%), "drive" (0.79%), and "time" (0.63%). Hence, even in terms of the language used, we can see there are differences in viewpoints, the discourses put forward by each group and the positions taken.

More detailed viewpoints are explored below in terms of conceived space, perceived space, and lived space.

Table 4.1: Key Language Used by Protagonists and Antagonists

Pro-LTN			Anti-LTN		
Word	**Count**	**Weighted %**	**Word**	**Count**	**Weighted %**
People Peoples’	226	2.31	Road Roads	212	2.31
Think Thinking, thinks	215	2.20	People Peoples’	171	1.87
Road Roads	134	1.37	Traffic	104	1.14
Like	96	0.98	Car Cars	94	1.03
LTN LTNs	93	0.95	Ealing	92	1.00
Participant Participated	79	0.81	Live Living, lived, lives	76	0.83
Know Knows	71	0.73	Now	75	0.82
Council Councils	64	0.65	Drive Driving	72	0.79
Traffic	62	0.63	Time Times	58	0.63
Change Changed, changes	59	0.60	Need Needs, needed	56	0.61
Data	54	0.55	LTN LTNs	53	0.58
Drive Driving, drives	51	0.52	Council Councils	47	0.51

LTN = low traffic neighborhood.

Note: Most frequently used words, including stemmed words.

Source: Authors.

4.4.4 Conceived Space (Representation)

Conceived space is viewed as the “official” representation of space, including the narrative given from the city authority. In the LTN example, it includes the strategies, knowledge, signs, and codes used to represent the revised allocation of space on the street. The use of the negative metaphor of rat running was used by Ealing Council to give a negative connotation to through traffic as opposed to traffic originating in the residential area, i.e., as the target for the street intervention. The term is also used by some of the residents interviewed. However, the negative framing proves objectionable to those who drive through the neighborhoods; indeed, most residents will take shortcuts through residential areas, and they do not like to be described in this way. The blaming of through traffic for congestion in neighborhoods underplays the problem that all traffic needs to be reduced, including that originating in the neighborhood.

> “The LTN was initially put forward to prevent rat running along the roads. It was also meant to nudge people out of their cars and deliver safer streets. It encouraged people to shop locally and things like that.” (Interview 1)

> “I think the LTNs were trying to address two issues. One was rat running—and this is a very genuine problem which has got worse in recent year because of these apps like Google and Waze, so if you are stuck in a traffic jam, your phone gives a ‘beep’ and says take first left on a sort of route that you wouldn’t have contemplated in the old days when you relied on maps [...] the second thing that the LTNs were trying to achieve was to persuade people to stop using their cars to just pop down to the end of the road to buy a newspaper and to get out and walk and ride a bicycle instead. All very laudable, but that presupposes that people were in fact making these short journeys by car which needn’t be, and I think that is something that one would need to evidence to see whether that is a general problem or not. I think a lot of people don’t make that sort of journey because they know that when they get back, they may not get a parking space, or a convenient parking space [...]. There are many ways to stop people making short city journeys, but I think that LTNs are not a very efficient way.” (Interview 2)

> “There have been several LTN-like measures that have been in place for years and they haven’t been even remotely controversial, just simple road closures to stop rat running traffic. The current LTNs purpose is not specifically an area wide traffic management scheme, but they’re just to stop people who are considering to rat run.” (Interview 6)

4.4.5 Perceived Space

Perceived space is the understanding and use of space. This can be seen as the understanding of street space allocation and usage in the neighborhood, in relation to the official meaning that is given. Some of the interviewees support the LTN, particularly for the reduced traffic levels within the residential neighborhood. Yet, there is concern that that data are limited to assess whether the neighborhood area and adjacent roads have experienced less or more traffic.

> "I think they [LTNs] have opened peoples' eyes to the fact that they could be living in a much more pleasant, calm, lovely environment than they were. Once it was embedded and they found their roads were blissfully quiet and there weren't cars from miles away doing speed runs down the road, it was actually incredibly pleasant. We should be demanding nicer environments to live in safety with good health—lots of trees, lots of planting, lots of open space—access to water and fresh air, good facilities, safety, quiet, peace. We should be allowed to have these things in a modernized country. Why wouldn't you want more of that? Everyone benefits." (Interview 5)

> "We've got red kites and buzzards here now, which I never saw before. It's just great to enjoy them. Lots more people, and this is purely anecdotal because we have no baseline, lots of people cycling, lots of families and kids [...]. For me, the inconvenience is irrelevant compared to the quality of environment" (Interview 6)

> "[The LTN led to] a massive reduction of traffic going past the house every day, and now it's back again. The noise, the beeping of horns and the arguments have got a little worse [with the removal of the LTN], although it's centered around a couple of times of the day, the peak hours. I have kids that go to the local school, the eldest one walks there by themselves. When the LTN was in place, and the traffic was reduced, they felt a lot of more comfortable. Whereas now we have delivery vans parked on the yellow lines and parents reversing up and down the road to try and avoid each other, so it is generally more discomfort than when it was there." (Interview 3)

> "I think they [LTNs] have reduced pollution – the data and the facts are now starting to come through and are backing that fact up. Unfortunately, people who are against them are now so embedded in their mission to remove them, they don't care about facts." (Interview 5)

> "Behavioral change takes time and anybody who expected on day one for everyone to change their behaviors wasn't being realistic. I feel like a lot of people have changed [...]. I've not done any surveys or anything like that, but there definitely was an increase of active travel to school (to Fielding school, for example). Prior to the LTNs there were probably two families that cycled to school on the roads, during LTNs that went up. Just on the route I walk every day, it went up to 10 or 12. It became a much more familiar experience to see people cycling to school." (Interview 1)

There are perceived problems with inconvenience, increased journey times, delays, and traffic displacement, particularly for those who deem their journeys as critical, either for work or other activities. The range of people affected, and their different circumstances, were significantly underestimated when the LTN was being planned.

> "Every time I go out of my house, instead of having a 3-minute journey to head towards the A40 and Pitshanger and that area, I now have to travel an extra 20-25 minutes, depending on the traffic to go all around Ealing, and I have to do that at least once a day, if not multiple times a day. It's my route to the people I work with, it's my route to my GP, it's my route to the supermarket, it's my route to the A40, it's basically my route to most of the places to which I go." (Interview 11)

> "I have been affected by being forced to drive further every time I wanted to go anywhere, therefore I was creating more congestion, more pollution [...]. I am in my 70s and I don't use my car a huge amount, but I drive to visit friends who are too far away to walk. I've got a friend who hasn't got a car, so I got to her house to collect her and take her out with me or to the supermarket [...]. When they were first implemented [the LTNs], many of us predicted what the effect would be and we were proved correct, but the Council absolutely refuses to believe it. They are adamant that it's all wonderful and does all the things it is expected to do, makes people walk and reduces pollution, which it doesn't at all and, incidentally,

they are also terribly keen on cycling and all we have now is cyclists riding on pavements and terrifying pedestrians half of the time." (Interview 7)

"I live on quite a busy road and there is quite a lot of traffic and you would often get stand offs and people not wanting to reverse, shouting at each other and beeping. I can see why they would want to reduce the traffic coming down the road, for sure. I know a lot of people drive to school or drive to local trips to the shop that you can do on foot. I'm not sure that was the case for us. I think we do a lot of journeys on our bikes or on foot anyway, we only use the car when it's necessary [...]. I make cakes for a living and I deliver a lot of them locally—I do a lot of local journeys by car that I need to do, and I found I was driving twice as far as I would have, because I had to drive such a long way around to get where I need to be. Taking our kids to sporting activities and the like, there are some journeys that you just have to do by car and for us to get out onto the main road it did mean driving a lot further." (Interview 4)

"I missed a really important cancer appointment, because it took me two and a half hours to do a 10–12-minute journey by bus normally." (Interview 8)

"I spoke to my neighbors and they said, oh, it will be a nice and quiet road, where children will play out. But children don't play out, because their parents don't trust anybody anymore—nobody plays out these days, it doesn't matter if the road is quiet or not." (Interview 9)

"I'm supposedly benefiting from cleaner air, according to Ealing Council propaganda, but I know for a fact that pollution has gone up. With LTN21, the traffic on Northfields Avenue was always queuing. Previously, if I open my back door, there was clean air. Now I open my back door and the pollution level goes right up to the maximum in terms of nitrous oxide and this is what triggers my asthma, so I couldn't open my back door when the LTN21 was there." (Interview 14)

"I think it's just moved the problem elsewhere. The traffic jams caused on the other roads, they weren't there before, so the traffic feels like it has moved from our road to elsewhere.

> I'm glad I don't live on those roads that have permanent stationary traffic. For people like us, our roads became quieter, it was lovely, there was much less traffic. But it's just been moved elsewhere, so other people are in a worse situation now." (Interview 4)

Some of the viewpoints counter these positions and suggest all should be driving less.

> "I'm afraid the solution is that people need to be driving less [...]. It's about making changes that might be not your favorite way of doing something, but it's the non-selfish way of adapting your life for the betterment of everybody. That's why I don't believe it is at all right to say, oh, but now I've got to drive all this way round because not everybody in Ealing is not disabled, elderly or immobile or a white van driver, for heaven's sake. It would be ludicrous to pretend that everybody is totally dependent on a car." (Interview 5)

There are consistent and widely held viewpoints that the consultation on the LTN implementation was poorly developed. The borough council is perceived as having imposed an unpopular project, very quickly, and deliberately withholding information to achieve unclear goals. The local authority is not trusted, with some suggesting there are abuses of power.

> "The council didn't do a great job of communicating that LTNs were going to exist. So, I suspect 99% of people didn't think about them until they were here, and I include myself in that number." (Interview 3)

> "They should have communicated better. The Council put in no effort at all in communicating. If you read the government justification for LTNs I think it makes sense. Particularly in a Covid scenario where you are trying to get people to move around with social distancing. Then widening pavements and things like that makes sense. If 60% of people say that they are too scared to cycle, then making the roads safer is a positive thing." (Interview 1)

> "People essentially got a week's notice for something that was going to change how they live [...]. It's important to recognize that, if you want people to change, they need to know that they need to change." (Interview 6)

> "The trouble is, whatever the outcome of the consultation, no one will trust the outcome and it will be very, very binary. You will have half the community delighted and half the community making it their life's mission to overturn it, just like Brexit." (Interview 5)

4.4.6 Lived Space (Representational Meaning)

Lived space is the meaning, value, and depiction of space by users. This covers the feeling of using the revised street space, and can include resistance, clandestine and underground activity, and the reclamation of space. Some strong support for LTNs is evident, with people enjoying the new quieter spaces, even independently monitoring traffic levels or removing vandalism. In addition, there are many vocal anti-LTN views, including vandalism to planters and oil poured onto cycle routes through junctions, to deter the cyclists.

> "I think you have to be aware of the religious fervor with which some people hold their views on these LTNs. It's divided the cycling group more than a lot of things have ever before." (Interview 2)

> "It's a really emotive issue and people for the most part are in one camp or the other, at least the vocal people. I guess 60-70% of people don't care." (Interview 3)

There are some broadly enjoying the use of streets with less traffic and improved conditions for walking and cycling.

> "I was surprised how much quieter it was. I felt almost guilty about how quiet it was. Obviously being forced to stick to the main roads is an inconvenience of people. But, yeah, it was really nice. I mean it's probably partly down to lockdown as well." (Interview 1)

> "It's a residential area and it feels like the cars have been given a gradual undue prominence over the last, well, 20-30 years. I think the streets were built for the people that live there to get around the place. I'm overwhelmingly in favor of them." (Interview 3)

There are many who do not agree with the revised arrangement of street space under the LTN. Some are concerned about the restricted traffic movements and impact on their lifestyles. The dominant use of roads by cars has become "naturalized," i.e., it has become so familiar and embedded in many people's lifestyles and viewpoints. The evidence behind their positions is sometimes unclear, and there are issues raised of exclusion and inequity. Metaphors are used in language, sometimes as root metaphors, illustrating the individual's perception of the world and interpretation of reality, e.g., the neighborhood has become "a ghost town," there are "empty streets," and crime has purportedly risen dramatically due to the LTN.

> "I found it much more inconvenient, because there are a lot more barriers, than I thought it would be. I didn't realize they would put so many in and how difficult it would be to actually get anywhere. Also, a couple of times, there was an accident on Boston Manor Road for example and they had to close off a section. There was no way to go in terms of an alternative route and you felt stuck in your road. The one exit out was blocked because of an accident, so there is no plan B when something like that happens." (Interview 4)

> "I think if children want to play they should go to the parks. I think it's completely irresponsible to make the roads a play area—completely irresponsible to make roads a play area. I think it's completely the wrong method. And, if they don't want to have roads, then we shouldn't charge all that road tax because we don't have the roads." (interview 11)

> "It does make me feel very anxious. I now worry that if there is any small disruption on the road that I will be seriously late to something, particularly picking up my daughter from school or an ambulance getting through because the road is blocked. Whereas, previously, they would have been able to go another route." (Interview 14)

> "It was such a relief when they removed [the LTN] and I could drive up to my friends in 5 minutes by a direct route, without sitting in traffic queues, as opposed to about 20 minutes sitting in a traffic queue idling my engine. And that was by a school of course and they're all worried about the children and their lungs, etc. And there were other schools and the shopkeepers on the road were complaining of loss of trade, because there weren't any passersby who stopped to by newspapers on the way to work." (Interview 7)

> "Even the cyclists came on the march with us because they said they feel really unsafe at night time, if you've got a bit of road traffic you feel safer. You know as a woman walking late from the pub, you've had a couple of drinks you know you won't feel safe. Every single road around here at night time is a ghost town, so stabbings have gone up like 90%, theft you know, like people stealing amazon packages, that's gone up, stealing of catalytic converters that's gone up by 70% because they can go around the empty streets all night thieving." (Interview 8)

> "Every pro LTN-er I know is middle aged or youngish, English, and very middle class and it's almost like because they don't need cars and they're not doing those sorts of jobs, like deliveries, taxi drivers. I feel like they don't have an appreciation for it. It feels like they want to live in the country, even though they're living in the city. If you want a nice quiet street, go somewhere else. This is London." (Interview 9)

> "It doesn't escape my attention that they didn't put an LTN in the Grange area of Ealing. That's the richest part of Ealing with very affluent people living there. Instead they decided to do it in the white middle classes of South Ealing/Northfields. They didn't necessarily do it in Southall. They are kind of racially profiling where they are putting it. They are putting it in the white areas where people will pay fines." (Interview 10)

> "I pay my taxes to support all of the roads in this area, why should I be banned from driving down some of them? If they want to turn them into private estates that's fine—the people who live on those roads can play on those roads, but I pay a tax for the whole borough. They're not needed, there's no point to them. We don't want people walking in the middle of the road, we don't want kids walking in the middle of the road. It's just absurd." (Interview 10)

Some are concerned about the unclear rationale behind the LTNs, perhaps being there to help raise funds for the local council. Again, metaphors are used in language, e.g., the LTN existing as a "cash cow" for the local authority.

> "Because of COVID they didn't make the usual revenue from parking tickets, so they knew it was another way to make a huge cash cow a lot of money [...]. Turns out they are fining everyone. I think it was initially £80 a time and then we soon realized they were making £1.5 million a month from this so-called green scheme. So, I wrote to Ealing Council, wrote to my MP, wrote to BBC News and said what is this thing that's going on [...]. I feel like I'm in a road prison and now I can't get anywhere." (Interview 8)

Beyond this, there are some trying to support Ealing Council in their interventions and to fight against the antagonists.

> "When they first installed them I ignored them for a month or so, then I noticed people were vandalizing the filters and stealing the bollards. So, initially, I was just walking around putting the bollards back in. Then I came across a group of people who were shoveling soil into one of the overturned planters, so got chatting with them and I realized there was a wider group of people, a kind of community group in support. So, I joined the WhatsApp and realized I already knew a couple of people in there, and so we have just been growing, a WhatsApp group of 50 people or so that has been trying to coordinate a bit of effort to act as a supportive voice to the Council" (Interview 3)

> "I bought the data from Google who collect that as part of their Satnav service and then make that available in a pretty raw form. Doing the analysis it is me and another person. The analysis came around just through the frustration of seeing a lot of the claims made by the anti-LTN lot are demonstrably false. They are lying [...] things like inflating crowd numbers at the marches, through to interpretation of some of the numbers and the data around traffic and flow. I don't want to create a war between two camps but some of the counter claims are massively inflated." (Interview 3)

> "I think the removal of the LTN is a real shame. I do think the Council should have made more tweaks [...]. They could've made more exceptions to allow people who are really inconvenienced to drive through the filters [...]. It's weird because it was in the manifesto for the governing party here in Ealing, it was in TfL's and the Mayor's manifesto and it

> was in the Conservative manifesto. For something that's supported at every level of government [...], I see this as an effect of social media drumming up fear, uncertainty and doubt about something, so I don't think the Council are going to reintroduce it." (Interview 1)

4.4.7 Potential Future Amendments to the LTN

There are some views on further steps for the LTNs in Ealing, mostly attempting to plan a way forward from the current problems in implementation.

> "I know that it has an adverse effect on some people with small business and I think the Council should be wary of affecting small businesses like that. They didn't have to have the filters completely impermeable. There are some who genuinely have to drive and they should have been accommodated better." (Interview 1)

> "I wonder if we could make some more changes around residential access or one-way residential access in some cases. So, there is clearly a bit more work to do. But, there's only so many adaptations that you can make before they become a bit pointless. Some of the suggestions I heard were just a bit ridiculous, like let's allow residential access but also for all their visiting family members and the delivery drivers [...]. On the surface people might say they're concerned about pollution on the main roads. But, by and large, people are voting on their own individual convenience. If they used to drive that way because it was five minutes quicker, then that's what they want to keep doing, and they don't like the Council telling them otherwise." (Interview 3)

> "The LTN is much bigger than anything that has been tried in London before and I think that it's a good thing that it has been withdrawn because it was too big. The way you had to go round if you were trying to get out in your car towards the far side, it was a very long way around." (Interview 2)

> "I think that we will probably end up with some kind of reduced form of what we had last year—I imagine they will keep some of them and put in a reduced version of LTN21.

> At the beginning there were all these stories of ambulances not being able to get through on time. That was certainly a concern at the beginning and it felt as if the ambulance service had not been consulted properly. They got around that by removing the posts and putting cameras in, which is great—they reacted to the problem. But, to me, that is a demonstration that they rushed it all through rather quickly and it was not considered in the beginning." (Interview 4)

> "I think in the Netherlands, where they have a lot of LTN-type situations, they normally have a much higher quality of cycle provision on the roads around the outside of the LTN. So, in an Ealing context, if you imagine roads like South Ealing Road, Northfields Avenue, and so on, as a minimum, you would have a segregated cycle track along each of those roads and then, if the cars have to queue up to get around, people just accept that." (Interview 2)

There are possibilities for improved participatory mechanisms, with improved discussion of project options, facilitated by impact monitoring data, and voting mechanisms to gradually reach consensus on options.

> "I think it's got people thinking about how much they use their cars, and what they can do to reduce that. It got the conversation started, but I just think it's all been done wrong [...]. Carrying out proper studies of traffic movement are required, when we're not locked down, not in a unique situation when people are not going to work, not going to school." (Interview 4)

> "If there are genuinely a range of options, there is no reason why you can't have a single transferable vote with more than three options. Because the whole essence of the single transferable vote system is that it whittles it down to the one that's least objectionable." (Interview 2)

The process of project planning and implementation can be much more deliberative—where the levels of awareness and support are gradually increased and a consensus reached on a particular project option. However, the LTN has led to political difficulties and a change of leadership in Ealing Council.

> "This is just now a political issue and they're just trying to exit from what the last administration did in a least chaotic way possible." (Interview 3)

> "They're in a situation where the politics of it [is dominating], because of the noise. Literally nobody knows how many people as a proportion of the population are for or against these things. Nobody yet has done a randomized survey on what people actually think about these things. It's always the way with anything like this, the negative voices, they always put a lot of their energy into these things. If you really hate something, you're really energized by it. If you think it's great, why do you need to do anything more." (Interview 6)

4.4.8 The Resulting Political Position and Project Status

There has been no formal before and after study of the LTN project by Ealing Council, e.g., in terms of traffic movements. This is mainly due to the speed of implementation of the project in response to COVID-19 and also reflects resource constraints for the local authority.

In May 2021, the Ealing Council leader (Labour), Julian Bell, was replaced in the local elections, with the LTNs viewed as a very significant factor in the voting. The new leader, Peter Mason, Leader of Ealing Council (Local Transport Today 2021), put forward his position.

> "Ealing Council promised to listen to local people's views on active travel initiatives like LTNs, and we have done just that [...]. The remaining LTNs will be subject to a [Controlled Parking Zone] CPZ style consultation, with a vote for local people on whether they think the LTNs will work in their neighborhoods [...]. I've pledged that the Council I lead will be open, transparent and inclusive. That means being honest about what works and what doesn't. This decision is about giving local people control over change in their neighborhoods. Our commitment to tackling the climate emergency and enabling active travel and cycling remains unchanged, but we know we must take people with us." (Peter Mason, Leader of Ealing Council)

A survey was produced by Ealing Council, using SurveyMonkey software. The resulting survey had 22,000 responses. About 4,000 people reported that they lived in the LTN and 1,000 on the adjacent roads; 17,000 were non-LTN residents. This was an unsampled survey with a very low response rate (6%), relative to the 345,000 residents in the borough, and indeed it is not known where respondents were located. The survey asked all respondents: "Would you like the LTN to be made permanent once the trial period ends?" In total, 82% of respondents said "no" (Steer 2021). A more robust sampling approach is needed when undertaking surveys of this type. Yet, on this basis, the trial was abandoned by Ealing Council and the planters and barriers have been removed. As a result, the neighborhood streets have been returned to the cars and traffic.

There are further views on the process of project implementation.

> "I think they've made a shocking mistake and have shown very weak leadership by not just taking a stance. They know very well they've got to reduced pollution, [traffic] is dangerous, its killing people, there are traffic accidents, people aren't getting the exercise they need to remain fit, it puts stress on the NHS. Everybody knows it and all it needed was for someone to say, I'm in charge of this [...]. If we did, people would forget that there was ever a time when they could just willfully drive around the block. Instead it's just left everybody unhappy." (Interview 5)

Hence, a problematic position has been reached. The climate change problem is recognized, at least at the abstract level, by most politicians and the public. But the politicians are not able to take a lead in supporting the LTNs, or even offer any alternative strategy. The levels of resident commitment are not consistent with their views on climate change; and there is much conflict in positions. The social equity of current car use, public transport, walking, and cycling is not well studied or assessed. Generally, among residents, there is support for some reduction in short journeys undertaken by car, yet the use of the car is seemingly too embedded in people's lifestyles to allow many to change their travel behaviors.

4.5 Conclusions: Reflections for Wider Contexts

Individual car use has become central to many people's lives as contemporary society has produced car-dependent neighborhoods. Moving away from this position, toward more sustainable travel behaviors, can be very difficult. The strategic transport strategy for London (Transport for London 2018) is relatively progressive, and includes many innovative projects, but struggles to implement projects that reallocate road space to public transport, walking, and cycling. There is a particular reliance on the private car in outer London.

The experience of LTN implementation in London helps to illustrate how changes to the street space can be controversial, even where the interventions are quite marginal. A well-intentioned project, aimed at reducing traffic levels in suburban outer London, is perceived to have been poorly implemented and, in effect, has been rejected by the local neighborhood, or at least a significant cohort within the local population. As Lefebvre (1974) suggests, decades of capitalism, and motorization, have affected the use of space. The motor manufacturers and associated organizations have been successful in persuading people that they need to travel around in their vehicles. Many streets and wider urban environments have been shaped around the use of the car. In residential neighborhoods in Ealing, this means much of the street space is given over to the private car, either for car-based travel or car parking. Pedestrians and cyclists have lost the opportunity to use the street. Many residents have become used to this way of life and find it difficult to imagine another way of living. There is a “fixity” of car-based travel (Matthies and Klöckner 2015), which is difficult to overcome.

Asia has different and varied urban contexts, with different problems and opportunities for sustainable mobility. Most Asian cities have busy urban areas, but many have poor public transport networks, traffic congestion, and little high-quality space for pedestrians or cyclists. There is a similar increased reliance on the private car and demands for increased traffic capacity, albeit with lower levels of car ownership and use. There is inequity in access to transport networks, street space, and the associated activity participation. Providing more space for walking and cycling can be very difficult. Hence, the controversy around the implementation of sustainable transport and streetscape projects reflects common issues internationally.

The experience of implementing streetscape projects in London and LTN21 can be generalized to wider contexts in the following ways:

1. Implementation of an Avoid–Shift–Improve strategy needs to include a wide-ranging, integrated strategy and projects. But the contribution to transport CO_2 reduction needs to be significant and the social equity impacts be considered.
2. At the local neighborhood level, street space reallocation projects can be used to gradually allocate space to public transport, walking and cycling, including away from the private car. Emphasis can be given to suburban areas, perhaps

where public transport accessibility is lowest. Over time, major improvements can be made to public transport, walking, and cycling networks, and public space and residential neighborhoods can become low traffic areas.

3. A proportion of funding can be focused on improving public transport, walking, and cycle access in low-income neighborhoods. This is particularly important for cities with high levels of social deprivation and inequity, as found in Asia.
4. Different viewpoints and discourses can be assessed within the process of project implementation, so that views of the protagonists and antagonists are well understood and can be mediated and responded to. Often the viewpoints on a project may be different to that envisaged by the project promoter.

In Ealing's LTN21, the use of Lefebvre's (1974) spatial triad of conceived, perceived, and lived space allows an understanding of how a new transport project is produced by the city authorities and transport planners, yet understood and used by residents and others in ways that were not envisaged. There is polarity and entrenchment of views, often informed by cultural positions. Using a participatory and deliberative approach is critical to the success of project delivery, particularly where projects affect local neighborhoods and aspirations to use the private car. This type of process will help raise the level of discussion and debate, so that the ownership of projects and effective delivery can be improved, consistent with wider public policy goals concerning climate change and social equity. The participatory process will differ for each project but should aim at raising awareness of the objectives for sustainable mobility, as well as achieving consensus on the agreed strategy and projects. The process for transport planning hence becomes more normative, and participatory and deliberative in nature—and progress toward sustainable mobility can be much more effective.

References

Afonin, A. 2021. Discourses on Low Traffic Neighbourhoods: Understanding the Impacts of Implementing an LTN in Ealing, London (unpublished MSc dissertation). London: Bartlett School of Planning, University College of London.

Aldred, R., and A. Goodman. 2021. The Impact of Low Traffic Neighbourhoods on Active Travel, Car Use and Perceptions of Local Environment During the COVID-19 pandemic. *Findings,* 5 March. https://doi.org/10.32866/001c.21390

Aldred, R., E. Verlinghieri, M. Sharkey, I. Itova, and A. Goodman. 2021. Equity in New Active Travel Infrastructure: A Spatial Analysis of London's New Low Traffic Neighbourhoods. *Journal of Transport Geography* 96: 103194.

Asian Development Bank (ADB). 2009. *Changing Course. A New Paradigm for Sustainable Urban Transport*. Manila: ADB.

Banister, D. 2008. The Sustainable Mobility Paradigm. *Transport Policy* 15: 73–80.

Banister, D., and R. Hickman. 2013. Transport Futures: Thinking the Unthinkable. *Transport Policy* 29: 283–293.

Berger P., and T. Luckman. E 1966. *The Social Construction of Reality: A Treatise in the Sociology of Knowledge*. New York, NY, US: Anchor Books.

CNBC. 2021. Uber Employment Rights Setback Is a "Gut Punch" to Its Prospects in the UK, 18 March. https://www.cnbc.com/2021/03/18/uber-is-reclassifying-uk-drivers-as-workers-heres-what-happens-next.html

Dalkmann, H., and C. Brannigan. 2007. *Transport and Climate Change. Module 5e. Sustainable Transport: A Sourcebook for Policy-makers in Developing Cities*. Bonn, Germany: Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH.

Dryzek, J. 1997. *The Politics of the Earth: Environmental Discourses*. Oxford, UK: Oxford University Press.

Ealing Council. 2021a. FAQs – Low Traffic Neighbourhoods (LTN) to Support Social Distancing. Ealing, UK: Ealing Council.

———. 2021b. LTN 21: West Ealing South Low Traffic Neighbourhood Plan. Ealing, UK: Ealing Council.

Erlingsson, C., and P. Brysiewicz. 2017. A Hands-on Guide to Doing Content Analysis. *African Journal of Emergency Medicine* 7: 93–99.

Gössling, S. and S. Cohen. 2014. Why Sustainable Transport Policies will Fail: EU Climate Policy in the Light of Transport Taboos. *Journal of Transport Geography* 39: 197–207.

Hickman, R., and D. Banister. 2014. *Transport, Climate Change and the City.* Abingdon, UK: Routledge.

Hickman, R., P. Fremer, M. Breithaupt, and S. Saxena. 2011. *Changing Course in Sustainable Urban Transport. An Illustrated Guide.* Manila: Asian Development Bank.

Hickman, R., and K. Huaylla Sallo. 2022. The Political Economy of Streetspace Reallocation Projects: Aldgate Square and Bank Junction, London. *Journal of Urban Design* 27(4): 1–24. https://doi.org/10.1080/13574809.2022.2033113

Hickman, R., B. Mella Lira, M Givoni, and K Geurs, eds. 2019. *A Companion to Transport, Space and Equity.* Cheltenham, GLOS, UK and Northampton, MA, US: Edward Elgar Publishing.

Keller, R. 2013. *Doing Discourse Research. An Introduction for Social Scientists.* London: Sage.

Leary-Owhin, M. 2016. *Exploring the Production of Urban Space. Differential Space in Three Post-Industrial Cities.* Bristol, UK: Policy Press.

Lefebvre, H. 1974. *The Production of Space.* Paris: Anthropos.

Living Streets, London Cycle Campaign, and Rosehill Highways. 2020. A Guide to Low Traffic Neighbourhoods. London: Living Streets, London Cycle Campaign, and Rosehill Highways.

Local Transport Today. 2021. New Council Leader Says Local People to Vote on Future of Low Traffic Neighbourhoods. 21 May.

Matthies, E., and C. Klöckner. 2015. Car-fixation, Socialization, and Opportunities for Change. In R. Hickman, D. Bonilla, M. Givoni, and D. Banister, eds. *Handbook on Transport and Development.* Cheltenham, GLOS, UK and Northampton, MA, US: Edward Elgar Publishing.

Mills, S. 1997. *Discourse.* London: Routledge, pp. 491–501.

Newman, P., and J. Kenworthy. 1999. *Sustainability and Cities: Overcoming Automobile Dependence.* Washington, DC: Island Press.

Silverman, D. 2013. *Doing Qualitative Research.* London: Sage.

Transport for London. 2018. *Mayor's Transport Strategy*. London: GLA, Transport for London.

____. 2019. *Travel in London. Report 12*. London: Transport for London.

5

Decarbonizing the Transport Sector through Electrification and Biofuel Use in Emerging Economies of Asia

Venkatachalam Anbumozhi, Citra Endah Nur Setyawati, and Rafi Aquary[1]

5.1 Introduction

The transport sector continues to be a significant contributor of global carbon emissions, accounting for approximately a quarter of energy-related greenhouse gas emissions (BP 2019). Economic growth, infrastructure connectivity programs, rapid urbanization, and rising private vehicle ownership are driving major increases in passenger and freight transportation throughout Asia. As a result, between 2015 and 2019, transportation-related carbon dioxide (CO_2) emissions increased by 41%, with the People's Republic of China (PRC) and India leading the way, followed by Southeast Asian countries (UNESCAP 2021). Continued growth in demand for private mobility, and the persistent reliance on fossil fuels for transport are a major challenge to the decarbonization efforts of the transport sector in the region (Pan et al. 2018; Kim and Mishra, 2021; Zhang et al. 2018). Formulating transport sector strategies will be crucial for meeting the goals of the Paris Agreement as expressed by the nationally determined contributions (NDCs) by 2030 (Toba et al. 2019; Zhang, Fujimori, and Hanaoka 2018; Anbumozhi 2021). Accordingly, several Asian countries that have set

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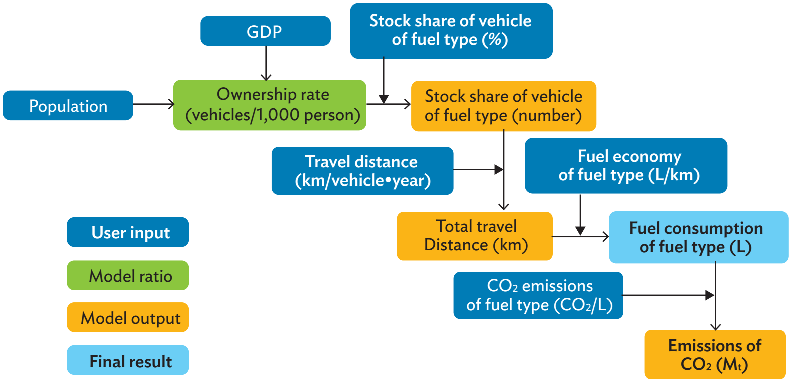
long-term targets for switching to electric vehicles, biofuels, and related development of transport infrastructure have an optimistic view for decarbonizing transport (Zhang and Fujimori 2021; Lam et al. 2018; Toyota 2019; Mitsubishi Motors 2012).

Although policies such as the electrification of passenger vehicles, the introduction of biofuel blends, vehicle battery technologies, and a hydrogen economy have attracted business interest and public debates on infrastructure development—the combined influence of alternative fuel use to gasoline and electrification of vehicles has not yet been evaluated from the viewpoint of decarbonization of the transport sector in developing countries. This chapter aims to build an interdisciplinary assessment framework to integrate electric vehicle introduction, hybrid fuel-efficient technologies, and biofuel on estimating the carbon emissions reduction potential. In an attempt to identify effective pathways toward deep decarbonization of the transport sector, the chapter addresses three policy research questions: (i) how the vehicle type can influence travel demand, energy use, and CO_2 emissions in the long term; (ii) which policies will deliver the least-cost results for decarbonizing the transport sector; and (iii) what innovative financing approaches could complement the policies that deliver deep decarbonization. The chapter is structured as follows. Section 5.2 describes the structure of an energy mix model and the basic assumptions for several scenarios. Sections 5.3–5.5 present the results of scenario simulations, focusing on travel demand, energy mix, and reduced carbon emissions in India, Indonesia, and Thailand, and section 5.6 provides a discussion of the main findings to draw policy implications. Section 5.7 reviews emerging financing modes, and section 5.8 concludes the chapter.

5.2 Research Methodology and Model Assumptions

The energy consumption trend and carbon emissions reduction potential of road transportation, both passenger and freight, during 2015–2030 were simulated by using an improved Energy Mix Model developed by the Toyota Motor Corporation based on the International Energy Agency's Sustainable Mobility Project Model as shown in Figure 5.1. The estimation of road transport CO_2 emissions is also possible by calculating well-to-tank (WTT) and tank-to-wheel (TTW) with the assumed emissions factor of each type of fuel. The Sustainable Mobility Project Model that could estimate all types of transportation energy consumption globally has been modified to fit the road transportation change analysis at local levels and constructed a country-specific energy mix model.

Figure 5.1: Calculation of Flow of Carbon Emissions by Energy Mix Model



CO_2 = carbon dioxide, GDP = gross domestic product, km = kilometer, L = liter, Mt = metric ton.

Source: Authors.

A country's specific data, such as vehicle fleet, fuel use, and current mileage traveled annually, are gathered from the published reports and national statistics. The information on transport policies, alternative fuels, climate policies including biofuels, and electric vehicle (EV) policies, among others, was also collected from the literature. The following steps are followed in the decarbonization scenario analysis building process:

- Identify a government's transport decarbonization strategy, e.g., EV introduction targets in numbers and year.
- Scenario building—a simulation that takes into account all types of EVs to determine the most cost-effective and efficient vehicle and fuel mix.
- Evaluate the effectiveness of vehicle mix scenarios in terms of reduction of oil consumption and CO_2 emissions while using biofuels and natural gas.
- Compare the total cost of EV introduction including infrastructure cost to judge and propose the most appropriate solutions.

The following assumptions are made to see the total cost of decarbonization until the target year 2030, either financed by the private sector or funded by the state:

- Higher vehicle costs for EVs compared to internal combustion engine (ICE) vehicles, hybrid electric vehicles (HEVs) 126%, plug-in hybrid electric vehicles (PHEVs) 146%, and battery electric vehicles (BEVs) 200% including home charger.
- Infrastructure cost required depending on the stage of vehicle introduction (for example, fast-charging stations cost $58,500 every 10 units for BEVs/PHEVs and compressed natural gas [CNG] facilities cost $1.8 million per 1,000 units for CNG vehicles). The overall cost of fuel for all automobiles on the market, including those that have just been introduced.

5.3 Decarbonization Potentials by Mobility Electrification and Alternative Fuel in India

Cars, taxis, buses, omnibuses, light commercial vehicles, heavy commercial vehicles (HCVs), three-wheelers, and two-wheelers are included in the base energy mix model for India. Gasoline, diesel fuel, CNG, biodiesel, ethanol, and electricity are among the fuels evaluated. The model parameter assumptions are described in further detail elsewhere (Toba et al. 2020). Based on a review of the literature and consultations with stakeholders, the costs of HEVs and BEVs are estimated to be 126% and 200% of those of conventional vehicles, respectively. The transport energy mix model for India illustrates six scenarios: business-as-usual (BAU) scenario, Alternative Fuels Scenario (AFS), Aggressive Electrification Scenario (AES), Moderate Electrification Scenario (MES), Moderate Electrification cum Hybrid Promotion Scenario (HPS), Aggressive Electrification Scenario (AES), and Only Electrification Scenario (OES). A brief description of these scenarios follows.

5.3.1 Business-as-Usual (BAU) Scenario

In this scenario, the status quo is maintained and is characterized by the continuation of the existing policy trends. Already existing national policy measures are not fully attained, thus limiting their effectiveness in attaining India's NDC objectives for the decarbonization of the transport sector. The transport sector's ambitions fall short of the 2030 NDC targets. The current trends in motorization will continue, with increased road transport shares, reduced reliance on public transport, and rising demand for petroleum-based fossil fuels. The basic assumptions made for this BAU scenario are presented in Table 5.1.

Table 5.1: Business-as-Usual Scenario Conditions in India

Vehicle/Fuel Type		2010	2015	2020	2025	2030
Electric two-wheelers	Share	0.1%	0.2%	0.4%	0.6%	0.8%
Electric taxis	Share	–	–	–	–	–
Electric passenger cars	Share	–	–	–	–	–
Hybrid passenger cars	Share	–	–	–	–	–
CNG three-wheelers	Share	2.5%	4.5%	5%	6%	7%
CNG buses	Share	1%	1.3%	1.5%	1.8%	2%
CNG taxis	Share	2.5%	4.4%	5%	6%	7%
CNG passenger cars	Share	2%	2%	2%	2%	2%
Fuel efficiency improvement	Per annum			0.1%		
Ethanol utilization	Blend ratio	2%	3.8%	4%	4%	4%
Biodiesel utilization	Blend ratio	–	–	–	–	–

– = negligible, CNG = compressed natural gas.

Source: Based on Department of Heavy Industry (2017, 2018a, 2018b).

5.3.2 Alternative Fuels Scenario (AFS)

The AFS is characterized by increasing the share of CNG-fueled vehicles coupled with the attainment of an increased target for ethanol blending with petrol and biodiesel blending with diesel. There is a determined effort to speed up the development of city gas distribution (CGD) infrastructure, which will be accompanied by an increase in the number of CNG dispensing stations. Furthermore, providing domestic gas to meet the CNG demand of all CGD companies is given high priority. The barriers to the uptake of CNG-fueled vehicles are removed partly due to these policy interventions causing the new sales of CNG-fueled vehicles to increase across all vehicle categories—i.e., three-wheelers, buses, taxis, and passenger cars—thereby increasing the share of CNG-fueled vehicles in the overall transport fleet. In the AFS, it is assumed that the country will attain the 10% ethanol blending mandate by 2030. The supply of ethanol for blending with petrol will increase with the commissioning of proposed ethanol-based projects based on a variety of feedstock including lignocellulosic biomass. The direct sale of biodiesel (B100) to bulk users such as railways, shipping, and state road transport firms is permitted in order to promote the use of biodiesel. A surge in domestic biodiesel supply will ensure that this happens gradually by

2030, until the 5% biodiesel blending rule is achieved. In regard to the other two decarbonization initiatives, road transport electrification and fuel efficiency improvements, the conditions of the BAU scenario persist with limited electrification levels of road transport and relatively slower growth in fuel efficiency.

5.3.3 Moderate Electrification Scenario (MES)

In the MES, the electrification targets as set out by national policies are moderately higher compared to the BAU scenario. In comparison to the BAU scenario, this scenario includes greater penetration and/or use of BEVs and HEVs for passenger movement. Further, in contrast to the BAU scenario, where there was a limited deployment of EVs in the two-wheeler category, the electrification will be across all categories of road transport vehicles including taxis, passenger cars, three-wheelers, and buses. There is moderate policy support for accelerating EV deployment in this scenario. Compared to the BAU scenario, there is an additional effort by all stakeholders for all the road transport modes to become more electrified. In terms of the decarbonization strategy of increasing the share of CNG-fueled vehicles and alternative fuels, the AFS conditions of increased fuel efficiency improvements remain unchanged, while the BAU scenario's condition of relatively slower growth in fuel efficiency holds.

5.3.4 Aggressive Electrification Scenario (AES)

In this scenario, the electrification targets as set out by national policies are high when compared to the BAU scenario and encompass the aggressive penetration and adoption of BEVs and HEVs for passenger movement by road. Furthermore, all types of road transport vehicles, including taxis, passenger cars, three-wheelers, and buses, will have higher electrification levels. There is strong policy support for EV deployment in this scenario. In contrast to the BAU scenario, there is a concerted effort by all stakeholders to create an EV ecosystem such that all the road transport modes become increasingly electrified. With regards to the decarbonization strategy of the increased share of CNG-fueled vehicles and alternative fuels, the conditions of the AFS persist, but with high fuel efficiency improvements.

5.3.5 Moderate Electrification cum Hybrid Promotion Scenario (HPS)

In the HPS, the percentage share of new sales of HEVs is enhanced compared to that in the MES. In terms of the decarbonization strategy of a higher share of CNG-fueled vehicles and alternative fuels, the AFS conditions of strong fuel efficiency increases, as well as the BAU scenario's condition of relatively slower fuel efficiency growth, apply in this scenario.

5.3.6 Only Electrification Scenario (OES)

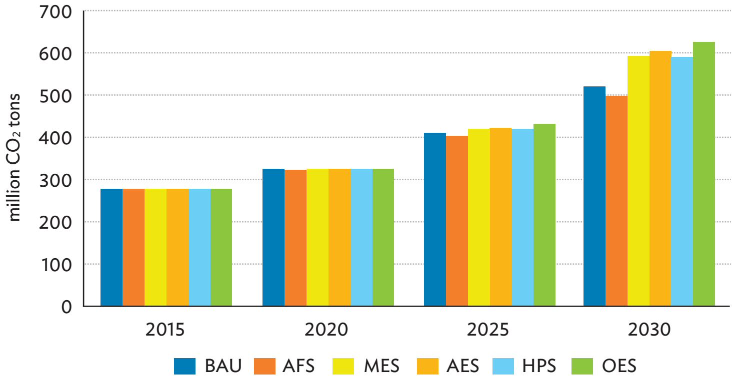
This scenario combines the BAU scenario and AES discussed previously. Except for the decarbonization plan of a higher share of CNG-fueled vehicles and alternative fuels and fuel efficiency improvements in the OES, the conditions of the BAU scenario remain with limited shares of CNG-fueled vehicles and slightly slower growth in fuel efficiency.

5.3.7 Changes in Carbon Emissions under Alternative Transport Scenarios

The results of the energy mix model application show that higher deployment of CNG-fueled vehicles and increased use of alternative fuels resulted in a marginal reduction in total final energy demand of 0.41% below BAU by 2025 and 0.64% below BAU by 2030. In comparison to the BAU scenario, the electrification-centric scenarios of the MES, AES, HPS, and OES show a slight rise in ultimate energy demand. The OES has a maximum increase to the extent of 0.57% by 2025 and 1.61% by 2030 when compared to their respective BAU levels. In the BAU scenario, the model results suggest that by 2030, HCVs will consume the most energy (55.3 million tons of oil equivalent [Mtoe] by 2030, accounting for about 36% of total energy consumption). This is followed by cars and jeeps at 14% (21.7 Mtoe) accounting for 14%, and buses accounting for 13% (20.5 Mtoe).

Figure 5.2 shows that total well-to-wheel (WTW) CO_2 emissions will more than double under the BAU scenario, rising from 278 million tons of CO_2 ($MtCO_2$) in 2015 to 523 $MtCO_2$ by 2030, a compound annual growth rate (CAGR) of 4.3%. In the AFS, higher use of alternative fuels and increased share of CNG-fueled vehicles in the road transport fleet result in a reduction of WTW CO_2 emissions to 502 $MtCO_2$ by 2030, which is a 4% reduction from the BAU levels in 2030. However, in electrification-related scenarios, the WTW CO_2 emissions exhibit an increase of 14% in the MES, 16% in the AES, 13% in the HPS, and 20% in the OES relative to BAU. The HPS witnesses the least percentage increase in WTW CO_2 emissions relative to the BAU levels. This implies that the gains from a reduction in aggressive electrification are more than offset by slow improvements in fuel efficiency and comparatively lower uptake of CNG-fueled vehicles and alternative fuels. Also, it shows that road transport electrification as a policy lever for reducing CO_2 emissions is effective only with deep decarbonization of the power sector. In terms of energy carriers, diesel is expected to account for around 70.5% of CO_2 emissions in BAU by 2030, which can be attributed to the high percentage of diesel consumed by HCVs. Gasoline comes in second with 26.8%, followed by LPG, biodiesel, and hydrogen, all of which contribute less than 1%.

Figure 5.2: Well-to-Wheel CO_2 Emissions from Road Transport Sector in India 2015–2030

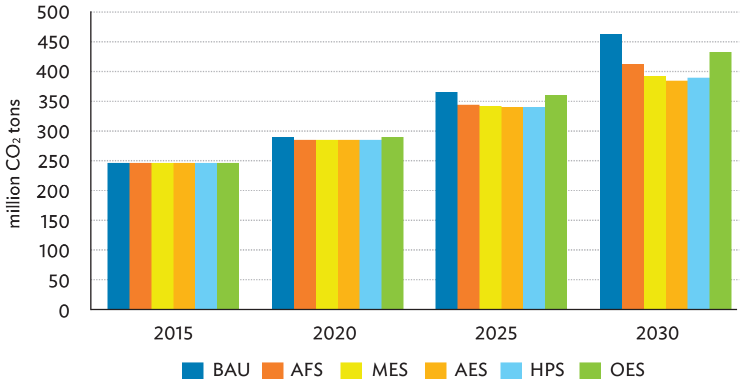


AES = Aggressive Electrification Scenario, AFS = Alternative Fuels Scenario, BAU = business as usual, CO_2 = carbon dioxide, HPS = Moderate Electrification cum Hybrid Promotion Scenario, MES = Moderate Electrification Scenario, OES = Aggressive Electrification Condition and Only Electrification Scenario.

Source: Authors.

The total tank-to-wheel (TTW) CO_2 emissions will be more than double, increasing from 247 $MtCO_2$ in 2015 to 463 $MtCO_2$ by 2030 in the BAU scenario registering a CAGR of 4.27% (Figure 5.3). In the AFS, higher use of alternative fuels and increased share of CNG-fueled vehicles in the road transport fleet result in a reduction of WTW CO_2 emissions to 412 $MtCO_2$ by 2030, representing a reduction of 11.1% from the BAU levels in 2030. This, however, contrasts sharply to the results of WTW CO_2 emissions. In the electrification-related scenarios, the TTW CO_2 emissions exhibit 15.2%, 16.5%, 15.5%, and 6.2% reductions, respectively, in MES, AES, HPS, and OES relative to the BAU scenario. The AES witnesses the maximum reduction in TTW CO_2 emissions relative to the BAU levels followed closely by the HPS.

Figure 5.3: Tank-to-Wheel CO_2 Emissions from Road Transport Sector in India 2015–2030



AES = Aggressive Electrification Scenario, AFS = Alternative Fuels Scenario, BAU = business as usual, CO_2 = carbon dioxide, HPS = Moderate Electrification cum Hybrid Promotion Scenario, MES = Moderate Electrification Scenario, OES = Aggressive Electrification Condition and Only Electrification Scenario.

Source: Authors.

5.3.8 Estimated Costs of Decarbonization

The overall cost of implementing EV policies depends on three main components—fuel cost, vehicle cost, and infrastructure cost. The model results show that fuel cost is the highest among the three components. The maintenance cost of the vehicles is not considered in the model. The electrification scenarios have a higher overall cost compared to the BAU conditions due to higher fuel and vehicle costs. The fuel cost is high as the cost of electricity is highest followed by the cost of gasoline

(Table 5.2). The vehicle cost is high as the cost of HEVs and BEVs are considered 1.26 and 2 times higher than conventional counterparts. For 2030, among all the electrification scenarios, HPS has the lowest cost of EVs introduction at $269 billion. For 2015 to 2030, the HPS has the lowest cost of EVs introduction.

Table 5.2: Overall Cost of Electrified Vehicle Introduction in India for 2030 and Cumulative from 2015 to 2030 ($ billion)

Cost Component	2030						2015–2030					
	BAU	AFS	AES	MES	HPS	OES	BAU	AFS	AES	MES	HPS	OES
Fuel cost	156	152	163	162	161	167	1,798	1,775	1,813	1,811	1,807	1,836
Vehicle cost	93	95	127	116	103	124	1,060	1,084	1,201	1,169	1,145	1,188
Infrastructure cost of charging stations	–	–	9	4	4	9	1	1	38	19	20	38
Total	249	248	299	283	269	300	2,858	2,859	3,052	3,000	2,971	3,062

AFS = Alternative Fuels Scenario, AES = Aggressive Electrification Scenario, BAU = business-as-usual, HPS = Moderate Electrification cum Hybrid Promotion Scenario, MES = Moderate Electrification Scenario, OES = Aggressive Electrification Condition and Only Electrification Scenario.

Source: Authors.

The six scenarios illustrate how the implementation of xEV policies affects CO_2 emissions. Even with aggressive EV adoption, the WTW CO_2 emissions levels are higher than the BAU scenario, implying that with the existing electricity generation mix, EVs alone cannot bring down emissions levels in India. Although the electrification scenarios show a reduction in tank-to-wheel CO_2 emissions, indicating if additional electricity demand for EVs is met through electricity generated from renewable energy, it would result in CO_2 emissions reduction. It is worth noting that HCVs, light commercial vehicles, and buses account for over 70% of energy consumption in India's transport sector; yet, in this model, EV penetration is assumed to be largely in the two-wheeler, three-wheeler, automobile, and taxi segments, with a relatively low level in buses. Therefore, scenarios assuming aggressive EV penetration do not reflect a major reduction in energy demand. However, this will have a benefit on air pollution reduction, particularly in major cities. When power is generated from renewable energy sources, electrification scenarios will have an impact on emissions levels.

It is important to note that India's power sector's installed capacity exceeds peak demand by a significant margin. Furthermore, the government is pushing the renewable energy strategy vigorously by increasing the country's solar power producing capacity. However, considering India's overall excess power conditions, state energy regulatory commissions have recently issued directives to state distribution corporations operating under state government sponsorship to halt acquiring and/or bidding solar power due to regulatory, financial, and technological difficulties. Thus, for additional power generation from renewable energy to happen and for solar power plant generators to find off-takers for the electricity generated by their plants, there is a need to increase the demand for electricity. Electric vehicles provide such an opportunity wherein solar power will be used to power EVs.

5.4 Decarbonization Potentials by Mobility Electrification and Alternative Fuel Uptake in Indonesia

For the transport energy mix model application in Indonesia, six scenarios are established with associated assumptions (Table 5.3).

Table 5.3: Scenario Assumptions for Mobility Electrification and Alternative Fuels in Indonesia

Business-as-Usual Scenario	• 0.5% per year of fuel economy improvement for all new vehicles for a given production year • no introduction of CNG vehicles • following the 2015 biodiesel mandate up to B20, but no utilization of ethanol
Increased Biodiesel Use Scenario	The increased biodiesel use scenario simulates full implementation of the biodiesel mandate to B30 without implementation of bioethanol. • 0.5% per year of fuel efficiency improvement for all vehicles • no introduction of CNG vehicles • implementation of the 2015 biodiesel mandate up to B30 • no ethanol implementation
Increased Bioethanol Use Scenario	The increased bioethanol use scenario simulates the mandatory content of the Ministry of Energy and Mineral Resources Regulation • 0.5% per year fuel efficiency improvement for all vehicles • no introduction of CNG vehicles • implementation of 2015 biodiesel mandate up to B20 • implementation of 2015 bioethanol mandate up to E20

continued on next page

Table 5.3 *continued*

CNG Implementation Scenario	The CNG implementation scenario simulates the introduction of new CNG vehicles for public transport with the adoption of biofuels, in accordance with the 2015 mandatory biodiesel content schedule. Based on 2013 taxi sales, this means that 1.5% of passenger car sales are attributed to CNG taxis. Regarding CNG buses, it is assumed that 40% of truck chassis sold were converted into buses based on the Badan Pusat Statistik (BPS) vehicle population increase ratios between buses and trucks. New CNG public transport and trucks are assumed to be introduced in 2020. Because CNG implementation is unlikely to include infrastructure construction over most of Indonesia until 2035, CNG will not be used in all new public transportation and trucks. Thus, this scenario assumes infrastructure constructed in Palembang, Jakarta, Surabaya, Bandung, and Medan, allowing CNG to be used in 48% public transportation and trucks. The following parameters are used to simulate CNG use in this scenario: • 0.5% per year of fuel efficiency improvement for all vehicles • introduction of CNG for public transport and trucks in Palembang, Bandung, Medan, Jakarta, and Surabaya, resulting in 48% of all new taxis, buses, and trucks being CNG-capable • adhering to the 2015 biofuel mandate up to B20, but no use of ethanol
Vehicle Electrification (EV) Scenario	This scenario investigates the plan to introduce xEVs and assumes the same conditions as the BAU scenario, with the addition of xEVs being introduced according to the government's schedule, which includes BEVs for trucks, buses, and motorbikes, all of which require additional charging stations. Separate xEV plan variations, such as the HEV, PHEV, and BEV scenarios, will be analyzed by treating all passenger cars as xEVs.

BAU = business as usual, BPS = Badan Pusat Statistik, BEV = battery electric vehicle, CNG = compressed natural gas, EV = electric vehicle, HEV = hybrid electric vehicle, PHEV = plug-in hybrid electric vehicle, xEV = electrified vehicle.

Source: Authors.

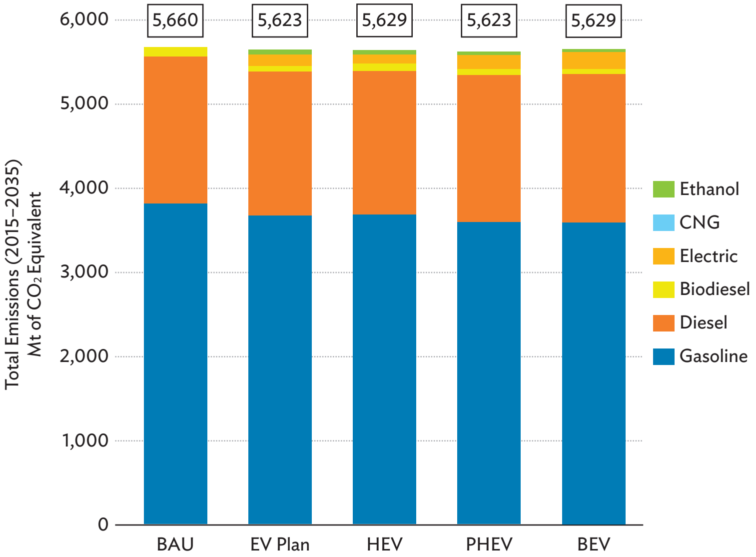
5.4.1 Changes in Carbon Emissions under Alternative Transport Scenarios

The model estimated WTW and TTW CO_2 emissions. In the BAU scenario, total WTW CO_2 emissions will more than double, rising from 256 $MtCO_2$ in 2015 to 626 $MtCO_2$ by 2030, a 6.1% CAGR. In the AFS, higher use of CNG-fueled vehicles in road transport fleets and increased use of alternative fuels result in a reduction of WTW CO_2 emissions to 608 $MtCO_2$ by 2030, which is a 3% reduction from the BAU level. In the electrification-related scenarios, however, WTW CO_2 emissions increase by 5% in the MES, 7% in the AES, 4.7% in the HPS, and 9% in the OES, compared to the BAU level. The HPS witnesses the smallest percentage increase in WTW CO_2 emissions relative to the BAU level. This implies that the gains from the reduction in aggressive electrification are more than offset by slow improvements in fuel efficiency and less uptake of CNG-fueled vehicles and alternative fuels. It also shows that road transport electrification as a policy lever for lowering CO_2 emissions is only successful if the electricity industry is deeply decarbonized. In terms of vehicle technology, in the BAU scenario, HCVs are seen to contribute about 36% of CO_2 emissions by 2030, which can be attributed to the large percentage of fossil fuels they consume, followed by buses with 18.2%, and cars and jeeps with 15.4%; three-wheelers are observed to account for the lowest amount of CO_2 emissions by 2030, with a share of only 4%.

Total TTW CO_2 emissions will more than double, increasing from 230 $MtCO_2$ in 2015 to 561 $MtCO_2$ by 2030 in the BAU scenario, registering a 6.1% CAGR. In the AFS, the increased share of CNG-fueled vehicles in road transport fleets and enhanced use of alternative fuels results in TTW CO_2 emissions reduction to 525 $MtCO_2$ by 2030, translating to a 6.3% reduction from the BAU level in 2030. TTW CO_2 emissions, on the other hand, show a reduction of 9.4% in the MES, 10.8% in the AES, 9.8% in the HPS, and 4.89% in the OES compared to the BAU level, in stark contrast to the results of WTW CO_2 emissions in the electrification-related scenarios. The AES has the greatest reduction in TTW CO_2 emissions compared to the BAU level, trailed by the HPS. From the above results, it is considered that the increase in CO_2 emissions of WTW due to the introduction of xEVs is caused by power generation.

The total carbon emissions from 2015 to 2035 are shown in Figure 5.4 for the combined EV and biofuel plans. The results are compared with the modified xEV plan and BAU. Regarding CO_2 emissions, increasing PHEV and BEV numbers increases emissions by around 0.1% compared with the government EV plan, while increasing HEV numbers will result in similar emissions. Despite the higher efficiency of EVs, a significant decrease in emissions was not observed. This is likely because of the higher specific emissions of electricity compared with the gasoline and bioethanol blend.

Figure 5.4: Comparison of Carbon Emissions of BAU, EV Plan, and Modified EV Plan with BEVs, HEVs, or PHEVs for the Entire Population of xEV Passenger Cars in Indonesia

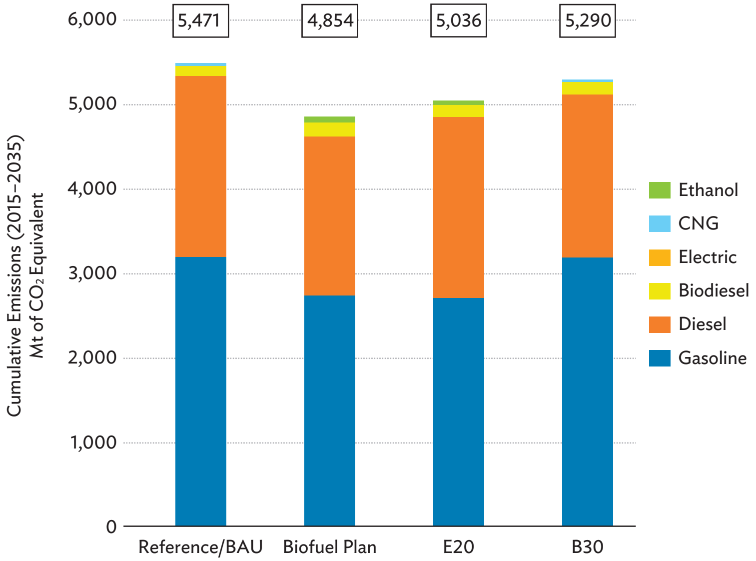


BAU = business as usual, BEV = battery electric vehicle, CNG = compressed natural gas, CO_2 = carbon dioxide, EV = electric vehicle, HEV = hybrid electric vehicle, Mt = million tons, PHEV = plug-in hybrid electric vehicle, xEV = electrified vehicle.

Source: Authors.

Oil consumption will be reduced if biofuels are introduced more aggressively in accordance with the 2015 mandated biofuel content regulations. Figure 5.5 depicts the oil consumption results for the biofuel scenarios. As observed, increasing implementation from B20 to B30 leads to a 4.6% savings in cost over BAU. Meanwhile, the implementation of E20 resulted in an 8.7% reduction, a larger effect. When these two are combined under the government's biofuel strategy, a total decrease of 13.2% is achieved. Similar to oil use, the E20 scenario reduces carbon emissions by 8% more than the B30 scenario (3.3%).

Figure 5.5: Comparison of Carbon Emissions from 2015 to 2035 of Biofuel Scenarios and BAU in Indonesia



BAU = business as usual, CNG = compressed natural gas, Mt = million tons.

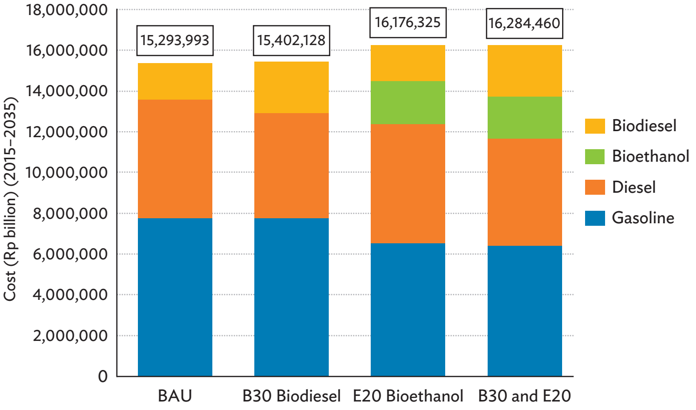
Source: Authors.

5.4.2 Estimated Costs of Decarbonization Choices

Figure 5.6 shows the costs associated with implementing the biofuel scenarios. In comparison to the BAU scenario, the cost of extra biodiesel deployment is less than 1% higher. Increasing the bioethanol concentration to E20, on the other hand, will result in a 5.9% cost rise. The cost of gasoline accounts for most of the costs in all scenarios.

The introduction of EVs expected to cut oil use as well as carbon emissions. However, despite their better efficiency , the large specific emissions factor of electricity raises uncertainties about whether or not xEVs will reduce emissions.

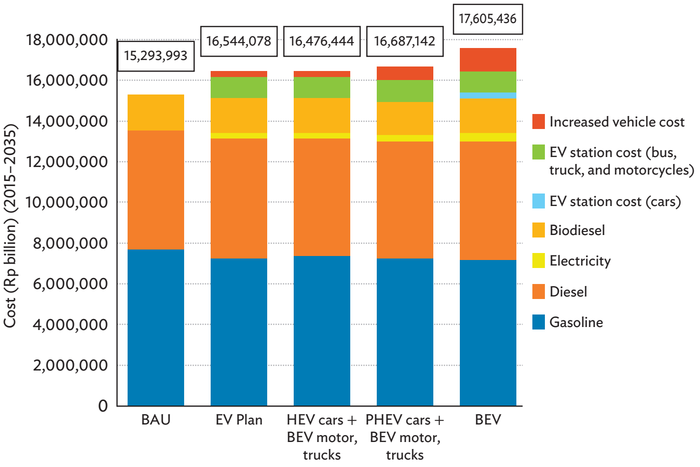
Figure 5.6: Comparison of Total Cost (cost of fuel, infrastructure, etc.) from 2015 to 2035 for Biofuel Scenarios and BAU in Indonesia



BAU = business as usual.

Source: Authors.

Figure 5.7: Comparison of Total Cost (cost of fuel, infrastructure, etc.) from 2015 to 2035 for xEV Scenarios and BAU in Indonesia



BAU = business as usual, BEV = battery electric vehicle, EV = electric vehicle, HEV = hybrid electric vehicle, PHEV = plug-in hybrid electric vehicle.

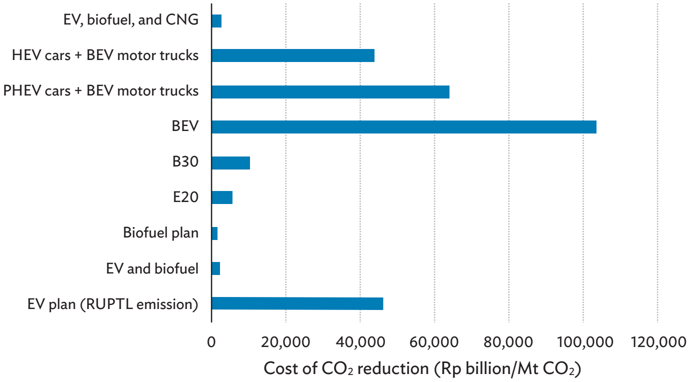
Source: Authors.

Figure 5.7 shows a comparison of the total cost for the xEV scenarios and the reference/BAU case. Building EV stations for buses, vehicles, and motorcycles accounts for a significant portion of the costs. Each charging point was estimated to cost $48,500; with each charging point facilitating 10 passenger cars. As buses and trucks will travel longer distances, it is estimated that one charging point can accommodate 2.5 buses and/or trucks. For motorcycles, a charging point is assumed to be able to accommodate 25 motorcycles. As such, the entire cost of accommodating BEV trucks, buses, and motorcycles is estimated to be around Rp1 quintillion, with EV motorcycles accounting for most of the expenditure.

Increased vehicle costs were considered as xEVs are more expensive. BEVs were assumed to cost 200% of the cost of equivalent internal combustion engine (ICE) vehicles (which were assumed at $20,000), while HEVs and PHEVs were assumed to cost 126% and 156% more, respectively. While there are increased passenger vehicle costs due to xEVs being more expensive, the effect is still limited as most passenger xEVs were HEVs. Due to the high cost of BEVs, the increased cost of vehicles in the BEV scenario is the most substantial, reaching as high as the cost of the installation of charging stations. As a result, this scenario is the most expensive, with a 15% increase in cost over the BAU scenario. Meanwhile, the government EV plan is more moderate at a 6.4% hike. A large portion of the cost is to accommodate charging stations for electric buses, trucks, and motorcycles, which will grow significantly according to the production numbers specified by the EV plan. By 2035, there will be more than 35 million electric motorcycles, 42,000 electric buses, and 112,000 trucks on the road. Figure 5.8 displays the cumulative costs for the combined scenarios in comparison to BAU and the isolated EV plan and biofuel plan. All plans have an increased cost compared to the BAU scenario: biofuels will cost more than fossil fuels, the EV plan will have an increased vehicle cost, and both the EV plan and CNG will require additional infrastructure. The combined EV and biofuel strategy has the highest cost, with a 14.3% increase in cost when compared to BAU. Interestingly, adding CNG to the combined EV and biofuel plan lowers the cost relative to the initial EV and biofuel plan combination, even though CNG station infrastructure still requires a significant investment. This is because CNG is significantly less expensive than gasoline, diesel, and biofuels. As measures taken to reduce oil consumption and carbon emissions will impact the total cost, two parameters have been introduced to describe the increase of cost required to reduce consumption by 1 Mtoe of oil and the cost required to reduce emissions by 1 million tons of CO_2.

A similar condition is obtained regarding the cost of the reduction of carbon emissions (Figure 5.8). The modified EV plan with BEVs has the highest cost per million ton of CO_2 reduction, whereas the biofuel plan has the lowest. Implementing an EV plan with a biofuel plan somewhat alleviates the high specific cost. In general, both in terms of CO_2 reduction and oil reduction per rupiah, xEV scenarios are the most expensive. The implementation of PHEVs costs the lowest per ton of CO_2 as it is assumed that PHEVs will be charged at home and thus do not require public charging stations. As a result, the PHEV scenario achieves a partial CO_2 reduction as if it operates partially as a BEV, but without the need for extra infrastructure. Nonetheless, as all xEV scenarios incorporate BEV trucks, buses, and motorcycles and thus require charging stations, the cost per million ton of oil equivalent oil consumption reduction and cost per million of CO_2 emissions reduction remain high.

Figure 5.8: Cost per Million Ton of CO_2 Emissions Reduction for Each Measure in Indonesia



BEV = battery electric vehicle, EV = electric vehicle, HEV = hybrid electric vehicle, Mt = million tons, PHEV = plug-in hybrid electric vehicle, RUPTL = Rencana Umum Penyediaan Tenaga Listrik (National Electricity Supply Business Plan).

Source: Authors.

The BEV scenario was also the most expensive, costing Rp103 billion per million tons of CO_2, compared to Rp46 billion per million tons of CO_2 for the government's EV plan. Likewise, the high cost of all xEV scenarios was due to the need for charging stations for BEV trucks, buses, and motorbikes. It was also observed that combining biofuels with the EV plan resulted in a large cost savings in terms of emissions.

In comparison to the isolated EV proposal, the cost was lowered from Rp46 billion per million tons of CO_2 to Rp2.2 billion per million tons of CO_2. Adding CNG for HDVs and taxis, on the other hand, resulted in a minor cost rise to Rp2.7 billion per million tons of CO_2.

5.5 Decarbonization Potentials by Mobility Electrification and Alternative Fuels in Thailand

For the Transport Energy Mix model application in Thailand, six scenarios are established with associated assumptions (Table 5.4).

Table 5.4: Scenario Assumptions for Transport Electrification and Alternative Fuels in Thailand

BAU Scenario	In addition to the current trends in road traffic systems, this scenario is based on the realization of the following biofuel policy objectives. • Gasoline-ethanol (gasohol) E20 and biodiesel B10 are achieved—the ethanol share shifting to gasohol E15 and biodiesel B10 for commercial-grade diesel; and 1,800 hybrid buses are purchased.
Alternative Fuels Scenario	This scenario assumes the promotion of biofuels with the following assumptions. • Gasohol E20 will succeed (90%) in the automotive market, with some E85 share (10%) (assuming the ethanol share in gasohol demand is E26.5) in 2036. Biodiesel demand for the transport sector will achieve half of the Alternative Energy Development Plan's target or 7 million liters per day in 2036 (assuming that the blending ratio of commercial-grade diesel fuel achieves B12).
Plug-in xEV Expansion Scenario	This scenario assumes that the on-road plug-in xEVs have been introduced. • By 2036, 1.2 million units of on-road plug-in xEVs (PHEV:BEV = 50:50) will have been sold.
Hybrid Expansion Scenario	This scenario assumes the case where the introduction of hybrid vehicles has been promoted. The following two cases are assumed: • Minimum HEVs: overall HEV sales reach 320,000 units by 2023, 5 years after the Board of Investment's commitment to the investment plan in 2018 and 4.7 million units in 2036. • Maximum HEVs: HEVs dominate 50% of passenger car sales (gasoline-originated) by 2036 and 7.1 million in 2036.
Combination Scenario	This combines the alternative fuel promotion scenario and the minimum HEV scenario.

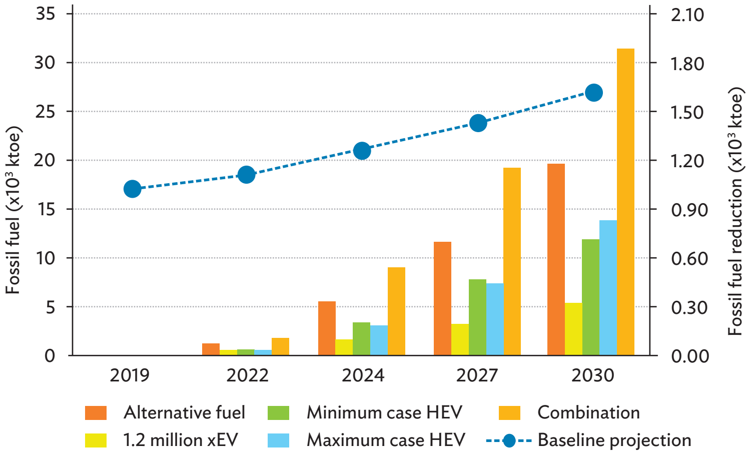
BAU = business as usual, BEV = battery electric vehicle, EV = electric vehicle, HEV = hybrid electric vehicle, PHEV = plug-in hybrid electric vehicle, xEV = electrified vehicle.

Sources: EPPO (2015, 2017); BOI (2018).

5.5.1 Changes in Carbon Emissions under Alternative Transport Scenarios

Figure 5.9 shows the potential of fossil fuel reduction and thus greenhouse gas emissions in the transport sector of Thailand for the BAU and five scenarios from 2019 to 2030. In comparison to the 1.2 million xEV scenario, the alternative fuels scenario produces lower TTW emissions. For WTT emissions, which rely on net energy consumption and the WTT CO_2 emissions factor, WTT emissions of hybrid expansion scenarios are better than the alternative fuels scenario, which implies that the impacts of HEV energy efficiency are higher than the difference in the WTT emissions between fossil fuel and biofuels. The combination scenario can help remove 6.12 million tons of WTW CO_2 emissions (5.79 million tons from TTW), an amount equivalent to about 5.3% of the baseline.

Figure 5.9: Transport Decarbonization Scenarios in Thailand



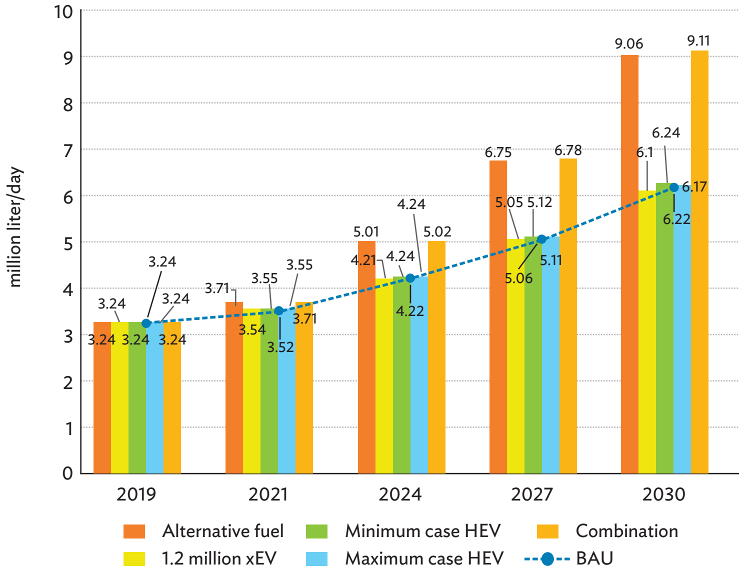
HEV = hybrid electric vehicle, ktoe = kiloton of oil equivalent, xEV = electrified vehicle.

Source: Authors.

Two HEV scenarios are more effective for the reduction of energy demand and carbon emissions. The most effective scenario to reduce energy demand is the combination (minimum HEV + alternative fuel) scenario. From the viewpoint of fossil fuel consumption from imports, the alternative fuel scenario is better than the introduction of xEVs, including HEVs. In this case, the most effective scenario to reduce fossil fuel consumption is the combination (minimum HEV + alternative fuel) scenario.

Aside from the difference in scenarios, the effects of introducing alternative fuels and xEVs on energy consumption and global warming gas emissions differ substantially between India and Indonesia and Thailand. It is presumed that this is due to the difference in the fuel used for power generation and the registration status of vehicles by fuel. India and Indonesia's power generation relies heavily on coal-fired power generation, while natural gas is the main source of power generation in Thailand.

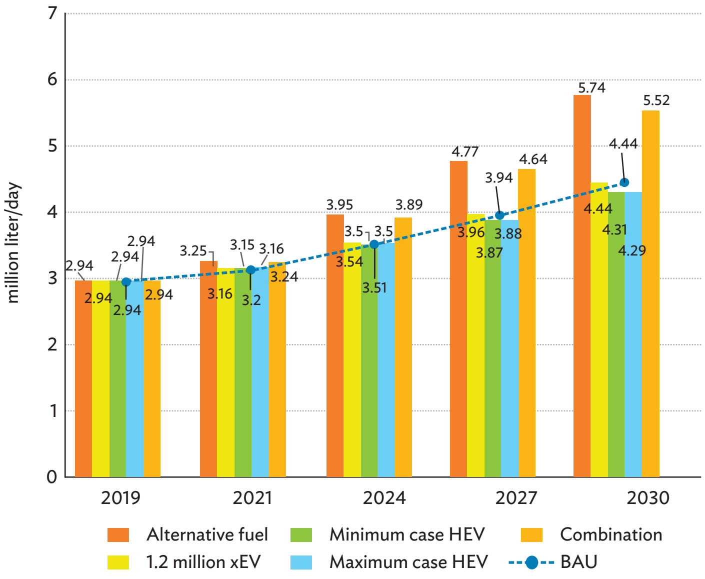
Figure 5.10: Increased Bioethanol Demand in the Transport Sector for Scenarios



HEV = hybrid electric vehicle, xEV = electrified vehicle.

Source: Authors.

Figure 5.11: Increased Biodiesel Demand in the Transport Sector for Scenarios



HEV = hybrid electric vehicle, xEV = electrified vehicle.

Source: Authors.

The alternative fuels scenario can produce an increase of 2.85 million liters per day of ethanol and 1.26 million liters per day of biodiesel in 2030, based on the biofuel demand factors indicated in Figure 5.10 (bioethanol) and Figure 5.11 (biodiesel). According to the scenario definition, the proportion of diesel automobiles will decrease as the proportion of xEVs increases. Therefore, biodiesel demand will be reduced in the 1.2 million xEVs scenario and both the minimum and maximum HEV scenarios. However, in those two HEV scenarios, ethanol consumption will be slightly higher, whereas in the 1.2 million xEVs scenario, it will be lower. In conclusion, the combined scenario can help increase ethanol demand by 2.90 million liters per day (46.7% of baseline) and biodiesel demand by 1.04 million liters per day (23.3% of baseline).

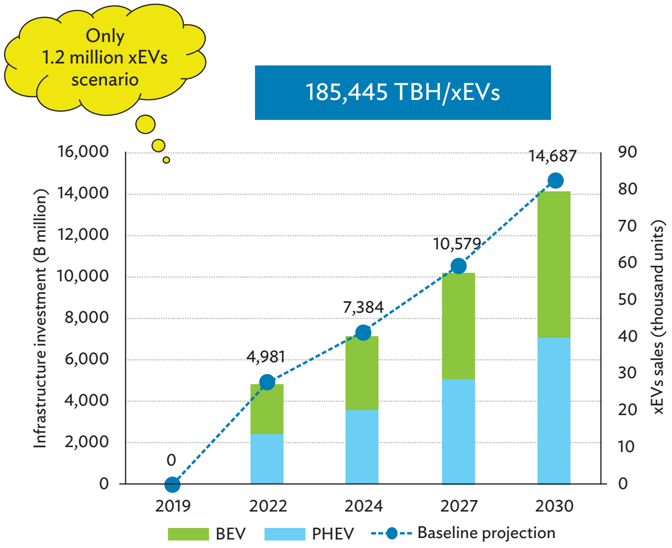
The alternative fuels scenario has lower TTW emissions than the 1.2 million xEVs scenarios in terms of carbon emissions reductions, both WTT and TTW greenhouse gas emissions, as shown by using biofuels as carbon-neutral fuel (considered as zero TTW CO_2 emissions).

For WTT emissions, which rely on net energy consumption and WTT CO_2 emissions factor, WTT emissions of the hybrid expansion scenarios are better than the alternative fuels scenario, which implies that the impacts of energy efficiency of HEVs is higher than the difference in WTT emissions between fossil fuel and biofuels. Combination scenarios (AES and HEV Board of Investment (BOI), AES and HEV extreme) can help cut 4.85 and 5.02 million tons of WTW CO_2 emissions (4.68 and 4.78 million tons from TTW), and this amount is equivalent to about 4.2%–4.3% of baseline WTW CO_2 emissions.

5.5.2 Estimated Costs of Decarbonization Choices

The simulation results from six scenarios: the alternative energy scenario, 1.2 million xEVs scenario, HEV BOI scenario, HEV extreme scenario, combination AE and HEV BOI scenario, and combination AE and HEV extreme scenario together with the BAU scenario (Baseline) as a reference. Figure 5.12 depicts the infrastructure cost for battery electric vehicles and plug-in hybrid vehicles from 2019 to 2030 under.

Figure 5.12: Comparison of Infrastructure Costs from 2019 to 2030 for Different Scenarios



BEV = battery electric vehicle, PHEV = plug-in hybrid electric vehicle, xEV = electrified vehicle.

Source: Authors.

From energy cost aspects shown in EV technology (plug-in xEVs or hybrid expansion scenarios) can help reduce total energy demand, but the alternative fuels scenario is preferable for lowering fossil fuel imports. Combination scenarios (in the order of AE and HEV BOI and AE and HEV extreme can help reduce imported fossil fuel imports by 1.50 and 1.55 thousand kilo tons of oil equivalent in 2030 (about 4.6%–4.7% of projected fossil fuel consumption). In addition, both minimum (HEV BOI) and maximum (extreme) HEV scenarios are better than the 1.2 million xEV scenario because of the larger stock of HEVs than xEVs (4.7 million for the minimum HEV scenario and 7.1 million for the maximum HEV scenario).

From an economic analysis of carbon reduction, the impact of HEV for both HEV scenarios (HEV BOI and HEV extreme) will be higher than that of the 1.2 million xEV scenarios according to the market share (Table 5.5). The government vehicle excise tax depends on both the tax incentive (per vehicle) and sale share (number of sales) in the automotive market. Therefore, the government excise tax will be reduced by B7.31 billion, B28.48 billion, and B45.26 billion in the 1.2 million xEVs, HEV BOI, and HEV extreme scenarios by 2030 compared to the BAU scenario.

Table 5.5: xEV Share in Various Scenarios

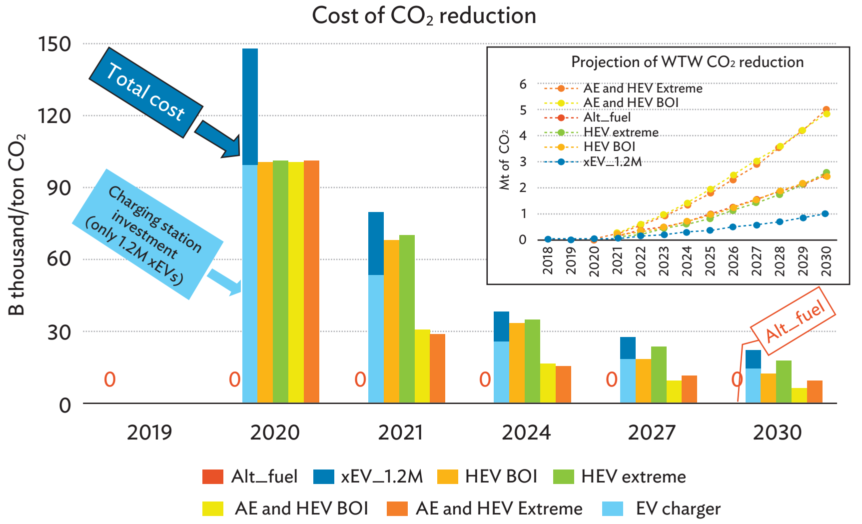
2030 sale share (%)	HEV	PHEV	BEV	Total
Baseline	1.57%	0.00%	0.00%	1.57%
1.2 million xEVs	1.46%	3.47%	3.47%	8.40%
Min HEV	28.02%	0.00%	0.00%	28.02%
Max HEV	43.60%	0.00%	0.00%	43.60%

BEV = battery electric vehicle, HEV = hybrid electric vehicle, PHEV = plug-in hybrid electric vehicle, xEV = electrified vehicle.

Source: Authors.

On the other hand, the 1.2 million xEVs scenario necessitates an investment cost for charging station installation, under the assumption of about B185,445 per xEV. Therefore, the total government cost of 1.2 million xEVs scenarios is the highest when comparing the others. Figure 5.13 displays the effects of alternative fuel vehicles on CO_2 emissions reduction, showing that the cost per unit of CO_2 emissions reduction (B per ton-CO_2) is reduced as the number of alternative fuel vehicles on the road increases.

Figure 5.13: Total Cost of Decarbonization and the Investment Required for Charging Stations



AE = alternative fuels, BOI = Board of Investment, EV = electric vehicle, HEV = hybrid electric vehicle, ICE = internal combustion engine, PHEV = plug-in hybrid electric vehicle, xEV = electrified vehicle.

Source: Authors.

From the total cost of ownership (TCO) aspect, the TCO of sedan xEVs (HEVs, PHEVs, and BEVs) introduction is still higher than conventional ICE sedans due to higher vehicle purchase cost and battery replacement cost, even though the operating cost is much lower. Because of current biofuels price incentives, the TCO of conventional ICE private cars operating on biofuels (gasohol E20 and E85) is lower than running on fossil fuel. The TCO of pickup-based vehicles, on the other hand, is similar for all three types of biodiesels. In terms of TCO, EV technology has a B7.31 billion, B28.48 billion, and B45.26 billion opportunity cost to the government (due to lower excise tax rates) of B7.31 billion, B28.48 billion, and B45.26 billion for 1.2 million xEVs, minimum and maximum HEV scenarios, respectively. Likewise, with 1.2 million xEVs on the road, the government will need to invest in public EV charging stations. In addition, the cost of CO_2 emissions reduction (baht per ton-CO_2) will be as high as B160,000 per ton-CO_2 in 2020 for the 1.2 million xEVs scenarios (in the early period of EVs entering the market). It could further be reduced to B26,500 ton-CO_2 in 2030, with declining infrastructure costs. The TCO shows that ICE vehicles are still the most cost-effective as from an ownership viewpoint (economic aspect) for both private cars and small pickup trucks.

5.6 Pathways for Decarbonization of Transport Sector in Developing Countries and Policy Implications

The scenarios on decarbonization choices demonstrate that electrification scenarios alone do not have much effect in reducing the CO_2 emissions levels. The use of alternative fuels such as CNG and biofuels in road transport will play a crucial role as the CO_2 emissions levels are highest for HCVs and buses. The electrification of HCVs and buses will be a major challenge as they operate for longer distances. The battery size required for these vehicles is demanding and dedicated efforts are required to develop charging infrastructure along important routes and highways to quell "range anxiety". Their switch to cleaner fuels, together with increased fuel efficiency, will amplify the impact of the adoption of xEVs in terms of emissions reduction. The policy strategy should consider both electrifications as well as alternative fuels at the same platform to boost its impact.

The adoption of xEVs alone will not be enough to cut emissions in nations with high greenhouse gas (GHG) emissions from power generation, such as India, Indonesia, and Thailand. First, it is necessary to promote power generation by using renewable energy, and in parallel with this, promote the introduction of xEVs. The cost of implementing biofuels and EVs depends on the fuel cost, vehicle cost, and infrastructure cost. The model findings show that the infrastructure cost is relatively cheap when compared to the other two costs. However, infrastructure development should account for the availability of parking for charging stations within city limits as most metropolitan cities face parking space constraints. The charging time also makes a significant difference as even the fast-charging stations require a minimum of 20 minutes to attain full charge, which is more than the time taken to fill up with fuel at traditional fuel stations. This in turn adds to the infrastructure cost in terms of land required. The vehicle and fuel costs determine the effectiveness of xEV introduction.

When compared to biofuel, the current cost of xEVs is higher, making it difficult for the end user to see it as a viable choice. New EV policy guidelines should consider both the needs of the manufacturer and the needs of the end user and provide incentives that are mutually beneficial. Among the electrification scenarios, it is seen that the

AES and HPS have the maximum impact in terms of CO_2 emissions reduction (TTW) and low costs of implementation. A combination of these two scenarios would have brought about a sizable impact on xEVs introduction. The major cost component of EVs is the cost of batteries. The policy strategy must include a more favorable outline for the battery manufacturing companies. To achieve a considerable reduction in CO_2 emissions, policies should adopt an aggressive approach toward xEV implementation as well as alternative fuel promotion.

India, Indonesia, and Thailand have undertaken various measures for faster adoption and manufacturing of EVs. Governments have offered incentives for electric buses, three-wheelers, and four-wheelers to be used for commercial purposes. PHEVs and those with sizable lithium-ion batteries and electric motors will also be included in the scheme and fiscal support offered depending on the size of the battery. Accordingly, it is advised that the current policies are sustained and improved to make xEVs affordable for the manufacturers and consumers and for CO_2 emissions reduction.

The EV sector, as well as biofuel industries are nascent in India, Indonesia, and Thailand, and there are not many companies that manufacture xEVs and produce industrial-grade ethanol locally. This also limits consumers' freedom to choose from different options. As the market for xEVs, biofuels, and other alternative fuels such as hydrogen expands in India, Indonesia, and Thailand, more manufacturers are projected to engage, resulting in increased competition and lower alternative fuel prices. As a result, it is imperative for governments to create an enabling environment for the private sector to drive local alternative production, while also attracting foreign investors to establish supporting infrastructure such as EV charging stations.

The effectiveness of both xEVs and biofuel introduction is also linked to the source of electricity generation, thus tying it with the power sector. Therefore, the policy requires a comprehensive mixture of all key components that have an impact on the effectiveness of EVs and alternative fuel introduction to reduce the CO_2 emissions levels. The power generation sector in India, Indonesia, and Thailand is currently dominated by fossil fuels. As a result, the adoption of xEVs will be effective only if it is accompanied by the development of alternative fuels to replace gasoline and diesel. CNG and biofuels will be major factors in lowering CO_2 emissions, and they can be applied effectively by focusing on their availability and affordability. The overall xEV and alternative biofuel fuel policy is effective only with deep decarbonization of the power sector. The electrification of vehicle scenario is effective only when the necessary incremental power is supplied from renewable sources. Biofuels, on the other hand, have proven to be beneficial in lowering fossil fuel consumption and carbon emissions. It is more effective to reduce energy use and GHG emissions when combined with improvements in fuel efficiency through the introduction of xEVs. Since current hybrid vehicles are mainly gasoline based, the introduction of xEVs may cause a shift from diesel to gasoline. Therefore, it is necessary to adjust the production amounts of bioethanol and biodiesel flexibly in accordance with the spread of xEVs. When introducing xEVs, it will be necessary to formulate a renewable energy introduction plan that takes into consideration both power generation and biofuel supply.

5.7 Financing Options for Decarbonizing the Transport Sector in Emerging Economies

5.7.1 Domestic and International Financing of Transport Sector Decarbonization

The cost of introducing decarbonization measures such as EVs and alternative biofuels to replace the current use of gasoline and ICE vehicles varies across the studied countries. While reliable data on the low-carbon investment trends in the transport sector are not readily available in India, Indonesia, and Thailand, it could be said from government budget outlays that nearly two-thirds of investment in transport infrastructure from 2015 to 2019 went to road transport.

Table 5.6 presents a list of available financial sources that include government budgets, the private sector, and special purpose financial vehicles in the three countries compiled through a literature survey and regional consultation process.

Table 5.6: Financing Channels for Low-Carbon Transport Infrastructure in India, Indonesia, and Thailand

Source	Description	Examples of Financing Channels
Mobilizing Public Budgets		
Intergovernmental transfer of public funds	Transfers of fiscal resources from national government or state governments to states and/or municipalities	Transport and urban infrastructure funds
Taxes	Collections and levies including fuel taxes, might help finance low-carbon urban infrastructure initiatives like electric vehicles (EVs) and biofuels	Property tax, tax on motor vehicles, tax on imported fossil fuels
Nonrepayable funds, grants, official development assistance	Transfer of monetary resources and/or other financial support without the need for repayments; usually involves small grant-in-aid type finance aimed at preparing technical studies, prototypes, and demonstration projects	Project facilitation fund, sectoral loans, technical and financial assistance programs of bilateral development agencies
Direct charges and user fees	Collection of fees for the provision of a certain type of services and/or the use of urban infrastructure	Charging for the use of roads for private vehicles and parking in public spaces
Fines	Financial penalties for transport rule violations and pollution	Fines for polluting vehicles and compensation for traffic rule violations
Land value capture	Financial mechanisms that allow recovery of appreciated monetary value of real estate's resulting from public actions in a designated area	Sale of construction rights to EV charging stations, certificates for additional procurement of biofuels
Mobilizing Private Finance		
Public–private partnerships (PPPs)	Contracts between city, state, and national governments and the private sector for the implementation of infrastructure projects Payment is to be made by the public sector, with other possible compensations	Most common examples of PPPs that make road transport infrastructure include EV charging stations, mass rapid transport systems, bioethanol plants

continued on next page

Table 5.6 *continued*

Source	Description	Examples of Financing Channels
Tax breaks and financial concessions	Tax concessions where the tariff charged to the road user and other transport service revenues are sufficient to remunerate the concessionaire; measures that reduce a certain amount of tax to encourage favorable private investments	Tax concessions for investment in public transportation; and municipal, state, and federal park concessions as occurs in megacities
Debt	Acquisition of monetary funds from private institutional investors, in addition to international, national, and regional development financial institutions and commercial banks	Financing through national and international private banks
Capital market	Includes public and corporate green bonds that can support specific low-carbon road transport infrastructure projects; investment in infrastructure system operators operating under a PPP or other operating authority	Government bonds, securities linked to EVs, hydrogen, biofuel projects, infrastructure debentures, incentive debentures, and shares
Special Purpose Financial Tools		
Dedicated funds	National and international climate and green funds that leverage private funding mechanisms specialized in serving new risky investments that can combat issues like climate change	Urban infrastructure development fund, fund for biofuel development, national environment fund for eco-car development
Credit assistance and guarantees	Arrangements and/or that improve the credibility of decarbonization activities and projects in the transportation sector by decreasing inherent risks and facilitating access to improved funding conditions. They may include, among others, insurance, revolving funds, guarantees, and currency hedge funds	Road infrastructure guarantee fund, PPP guarantee fund and sovereign guarantees

Source: Authors.

Low-carbon investments, including EVs and biofuels, are traditionally financed by taxpayers and/or by users, while in some instances, private entities build them and finance them through project-based bond issuance. In India, Indonesia, and Thailand, blended financing schemes that combine local resources, development aid, and private capital have shown to be effective. It is estimated that about 37% of infrastructure development finance (transport, airports, energy and water supply, and sanitation) flows into the transport sector. It is difficult to estimate how much would be on decarbonization outlays including general education, research, and training for the transport sector. However, the transport sector is gaining prominence in "green" and other climate-themed bonds, in which the proceeds are earmarked for projects with climate benefits. The transport sector represents 20% of green bond proceeds in the Association of Southeast Asian Nations member states, the PRC, and India, making it the third-largest sector after energy (32%) and buildings (30%). At the global level, green bonds for transport reached $52 billion in 2019, up 71% from 2015 to 2019 (Anbumozhi 2021). Green and/or climate bond transportation projects have been driven by government-backed entities. Between 2018 and 2020, there were 10 certified bonds to finance the expansion of metro lines in Thailand. In August 2020, a B30 billion ($1 billion) Sustainability Bond in August 2020 was issued, with one-third of the sum allocated for the construction of the Bangkok Mass Rapid Transit. Meanwhile, Indonesian automakers issued certified green bonds to fund their electric vehicle and mixed biofuel programs. For urban transport infrastructure, other potential sources of revenue include land value capture (Yoshino and Taghizadeh-Hesary 2018).

Given the need to expand and update low-carbon transport infrastructure, public revenue sources are insufficient to meet rising demand (Anbumozhi 2021). Additional private investment and international development finance are required, including the issuance of loan guarantees. Another promising option for financing low-carbon transportation infrastructure is through public procurement processes. Almost all publicly procured services have an impact on road transportation, and as such can make a significant contribution to reducing carbon emissions in the sector. For public procurement to regularly support sustainable transport, necessary factors include frameworks and regulations that use multi-criteria cost-benefit analyses to assess the full carbon costs and benefits of purchasing decisions.

Carbon pricing mechanisms such as taxes on fuels and vehicles, fossil fuel subsidy reforms, congestion charging, and parking prices, among others, can help address the financing gaps in transport sector decarbonization. While different types of fossil fuels and industrial decarbonization are covered in the discussions in India, Indonesia, and

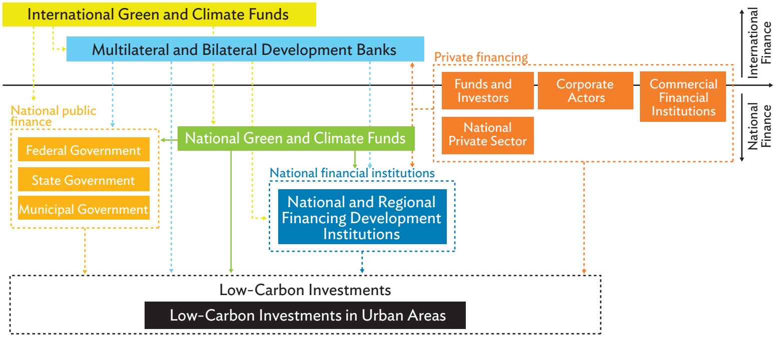
Thailand, road transport is mostly ignored in talks of carbon pricing and emission trading schemes., with few exceptions like Singapore.

5.7.2 Barriers to Low-Carbon Investments in the Transport Sector

The international financial mechanisms such as the Clean Development Mechanism, the Clean Technology Fund, the Green Climate Fund, the Global Environment Facility, the International Climate Initiative, the Joint Crediting Mechanism, and Joint Implementation can help to leverage private finance. Figure 5.14 shows several ways that international finance can be channeled for decarbonization of the transport sector. Even though there are some conceptual and methodological controversies about the leveraging effects of international financial flows, they typically include credits provided by bilateral and multilateral development banks to support national public banks, as well as private sector investments. The goal of such a fund is to attract support for turning low-carbon, climate-resilient investment priorities into finance-ready, implementable projects (CPI 2019; OECD 2015; Gupta et al. 2014; Flynn 2011).

The challenges to financing decarbonization in India, Indonesia, and Thailand include local issues related to financial and technical capacity gaps, to issues that go beyond the scope of infrastructure ministries, such as the regulatory environment on carbon emissions,

Figure 5.14: International and National Financing Channels of Low-Carbon Investments in the Transport Sector



Source: Authors.

including clear climate action guidelines for the transport sector and incentives for participation from different funding sources (Conway et al. 2020; ERIA 2020; Zulueta 2018). The challenges listed below were collected through regional policy dialogues between November 2019 and March 2020 in New Delhi, Jakarta, and Bangkok. Representatives of international, national, and regional financial institutions, as well as participants from national and international project preparation facilities and public entities, such as municipal technicians, federal government, and state entities attended these events.

The barriers to financing low-carbon investments in the transport sector can be divided into three major areas:

(1) National institutional environment
  - Low level of coordinated governance and integrated planning
  - Uncertainties in the regulatory environment

(2) Planning and preparation of low-carbon transport sector projects
  - Lack of urban planning
  - Difficulties in preparing project activities at the local level

(3) Financing and resource mobilization
  - Deficiency in directing resources to sustainable urban development
  - Disability in directing funds to sustainable urban development and priority areas
  - Precarious municipal fiscal situation
  - Difficulties in overcoming the financing processes of international, national, and regional development banks

To help overcome these challenges, coordinated actions are needed to deepen existing and new initiatives on EVs and biofuels, which foresee the inclusion of different actors, including central, state, and local governments, the private sector, and environmental agencies. Under the leadership of a coordinating agency, long-term policy coordination among regulatory, fiscal, and tax policies is required. It is necessary to transform the national commitments to the Paris Agreement targets into the transport sector action plan ensuring a coordinated monitoring and reporting implementation mechanism. Institutions that are part of the financial system, such as central banks, can strengthen their ability to support the finance, investments, and innovations required for a low-carbon transportation transformation. Further monitoring and research to understand, quantify, and manage exposure to climate-related risks in investors' portfolios and increasing support for sectoral investments such as EVs and biofuels are to be aligned with NDC targets. Furthermore, it is recommended to increase the transparency and standardization of the availability and methodology of transport sector emissions and climate finance data at the national level.

For financial institutions and development aid providers, developing a taxonomy for decarbonizing the transport industry is a growing opportunity to support new investments. Such guidance can assist with loans, credits, and guarantees, as well as assisting private investors in identifying opportunities for impact investments that meet sustainability objectives or meet the Paris Agreement's climate targets.

5.8 Conclusion

One-quarter of the Asian region's energy-related GHG comes from transport due to the high amount of fossil fuel used. Efforts to decarbonize the transport sector are now greater than ever in the developing countries of Asia with ambitious targets set for the electrification of vehicle fleets and replacement of gasoline fuels with biofuels. The scenario analysis indicates that a moderate electrification strategy alone will not be enough to reduce carbon emissions to the required levels by 2030, and a moderate to aggressive electrification strategy combined with hybrid promotion will have the greatest impact on decarbonization.

The cost of decarbonization options and measures varies by country because they require a combination of additional energy, transportation, and industry infrastructure investments. While multiple funding channels are available, funding gaps for transport decarbonization are a significant roadblock to meeting decarbonization targets and ambitions. Innovative finance can help in achieving the scale needed to fund transport decarbonization. These include climate bonds, asset recycling, and carbon pricing.

The road map for decarbonizing the transport sector and meeting the 2030 time line will not be easy. The following actions could address several technical, market, and financing barriers.

Vision, leadership, and coordinated policies. Changes around decarbonization and actions toward net-zero economy may be slow. Still, only a few countries in developing Asia have committed to zero-emissions mobility, with many countries focusing their efforts on phasing out fossil fuel and internal combustion engine cars. However, additional commitments made in Glasgow at COP26, as well as targets for EVs, can only be met with strong political will and integrated policies. Ministries of energy, transportation, and industry should work closely with other government ministries, including the ministries of environment and finance, to scale up incentive schemes for decarbonization.

Countries need to make the right decarbonization investment decisions based on data and evidence. Tools such as the WTW or TTW emissions based on a life cycle analysis can help governments make better infrastructure investment and policy decisions based on data and evidence to achieve low-carbon mobility. Government leaders and transport stakeholders also need to be proactive in adapting to shifting market demands and needs.

Optimize public and private finance instruments. The existing investment gap in transport decarbonization might be viewed as either a challenge or an unrealized economic opportunity. As transport decarbonization does not affect only one transport mode or one stakeholder, comprehensive investment strategies that generate synergies across the transport, industry energy, and infrastructure sectors are essential. For example, while the electrification of private cars has made steady progress, we cannot leave battery technologies, biofuels, and charging stations out of the conversation.

Develop a regional policy framework for decarbonization of the road sector. The Association of Southeast Asian Nations member states and East Asian economies are economically integrated with new trade and investment agreements and infrastructure connectivity programs. They must, however, construct a decarbonization policy framework that resonates with all policy makers and can be implemented regionally. It is necessary to assist nations in integrating transportation mitigation targets and policies into their NDCs, as well as to support substantial demonstration projects that demonstrate that mobility and zero emissions are compatible.

References

Anbumozhi V. 2021. Mobilizing Private Finance for Low-Carbon Energy Transition. In B. Susantono, Y. Zhai, R. M. Shrestha, and L. Mo, eds. *Financing Clean Energy in Developing Asia*. Manila: Asian Development Bank, pp. 196–226.

Board of Investment (BOI). 2018. Investment Promotions for xEV and Components in Thailand. Presentation, 6 June. Bangkok: Office of the Board of Investment.

BP. 2019. *BP Statistical Review of World Energy*. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2019-full-report.pdf

Conway, S. P. Negreiro, B. Tonkonogy, and K. Yang. 2020. Enhancing the Role of National Development Banks in Supporting Climate-Smart Urban Infrastructure. A Policy Brief for the Cities Climate Finance Leadership Alliance. https:// www.citiesclimatefinance.org/wp-content/uploads/2020/08/Enhancing-the-Role-of-National-Development-Banks-1.pdf

Climate Policy Initiative (CPI). 2019. Global Landscape of Climate Finance 2019. https://www.climatepolicyinitiative.org/pt-br/publication/global-landscape-of-climate-finance-2019/#:~:text=The%20 2019%20edition%20of%20Climate,global%20climate%2Drelated%20primary%20investment

Department of Heavy Industry, Ministry of Heavy Industries & Public Enterprises, Government of India. 2017. ‘Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles in India. New Delhi: Department of Heavy Industry. https://dhi.nic.in/UserView/index?mid=2418

———. 2018a. *National Auto Policy 2018*. New Delhi: Department of Heavy Industry. https://dhi.nic.in/writereaddata/UploadFile/DHI-NAB-Auto%20Policy%20Draft%20Document_vDRAFT.pdf

———. 2018b. *National Electric Mobility Mission Plan 2020*. New Delhi: Department of Heavy Industry. https://www.dhi.nic.in/UserView/index?mid=1347

Energy Policy and Planning (EPPO). Ministry of Energy, Government of Thailand. 2015. *Energy Efficiency Plan 2015–2036*. Bangkok: Energy Policy and Planning Office. http://www2.eppo.go.th/encon/EEP2015/Draft-EEP2015.pdf

———. 2017. Policy and Promotion of Electric Vehicles in Thailand. Presentation to the Engineering Institute of Thailand, 18 April. http://www.eppo.go.th/images/Infromation_service/NEWS/2017/04April/19Apr/EIT_18-04-2017.pdf

Economic Research Institute for ASEAN and East Asia (ERIA). 2020. Policy Dialogue on Mobility Electrification – New Delhi, Jakarta, Bangkok. Jakarta: ERIA.

Flynn, C. 2011. Blending Climate Finance through National Climate Funds: A Guidebook for the Design and Establishment of National Funds to Achieve Climate Change Priorities. New York, NY, US: United Nations Development Programme.

Gupta, S. et al. 2014. Cross-Cutting Investment and Finance Issues. In *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY, US: Cambridge University Press, pp. 1207–1246.

Kim, K., and J. Mishra. 2021. R. E-Mobility: Transition to Sustainable Transport. In B. Susantono and R. Guild, eds. *Creating Livable Asian Cities*. Manila: Asian Development Bank, pp. 147–164.

Lam, A. et al. 2018. Policies and Predictions for a Low-Carbon Transition by 2050 in Passenger Vehicles in East Asia. Based on an Analysis Using the E3ME-FTT Model. *Sustainability* 10: 1612.

Mitsubishi Motors. 2012. Mitsubishi Motors Philippines Collaborates with DOE and Meralco on I-Miev Electric Car Evaluation. Press Release, 17 January. https://mmpc.ph/pressrelease/mitsubishi-motors-philippines-collaborates-doe-meralco-miev-electric-car-evaluation/

National Institution for Transforming India, Government of India. 2017. Draft National Energy Policy. Version as on 27 June 2017. New Delhi: National Institution for Transforming India. http://niti.gov.in/writereaddata/files/new_initiatives/NEP-ID_27.06.2017.pdf

Organisation for Economic Co-operation and Development (OECD). 2015. *Climate Finance in 2013-14 and the USD 100 Billion Goal. A Report by the Organisation for Economic Co-operation and Development (OECD) in Collaboration with Climate Policy Initiative*. Paris: OECD. https://www.oecd.org/env/climate-finance-in-2013-14-and-the-usd-100-billion-goal-9789264249424-en.htm

Pan, X., H. Wang, L. Wang, and W. Chen. 2018. Decarbonization of China's Transportation Sector: In Light of National Mitigation Toward the Paris Agreement Goals. *Energy* 155: 853–864.

Toba, M., S. Goto, S. Ichikawa, N. Chollacoop, and V. Anbumozhi. 2020. Evaluation of CO2 Emissions Reduction by Mobility Electrification and Alternate Biofuel Introduction in East Asia Summit Countries. Jakarta: Economic Research Institute for ASEAN and East Asia.

Toyota. 2019. Toyota Partners with Mapúa for the First Hybrid Electric Vehicle Campus Tour. New Release, 18 March. http://toyota.com.ph/news/toyota-news/partners-with-mapua

United Nations Economic and Social Commission (UNESCAP). 2021. SUTI Mobility Assessment Reports. Bangkok: UNESCAP. https://www.unescap.org/sites/default/d8files/knowledge-products/SUTI_and_COVID-19_Impact_Bangkok_0.pdf

Yoshino, N., and F. Taghizadeh-Hesary. 2018. Alternatives to Private Finance: Role of Fiscal Policy Reforms and Energy Taxation in Development of Renewable Energy Projects. In V. Anbumozhi, K. Klairajan, and F. Kimura, eds. *Financing for Low-Carbon Energy Transition: Unlocking the Potential of Private Capita*. Springer, pp. 335–358.

Zhang, R., S. Fujimori, H. Dai, and T. Hanaoka. 2018. Contribution of the Transport Sector to Climate Change Mitigation: Insights from a Global Passenger Transport Model Coupled with a Computable General Equilibrium Model. *Applied Energy* 211: 76–88.

Zhang, R., S. Fujimori, and T. Hanaoka. 2018. The Contribution of Transport Policies to the Mitigation Potential and Cost of 2°C and 1.5°C Goals. *Environmental Research Letters* 13(5): 054008.

Zhang, R., and S. Fujimori. 2020. The Role of Transport Electrification in Global Climate Change Mitigation Scenarios. *Environ. Res. Lett*. 2020,

Zulueta, A. M. 2018. Mitsubishi Motors Donates EVs, a Quick Charging Station to DTI. AutoDeal News, 24 May. https://www.autodeal.com.ph/articles/car-news-philippines/mitsubishi-motors-donates-evs-quick-charging-station-dti

PART IV

Decarbonizing through the Agriculture Sector

6

Contribution of Agriculture to Climate Change and Low-Emissions Agricultural Development in Asia and the Pacific

Jeetendra Prakash Aryal

6.1 Introduction

The Asia and Pacific region accounts for almost 60% of the total global human population[1] and has the largest agricultural production share. With large areas under rice cultivation, increased use of synthetic fertilizer, and increased livestock production, this region substantially contributes to global greenhouse gas (GHG) emissions from the agriculture sector (FAO 2020). Over the last 5 decades, the regional emissions from agriculture (crops and livestock) have increased by 144% (i.e., from 1,006 million tons of carbon dioxide [CO_2] equivalent emissions in 1961 to 2,459 million tons of CO_2 equivalent emissions in 2012) (FAO 2020). Moreover, the demand for livestock products is predicted to double in developing countries by 2050 due to population growth.

The contribution of agriculture, forestry, and other land use (AFOLU) constituted nearly 24% of total global GHG emissions in 2010 (IPCC 2007, 2014). Of the total global GHG emissions from the AFOLU sector in 2010, Asia's share (i.e., 44%) was the largest (IPCC 2014). During the same period, the share of the AFOLU sector in total GHG

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[1] UNFPA. Population Trends. https://asiapacific.unfpa.org/en/node/15207 (accessed 25 June 2022).

emissions was relatively much larger in some Southeast Asian countries (e.g., 39% in Malaysia, 71% in Indonesia, and 97% in the Lao People's Democratic Republic) (USAID 2017). In addition, Asia includes the two most populous and emerging economies of the world, India and the People's Republic of China (PRC), where agriculture is still one of the major sectors contributing significantly to their gross domestic product (GDP) and also to total GHG emissions (Huang et al. 2019; Aryal et al. 2020b). Therefore, a clear understanding of GHG emissions from this sector and its transformation toward low-emissions development is essential to reduce GHG emissions and to avert the worst impacts of future climate change.

Another crucial issue with the AFOLU sector is that it has to address the challenges of climate change and the growing demand for food, fiber, and wood simultaneously (Smith et al. 2013). Emissions reduction in this sector, therefore, needs to be achieved such that the production of food, fiber, and wood products that are essential for human consumption is not compromised. Looking into future human population growth, dietary changes due to economic growth, and climate challenges, it is estimated that the total demand for crops and grass could increase by 35% to 165% between 2010 and 2100 (Bijl et al. 2017). More importantly, the global food demand scenarios show a strong increase in animal-based products, primarily in developing countries (Bodirsky et al. 2015). Accordingly, there is a need to assess multiple factors, including demand, supply, and other institutional factors, while transforming the AFOLU sector into a low-emissions development pathway (Sutton, Erisman, and Oenama 2007; Smith et al. 2013; Pradhan et al. 2017; Pradhan, Chaichaloempreecha, and Limmeechokchai 2019; Zeng et al. 2020).

The AFOLU sector is one of the major emitters of non-CO_2 GHGs, mainly nitrous oxide (N_2O) and methane (CH_4) (Sirohi and Michaelowa 2007; Chhabra et al. 2013; Zhang et al. 2013; Zhang et al. 2021). Given that existing agricultural production practices are more carbon intensive, there is a substantial potential to reduce GHG emissions from this sector if proper policies to promote the use of less carbon-intensive production methods are applied (Huppmann et al. 2018; IPCC 2018). Responsible consumption and preventing food waste and loss can contribute immensely to avoiding the GHG emissions from agriculture (UNEP 2021a). Therefore, agriculture is one of the critical sectors in the climate change solution.

After 1990, the relative share of GHG emissions from the AFOLU sector to total GHG emissions (including emissions from energy, transportation, industry, etc.) has declined. This is primarily due to the more rapid increase in emissions from other economic sectors, such as energy and transport, as well as the declining rate of deforestation

(FAO and IFA 2001; FAO 2013). Against this backdrop, this study has the following objectives: (i) to examine the trend of GHG emissions in the agriculture sector, primarily agriculture and livestock; (ii) to review the potential to reduce GHG emissions from agriculture and livestock; and (iii) to analyze critically how this sector can contribute to both climate change mitigation and food security goals simultaneously. This study uses data and information from many national and international organizations, including the Food and Agriculture Organization of the United Nations (FAO), the World Bank, the Asian Development Bank and the Asian Development Bank Institute (ADB and ADBI), the United Nations Framework Convention on Climate Change (UNFCCC), and the Intergovernmental Panel on Climate Change (IPCC). Further, this chapter extensively reviews the varied literature on climate change and agriculture to examine the challenges and prospects of agricultural GHG mitigation in the Asia and Pacific region.[2]

The remaining sections of the study are outlined as follows. Section 6.2 highlights the current status of GHG emissions from the AFOLU sector in the Asia and Pacific region. Section 6.3 reviews the potential of GHG mitigation from the AFOLU sector, and section 6.4 presents the critical analysis and reviews of climate change mitigation policies and measures taken to reduce GHG emissions at multiple levels, with a focus on attaining both low-emissions agriculture (i.e., in line with the United Nations Sustainable Development Goal [SDG] of climate action) and also improving food security (i.e., in line with the SDG of reducing poverty). Section 6.5 concludes the study with some key recommendations.

6.2 GHG Emissions from the AFOLU Sector in Asia and the Pacific

This section presents the total GHG emissions from the AFOLU sector from 1960 to 2018 in Asia and the Pacific and compares this with other regions of the world. Overall, this section presents the importance of reducing GHG emissions from the AFOLU sector to achieve the Paris Agreement climate goals of keeping the temperature rise to below 2°C and averting the catastrophic impacts of future climate change.

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[2] This study follows the definition set by the Asian Development Bank (ADB) while defining the region and countries under it.

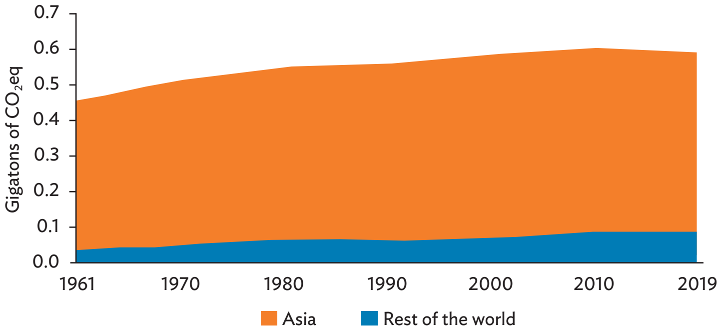
6.2.1 Emissions from Agricultural Activities

Methane Emissions from Paddy Rice

Countries in the Asia and Pacific region are the major producers and consumers of rice globally. About 90% of global rice is produced in this region, and the region accounts for nearly 87% of global rice consumption (Papademetriou 2000). Of the top 10 rice-producing countries globally, the first nine countries belong to this region. The PRC is the largest producer of rice globally (about 30%), which is followed by India (24%), Indonesia (7%), Bangladesh (7%), Viet Nam (5%), Thailand (4%), and Myanmar, the Philippines, and Japan (about 1% each). In 2018–2019, the PRC produced 148.5 million metric tons of rice and India 116.48 million metric tons. As methane emissions from global rice cultivation account for almost 50% of all crop-related GHG emissions, Asia and the Pacific contributes significantly to global anthropogenic methane emissions (Kritee et al. 2018).

Global warming may increase methane emissions from rice paddies in the future (van Groenigen, van Kessell, and Hungate 2013; Zhang et al. 2020). The PRC's share of GHG emissions from agriculture is thus expected to increase with higher methane emissions from paddy rice (Yue et al. 2017). Figure 6.1 presents the methane emissions from rice production (in carbon dioxide equivalent, or CO_2eq) in Asia and the rest of the world. It shows that about 87% of the methane emissions from rice cultivation come from Asia.

Figure 6.1: Emissions from Rice Cultivation in Asia and the Rest of the World



CO_2eq = carbon dioxide equivalent.

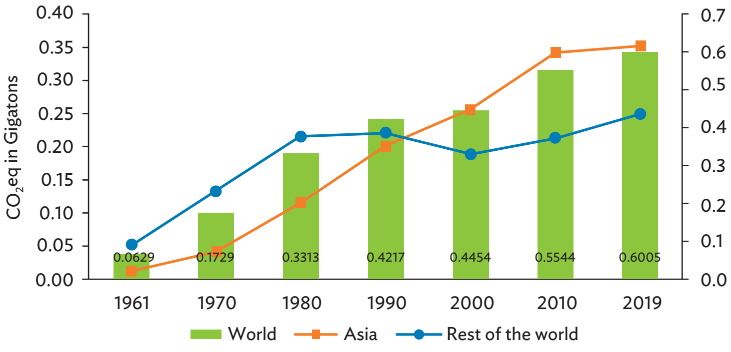
Source: Author's compilation from FAOSTAT. https://www.fao.org/faostat/en/#home (accessed 25 June 2022).

Emissions from Inorganic Fertilizer Use

Inorganic fertilizer use is accountable for almost 30% of N_2O emissions from the agriculture sector (IPCC 2014). A large quantity of GHGs, including CO_2, CH_4, and N_2O, are also emitted during the manufacturing and transportation of inorganic fertilizer (Tian et al. 2020; Cui et al. 2021; Liang et al. 2021). In total, agriculture contributes around 60% of global N_2O emissions (Foley et al. 2011). As excessive use of inorganic fertilizer in agriculture is a major source of N_2O emissions from agriculture (Lu and Tian 2017; Aryal et al. 2021a), its proper use is essential for achieving climate goals stated in the SDGs and the target of the Paris Agreement to remain below a 2°C warming threshold.

Emissions from inorganic fertilizer vary with management factors and variations in climatic and edaphic factors (Chen et al. 2015). The loss of applied nutrients into the environment during agricultural production results in fertilizer-induced N_2O emissions (Sutton, Erisman, and Oenama 2007). Almost 60% of the nitrogen pollution that emanates from crop production is related to nitrogen fertilizer application (Sapkota et al. 2018). In Asia and the Pacific, India and the PRC are the largest emitters, responsible for about 70% of total fertilizer-related N_2O emissions (Lassaletta et al. 2014). The GHG emissions (CO_2eq) from synthetic fertilizer increased by 9.5 times from 0.0629 gigatons (Gt) in 1961 to 0.6005 Gt in 2019, primarily due to an increase in the use of synthetic fertilizer in Asia. Until 1990, GHG emissions from synthetic fertilizer in Asia were lower than those in the rest of the world, but after 1990, emissions were greater than in the rest of the world (Figure 6.2).

Figure 6.2: Synthetic Fertilizer Emissions in Asia and the Rest of the World



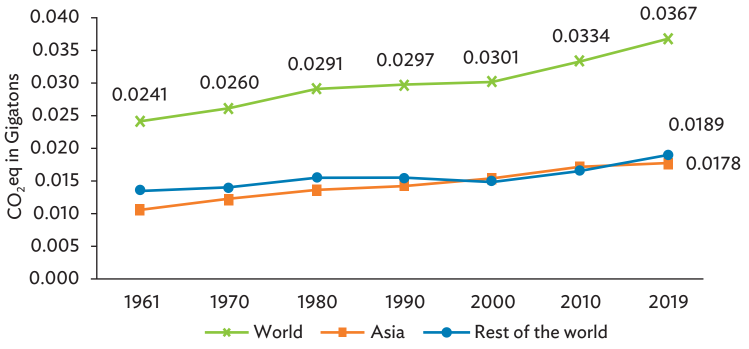
CO_2eq = carbon dioxide equivalent.

Source: Author's compilation from FAOSTAT. https://www.fao.org/faostat/en/#home (accessed 25 June 2022).

Emissions from Burning of Crop Residues

Burning crop residues on farms contributes substantially to CO_2 emissions and air pollution in many countries of Asia (Streets et al. 2003; Lohan et al. 2018; Wu et al. 2020; Bajracharya, Mishra, and Maharjan 2021; Shen et al. 2021). In 2017–2018, nearly 116 million tons of crop residue were burned in India, which emitted 176.1 teragrams (Tg) of CO_2, 313.9 gigagrams (Gg) of CH_4, and 8.14 Gg of N_2O (Venkatramanan et al. 2021). In 2003, it was estimated that about 110 Tg of crop residue were burned in the PRC, which is almost 44 % of all crop residues burned in Asia in that year (Streets et al. 2003). GHG emissions from residue burnings of rice, wheat, and corn comprise more than 85% of the total crop residue burned (Zhang et al. 2019). Figure 6.3 shows that emissions from crop residue burning increased from 0.241 Gt to 0.367 Gt over the last 6 decades, and the trend of growth is comparatively similar in Asia and the rest of the world.

Figure 6.3: Emissions from Crop Residue Burning in Asia and the Rest of the World



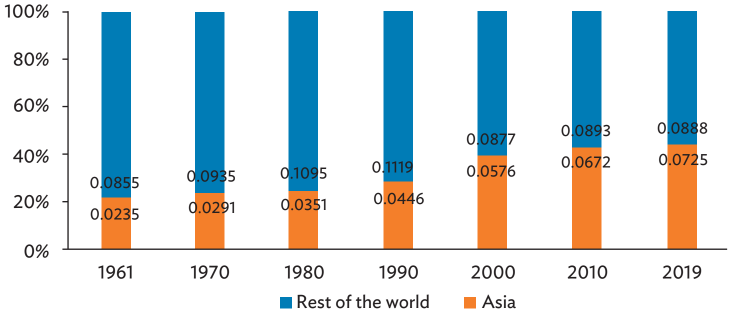
CO_2eq = carbon dioxide equivalent.

Source: Author's compilation from FAOSTAT. https://www.fao.org/faostat/en/#home (accessed 25 June 2022).

Emissions from Manure Left on Pasture and Manure Management

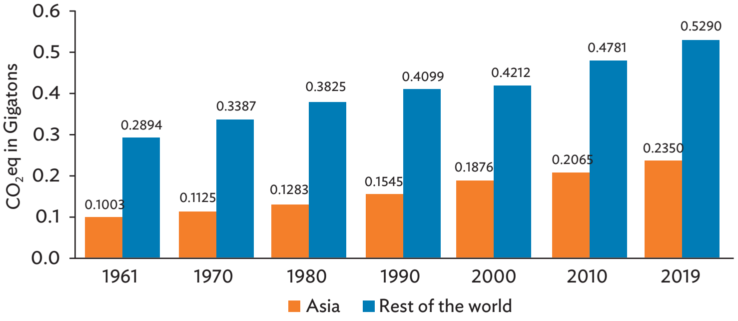
Manure left on pasture and manure management emit large amounts of methane and N_2O, which jointly account for almost 18% of total agricultural emissions in 2018 (almost equivalent to the emissions from synthetic fertilizer use in agriculture) (FAO 2020). The emissions factors and inventory from manure management differ by region and management system, due to the multitude of microbial activities in the manure environment. For instance, in India, methane emissions from bovine manure management varied from 0.8 to 3.3 kg head^{-1}year^{-1}, while the N_2O emissions varied from 3 to 11.7 megagrams (Mg) head^{-1}year^{-1} from solid storage of manure (Gupta et al. 2007). In the Asia and Pacific region, manure management has become a major problem due to more intensive production of livestock (Petersen et al.2013).

Figure 6.4: Emissions from Manure Applied to Soil in Asia and Rest of the World



Source: Author's compilation from FAOSTAT.

Figure 6.5: Emissions from Manure Left on Pasture in Asia and the Rest of the World



CO_2eq = carbon dioxide equivalent.

Source: Author's compilation from FAOSTAT. https://www.fao.org/faostat/en/#home (accessed 25 June 2022).

Figures 6.4 and 6.5 show emissions from manure applied to soil and manure left on pasture, respectively in Asia and the rest of the world. Manure applied to soil increased from 0.11 Gt in 1961 to 0.16 Gt in 2019, while the share of application in Asia increased from 22% to 45%. Emissions from manure left on pasture increased from 0.39 Gt in 1961 to 0.76 Gt in 2019, and Asia is responsible for 69% of the total emissions from manure left on pasture.

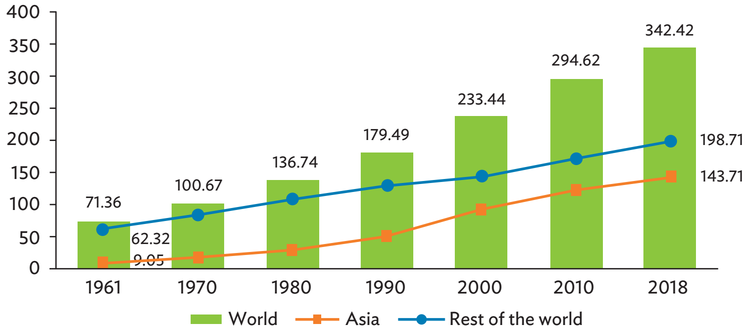
Emissions due to Irrigation and Other Management Practices

Irrigation, input management practices, and energy use in farm operations affect the GHG emissions from agricultural production. With the second-largest quantity of irrigated land in the world, GHG emissions from irrigation in the PRC significantly influence the global mitigation potential. In 2010, it was estimated that agricultural irrigation in the PRC emitted 36.72 million–54.16 million tons of CO_2 equivalent emissions (Zou et al. 2015). Energy used for irrigation is responsible for about 70% of total emissions from energy activities in the agriculture sector (Wang et al. 2012; Zou et al. 2015). Nevertheless, irrigation strategies matter a lot for GHG emissions (Islam et al. 2020; Sapkota et al. 2020). Flood irrigation is the major source of methane emissions from rice, indicating that reduced irrigation would be an effective way to lower methane emissions. Conversely, the rate of CO_2 emissions is usually higher under low irrigation, while most studies found low N_2O emissions in continuously flooded irrigation (Sapkota et al. 2020). Between 1980 and 2015, the intensification of agriculture increased food production in India 2.5-fold and GHG emissions threefold (Benbi 2018).

6.2.3 Emissions from Livestock

Livestock constitutes an integral component of the agriculture sector in the Asia and Pacific region, though in varying degrees. It is also a major source of GHG emissions. In East Asia, annual methane emissions from livestock in 2019 was 13.22 Tg, accounting for an increase of 231% since 1961 (Zhang et al. 2021). A major reason behind the increasing emissions from livestock is the rising demand for meat products in Asia over the past 6 decades. Figure 6.6 shows that meat production increased 4.8 times from 71.4 million tons in 1961 to 342.4 million tons in 2018. Asia's share in global meat production increased from 12.7% to 42% during the same period.

Figure 6.6: Meat Production in Asia and the Rest of the World (million tons)



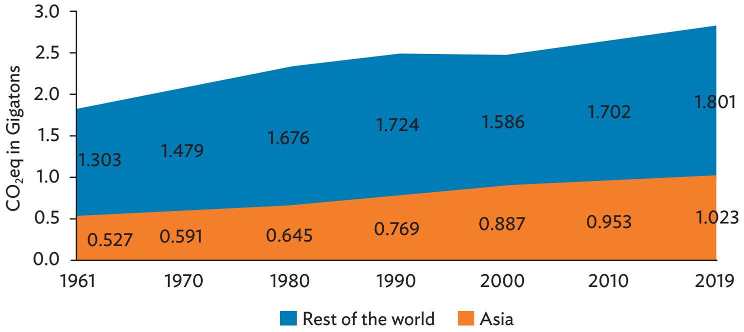
Source: Author's compilation from FAOSTAT. https://www.fao.org/faostat/en/#home (accessed 25 June 2022).

6.2.4 Emissions from Enteric Fermentation

Emissions from enteric fermentation vary by region, age group, and animal breed. Methane emissions due to enteric fermentation is higher among ruminant livestock (cattle, buffalo, sheep, and goats) (Chang et al. 2019). In India, of the total methane emissions from livestock in 2003, enteric fermentation constituted nearly 91% (Chhabra et al. 2013). Cattle (55%) and buffalo (37%) are the major contributors to GHG emissions, and enteric CH_4 constituted almost 90% of the total GHG emissions from livestock (Patra 2017).

Figure 6.7 compares the emissions from enteric fermentation between Asia and the rest of the world. The emissions from enteric fermentation increased 1.5 times from 1.8 Gt in 1961 to 2.8 Gt in 2019, and Asia's share in global enteric fermentation emissions increased from 29% to 36%.

Figure 6.7: Emissions from Livestock Enteric Fermentation in Asia and the Rest of the World



CO_2eq = carbon dioxide equivalent.

Source: Author's compilation from FAOSTAT. https://www.fao.org/faostat/en/#home (accessed 25 June 2022).

Feed Management

Feed efficiency is one of the key drivers of productivity, resource use, and GHG emissions intensities from the livestock sector; however, it varies largely across production systems, animal types, and animal products (Herrero et al. 2013). Therefore, application of better feed management measures in forage quality, feed processing, and precision feeding can help reduce methane emissions and prevent excessive nitrogen release into the environment by the livestock sector (Gerber et al. 2013).

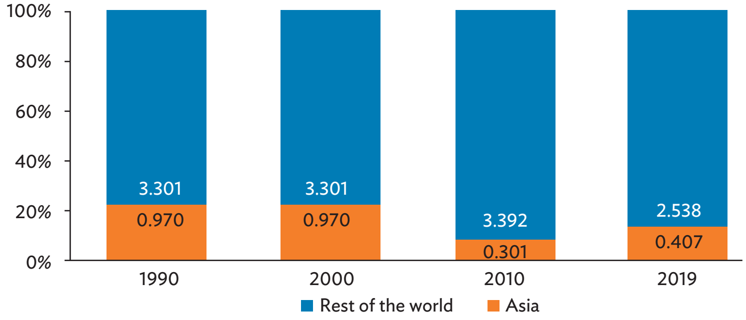
Lower-quality feeding practices explain why Asia has the highest share of enteric methane emissions compared to other regions in the world. For instance, the enteric methane emissions of producing nearly 46.3% of ruminant milk and meat energy by North America, Eastern and Western Europe, and the non-European Union former Soviet states in 2005 was only 25.5%. Conversely, in the same year, Asia, Africa, and Latin America produced 47.1% of ruminant meat and milk energy, which was associated with 69% of enteric methane emissions (O'Mara 2011). The livestock sector has a large influence on global nitrogen flows and emissions, as it currently emits one-third of current human-induced nitrogen emissions (Uwizeye et al. 2020).

6.2.5 Emissions from Forest and Land Use

Deforestation and other land-use changes due to agricultural practices are projected to contribute about 17% of total global GHG emissions (IPCC 2007, 2014). Forest and other land uses were responsible for about

12% of emissions from 2000 to 2009 (IPCC 2014). Analyzing satellite observations of gross forest cover loss and a map of forest carbon stocks across tropical regions, it was estimated that 0.81 petagrams of carbon emissions per year are due to deforestation (Harris et al. 2012). Moreover, in the 1990s, the highest level of deforestation occurred in insular Southeast Asia, especially in humid tropical regions (Miettinen, Shi, and Liew 2011). Given that the forest ecosystems in insular Southeast Asia are an area with exceptionally high biodiversity and also with a large amount of carbon stored in forested peat lands, deforestation in this region has severe consequences for global GHG emissions and climate change. Figure 6.8 shows the emissions from net forest conversion to other land use in Asia and the rest of the world since 1990.

Figure 6.8: Emissions from Net Forest Conversion to Other Land Use in Asia and Rest of the World



Source: Author's compilation from FAOSTAT. https://www.fao.org/faostat/en/#home (accessed 25 June 2022).

6.3 Mitigation Potential in the AFOLU Sector

The AFOLU sector has a large potential to mitigate GHG emissions and to sequester carbon in soils. To realize these potentials, we need to adopt improved technology in the farming system (Malla et al. 2005; Kahrl et al. 2010; Aryal et al. 2015; Hasegawa and Matsuoka 2015; Pradhan, Chaichaloempreecha, and Limmeechokchai 2019); better management of inputs such as water, energy, and fertilizer (Zhang et al. 2013); improved irrigation methods (Wang et al. 2012); better livestock management (Mottet et al. 2017; Enahoro et al. 2019); and better institutional arrangements (Aryal et al. 2020b). In the agriculture sector, livestock manure and enteric fermentation represent about 32% of emissions, and rice cultivation produces 8% of global anthropogenic emissions (UNEP 2021b). In addition to these supply-side mitigation measures in the AFOLU sector, the use of demand-side mitigation measures is also crucial if the target of keeping the temperature rise below 2°C is to be achieved. To achieve low-emissions agricultural development, it is essential to address the root cause of agricultural emissions, particularly the rising demand for carbon-intensive agricultural products (Dickie et al. 2014). Both supply- and demand-side GHG mitigation measures in the agriculture sector are discussed.

6.3.1 Supply-Side Mitigation Measures

Mitigation Options in Agriculture

The agriculture sector has a large potential to mitigate GHG emissions by employing efficiency-enhancing agricultural practices (Smith et al. 2008; Aryal et al. 2020b; Kiran Kumara, Kandpal, and Pal 2020). Conservation agriculture, improved agronomic practices, appropriate nutrient management, reduced tillage and residue management, water management, and agro-forestry are some of the key management practices that have GHG mitigation potential (IPCC 2007).

Conservation Agriculture

Conservation agriculture (CA) is an agricultural practice that combines reduced or zero tillage with permanent soil cover and crop diversification, including legumes.[3] Unlike conventional, tillage-based agricultural practices, CA contributes to GHG mitigation by increasing soil organic carbon (SOC) (Lal 1997) and also improving soil quality parameters compared to conventional agriculture (Page, Dang, and Dalal 2020). Yet, some studies report carbon sequestration potential under CA is much less than what is usually claimed (Powlson et al. 2014, 2016).

Practicing conventional, tillage-based rice-wheat cropping systems on 1 million hectares of the Indo-Gangetic Plains emits about 29 Mg $CO_2 year^{-1}$, while it would be 14 Mg $CO_2 year^{-1}$ if CA is applied to the same area of land (Grace et al. 2003). Grace et al. (2012) projected that following zero tillage in India's rice-wheat system could sequester 44,100 Gg of carbon over 20 years. Shifting from a conventional, tillage-based wheat production system to a zero-tillage-based wheat production

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[3] https://www.fao.org/conservation-agriculture/overview/what-is-conservation-agriculture/en/

reduces GHG emissions by 1.5 Mg CO_2eq hectare^{-1} year^{-1} (Aryal et al. 2015), and following zero tillage with residue retention helps reduce GHG emissions from residue burning (Jat et al. 2021). Nevertheless, regional climate variation largely determine the carbon sequestration potential of CA (Sun et al. 2020). Residue retention in the CA system is crucial to SOC concentration (Zhang et al.2014).

Site-Specific Nutrient Management

Soil nutrient management is a crucial factor associated with the GHG emissions from agriculture and, thus, has massive mitigation potential (Lenka et al. 2017). Proper use of chemical fertilizers is crucial to nutrient management. Studies on the North China Plain show that both cumulative and yield-scaled N_2O emissions from maize fields increase exponentially if fertilizer-N is applied above the optimum rate (Song et al. 2018). Site-specific nutrient management in rice helps reduce global warming potential by 2.5%, or about 12%–20% in wheat (Sapkota et al. 2021). Following nutrient expert (NE)-based fertilizer recommendations in the rice-wheat cropping system, India could produce more food with less synthetic fertilizer and reduce GHG emissions by about 5.34 Mt CO_2eq per year (Sapkota et al. 2021). In the northeast PRC, the adoption of the NE system in maize production has reduced reactive nitrogen losses by 47% and GHG emissions by 37.2% (Wang et al. 2020). Similarly, the adoption of NE in rice production has reduced reactive nitrogen losses by 10.1% and GHG emissions by 6.6% (Wang et al. 2020).

Laser Land Leveling

Laser land leveling (LLL) helps reduce irrigation water loss and thus energy use for irrigation. Compared to traditionally leveled and unleveled fields, LLL helps reduce total irrigation duration significantly—by about 70 h hectare^{-1} rotation^{-1} (Aryal et al. 2015). Further, energy use for irrigation in the rice-wheat system is much lower in laser-leveled fields (almost 754 kilowatt-hour less) compared to traditionally leveled fields (Aryal et al. 2015). Given the coal-dependent electricity generation system in India, LLL reduces about 0.15 Mg of CO_2eq of emissions per year if the rice-wheat system is followed in a hectare of land (Gill 2014). A study of Cambodia, the Philippines, Thailand, Viet Nam, and India showed that LLL saved energy of 3.0–6.9 gigajoules hectare^{-1},[4] thereby decreasing GHG emissions by 1,151–1,186 kilograms of CO_2eq hectare^{-1} in rice production (Nguyen et al. 2022).

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[4] A gigajoule is equivalent to 1,000 million joules.

Water Management

Water management practices like alternate wetting and drying (AWD) in rice, soil-water potential scheduling in crops, and alternative irrigation methods such as drip and sprinkler irrigation are crucial in mitigating GHG emissions from agriculture, along with maintaining production under water stress (Sibayan et al. 2018; Sapkota et al. 2020; Enriquez et al. 2021). At the global level, flooded rice accounts for approximately 12% of anthropogenic emissions from agriculture (Wassmann, Hosen, and Sumfleth 2009; Richards and Sander 2014). Although studies have shown variations in the reduction of methane emissions under AWD practices, most studies agree that it reduces methane emissions. For example, IPCC (2006) reports a 48% reduction in methane emissions under AWD practices; Richards and Sander (2014) report that it can be between 20% and 70%; and LaHue et al. (2016) showed that it reduces methane emissions by 60%–87%.

Soil and water potential (SWP) scheduling is another option to reduce N_2O and methane from rice production. Compared to AWD, seasonal N_2O emissions were significantly lower in the broadcast-SWP (by 64%) and liquid fertilizer-SWP (by 66%) treatments (Islam et al. 2020). Also, SWP reduced methane emissions by 34%. Water management and irrigation intensity considerably affect the GHG emissions from intensive vegetable production in the Republic of Korea (Kim et al. 2014). The global warming potential per unit of pepper fruit yield was reduced by almost 50% in a treatment that maintains soil water potential at 50 kilopascals through controlled irrigation. In the North China Plain, Mehmood et al. (2021) found that irrigation methods and irrigation scheduling levels affect cumulative CO_2 and methane emissions. Drip irrigation at 60% field capacity reduces global warming potential by 9% compared to the other irrigation methods examined (Mehmood et al. 2021).

Agroforestry System

The agroforestry system (AFS) contributes to GHG mitigation by storing carbon aboveground in the form of biomass and belowground in the form of soil organic carbon (Dhyani et al. 2020; Mayer et al. 2022). Compared to coniferous species, an AFS with broadleaf tree species sequesters more soil organic carbon (Mayer et al. 2022). Although the carbon sequestration potential of AFS can be improved and can vary by climatic zones, its basic potential is estimated to be 0.29–15.21 Mg hectare^{-1} year^{-1} (Dhyani et al. 2020). The mitigation potentials of AFS in India and Pakistan are 25.4 Mg C hectare^{-1} and 29.7 Mg C hectare^{-1}, respectively

(Sathaye et al. 2001). Under the AFS, carbon sequestration aboveground is between 0.23 and 23.55 Mg C hectare^{-1} year^{-1}and belowground is from 0.03 to 5.08 Mg C hectare^{-1} year^{-1} (Kumar and Kunhamu 2021).

Mitigation Options for Livestock

Improving livestock management can reduce the emissions intensity of livestock production (Nugrahaeningtyas et al. 2018). Feed management, genetics, and animal health improvements; improved grazing management practices; and the use of energy-efficient livestock shelters are among the major strategies to reduce GHG emissions from livestock (Thornton and Gerber 2010; Thornton and Herrero 2010). Given that the livestock sector emits more GHGs to the atmosphere than the entire global transport sector (Gerber and FAO 2013; Rojas-Downing et al. 2017), improved livestock management is essential to reduce its environmental footprint (Tullo, Finzi, and Guarino 2019).

Feed management substantially reduces GHG emissions from livestock (Ouatahar et al. 2021). Nutrition and feeding approaches can reduce methane per unit of energy-corrected milk by 2.5%–15.0% (Knapp et al. 2014). Improved fodder management, along with better herd health and genetics, reduces methane intensity by almost 14.6%–43.2% and also increases milk yield (Habib and Khan 2018). In the case of lactating dairy cows, diet management can reduce enteric methane emissions by almost 60% (Roque et al. 2019). Similarly, a combination of hydrolysable tannin and condensed tannin at a concentration of 1.5% dietary dry matter helps reduce methane emissions from beef cattle without negatively affecting animal performance (Aboagye et al. 2018). Table 6.1 provides some estimates of methane emissions from improved feeding practice, dietary additives, and animal breeding.

Table 6.1: Methane Emissions from Improved Livestock Management

Mitigation Potential	Dairy Cows	Beef Cattle	Sheep	Dairy Buffalo	Non-dairy Buffalo
Improved feeding practice	0.04	0.02	0.02	0.04	0.02
Dietary additives	0.01	0.01	0.0005	0.01	0.002
Animal breeding	0.01	0.01	0.001	0.01	0.02

Note: All figures are in Mg CO_2 ha^{-1} yr^{-1}.

Source: Smith et al. (2007a).

Mitigation Options in Forestry and Other Land Use

Afforestation, reducing energy use in forestry, and better land-use planning are important GHG mitigation strategies. Forster et al. (2021) have shown that forest growth rate is crucial in determining cumulative mitigation. Non-forested degraded lands and forested degraded lands in India account for 93.68 million hectares (mha) and 35.89 mha, respectively, so there is a massive potential to sequester increased CO_2 through massive afforestation programs. For instance, converting 40 mha of the surplus degraded lands into forest area can mitigate approximately 3.32 Gt in the next 50 years (Singh and Lal 2000). Afforestation also improves soil organic carbon storage and reduces soil erosion (Shi et al. 2015). Edaphic properties and microbial attributes induced by land-use change can, however, influence the level of GHG mitigation (Chen et al. 2021).

6.3.2 Demand-Side Mitigation Measures

Reduce Food Loss and Waste

Reducing food loss and waste (FLW) can substantially help reduce GHG emissions from agriculture (FAO 2018). About 40% of all food produced is not consumed by human beings and is either lost or wasted. FLW accounts for about10% of global GHG emissions from food production (UNEP 2021a). Approximately 1.2 billion tons of food are lost on farms, while about 931 million tons are wasted at the retail and consumption stages.[5]

A recent study by Xue et al. (2021) has shown that nearly 27% of food annually produced is lost or wasted in the PRC. Their study also claims that the land, water, carbon, nitrogen, and phosphorus footprints associated with total FLW in the PRC is almost equivalent to the total carbon footprint of the United Kingdom. In 2013, South Asia and Southeast Asia had the highest FLW-associated GHG emissions. Compared with other regions of the world, industrialized Asia has the highest FLW and the highest FLW-associated GHG emissions (Guo et al. 2020). More interestingly, the household-level average food waste (in kilograms per capita per year) is highest among the lower-middle-income countries (91 kg $capita^{-1}year^{-1}$), followed by high-income countries (79 kg $capita^{-1}year^{-1}$) and upper-middle-income countries (76 $kgcapita^{-1}year^{-1}$) (UNEP 2021a). This shows that reducing FLW is

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[5] https://www.worldwildlife.org/press-releases/over-1-billion-tonnes-more-food-being-wasted-than-previously-estimated-contributing-10-of-all-greenhouse-gas-emissions

one of the possible alternatives to reduce GHG emissions. For this, there is a need to develop specific programs related to consumer awareness about the adverse impacts of FLW on overall human society.

Reduce Demand for Livestock Products or High Carbon-Intensity Food

Increasing demand for livestock products is one of the reasons behind the higher GHG emissions from agriculture. The contribution of livestock to total global GHG emissions is about 10% of global GHG emissions, and this reaches almost 18% if lifecycle assessment (i.e., including emissions occurring at input levels such as feed production, processing, and land-use change, and emissions related to processing and transportation) is followed (Gerber et al. 2011; O'Mara 2011; FAO 2013). For instance, as livestock units in the PRC have more than tripled in the last 3 decades, the GHG emissions from this sector have almost doubled, and nitrogen losses to watercourses have tripled (Bai et al. 2021). Such a massive change in the PRC has a global impact on GHG mitigation (Yue et al. 2017; Bai et al. 2021; Si, Aziz, and Raza 2021). As the production of 1 kilogram (kg) of cattle meat emits nearly 45 times more GHGs than producing the same amount of chicken meat,[6] shifting from high- to low-carbon intensive food can substantially reduce GHG emissions. Although it is difficult to apply regulatory mechanisms to consumption behavior, it is possible to disseminate knowledge of how carbon-intensive food can deteriorate our environment and our existence. Some incentive mechanisms for the consumption of low-carbon intensive food can also be applied.

Reduce Emissions from Overall Food System

Existing food systems are accountable for one-third of global anthropogenic GHG emissions, so it is crucial to modify these food systems to reduce emissions (Clark et al. 2020). In 2015, food-system emissions were estimated to be 18 Gt CO_2eq globally (i.e., 34% of global GHG emissions) of total emissions, 71% was from agriculture and land-use change, and the remaining 29% was from supply chain activities (Crippa et al. 2021). Household consumption patterns and level of economic progress will largely determine the GHG emissions from the future food system. Therefore, lifestyle changes, including changes in food habits, are crucial to complement low-emissions development (Bjelle et al. 2021).

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[6] https://www.fao.org/3/cb1329en/online/cb1329en.html#chapter-4

6.3.3 Cross-cutting Issues

Agricultural Subsidies

The agriculture sector annually receives around $600 billion in government support worldwide (Laborde et al. 2021). Although agricultural subsidies can have heterogeneous effects on agricultural emissions (Guo et al. 2021), they can also incentivize high-emissions farming systems. Beef, dairy, and rice are three major agricultural products that account for over 80% of agricultural GHG emissions. In many Asian countries, the production of these emissions-intensive commodities is supported by subsidies and other government supports (Badiani, Jessoe, and Plant 2012; Aryal et al. 2015). For instance, the fertilizer subsidy policy has led to unbalanced fertilizer use in India, thereby increasing N_2O emissions from agriculture (Some, Roy, and Ghose 2019; Aryal et al. 2021a). Hence, reducing GHG emissions from agriculture requires careful management of subsidies and taxes on agricultural inputs (Luo et al. 2017).

Better Spatial Targeting and Informed Policy

Improved spatial targeting is essential to achieve GHG mitigation in agriculture. In mitigating soil N_2O emissions, accurate assessments of crop-specific mitigation potentials are crucial. Using modern technology such as geo-referenced field observations helps estimate precise emissions factors and design better management practices (Cui et al. 2021). About 30% of direct soil emissions of N_2O can be mitigated without compromising food production; however, almost 65% of this potential could be achieved in only 20% of the global harvested land area, which thus requires a spatially targeted policy for GHG mitigation (Cui et al. 2021, 2014; Tian et al. 2020).

Equitable Access to Improved Technology

Gender, caste, and class play important roles in defining the adoption of improved technologies that are crucial to GHG mitigation in agriculture (Paudyal et al. 2019; Aryal et al. 2020a, 2021b; Bryan, Kato, and Bernier 2021). Regional disparity in clean technology has also been raised as a critical issue at the 26th United Nations Climate Conference of the Parties in Glasgow (COP26). Transferring innovative technologies across countries to enhance the efficient use of agricultural resources, while acknowledging the need for policies that benefit both climate and social-environmental factors, can contribute largely to GHG mitigation initiatives in agriculture (Smith et al. 2007b, 2013; Gołasa et al. 2021).

6.4 Current Policies and Implications for Low-Emissions Agricultural Development

Most countries have now acknowledged the critical role of the agriculture sector in mitigating GHG emissions and in achieving the target of keeping the global temperature rise below 2°C, as well as in attaining several SDGs. This has increased the scope for low-emissions agriculture in the Asia and Pacific region. In their nationally determined contributions submitted to the United Nations Framework Convention on Climate Change (UNFCCC), many countries have mentioned the agricultural mitigation potential. This has been reflected in national climate policies also. There has been a massive transformation in the consideration of the AFOLU sector in international climate change negotiations and priorities. At COP11 in 2005, the UNFCCC agreed to initiate a program to explore a variety of policy approaches for reducing emissions from deforestation and degradation (REDD), which was further strengthened in COP13 by considering REDD as an option to GHG mitigation in developing countries (Corbera, Estrada, and Brown 2010). Although the Bali Action Plan adopted at UNFCCC COP13 in 2007 acknowledged low-emissions development strategies through the concept of nationally appropriate mitigation actions (NAMAs), it did not mention agriculture specifically, and the NAMAs were discussed more as strategies to attain sustainable development (Wilkes, Tennigkeit, and Solymosi 2013). Issues related to GHG mitigation in agriculture were considered as an agenda for climate action only in COP17 in Durban. The UNFCCC's Subsidiary Body for Scientific and Technological Advice included agriculture as an important sector for GHG mitigation in COP17, which was further defined in COP21 in Paris, and then in COP23 in Bonn (Aryal et al. 2020b). Finally, COP23 proved to be a milestone in prioritizing agriculture in climate action. It managed to establish the Koronivia Joint Work on Agriculture to design new strategies or address global climate change adaptation and mitigation actions in the agriculture sector (UNFCCC 2017).

Over the years, many countries in Asia have included GHG mitigation in agriculture in their climate plans, and some have developed NAMAs that explicitly mention GHG mitigation measures in agriculture sectors (Wilkes, Tennigkeit, and Solymosi 2013). For example, Cambodia included mitigation from the agriculture sector in its National Green Growth Roadmap of 2009; the PRC and the Republic of Korea followed with the National Climate Change Program (2007–2010) and National Strategies for Green Growth (2009), respectively. The Thai Rice NAMA is one of the major initiatives to reduce GHG emissions from rice production in Thailand.[7] As rice farming in Thailand accounts for almost 60% of its total emissions from agriculture (i.e., the fourth largest emitter of rice-related GHG emissions globally), a shift from conventional to low-emissions rice farming could substantially reduce GHG emissions from rice in Thailand. The introduction of climate-smart rice farming in Viet Nam,[8] soil health card schemes for crop nutrient management in India,[9] and zero increases in chemical fertilizer use in 2020 in the PRC (Ji, Liu, and Shi 2020) are some of the crucial steps taken by Asian nations toward GHG mitigation in the agriculture sector. In 2015, the PRC introduced an action plan proposing the goal of zero growth in fertilizer use. To facilitate this goal, the PRC set up a scientific fertilizer management technology system that improves fertilizer use efficiency; this program has been successful, and chemical fertilizer use in the PRC declined from 60.226 million tons in 2015 to 58.59 million tons in 2017 (Ji, Liu, and Shi 2020).

Government policies alone cannot solve the problem as expected. A glaring example of the policy–practice gap is observed in the case of crop residue burning in India (Kaushal 2020). Although crop residue burning is a crime under Section 188 of the Indian Penal Code and the Air and Pollution Control Act of 1981, a lack of effective implementation is apparent across the country (Porichha et al. 2021), which indicates a need to explore cost-effective alternatives to burning to manage crop residues.

National policies targeting GHG mitigation can have a differential impact across economic sectors. For instance, the potential impact of the GHG mitigation policies under the nationally determined contributions in Indonesia is estimated to reduce GDP by 1.7% by 2030 compared to the business-as-usual (BAU) scenario. Furthermore, there are likely to be large negative impacts on agricultural GDP in Indonesia (by about 13.4% compared to BAU) due to GHG mitigation policies, while the share of the energy sector in GDP is more likely to have positive impacts (+3.5% compared to BAU) (Malahayati and Masui 2021). Although agriculture has the highest potential to follow a path of low-emissions development, there are multiple barriers to implementing these strategies (Norse 2012; Ghosh et al. 2020; Li et al. 2021).

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[7] https://www.nama-facility.org/projects/thailand-thai-rice-nama/

[8] https://www.cgiar.org/annual-report/performance-report-2020/low-emission-technologies-transform-vietnams-rice-sector/

[9] Soli Health Card. https://www.soilhealth.dac.gov.in/

6.5 Conclusion and Way Forward

The agriculture sector in the Asia and Pacific region emits a large amount of GHGs. Rice production, use of nitrogen fertilizer, use of energy for agricultural production, and livestock production are the four major supply-side sources of GHGs emissions from agriculture. Several agronomic measures and improved technologies and practices are found to have a high potential to make agriculture less carbon intensive on the supply side. On the demand side, rising demand for livestock products and increasing FLW are key issues for increasing GHG emissions from the agriculture sector. Thus, GHG mitigation in agriculture needs an assessment agricultural production and agricultural value chains and consumption patterns. Although there is huge potential to reduce GHG emissions from agriculture, there are crucial challenges to monitoring and verifying emissions from supply-side measures. Similarly, on the consumption side, though it has very high potential to avoid GHG emissions, its effectiveness is more constrained by regulatory mechanisms on human consumption behavior. Overall, the transformation of agriculture to a low-emissions pathway requires the integration of policies at multiple levels to enhance the adoption of better agricultural technologies and practices, to encourage consumption of less carbon-intensive food, and to reduce FLW.

Achieving low-emissions agriculture requires policy change in multiple directions. On the supply side, agricultural policies should focus on upscaling climate-smart agriculture, primarily through expanding knowledge and improving input use efficiency in agriculture, such as through more incentives to use site-specific nutrient management can reduce fertilizer use without compromising crop yield. On the demand side, dissemination of knowledge on sustainable consumption and the use of both regulatory and incentive mechanisms are essential. Increasing people’s knowledge and awareness of the adverse impacts of their consumption behavior on the natural environment may help reduce such behavior. Therefore, governments need to mobilize multiple organizations and civil society to transform human behavior to food consumption and to reduce FLW along the value chains.

References

Aboagye, I. A., M. Oba, A. R. Castillo, K. M. Koenig, A. D. Iwaasa, and K. A. Beauchemin. 2018. Effects of Hydrolyzable Tannin with or Without Condensed Tannin on Methane Emissions, Nitrogen Use, and Performance of Beef Cattle Fed a High-forage Diet. *Journal of Animal Science* 96: 5276–5286. https://doi.org/10.1093/jas/sky352

Aryal, J. P., C. R. Farnworth, R. Khurana, S. Ray, T. B. Sapkota, and D. B. Rahut. 2020a. Does Women's Participation in agricultural Technology Adoption Decisions Affect the Adoption of Climate-Smart Agriculture? Insights from Indo-Gangetic Plains of India. *Review of Development Economics* 24: 973–990. https://doi.org/10.1111/rode.12670

Aryal, J. P., M. Mehrotra, M. Jat, and H. Sidhu. 2015. Impacts of Laser Land Leveling in Rice-Wheat Rotations of the North-western Indo-Gangetic Plains of India. *Food Security* 7: 725–738. https://doi.org/10.1007/s12571-015-0460-y

Aryal, J. P., D. B. Rahut, T. B. Sapkota, R. Khurana, and A. Khatri-Chhetri. 2020b. Climate Change Mitigation Options Among Farmers in South Asia. *Environment, Development and Sustainability* 22: 3267–3289. https://doi.org/10.1007/s10668-019-00345-0

Aryal, J. P., T. B. Sapkota, M. L. Jat, and D. K. Bishnoi. 2015. On-farm Economic and Environmental Impact of Zero-Tillage Wheat: A Case of North-West India. *Experimental Agriculture* 51: 1–16. https://doi.org/10.1017/S001447971400012X

Aryal, J. P., T. B. Sapkota, T. Krupnik, D. B. Rahut, M. L. Jat, and C. Stirling.2021a. Factors Affecting Farmers' Use of Inorganic Fertilizers and Manure in South Asia. Preprint. https://doi.org/10.21203/rs.3.rs-206349/v1

Aryal, J. P., T. B. Sapkota, D. B. Rahut, P. Marenya, and C. M. Stirling. 2021b. Climate Risks and Adaptation Strategies of Farmers in East Africa and South Asia. *Scientific Reports* 11: 10489. https://doi.org/10.1038/s41598-021-89391-1

Badiani, R., K. K. Jessoe, and S. Plant. 2012. Development and the Environment. *Journal of Environment and Development* 21: 244–262.

Bai, Z. et al. 2021. China's Livestock Transition: Driving Forces, Impacts, and Consequences. *Science Advances* 4: eaar8534. https://doi.org/10.1126/sciadv.aar8534

Bajracharya, S. B., A. Mishra, and A. Maharjan. 2021. Determinants of Crop Residue Burning Practice in the Terai Region of Nepal. *PLoS One* 16: e0253939

Benbi, D. K. 2018. Carbon Footprint and Agricultural Sustainability Nexus in an intensively Cultivated Region of Indo-Gangetic

Plains. *Science of the Total Environment* 644: 611–623. https://doi.org/10.1016/j.scitotenv.2018.07.018

Bijl, D. L., P. W. Bogaart, S. C. Dekker, E. Stehfest, B. J. M. de Vries, and D. P. van Vuuren. 2017. A Physically-Based Model of Long-Term Food Demand. *Global Environmental Change* 45: 47–62. https://doi.org/10.1016/j.gloenvcha.2017.04.003

Bjelle, E. L. et al. 2021. Future Changes in Consumption: The Income Effect on Greenhouse Gas Emissions. *Energy Economics* 95: 105114. https://doi.org/10.1016/j.eneco.2021.105114

Bodirsky, B. L., S. Rolinski, A. Biewald, I. Weindl, A. Popp, and H. Lotze-Campen. 2015. Global Food Demand Scenarios for the 21st Century. *PLoS One* 10: e0139201.

Bryan, E., E. Kato, and Q. Bernier. 2021. Gender Differences in Awareness and Adoption of Climate-Smart Agriculture Practices in Bangladesh. In J. Eastin and K. Dupuy, eds. *Gender, Climate Change and Livelihoods: Vulnerabilities and Adaptations*. Wallingford: CABI, pp. 123–142.

Chang, J. et al. 2019. Revisiting Enteric Methane Emissions from Domestic Ruminants and Their δ13CCH4 Source Signature. *Nature Communications* 10: 3420. https://doi.org/10.1038/s41467-019-11066-3

Chen, J., W. Cao, Y. Li, D. Cao, and F. Wang. 2015. Estimating Nitrous Oxide Emission Flux from Arable Lands in China Using Improved Background Emission and Fertilizer-Induced Emission Factors. *Atmospheric Pollution Research* 6: 343–350. https://doi.org/10.5094/APR.2015.038

Chen, Q., C. Long, J. Chen, and X. Cheng. 2021. Differential Response of Soil CO2, CH4, and N2O Emissions to Edaphic Properties and Microbial Attributes Following Afforestation in Central China. *Global Change Biology* 27: 5657–5669. https://doi.org/10.1111/gcb.15826

Chhabra, A., K. R. Manjunath, S. Panigrahy, and J. S. Parihar. 2013. Greenhouse Gas Emissions from Indian Livestock. *Climate Change* 117: 329–344. https://doi.org/10.1007/s10584-012-0556-8

Clark, M. A. et al. 2020. Global Food System Emissions Could Preclude Achieving the 1.5° and 2°C Climate Change Targets. *Science* 70(6517): 705–708. https://doi.org/10.1126/science.aba7357

Corbera, E., M. Estrada, and K. Brown. 2010. Reducing Greenhouse Gas Emissions from Deforestation and Forest Degradation in Developing Countries: Revisiting the Assumptions. *Climate Change* 100: 355–388. https://doi.org/10.1007/s10584-009-9773-1

Crippa, M., E. Solazzo, D. Guizzardi, F. Monforti-Ferrario, F. N. Tubiello, and A. Leip. 2021. Food Systems Are Responsible for a Third of

Global Anthropogenic GHG Emissions. *Nature Food* 2: 198–209. https://doi.org/10.1038/s43016-021-00225-9

Cui, X. et al. 2021. Global Mapping of Crop-Specific emission Factors Highlights Hotspots of Nitrous Oxide Mitigation. *Nature Food* 2: 886–893. https://doi.org/10.1038/s43016-021-00384-9

Cui, Z. L., L. Wu, Y. L. Ye, W. Q. Ma, X. P. Chen, and F. S. Zhang. 2014. Trade-offs Between High Yields and greenhouse Gas Emissions in Irrigation Wheat Cropland in China. *Biogeosciences* 11: 2287–2294. https://doi.org/10.5194/bg-11-2287-2014

Dhyani, S. K., A. Ram, R. Newaj, A. K. Handa, and I. Dev. 2020. Agroforestry for Carbon Sequestration in Tropical India. In P. K. Ghosh, S. K. Mahanta, D. Mandal, B. Mandal, and S. Ramakrishnan, eds. *Carbon Management in Tropical and Sub-Tropical Terrestrial Systems* Singapore: Springer, pp. 313–331. https://doi.org/10.1007/978-981-13-9628-1_19

Dickie, A., C. Streck, S. Roe, M. Zurek, F. Haupt, and A. Dolginow. 2014. Strategies for Mitigating Climate Change in Agriculture: Abridged Report. San Francisco, CA, US: Climate Focus and California Environmental Associates. www.agriculturalmitigation.org

Enahoro, D. et al. 2019. Supporting Sustainable Expansion of Livestock Production in South Asia and Sub-Saharan Africa: Scenario Analysis of Investment Options. *Global Food Security* 20: 114–121. https://doi.org/10.1016/j.gfs.2019.01.001

Enriquez, Y., S. Yadav, G. K. Evangelista, D. Villanueva, M. A. Burac, and V. Pede. 2021. Disentangling Challenges to Scaling Alternate Wetting and Drying Technology for Rice Cultivation: Distilling Lessons From 20 Years of Experience in the Philippines. *Frontiers in Sustainable Food Systems* 5: 194. https://doi.org/10.3389/fsufs.2021.675818

Foley, J. A. et al. 2011. Solutions for a Cultivated Planet. *Nature* 478: 337–342. https://doi.org/10.1038/nature10452

Food and Agriculture Organization of the United Nations (FAO). 2013. Tackling Climate Change Through Livestock a Global Assessment of Emissions and Mitigation Opportunities. Rome: FAO.

———. 2018. Save Food for a Better Climate: Converting the Food Loss and Waste Challenge into Climate Action. Rome: FAO.

———. 2020. Emissions Due to Agriculture. Global, Regional and Country Trends 2000–2018. FAOSTAT Analytical Brief Series No 18. Rome Cover, No.18. https://www.fao.org/3/cb3808en/cb3808en.pdf

Food and Agriculture Organization of the United Nations (FAO) and International Fertilizer Industry Association (IFA). 2001. *Global Estimates of Gaseous Emissions of* NH_3*, NO and* N_2O *from Agricultural Land*. Rome: FAO and IFA.

Forster, E. J., J. R. Healey, C. Dymond, and D. Styles. 2021. Commercial Afforestation Can Deliver Effective Climate Change Mitigation

Under Multiple Decarbonisation Pathways. *Nature Communications* 12: 3831. https://doi.org/10.1038/s41467-021-24084-x

Gerber, P., T. Vellinga, C. Opio, and H. Steinfeld. 2011. Productivity Gains and greenhouse Gas Emissions Intensity in Dairy Systems. *Livestock Science* 139: 100–108. https://doi.org/10.1016/j.livsci.2011.03.012

Gerber, P. J., and FAO. 2013. Tackling Climate Change Through Livestock: A Global Assessment of Emissions and Mitigation Opportunities. Rome: FAO.

Gerber, P. J. et al. 2013. Technical Options for the Mitigation of Direct Methane and Nitrous Oxide Emissions from Livestock: A Review. *Animal*7: 220–234. https://doi.org/DOI: 10.1017/S1751731113000876

Ghosh, A. et al. 2020. Agriculture, Dairy and Fishery farming Practices and Greenhouse Gas Emission Footprint: A Strategic Appraisal for Mitigation. *Environmental Science and Pollution Research* 27: 10160–10184. https://doi.org/10.1007/s11356-020-07949-4

Gill, G. J. 2014. An Assessment of the Impact of Laser-Assisted Precision Land Leveling Technology as a Component of Climate-Smart Agriculture in the State of Haryana, India. New Delhi: International Maize and Wheat Improvement Center.

Gołasa, P. et al. 2021. Sources of Greenhouse Gas Emissions in Agriculture, with Particular Emphasis on Emissions from Energy Used. *Energies* 14(13): 3784. https://doi.org/10.3390/en14133784

Grace, P. R., J. Antle, P. K. Aggarwal, S. Ogle, K. Paustian, and B. Basso. 2012. Soil Carbon Sequestration and Associated Economic Costs for Farming Systems of the Indo-Gangetic Plain: A Meta-analysis. *Agriculture, Ecosystems and Environment* 146: 137–146. http://dx.doi.org/10.1016/j.agee.2011.10.019

Grace, P. R., M. C. Jain, L. Harrington, and G. P. Robertson. J. Antle. 2003. Long-Term Sustainability of the Tropical and Subtropical Rice-Wheat System: An Environmental Perspective. In J. K. Ladha, J. Hill, R. K. Gupta, J. Duxbury, and R.J. Buresh, eds. *Improving the Productivity and Sustainability of Rice-Wheat Systems: Issues and Impact*. Madison: ASA Special Publications 65, pp. 1–18. https://doi.org/10.2134/asaspecpub65.c2

van Groenigen, K. J., C. van Kessel, and B. A. Hungate.2013. Increased Greenhouse-Gas Intensity of Rice Production Under Future Atmospheric Conditions. *Nature Climate Change* 3: 288–291. https://doi.org/10.1038/nclimate1712

Guo, L., H. Li, X. Cao, A. Cao, and M. Huang. 2021. Effect of Agricultural Subsidies on the Use of Chemical Fertilizer. *Journal of Environmental Management* 299: 113621. https://doi.org/10.1016/j.jenvman.2021.113621

Guo, X., J. Broeze, J. J. Groot, H. Axmann, and M. Vollebreg. 2020. A Worldwide Hotspot Analysis on Food Loss and Waste, Associated

Greenhouse Gas Emissions, and Protein Losses. *Sustainability* 12(18): 7488. https://doi.org/10.3390/su12187488

Gupta, P. K. et al. 2007. Methane and Nitrous Oxide Emission from Bovine Manure Management Practices in India. *Environmental Pollution* 146: 219–224. https://doi.org/10.1016/j.envpol.2006.04.039

Habib, G. and A. A. Khan. 2018. Assessment and Mitigation of Methane Emissions from Livestock Sector in Pakistan. *Earth Systems and Environment* 2: 601–608. https://doi.org/10.1007/s41748-018-0076-4

Harris, N. L. et al. 2012. Baseline Map of Carbon Emissions from Deforestation in Tropical Regions. *Science* 336: 1573–1576. https://doi.org/10.1126/science.1217962

Hasegawa, T. and Y. Matsuoka. 2015. Climate Change Mitigation Strategies in Agriculture and Land Use in Indonesia. *Mitigation and Adaptation Strategies for Global Change* 20: 409–424. https://doi.org/10.1007/s11027-013-9498-3

Herrero, M. et al. 2013. Biomass Use, Production, Feed Efficiencies, and Greenhouse Gas Emissions from Global Livestock Systems. *Proceedings of the National Academy of Sciences* 110: 20888–20893. https://doi.org/10.1073/pnas.1308149110

Huang, X., X. Xu, Q. Wang, L. Zhang, X. Gao, and L. Chen. 2019. Assessment of Agricultural Carbon Emissions and Their Spatiotemporal Changes in China, 1997–2016. I*nternational Journal of Environmental Research and Public Health* 16: 3105. https://doi.org/10.3390/ijerph16173105

Huppmann, D., J. Rogelj, E. Kriegler, V. Krey, and K. Riahi. 2018. A New Scenario Resource for Integrated 1.5°C Research. *Nature Climate Change* 8: 1027–1030. https://doi.org/10.1038/s41558-018-0317-4

Intergovernmental Panel on Climate Change (IPCC). 2007. *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

———. 2014. *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

———. 2018. Global Warming of 1.5°C. *An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Policy*. Cambridge: Cambridge University Press.

Islam, S. F., B. O. Sander, J. R. Quilty, A. de Neergaard, J. W. van Groenigen, and L.S. Jensen. 2020. Mitigation of Greenhouse Gas Emissions and Reduced Irrigation Water Use in Rice Production Through Water-Saving Irrigation Scheduling, Reduced Tillage and Fertiliser Application Strategies. *Science of the Total Environment* 739: 140215. https://doi.org/10.1016/j.scitotenv.2020.140215

Jat, H. S., A. Datta, M. Choudhary, P.C. Sharma, and M.L. Jat. 2021. Conservation Agriculture: Factors and Drivers of Adoption and Scalable Innovative Practices in Indo-Gangetic Plains of India–a review. *International Journal of Agricultural Sustainability* 19: 40–55. https://doi.org/10.1080/14735903.2020.1817655

Ji, Y., H. Liu, and Y. Shi. 2020. Will China's Fertilizer Use Continue to Decline? Evidence from LMDI Analysis Based on Crops, Regions and Fertilizer Types. *PLoS One* 15: e0237234.

Kahrl, F., Y. Li, Y. Su, T. Tennigkeit, A. Wilkes, and J. Xu. 2010. Greenhouse Gas Emissions from Nitrogen Fertilizer Use in China. *Environmental Science and Policy* 13: 688–694. https://doi.org/10.1016/j.envsci.2010.07.006

Kaushal, L. A. 2020. Examining the Policy-Practice Gap- The Issue of Crop Burning Induced Particulate Matter Pollution in Northwest India. *Ecosystem Health and Sustainability* 6: 1846460. https://doi.org/10.1080/20964129.2020.1846460

Kim, G.-Y., H.-C. Jeong, Y.-K. Sonn, S. Y. Kim, J.-S. Lee, and P. J. Kim. 2014. Effect of Soil Water Potential on Methane and Nitrous Oxide Emissions in Upland Soil During Red Pepper Cultivation. *Journal of the Korean Society for Applied Biological Chemistry* 57: 15–22. https://doi.org/10.1007/s13765-013-4228-9

Kiran Kumara, T. M., A. Kandpal, and S. Pal. 2020. A Meta-analysis of Economic and Environmental Benefits of Conservation Agriculture in South Asia. *Journal of Environmental Management* 269: 110773. https://doi.org/10.1016/j.jenvman.2020.110773

Knapp, J. R., G. L. Laur, P. A. Vadas, W. P. Weiss, and J. N. Tricarico. 2014. Invited Review: Enteric Methane in Dairy Cattle Production: Quantifying the Opportunities and Impact of Reducing Emissions. *Journal of Dairy Science* 97: 3231–3261. https://doi.org/10.3168/jds.2013-7234

Kritee, K. et al. 2018. High Nitrous Oxide Fluxes from Rice Indicate the Need to Manage Water for both Long- and Short-Term Climate Impacts. *Proceedings of the National Academy of Sciences* 115: 9720–9725. https://doi.org/10.1073/pnas.1809276115

Kumar, B. M., and T. K. Kunhamu. 2021. Carbon Sequestration Potential of Agroforestry Systems in India: A Synthesis. In R. P. Udawatta and

S. Jose, eds. *Agroforestry and Ecosystem Services*. Cham: Springer, pp. 389–430. https://doi.org/10.1007/978-3-030-80060-4_15

Laborde, D., A. Mamun, W. Martin, V. Piñeiro, and R. Vos. 2021. Agricultural Subsidies and Global Greenhouse Gas Emissions. *Nature Communications* 12: 2601. https://doi.org/10.1038/s41467-021-22703-1

LaHue, G. T., R. L. Chaney, M. A. Adviento-Borbe, and B. A. Linquist. 2016. Alternate Wetting and Drying in High Yielding Direct-Seeded Rice Systems Accomplishes Multiple Environmental and Agronomic Objectives. *Agriculture, Ecosystems and Environment* 229: 30–39. https://doi.org/10.1016/j.agee.2016.05.020

Lal, R. 1997. Residue Management, Conservation Tillage and Soil Restoration for Mitigating Greenhouse Effect by CO2-enrichment. *Soil Tillage Research* 43: 81–107. https://doi.org/http://dx.doi.org/10.1016/S0167-1987(97)00036-6

Lassaletta, L., G. Billen, B. Grizzetti, J. Anglade, and J. Garnier. 2014. 50 Year Trends in Nitrogen Use Efficiency of World Cropping Systems: The Relationship Between Yield and Nitrogen Input to Cropland. *Environmental Research Letters* 9: 105011. https://doi.org/10.1088/1748-9326/9/10/105011

Lenka, S., N. K. Lenka, A. B. Singh, B. Singh, and J. Raghuwanshi. 2017. Global Warming Potential and Greenhouse Gas Emission Under Different Soil Nutrient Management Practices in Soybean–Wheat System of Central India. *Environmental Science and Pollution Research* 24: 4603–4612. https://doi.org/10.1007/s11356-016-8189-5

Li, W., J. Ruiz-Menjivar, L. Zhang, and J. Zhang. 2021. Climate Change Perceptions and the Adoption of low-Carbon Agricultural Technologies: Evidence from Rice Production Systems in the Yangtze River Basin. *Science of the Total Environment* 759: 143554. https://doi.org/10.1016/j.scitotenv.2020.143554

Liang, D. et al. 2021. China's Greenhouse Gas Emissions for Cropping Systems from 1978–2016. *Scientific Data* 8: 171. https://doi.org/10.1038/s41597-021-00960-5

Lohan, S. K. et al. 2018. Burning Issues of Paddy Residue Management in North-West States of India. R*enewable and Sustainable Energy Reviews* 81: 693–706. https://doi.org/10.1016/j.rser.2017.08.057

Lu, C. and H. Tian. 2017. Global Nitrogen and Phosphorus Fertilizer Use for Agriculture Production in the Past Half Century: Shifted Hot Spots and Nutrient Imbalance. *Earth System Science Data* 9:181–192. https://doi.org/10.5194/essd-9-181-2017

Luo, Y., X. Long, C. Wu, and J. Zhang. 2017. Decoupling CO_2 Emissions from Economic Growth in Agricultural Sector Across 30 Chinese Provinces from 1997 to 2014. *Journal of Cleaner Production* 159: 220–228. https://doi.org/10.1016/j.jclepro.2017.05.076

Malahayati, M. and T. Masui. 2021. Potential Impact of Introducing Emission Mitigation Policies in Indonesia: How Much Will Indonesia Have to Spend? *Mitigation and Adaptation Strategies for Global Change* 26: 37. https://doi.org/10.1007/s11027-021-09973-2

Malla, G., A. Bhatia, H. Pathak, S. Prasad, N. Jain, and J. Singh. 2005. Mitigating Nitrous Oxide and Methane Emissions from Soil in Rice–Wheat System of the Indo-Gangetic Plain with Nitrification and Urease Inhibitors. *Chemosphere* 58: 141–147. http://dx.doi.org/10.1016/j.chemosphere.2004.09.003

Mayer, S. et al. 2022. Soil Organic Carbon Sequestration in Temperate Agroforestry Systems – A Meta-analysis. *Agriculture, Ecosystems and Environment* 323: 107689. https://doi.org/10.1016/j.agee.2021.107689

Mehmood, F. et al. 2021. Impacts of Irrigation Managements on Soil CO_2 Emission and Soil CH4 Uptake of Winter Wheat Field in the North China Plain. *Water* 13(15): 2052. https://doi.org/10.3390/w13152052

Miettinen, J., C. Shi, and S. C. Liew. 2011. Deforestation Rates in Insular Southeast Asia Between 2000 and 2010. *Global Change Biology* 17: 2261–2270. https://doi.org/10.1111/j.1365-2486.2011.02398.x

Mottet, A. et al. 2017. Climate Change Mitigation and Productivity Gains in Livestock Supply Chains: Insights from Regional Case Studies. *Regional Environmental Change* 17: 129–141. https://doi.org/10.1007/s10113-016-0986-3

Nguyen, V. C. et al. 2022. Precision Land Leveling for Sustainable Rice Production: Case Studies in Cambodia, Thailand, Philippines, Vietnam, and India. *Precision Agriculture* 23: 1633–1652. https://doi.org/10.1007/s11119-022-09900-8

Norse, D. 2012. Low Carbon Agriculture: Objectives and Policy Pathways. *Environmental Development* 1:25–39. https://doi.org/10.1016/j.envdev.2011.12.004

Nugrahaeningtyas, E., C.-Y. Baek, J.-H. Jeon, H.-J. Jo, and K.-H. Park. 2018. Greenhouse Gas Emission Intensities for the Livestock Sector in Indonesia, Based on the National Specific Data. *Sustainability* 10(6): 1912. https://doi.org/10.3390/su10061912

O'Mara, F. P. 2011. The Significance of Livestock as a Contributor to Global Greenhouse Gas Emissions Today and in the Near Future. *Animal Feed Science and Technology* 166–167: 7–15. https://doi.org/10.1016/j.anifeedsci.2011.04.074

Ouatahar, L., A. Bannink, G. Lanigan, and B. Amon. 2021. Modelling the Effect of Feeding Management on Greenhouse Gas and Nitrogen Emissions in Cattle Farming Systems. *Science of the Total Environment* 776: 145932. https://doi.org/10.1016/j.scitotenv.2021.145932

Page, K. L., Y. P. Dang, and R. C. Dalal. 2020. The Ability of Conservation Agriculture to Conserve Soil Organic Carbon and the Subsequent

Impact on Soil Physical, Chemical, and Biological Properties and Yield. *Frontiers in Sustainable Food Systems* 4: 31. https://doi.org/10.3389/fsufs.2020.00031

Papademetriou, M. K. 2000. Rice Production in the Asia-Pacific Region: Issues and Perspectives. In M. K. Papademetriou, K. Minas, F. J. Dent, and E. M. Herath eds. *Bridging the Rice Yield Gap in the Asia-Pacific Region*. Bangkok: Food and Agriculture Organization of the United Nations, Regional Office for Asia and the Pacific.

Patra, A. K. 2017. Accounting Methane and Nitrous Oxide Emissions, and Carbon Footprints of Livestock Food Products in Different States of India. *Journal of Cleaner Production* 162: 678–686. https://doi.org/10.1016/j.jclepro.2017.06.096

Paudyal, B. R., N. Chanana, A. Khatri-Chhetri, L. Sherpa, I. Kadariya, and P. Aggarwal. 2019. Gender Integration in Climate Change and Agricultural Policies: The Case of Nepal. *Frontiers in Sustainable Food Systems* 3: 66. https://doi.org/10.3389/fsufs.2019.00066

Petersen, S.O. et al. 2013. Manure Management for Greenhouse Gas Mitigation. *Animal* 7: 266–282. https://doi.org/10.1017/S1751731113000736

Porichha, G. K., Y. Hu, K. T. Rao, and C. C. Xu. 2021. Crop Residue Management in India: Stubble Burning vs. Other Utilizations including Bioenergy. *Energies* 14(14): 4281. https://doi.org/10.3390/en14144281

Powlson, D. S. et al. 2014. Limited Potential of No-till Agriculture for Climate Change Mitigation. N*ature Climate Change* 4: 678–683. https://doi.org/10.1038/NCLIMATE2292

Powlson, D. S., C. M. Stirling, C. Thierfelder, R. P. White, and M. L. Jat. 2016. Does Conservation Agriculture Deliver Climate Change Mitigation Through Soil Carbon Sequestration in Tropical Agro-Ecosystems? *Agriculture, Ecosystems and Environment* 220: 164–174. https://doi.org/10.1016/j.agee.2016.01.005

Pradhan, B. B., A. Chaichaloempreecha, and B. Limmeechokchai. 2019. GHG Mitigation in Agriculture, Forestry and Other Land Use (AFOLU) sector in Thailand. *Carbon Balance and Management* 14: 3. https://doi.org/10.1186/s13021-019-0119-7

Pradhan, B. B., R. M. Shrestha, N. T. Hoa, and Y. Matsuoka. 2017. Carbon Prices and Greenhouse Gases Abatement from agriculture, Forestry and Land Use in Nepal. *Global Environmental Change* 43: 26–36. https://doi.org/10.1016/j.gloenvcha.2017.01.005

Richards, M., and B. O. Sander. 2014. Alternate Wetting and Drying in Irrigated Rice: Implementation Guidance for Policymakers and Investors. Practice Brief on Climate-Smart Agriculture. Copenhagen: CGIAR Research Program on Climate Change, Agriculture and Food Security.

Rojas-Downing, M. M., A. P. Nejadhashemi, T. Harrigan, and S. A. Woznicki. 2017. Climate Change and livestock: Impacts, Adaptation, and Mitigation. *Climate Risk Management* 16:145–163. https://doi.org/10.1016/j.crm.2017.02.001

Roque, B. M., J. K. Salwen, R. Kinley, and E. Kebreab. 2019. Inclusion of Asparagopsis Armata in Lactating Dairy Cows' Diet Reduces Enteric Methane Emission by Over 50 Percent. J*ournal of Cleaner Production* 234: 132–138. https://doi.org/10.1016/j.jclepro.2019.06.193

Sapkota, A., A. Haghverdi, C. C. E. Avila, and S. C. Ying. 2020. Irrigation and Greenhouse Gas Emissions: A Review of Field-Based Studies. *Soil Systems* 4(2): 20. https://doi.org/10.3390/soilsystems4020020

Sapkota, T. B. et al. 2018. Identifying high-Yield Low-Emission Pathways for the Cereal Production in South Asia. *Mitigation and Adaptation Strategies for Global Change* 23: 621–641. https://doi.org/10.1007/s11027-017-9752-1

Sapkota, T. B. et al. 2021. Crop Nutrient Management Using Nutrient Expert Improves Yield, Increases Farmers' Income and Reduces Greenhouse Gas Emissions. *Scientific Reports* 11: 1564. https://doi.org/10.1038/s41598-020-79883-x

Sathaye, J. A. et al. 2001. Carbon Mitigation Potential and Costs of Forestry Options in Brazil, China, India, Indonesia, Mexico, the Philippines and Tanzania. *Mitigation and Adaptation Strategies for Global Change* 6(3): 185–211. https://doi.org/10.1023/A:1013398002336

Shen, Y., C. Jiang, K. L. Chan, C. Hu, and L. Yao. 2021. Estimation of Field-Level NOx Emissions from Crop Residue Burning Using Remote Sensing Data: A Case Study in Hubei, China. *Remote Sensing* 13(3): 404. https://doi.org/10.3390/rs13030404

Shi, S., P. Han, P. Zhang, F. Ding, and C. Ma. 2015. The Impact of Afforestation on Soil Organic Carbon Sequestration on the Qinghai Plateau, China. *PLoS One* 10: e0116591.

Si, R., N. Aziz, and A. Raza. 2021. Short and Long-Run Causal Effects of Agriculture, Forestry, and Other land Use on Greenhouse Gas Emissions: Evidence from China using VECM Approach. *Environmental Science and Pollution Research* 28: 64419–64430. https://doi.org/10.1007/s11356-021-15474-1

Sibayan, E. B. et al. 2018. Effects of Alternate Wetting and Drying Technique on Greenhouse Gas Emissions from Irrigated Rice Paddy in Central Luzon, Philippines. *Journal of Soil Science and Plant Nutrition* 64: 39–46. https://doi.org/10.1080/00380768.2017.1401906

Singh, R., and M. Lal. 2000. Sustainable Forestry in India for Carbon Mitigation. *Current Science* 78: 563–567.

Sirohi, S., and A. Michaelowa. 2007. Sufferer and Cause: Indian Livestock and Climate Change. *Climate Change* 85: 285–298. https://doi.org/10.1007/s10584-007-9241-8

Smith, P. et al. 2013. How Much Land-based Greenhouse Gas Mitigation can be Achieved without Compromising Food Security and Environmental Goals? *Global Change Biology* 19: 2285–2302. https://doi.org/10.1111/gcb.12160

Smith, P. et al. 2007a. Agriculture. In *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by B. Metz, O. R. Davidson, P. R. Bosch, R. Dave, and L. A. Meyer. Cambridge: Cambridge University Press, pp. 499–541.

———. 2007b. Policy and Technological Constraints to Implementation of Greenhouse Gas Mitigation Options in Agriculture. *Agriculture, Ecosystems and Environment* 118: 6–28. https://doi.org/http://dx.doi.org/10.1016/j.agee.2006.06.006

———. 2008. Greenhouse Gas Mitigation in Agriculture. *Philosophical Transactions of the Royal Society B* 363: 789–813. https://doi.org/10.1098/rstb.2007.2184

Some, S., J. Roy, and A. Ghose 2019. Non-CO2 Emission from Cropland Based Agricultural Activities in India: A Decomposition Analysis and Policy Link. *Journal of Cleaner Production* 225: 637–646. https://doi.org/10.1016/j.jclepro.2019.04.017

Song, X. et al. 2018. Nitrous Oxide Emissions Increase Exponentially When Optimum Nitrogen Fertilizer Rates Are Exceeded in the North China Plain. *Environmental Science and Technology* 52: 12504–12513. https://doi.org/10.1021/acs.est.8b03931

Streets, D. G., K. F. Yarber, J.-H. Woo, and G. R. Carmichael. 2003. Biomass Burning in Asia: Annual and seasonal Estimates and Atmospheric Emissions. *Global Biogeochemical Cycles* 17: 1099. https://doi.org/10.1029/2003GB002040

Sun, W. et al. 2020. Climate Drives Global Soil Carbon Sequestration and Crop Yield Changes Under Conservation Agriculture. *Global Change Biology* 26: 3325–3335. https://doi.org/10.1111/gcb.15001

Sutton, M. A., J. W. Erisman, and O. Oenema. 2007. Strategies for Controlling Nitrogen Emissions from Agriculture: Regulatory, Voluntary and Economic Approaches. Paper presented at IFA International Workshop on Fertilizer Best Management Practices, Brussels, Belgium, 7–9 March.

Thornton, P., and P. Gerber. 2010. Climate Change and the Growth of the Livestock Sector in Developing Countries. *Mitigation and Adaptation Strategies for Global Change* 15: 169–184. https://doi.org/10.1007/s11027-009-9210-9

Thornton, P. K., and M. Herrero. 2010. Potential for Reduced Methane and Carbon Dioxide Emissions from Livestock and Pasture Management in the Tropics. *Proceedings of the National Academy of Sciences* 107: 19667–19672. https://doi.org/10.1073/pnas.0912890107

Tian, H. et al. 2020. A Comprehensive Quantification of global Nitrous Oxide Sources and Sinks. *Nature* 586: 248–256. https://doi.org/10.1038/s41586-020-2780-0

Tullo, E., A. Finzi, and M. Guarino. 2019. Review: Environmental Impact of Livestock Farming and Precision Livestock Farming as a Mitigation Strategy. *Science of the Total Environment* 650: 2751–2760. https://doi.org/10.1016/j.scitotenv.2018.10.018

United Nations Environment Programme (UNEP). 2021a. Food Waste Index Report 2021. Nairobi: UNEP.

———. 2021b. Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions. Nairobi: UNEP.

United Nations Framework Convention on Climate Change (UNFCCC). 2017. Land Use and Climate Change. http://unfccc.int/land_use_and_climate_change/items/8792.php (accessed 9 April 2018).

United States Agency for International Development (USAID). 2017. Assessment of Business Models for Low Emission Land-Use Management in Asia. Bangkok: USAID/RDMA Regional Environmental Office.

Uwizeye, A. et al. 2020. Nitrogen Emissions Along Global Livestock Supply Chains. *Nature Food* 1: 437–446. https://doi.org/10.1038/s43016-020-0113-y

Venkatramanan, V., S. Shah, A. K. Rai, and R. Prasad. 2021. Nexus Between Crop Residue Burning, Bioeconomy and Sustainable Development Goals Over North-Western India. *Frontiers in Energy Research* 8: 392. https://doi.org/10.3389/fenrg.2020.614212

Wang, J. et al. 2012. China's Water–Energy Nexus: Greenhouse-Gas Emissions from Groundwater Use for Agriculture. *Environmental Research Letters* 7: 14035. https://doi.org/10.1088/1748-9326/7/1/014035

Wang, Y. et al. 2020. Agronomic and Environmental Benefits of Nutrient Expert on Maize and Rice in Northeast China. *Environmental Science and Pollution Research* 27: 28053–28065. https://doi.org/10.1007/s11356-020-09153-w

Wassmann, R., Y. Hosen, and K. Sumfleth. 2009. Reducing methane Emissions from Irrigated Rice. 16(3). Washington, DC: International Food Policy Research Institute.

Wilkes, A., T. Tennigkeit, and K. Solymosi. 2013. National Integrated Mitigation Planning in Agriculture: A Review Paper. Rome: FAO.

Wu, J. et al. 2020. The Moving of High Emission for Biomass Burning in China: View from Multi-year Emission Estimation and Human-Driven Forces. *Environment International* 142:105812. https://doi.org/10.1016/j.envint.2020.105812

Xue, L. et al. 2021. China's Food Loss and Waste Embodies Increasing Environmental Impacts. *Nature Food* 2: 519–528. https://doi.org/10.1038/s43016-021-00317-6

Yue, Q., X. Xu, J. Hillier, K. Cheng, and G. Pan. 2017. Mitigating Greenhouse Gas Emissions in Agriculture: From Farm Production to Food Consumption. *Journal of Cleaner Production* 149: 1011–1019. https://doi.org/10.1016/j.jclepro.2017.02.172

Zeng, Y. et al. 2020. Economic and Social Constraints on Reforestation for Climate Mitigation in Southeast Asia. *Nature Climate Change* 10: 842–844. https://doi.org/10.1038/s41558-020-0856-3

Zhang, G. et al. 2020. Fingerprint of Rice Paddies in Spatial–Temporal Dynamics of Atmospheric Methane Concentration in Monsoon Asia. *Nature Communications* 11: 554. https://doi.org/10.1038/s41467-019-14155-5

Zhang, H.-L., R. Lal, X. Zhao, J.-F. Xue, and F. Chen. 2014. Chapter One – Opportunities and Challenges of Soil Carbon Sequestration by Conservation Agriculture in China. *Advances in Agronomy* 124: 1–36. https://doi.org/10.1016/B978-0-12-800138-7.00001-2

Zhang, L. et al. 2021. Methane Emissions from Livestock in East Asia During 1961−2019. *Ecosystem Health and Sustainability* 7: 1918024. https://doi.org/10.1080/20964129.2021.1918024

Zhang, W. et al. 2013. New Technologies Reduce Greenhouse Gas Emissions from Nitrogenous Fertilizer in China. *Proceedings of the National Academy of Sciences* 110: 8375–8380. https://doi.org/10.1073/pnas.1210447110

Zhang, X., Y. Lu, Q. Wang, and X. Qian. 2019. A High-Resolution Inventory of Air Pollutant Emissions from Crop Residue Burning in China. *Atmospheric Environment* 213: 207–214. https://doi.org/10.1016/j.atmosenv.2019.06.009

Zou, X. et al. 2015. Greenhouse Gas Emissions from Agricultural Irrigation in China. *Mitigation and Adaptation Strategies for Global Change* 20: 295–315. https://doi.org/10.1007/s11027-013-9492-9

7

Best Bets for Achieving a Carbon-Neutral Global Food System

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7.1 Introduction

Global annual emissions of greenhouse gases (GHGs) remain far above levels needed to meet ambitious climate goals, such as limiting global warming to 1.5° or 2°C above preindustrial levels. The role of food systems in global emissions is increasingly recognized, with estimates typically attributing 20%–30% of total emissions to food-related activities (Poore and Nemecek 2018; Crippa et al. 2021; Tubiello 2018; Hong et al. 2021). GHG emissions related to food also show little sign of declining, with notable increases in the past 2 decades (Tubiello 2018; Hong et al. 2021), although to a lesser extent than emissions from fossil fuel use.

The growing recognition of the costs of inaction on climate change, coupled with the growing recognition of the food system's role in driving emissions, has led to renewed interest by policy makers in ways to reduce food's climate footprint. Added to this is the prospect that revenues from reducing or removing emissions could provide a significant boost to rural economies, which is often an important mandate for policy makers. For example, a simple calculation suggests that if carbon dioxide (CO_2) is priced at $70 per ton[2] and food systems contribute one-quarter of the world's 50 billion tons of CO_2 equivalent (CO_2eq) of emissions, then emissions from food systems represent roughly $1 trillion each year.

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[1] The author thanks Nelson Villoria for providing the data presented in Figure 7.4, and Tom Hertel, Keith Fuglie, Chaopeng Hong, Steve Davis, and Jen Burney for helpful discussions.

[2] The cost of a European Union carbon permit in October 2021. Estimates of the true social cost of CO_2 can be much higher than this value.

Predictably, there has been a flurry of claims about how different actions can help promote a carbon-neutral food system, some more grounded in evidence than others. This has led to widespread confusion about which actions are truly effective and scalable enough to make a meaningful contribution to climate mitigation. The main goal and contribution of this chapter is to synthesize the most recent evidence on what the most promising directions for policy may be.

The primary focus of this discussion is on Asia. In several places, I present both global and region-specific estimates, and rely on examples from the region. However, the international nature of the food system makes consideration of any region in isolation of the rest of the world a fool's errand. This is perhaps especially true when the topic is GHG emissions, since deforestation looms very large in accounting of emissions, and global commodity markets play a key role in driving deforestation (Hosonuma et al. 2012; Pendrill et al. 2019). Thus, domestic policies that constrain local producers can often cause leakage of emissions to other regions. A more positive but equally strong interdependence is seen in the positive spillovers resulting from innovation in one region to the rest of the world (Fuglie 2018). As innovation will be critical to reducing emissions, factoring in these positive spillovers are no less important than accounting for negative spillovers like deforestation.

Although the discussion here focuses on the supply side—that is, the systems that produce food and the associated GHG emissions—there are also potential policy interventions that can affect the demand side. Examples of demand-side policies include renewable fuels standards that incentivize ethanol or biodiesel production, subsidies for GHG-intensive food products (e.g., beef or milk) that inflate demand, nutritional guidelines that promote some food groups over others, or industrial policies that affect the growth of the alternative protein industry. I pay limited attention to these policies here, largely because of space constraints. In aggregate, these policies can be an important lever for influencing total food system emissions and are largely complimentary to the supply side measures discussed here. The focus here on the supply side should therefore not be interpreted as a statement on the potential importance of demand-side measures, as both will likely be needed to achieve ambitious climate goals.

Section 7.2 provides a quantitative overview of emissions from food systems, followed by a summary of the potential mitigation benefits of different actions deemed to be cost-effective. Section 7.3 outlines the general market failures that underlie current emissions and the associated roles for policy in addressing these market failures. Sections 7.4 and 7.5 focus on two issues that in the author's view are critical to implementing cost-effective solutions at scale—the need to verify emissions reductions on farms, and the need to measure the aggregate emissions benefits of investments in research and development (R&D). Section 7.6 outlines specific priorities for accelerating progress toward the goal of net-zero emissions, and section 7.7 presents some brief conclusions and policy recommendations.

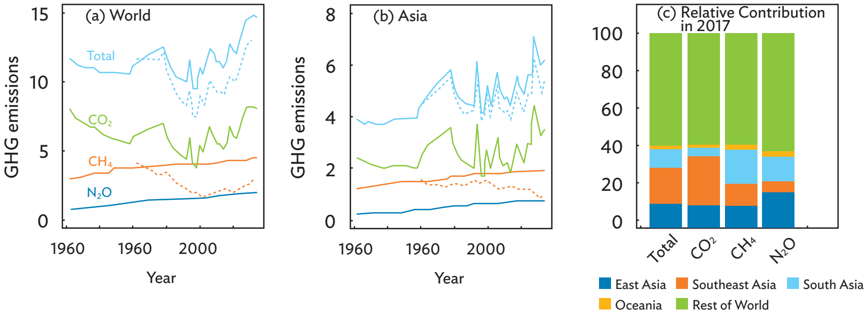
7.2 The Contribution of Agriculture to Greenhouse Gas Emissions

Most food-related emissions come from agriculture and land use change (LUC), the topic of this chapter, with small but non-trivial contributions from post-farm gate activities such as transport, processing, and food preparations (Poore and Nemecek 2018). Two key difficulties arise when attempting to quantify total emissions from agriculture and LUC, both of which are often underappreciated. One relates to measurement itself. Emissions are distributed across many small emitters, making direct measurement of emissions nearly impossible. In addition, the processes giving rise to emissions are complex and difficult to model, especially when compared to fossil fuel combustion where emissions are directly proportional to use. One manifestation of these measurement challenges is that different estimates can often disagree. Global nitrous oxide (N_2O) emissions from agriculture, for example, are reported by the Food and Agriculture Organization of the United Nations (FAO) as 2.1 gigatons (Gt) CO_2eq but estimates from some global models are nearly twice this estimate (Tian et al 2020). The recent estimate of the Global Carbon Project is a mean of 3.8 Gt CO_2eq, with a range of 2.5 to 5.8 Gt CO_2eq (Tian et al 2020).

A second considerable challenge is that a substantial portion of agriculture's emissions are from methane (CH_4), which is a much more potent GHG but also much shorter lived than CO_2. The average lifetime of a newly emitted molecule of CH_4 is just 12 years, compared to well over 1 century for CO_2 and N_2O. Many metrics have been developed to convert different GHG to CO_2-equivalents, the most prominent being the 100-year Global Warming Potential (GWP) that underlies the standard CO_2eq measure. While an extremely helpful construct, GWP is often criticized both for overstating the long-term and understating the short-term impact of changes in CH_4 emissions. The recently proposed GWP* metric focuses more directly on the rate of change in CH_4 emissions, by contrasting current emissions with those from 20 years prior (Allen et al 2016; Lynch et al 2020). Even if CH_4 emissions are positive, atmospheric concentrations (and associated effects on climate) can decrease if emissions are below the level needed to "replace" emissions from 20-year prior. This is in stark contrast to CO_2, where even small emissions will continue to increase atmospheric concentrations.

Notwithstanding these complications, a few stylized facts about agriculture's role in emissions are clear and worth emphasizing. First, the primary contribution stems from CO_2 emissions associated with LUC, followed by CH_4 and N_2O (Figure 7.1). The relative importance of CH_4 and N_2O depends on both issues discussed above, namely measurement uncertainties and different lifetimes. Traditional GWP shows CH_4 as considerably more important than N_2O, but GWP* shows them as more equal drivers of warming.

Figure 7.1: Greenhouse Gas Emissions from Land Use Activities



GHG = greenhouse gas.

Notes: (a) Total annual GHG emissions (in Gt CO_2eq) based on estimates in Hong et al. (2021). Contributions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are shown in colored lines. Solid lines indicate values using traditional 100-year global warming potential, and dashed lines represent values using GWP*, which treats CH_4 differently as discussed in section 7.2. (b) Total emissions in Asia show similar trends and breakdown by gas as compared to global aggregates. (c) The share of total Asian contribution to emissions of land-use-related GHG and each component gas. While Asia contributes about 40% to each gas, the relative importance of each subregion varies with gas.

Source: Hong et al. (2021).

Second, whereas CO_2 emissions from LUC were stable and even declining toward the end of the 20th century, expansion of cropland and the associated emissions have increased in the past 2 decades (Figure 7.1). As emphasized by others (Cassman and Grassini 2020), these trends are the predictable result of high food prices in the 2000s that increased incentives to cultivate new land or reclaim formerly abandoned land.

Third, Asia represents a major source of emissions in all three categories, contributing roughly 40% of each of the three main GHGs (Figure 7.1b, c). Although the overall contribution of each gas in Asia is similar to the global aggregate, marked differences exist between different subregions within Asia. In Southeast Asia, emissions of CO_2 associated with LUC dominate the overall land use emissions, whereas in South Asia CH_4 (associated with both ruminant and rice production) is particularly important. East Asia, in contrast, contributes more N_2O than any of the other subregions, and alone comprises nearly 20% of the global agriculturally related N_2O emissions. Based on these differences, the best strategy for emissions reductions is clearly likely to differ considerably for countries within the region.

7.3 Market Failures and Strategies to Reduce Emissions

Based on the discussion above, the goal of achieving a carbon-neutral agriculture sector will likely include at least three key objectives: to greatly reduce CO_2 emissions arising from LUC, on-farm emissions of CH_4, and on-farm emissions of N_2O. A fourth objective that is often raised is to actively sequester carbon in agricultural soils, using a variety of so-called “climate-smart” practices such as no-till or cover cropping as well as application of soil amendments such as biochar or crushed rock (Beerling et al. 2020; Roe et al. 2019; Griscom et al 2017).

The key question for policy makers is how to best accelerate progress toward achieving these objectives. In general, it is widely acknowledged that policy interventions aimed at reducing environmental damage must deal with at least two distinct types of market failures (Popp 2010; Acemoglu et al. 2012). The first relates to the negative externalities caused by human activities, in this case emissions resulting from farm activities, for which the costs are borne by the public rather than by the individuals or firms causing the pollution. Regulations and taxes are the main tools to address this negative externality, and these are often accompanied by the formation of markets in which firms can trade the right to pollute and thereby lower the overall cost of compliance. In carbon markets, firms that actively sequester carbon can also sell credits to others seeking to reduce their pollution liabilities. Critical to the functioning of such markets is the ability to accurately measure the net flow of emissions from individual firms.

A second market failure relates to the positive externalities that arise from innovation in green technologies. For example, an inventor of a new type of fertilization method that reduces N_2O emissions will only be able to capture a small part of the overall societal benefits of the new technology, as other firms will be able to learn from and build on the innovation. As a result, societies tend to under invest in innovation on pollution-reducing technologies despite their public benefit. The policy response to this failure is to subsidize R&D for green technologies in order to encourage more investment. Several authors have shown that such subsidies are critical to reducing the cost and time spent achieving climate goals (Popp 2010; Acemoglu et al. 2012), especially when combined with regulations and taxes that spur adoption of the innovations.

Policy makers thus play a central role in both (i) defining rules that incentivize adoption of existing technological solutions as well as further development of new solutions and (ii) directly funding the R&D of new solutions. For the first of these to be effective, it is important both that cost-effective solutions exist, and that regulators and businesses have an ability to reliably and cheaply verify that solutions have been properly implemented. If cost-effective solutions are lacking, then effort is better spent on funding R&D to develop new technologies. Similarly, if verification is difficult, then policy makers should prioritize reducing the costs of monitoring, either by funding new monitoring technologies or by subsidizing the cost of (otherwise expensive) monitoring systems.

In this context, this chapter focuses on three key questions before identifying priorities for mitigation in agriculture:

I. What is the plausible mitigation potential of existing solutions for different sources of agricultural emissions?
II. What are the prospects for verifying the adoption of these solutions at the level of individual actors (e.g., farmers or ranchers)?
III. What is the historical return on R&D in terms of agricultural mitigation, and what does this imply for future investments in R&D?

7.4 Cost-Effective Potential of Different Solutions

Many studies in recent years have attempted to compile estimates of mitigation potential for specific activities related to land management, both globally and for specific regions (Roe et al. 2019; Griscom et al. 2017; Roe et al. 2021). These activities are alternatively referred to as land-based solutions, nature-based solutions, natural climate solutions, or agriculture, forestry, and other land use (AFOLU) mitigation. Here I rely primarily on the recent study of Roe et al. (2021), which includes both global and national estimates and distinguishes total potential from cost-effective potential—defined as solutions that would cost under \$100 per ton of CO_2eq to implement. As Roe et al. (2021) state, cost-effective potentials "represent a more realistic and actionable target grounded in public willingness to pay for climate mitigation, and therefore, are more relevant in policy-making than technical potentials." Accordingly, I focus on these estimates and do not discuss those for total biophysical potential.

Table 7.1 presents some selected values from Roe et al. (2021) for global estimates as well as totals for the Asia region, which includes the developing Pacific countries. Globally, the total cost-effective potential is estimated as 13.8 Gt CO_2eq per year, or roughly one-quarter of total global GHG emissions. Notably, this value is nearly equivalent to the total current emissions from agriculture shown in Figure 7.1, suggesting

Table 7.1: Summary of the Potential for Different Approaches to Land-Based Mitigation

		Cost-Effective Potential (Gt CO_2eq per year)	
Main Categories	**Selected Subcategories**	**Global**	**Asia**
All land-based		13.80	4.75
Forests and other ecosystems		6.58	1.92
	Protect	3.84	1.02
	Manage	0.93	0.25
	Restore	1.81	0.64
Agriculture		5.33	2.04
	Reduced enteric fermentation	0.10	0.03
	Improved manure management	0.09	0.03
	Improved rice production	0.17	0.15
	Improved nutrient management	0.22	0.16
	Cropland soil carbon storage	0.92	0.34
	Agroforestry	1.12	0.37
	Biochar	1.82	0.79
Demand-side		1.89	0.80

Notes: Cost-effective is defined as costing less than $100 per ton of CO_2eq mitigation. Potentials are shown both for the global total and for the Asia and developing Pacific region.

Source: Based on synthesis of cost-effective measures by Roe et al. (2021).

that implementation of all cost-effective measures could make the sector carbon neutral.

Nearly half (48%) of this potential is associated with forests and other non-agricultural ecosystems, with protection of existing forests being the single biggest mitigation measure. This finding is consistent with the observation that CO_2 from LUC is currently the biggest source of total agricultural emissions (Figure 7.1). Actions within agricultural lands represent 38% of the total cost-effective potential at the global scale, with biochar and agroforestry judged to be the two biggest potential measures within agriculture. Demand-side measures, which include changes in diets and reducing food waste, represent a smaller but non-negligible 10% of total potential. As with current emissions, the picture for mitigation potential in Asia is similar to the world. Roughly 35% of mitigation potential is identified in Asia, only slightly less than its 40% contribution to current global agricultural emissions.

Whereas CH_4 emissions were a substantial fraction (around 30%) of total agricultural emissions (Figure 7.1), they represent a small share of the estimated cost-effective potential. Specifically, the sum of measures to improve enteric fermentation, manure management, and rice emissions amount to roughly 0.36 Gt CO_2eq per year, which is less than 3% of the total cost-effective potential for the land sector. These numbers highlight the difficulty of reducing CH_4 with current technologies, in part because most of the world's ruminant production is dispersed and not amenable to the type of interventions possible in industrial systems, such as feed alterations or methane capture. Other estimates of CH_4 mitigation potential are somewhat higher, with Smith, Reay, and Smith (2021) reporting roughly twice the potential at $100 per ton CO_2eq. Yet even this doubling would not represent a substantial fraction of current CH_4 emissions. As Nisbet (2020) points out, other sectors provide considerably more low-cost potential to reduce CH_4 emissions than agriculture.

Similarly, only a fraction of N_2O emissions associated with agriculture are deemed to be cost-effective to eliminate with current technologies. Improved nutrient management is estimated to deliver 0.22 Gt CO_2eq per year globally, with much of that potential (0.16 Gt CO_2eq per year) from Asia. These numbers represent roughly 10% of global agricultural N_2O emissions, or 20% for Asia.

In most estimates, including Roe et al. (2021), the bulk of on-farm mitigation potential comes not from reducing CH_4 or N_2O emissions but from increasing soil carbon. Adding biochar to soils and increasing tree cover within agricultural lands are each estimated to provide well over 1 Gt CO_2eq per year for carbon prices up to $100 per ton CO_2eq.

Not included in these estimates is the additional potential to add crushed rock such as basalt to soils to enhance CO_2 storage through rock weathering. A recent assessment (Beerling et al. 2020) suggests that net CO_2 removal (i.e., after accounting for emissions associated with the energy needed for extraction, grinding, distributing, and spreading) could reach as much as 2 Gt CO_2eq per year, with costs below \$200 per ton CO_2eq in most countries and below \$100 per ton CO_2eq in several countries, including India.

One message from current assessments is that reducing on-farm emissions of CH_4 and N_2O is expensive relative to sequestering carbon in trees or soils. Potential reduction in CH_4 and N_2O is therefore a small fraction of the overall cost-effective mitigation potential. Again, it is worth emphasizing that the above discussion pertains to estimates that consider current cost curves associated with current technologies. As more investment and experience accrues, the costs would decline and thus the mitigation potential for a given carbon price would increase.

7.5 Monitoring and Verification

As mentioned, designing effective regulatory and market approaches to emissions reductions requires an ability to either directly measure emissions from individual firms, or to accurately measure practices that can be reliably used to estimate emissions. In policy design discussions, these approaches are sometimes referred to as results based or actions based, respectively (COWI, Ecological Institute, and IIEP 2021).

Results-based schemes are attractive because they directly target the outcome of interest. At the same time, they are often infeasible because of an inability to measure the relevant outcomes cheaply and accurately at the spatial scales of individual decision makers. An additional downside of results-based schemes is that farmers can be penalized for changes in outcomes due to factors outside of their control, such as weather or pest infestations. Actions-based schemes can help to reduce these problems but can be limited when the effects of specific actions vary a lot depending on local context. Hybrid schemes, which link part of overall payments to actions and part to results, provide a middle ground between these two options (COWI, Ecological Institute, and IIEP 2021).

Here I discuss the prospects for monitoring both results and actions related to each of the four objectives: reducing CO_2 emissions from LUC, reducing on-farm CH_4, reducing on-farm N_2O, and enhancing soil carbon. I argue that, with some important exceptions, accurate measurement at the scale of individual actors (i.e., farms) will remain very difficult for the foreseeable future. This challenge exists for three fundamental reasons: (i) measurements of the gases themselves are still limited (although improving) at the scale of individual farms; (ii) the biogeochemical processes governing the release of on-farm CH_4 or N_2O or build up of soil carbon are very complex, which can result in very loose relationships between most actions and the resulting emissions; and (iii) many of the practices that consistently result in reduced emissions, such as split application of fertilizers, are themselves hard to measure across large numbers of farms.

The next section focuses on prospects for measuring GHG fluxes themselves, before turning in the following section to measuring specific practices thought to be associated with GHG fluxes.

7.5.1 Monitoring GHG Fluxes from Individual Firms

I take as a starting point the assumption that sampling of CO_2, CH_4, or N_2O gases at the ground level would be an intractable approach for monitoring emissions in agriculture, given the millions of locations involved. It is plausible that ground-based approaches will someday become cost-effective, for instance if companies promising rapid measurement of soil carbon are successful. Measurements at tall towers may also play some role for monitoring, particularly in the vicinity of large point sources such as confined animal feedlot operations but are also unlikely to be cost-effective in most situations. Therefore, I focus on the ability to measure GHG fluxes remotely, by utilizing sensors on airplanes, satellites, or perhaps other platforms such as drones or hot air balloons.

Remote measurement of gas concentration utilizes the fact that gases interact with light at specific wavelengths. Spectrometers designed to measure the light reflected from the Earth at key wavelengths can therefore provide relatively precise measures of gas concentrations in the atmosphere. For CO_2 and CH_4, there are sufficiently strong absorptions in the solar spectrum to facilitate measurement, and these measurements have been available from satellite sensors in some form for over two decades. These data have been widely used for a variety of purposes, including to understand broad patterns of sources and sinks of GHG. For example, comparisons of the spatial and seasonal patterns of CH_4 in satellite data with rice paddy areas and seasons has been used to understand the contribution of rice to CH_4 budgets and trends in India (Ganesan et al. 2017) and the People's Republic of China (PRC)

(Zhang et al. 2020). However, the spatial resolution of these sensors is typically much too coarse to resolve emissions from individual point sources.

Recently, efforts have intensified to monitor CH_4 emissions at high spatial resolution. For example, an airborne spectrometer flown over California over a 2-year period identified CH_4 fluxes from over 500 point sources, including 26% associated with dairies (Duren et al. 2019). The MethaneSAT instrument, led by the Environmental Defense Fund in the United States and planned to be launched in late 2022, will provide similar capabilities from space, with a spatial resolution of roughly 100 meters. Therefore, remote measurement of large point-source emitters should be possible in the near term, and this will almost certainly be useful in the case of confined animal feedlot operations. Whether satellites prove useful for detecting the smaller magnitude of emissions typical for the more diffuse animal operations in Asia, or for emissions from rice fields, remains an open question.

In contrast to CO_2 and CH_4, direct measurement of N_2O from satellite is not currently plausible even at coarse resolution, because N_2O does not have strong absorption features at wavelengths with significant solar radiation (about 400–2,500 nanometers). Some recent work has used a combination of real-time airborne gas sampling and inverse modeling to estimate surface emissions of N_2O, with some potential to discriminate high-emitting fields (Gvakharia et al. 2020). However, direct monitoring of N_2O from remote sensing is unlikely to be available in the next decade. Therefore, monitoring efforts must focus on specific practices associated with reduced N_2O flux.

7.5.2 Monitoring Practices Associated with GHG Fluxes

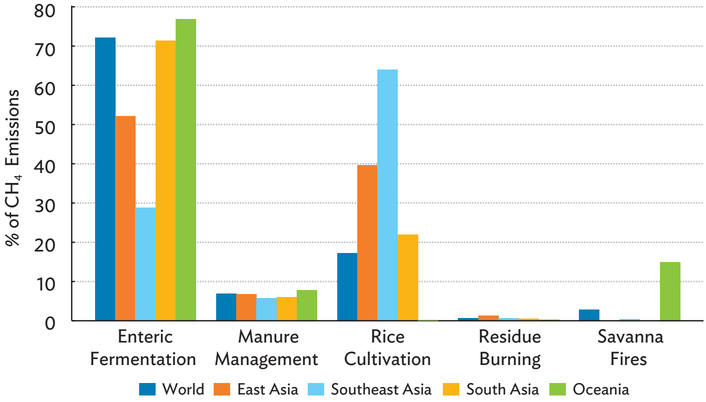
Land Use Change

As mentioned, the single biggest contributor to GHG fluxes from agriculture is CO_2 emissions associated with the conversion of native ecosystems into new agricultural land (Figure 7.1). Fortunately, monitoring of LUC is one of the most mature applications of satellite remote sensing. Efforts such as the Global Forest Watch provide real-time monitoring of forest loss down to very fine special resolutions and include estimates of CO_2 loss associated with the detected LUC at both local and national levels. As new satellites and associated data products improve, these estimates of LUC emissions are likely to advance even further. For example, an important current source of uncertainty is the carbon uptake associated with ecosystem regrowth on abandoned agricultural lands (Harris et al. 2021). New instruments to measure aboveground biomass, such as the Global Ecosystem Dynamics Investigation should help to reduce these and other uncertainties (Dubayah et al. 2020).

Methane

The most relevant practices associated with CH_4 emissions relate to ruminant husbandry and rice cultivation, because the main sources of CH_4 associated with agriculture, both globally and within Asia, are from just two processes: enteric fermentation in ruminant animals and anaerobic soil emissions in rice systems (Figure 7.2). As a global average, roughly three-quarters of all CH_4 emissions comes from enteric fermentation of ruminants, with a similar proportion in South Asia and Oceania. Rice cultivation contributes roughly 20% globally but with a higher percentage in East Asia (about 40%) and Southeast Asia (about 60%).

Figure 7.2: Percentage of Total Agricultural Methane (CH_4) Emissions from Each Source Activity



Note: More than 70% of CH_4 emissions globally and in South Asia and Oceania are from enteric fermentation in ruminants. The percentage is significantly lower in East Asia and Southeast Asia, where rice cultivation plays a more important role.

Source: Data correspond to 2019 and are obtained from FAOstat (faostat.fao.org) (1 November 2021).

As mentioned, few cost-effective practices currently exist to dramatically reduce enteric fermentation emissions. Historically, emissions per kilogram of product have declined as the result of general efficiency gains associated with new cattle breeds and greater growth rates and slaughter weights. For example, in the PRC, GHG emissions per gram of animal protein in 2010 was less than half what it was in 1980, although total emissions more than doubled over that period as total production nearly quintupled (Bai et al. 2018).

Several practices to reduce per animal emissions are currently being researched and may gain traction in the future as the technologies mature and policy incentives increase. These include feed additives such as synthetic CH_4 inhibitors or red seaweed, breeding for low-emission animals, and vaccination against rumen methanogens (Roque et al. 2021; Reisinger et al. 2021).

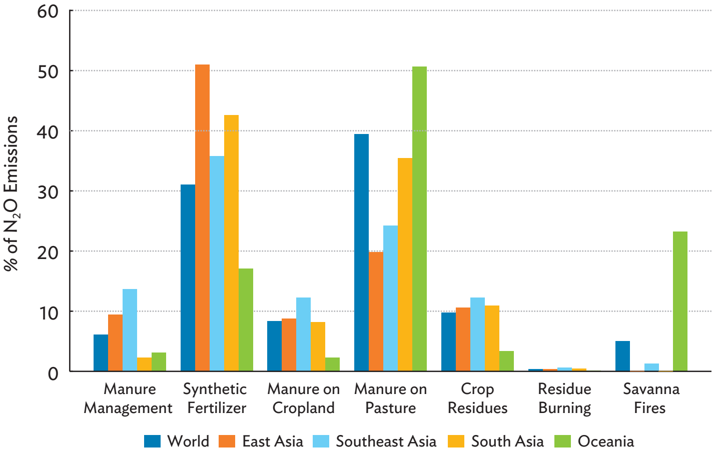
For rice production, the most widely recognized practice used to reduce CH_4 emissions is alternate wetting and drying (AWD) of the soil to reduce the amount of time that the system experiences anaerobic conditions. For example, changes to flooding practices in rice systems are already recognized as a compliance offset project within California's cap-and-trade program. A recent meta-analysis of experiments in Southeast Asia reported an average 35% decline in CH_4 emissions from AWD (Yagi et al. 2019). Yet other studies have cautioned that AWD also often leads to increases in N_2O fluxes (Kritee et al. 2018) and reductions in soil carbon (Shang et al. 2021). Thus, AWD is an example of how complex biogeochemical processes can cause imperfect links between practices and GHG reductions.

One appeal of AWD as a mitigation strategy is that the ability to remotely monitor the practice is quickly improving. Radar measurements from the European Space Agency's Sentinel-1 sensors have shown promise for mapping AWD in Viet Nam (Lovell 2019; Phan et al. 2021). Integrating these methods into verification protocols will likely require more research—for instance, inundation status gets harder to detect toward the end of the season when crops are fuller in size (Phan et al. 2021) and yet these stages may be important for determining net GHG impact. Overall, though, changes in rice cropping practices are likely to be much easier to verify remotely than any changes in animal management practices.

Nitrous Oxide

Practices relevant to N_2O pertain mainly to the use of fertilizers (both synthetic fertilizer and manure), although practices related to residue and manure management are also important in some cases (Figure 7.3). Globally, roughly 40% of all agricultural N_2O is from fertilizer use on cropland (with three-fourths of that from synthetic fertilizer), with another 40% associated with manure on grazing lands. These numbers are also representative of most Asian countries, although synthetic fertilizers play an even larger role in East Asia (Figure 7.3).

Figure 7.3: Percentage of Total Agricultural Nitrous Oxide (N_2O) Emissions from Each Source Activity



Note: Emissions from synthetic fertilizers and manures on cropland or pasture account for the bulk of N_2O emissions globally and in all Asian regions.

Source: Data correspond to 2019 and are obtained from FAOstat (faostat.fao.org) (1 November 2021).

As observed N_2O fluxes are higher on acidic soils, efforts to raise soil pH can also result in significant reductions in N_2O, for instance following application of lime or crushed basalt (Wang et al. 2021; Blanc-Betes et al. 2021). Application of biochar has also been found to reduce N_2O, by as much as 38% on average in a recent meta-analysis (Borchard et al. 2019), through a combination of mechanisms including increasing soil pH.

The practices mentioned above, with the exception of biochar application, are extremely difficult to monitor. While research may improve the situation, it therefore appears risky to rely on any market-based or regulatory approach to N_2O that requires verification of farmers uptake of specific practices.

On-farm Carbon Sequestration

Conversion of native ecosystems to agriculture historically resulted in a large loss of CO_2 to the atmosphere, and a litany of practices have been studied for their ability to rebuild carbon stocks in the cropping system. Many of these focus on rebuilding soil carbon, either through practices such as using reduced tillage and cover cropping or by adding external sources of carbon such as biochar or crushed basalt. Agroforestry instead focuses on rebuilding woody biomass in trees or shrubs within agricultural landscapes.

As with methods to reduce CH_4 and N_2O fluxes, methods to increase soil carbon tend to exhibit large variability in their effectiveness because of many complex interactions with local conditions. Two additional factors often complicate analyses of the effectiveness of on-farm carbon sequestration. First, many of these practices can also affect CH_4 and N_2O fluxes, which can either counteract or enhance the mitigation benefits. For example, cover cropping and no-till have been associated with increased N_2O fluxes, whereas biochar applications appear to reduce N_2O flux. Second, soil carbon accumulation can be easily reversed if the practices are discontinued, leading to concerns about the permanence of the mitigation benefit. Although these concerns can be addressed in market design (e.g., through the use of discounts or buffer reserves), they also mean that the estimates of cost-effective potentials in Table 7.1 are likely an upper bound on their potential contribution (Bossio et al. 2020).

For some of the practices related to building soil carbon, approaches to successfully monitoring their implementation have already been established in some settings. These include mapping adoption of no-till (Azzari et al. 2019), cover cropping (Seifert et al. 2018), and increasing tree cover (Chapman et al. 2020). Additional methods development is likely needed for robust application across the world, but it appears a safe bet that verification of these practices will be feasible. Other practices, including large scale applications of biochar or crushed basalt, should also be feasible to monitor from satellites given the distinct change in soil color likely to occur upon application, although limited research has been done to date. Some practices aimed at raising soil carbon, such as adding legumes to pasture species mixes, present a more difficult challenge for remote verification.

7.5.3 Returns on R&D in Agriculture

Here I consider whether public subsidies for R&D are likely to be effective in reducing agricultural emissions. Is there evidence, for instance, that past investments in new technologies have helped to reduce emissions from the sector? A longstanding literature on the returns from public and private investments in agricultural R&D has shown large positive returns for a range of outcomes, including crop yields and total factor productivity (Pardey et al. 2018; Fuglie 2018). Of interest here is whether this evidence would also imply that returns in terms of GHG reductions are likely to be high. Historically, very few R&D efforts have had an explicit goal of reducing GHG emissions, and I am not aware of any studies attempting to evaluate the returns on these specific investments. At the same time, many efforts have focused on reducing the amount of fertilizer and pesticide inputs for a given output. Indeed a large fraction of total factor productivity growth in developed countries has come from increasing output with constant inputs (Fuglie 2018). Given the strong dependence of N_2O fluxes on excess nitrogen, as discussed in section 7.5.2, it is likely that many R&D investments have already helped to reduce on-farm emissions, even if that was not their aim.

More importantly, past R&D efforts have led to large yield increases, and these yield changes, when aggregated over large areas, are one of the most important determinants of large-scale LUC. Several studies have attempted to estimate the net CO_2 emissions that result from investment in agricultural R&D, by linking models that describe the effects of R&D on yields, the effects of yields on LUC, and the effects of LUC on CO_2 emissions. These studies (Burney, Davis, and Lobell 2010; Lobell, Baldos, and Hertel 2013; Stevenson et al. 2012; Villoria 2019) have supported a few broad conclusions.

First, the aggregate impacts can be large. As already noted, CO_2 emissions associated with LUC are the biggest single contributor to agricultural emissions (Hong et al. 2021), and yield changes are a major driver of LUC at the global scale. Villoria (2019), for example, estimates that global LUC emissions for 2001–2010 would have been up to 70 Gt CO_2 higher over that period in a counterfactual where productivity was stagnant over the same period.

Second, the cost-effectiveness of these investments is very favorable compared to many alternative approaches to reducing emissions. Table 7.2 summarizes literature estimates of the return on R&D in terms of cost per metric ton of CO_2 saved (Burney, Davis, and Lobell 2010; Lobell et al. 2013; Fuglie et al. 2022). Even the high end of the range reported in Table 7.2 are well under \$100 per ton of CO_2eq.

Table 7.2: Estimates of the Effective Cost of Avoiding CO_2 Emissions via Investments in Agricultural Research and Development

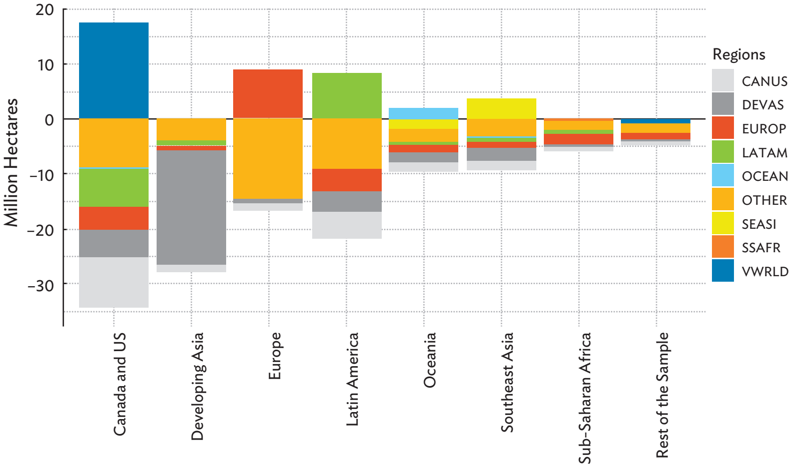
Study	Time Period	Method	Estimate of $/ton CO_2	Notes
Burney et al. (2010)	1961–2005	CO_2 from simple counterfactuals of LUC in absence of yield progress For cost of yield gains, assumes 70% of R&D devoted to yields, 1/3 of yield gains from R&D	\$4–\$8	Estimate for past investments, using counterfactual land use scenarios
Lobell et al. (2013)	2006–2050	Based on SIMPLE Model Uses elasticity of crop total factor productivity with respect to R&D	\$11–\$22	Estimate for future investments, distributed across the world in order to offset climate damages in each region
Fuglie et al. (2022)	2020–2050	Based on SIMPLE Model	\$56	605B in extra R&D over 20-year period Spending only in lesser developed countries (LDCs), no protection of carbon rich lands
Fuglie et al. (2022)	2020–2050	Based on SIMPLE Model	\$11	Spending only in LDCs, with protection of carbon rich lands
Fuglie et al. (2022)	2020–2050	Based on SIMPLE Model	\$37	Some spending in developed countries, no protection of carbon rich lands

CO_2 = carbon dioxide, R&D = research and development, SIMPLE = Simplified International Model of agricultural Prices, Land Use and the Environment.

Sources: Taken from peer-reviewed literature.

Third, the local (i.e., in-country) emissions impact of innovations that emerge from R&D can differ considerably from the effects in other regions. Specifically, yield increases can often lead to local land expansion by increasing the profitability of growing a particular crop. The degree to which this happens depends on the degree to which the local markets are connected to international demand, the responses of both consumers and producers around the world to the price changes associated with the innovation, and the local availability of new cropland (Hertel 2018). In countries in Latin America, for example, which are closely integrated into international markets and where land that can be converted to new cropland is relatively abundant, local innovations can lead to significant increases in local emissions (Villoria 2019). In other countries, including many in developing Asia, local innovations typically lead to reduced pressure on land expansion and thus emissions savings.

Figure 7.4: The Impact of Total Factor Productivity Increases over 2001–2010 in Each Region on Cropland Expansion



US = United States.

Note: The label on the horizontal axis shows the region of total factor productivity (TFP) change, and the bars for that region indicate the impact of that TFP change on each other region, as well as the region itself. In many regions (e.g., Southeast Asia), local TFP gains lead to local land expansion, as agriculture becomes more profitable, but also to contraction of agriculture in other regions that outweighs the local expansion. In other regions (e.g., Developing Asia), TFP gains lead to land-saving in all regions, including the region of TFP growth. Countries for Asian regions are as follows. Developing Asia: Bangladesh, the PRC, India, Nepal, Pakistan, Sri Lanka; Southeast Asia: Indonesia, Lao People’s Democratic Republic, Malaysia, Philippines, Thailand, Viet Nam; Oceania: Australia.

Source: Data taken from Villoria (2019).

Regardless of the local effects, innovations nearly always lead to significant land savings in other regions, and these savings tend to dominate any local effects. Figure 7.4, adopted from Villoria (2019), shows the estimated impact of total factor productivity (TFP) gains in different regions for 2001–2010 on cropland area, using models that account for the various factors discussed above. Regions such as Canada and the United States, Europe, and Latin America show sizable in-country expansion associated with the TFP gains, but all these regions also show even bigger declines in area outside of the country where the gains occurred.

In Southeast Asia and Oceania, local TFP gains also lead to some local expansion but net-saving at the global scale, since out-of-country effects again more than compensate for the in-country effects. In Developing Asia, which includes the PRC and most of South Asia, even the local effects are net land saving, because these countries tend to have less room for local land expansion as well as lower exposure to international trade than other regions (Villoria 2019).

If these investments are so attractive for reducing GHG emissions, a reasonable question is why they have not played a more prominent role in national climate mitigation plans. A key conundrum, as mentioned, is that the emissions benefits are most often realized outside of the country in which the investments and resulting innovations occurred. For example, if R&D in the PRC leads to significant gains in local soybean production, which then leads to a reduction in global export prices for soybean and palm oil, which then leads to reduced deforestation in Brazil and Indonesia, which country deserves credit for the avoided emissions? In most accounting schemes, countries are only responsible for—and only receive credit for—emissions reductions within their own territories. The nationally determined contributions (NDCs) that underlie the Paris Agreement, for example, typically include a large role for reducing emissions from LUC (Grassi et al. 2017) but these only pertain to domestic emissions. In this scheme, a country would not get credit for innovation that contributes to a significant lowering of global food prices that reduces pressure on LUC around the world. In many ways, this domestic emphasis is sensible, in part because credit for progress in other countries could easily lead to double counting of emissions reductions. Nonetheless, it leads to diminished incentives to pursue an effective strategy from the global perspective.

In summary, agricultural R&D results in large and cost-effective reductions in global emissions, yet at the same time nearly all these reductions occur outside of the country from which the R&D investments are made. The domestic effects of innovation are often very small and can even be net positive, with emissions higher than they would have been without the innovation, especially for countries that are well integrated with global markets. This situation creates a dilemma that has not yet been solved. One partial solution could be for countries to receive credit toward their NDCs for donations to multilateral R&D organizations such as the Consortium of International Agricultural Research Centres. However, this would only cover a small fraction of potential global R&D, and not necessarily the type of R&D that is most effective for reducing global LUC.

7.5.4 Best Bets for Large-Scale Mitigation

Given the above discussion, what areas deserve priority from policy makers? Here I first outline a few principles or criteria that, in my view, should be used when identifying priorities. I then highlight specific areas that deserve the focus of the policy community.

Key Criteria

Scale: First and foremost is the question of whether the proposed action, if successful, would result in significant climate benefits. As shown in Table 7.1, some actions are estimated to have much more potential than others. Of course, Table 7.1 refers only to global and regional potentials, and it is possible that an action for an individual country could rank much higher or lower locally than it does globally.

Cost-effectiveness: Agriculture is just one of many sectors in which mitigation needs to occur, and governments and businesses need to allocate scarce resources across many potential mitigation efforts. Some agricultural actions provide opportunities at much lower cost than others, and these lower-cost options should be prioritized.

Feasibility: Actions with large potential impact at relatively low cost could still fail for other reasons. One point emphasized in section 7.4 is that an inability to verify whether the action was taken could hamper markets that incentivize such actions. This could be considered another aspect of cost, in that an action that is difficult to monitor will involve large transaction costs that are typically not included in estimates of cost-effectiveness. Another key aspect of feasibility is whether the action has significant risks or co-benefits outside of mitigation which would hamper or accelerate its adoption. Fortunately, many mitigation actions present substantial benefits for soil health, crop and animal productivity, and rural livelihoods. These co-benefits should be factored into priority setting alongside issues such as scale and cost.

Time scale: A final criteria is how long it will take to realize the benefits of an action. On the one hand, given the urgent need for mitigation, actions that can leverage existing infrastructure and expertise should be preferred to those that require entirely new supply chains. For example, proponents of adding ground basalt to agricultural soils point out that rock crushing machinery is already widespread in some countries and farmers already have practice in spreading limestone to control soil acidity (Beerling et al. 2018). On the other hand, policy makers should also ensure that longer-term investments needed in research and development are not completely neglected, as these will play a key role in lowering costs and increasing mitigation potential.

7.6 Priority Areas

7.6.1 Protecting Forests

Emissions of CO_2 from LUC represent both the single biggest source of current GHG emissions (Figure 7.1) and the single biggest opportunity for cost-effective reduction (Table 7.1). Establishing and enforcing policies that discourage deforestation are widely recognized as critical to reducing these sources of emissions, and deservedly so. However, these efforts must be matched by an equally robust effort to sustain productivity increases in the agriculture sector, to reduce the economic pressures that contribute to deforestation. A key policy challenge is that national climate plans typically focus on domestic emissions budgets whereas productivity gains have much of their impact beyond national borders (Figure 7.4).

In the long-term, investing in R&D has proven to be a very cost-effective mitigation strategy (Table 7.2), even when only considering the yield benefits of R&D and the associated impacts on global LUC. Further R&D directed at reducing CH_4 or N_2O emissions, or enhancing soil carbon storage, could be equally cost-effective. In the near term, policies other than R&D investment can have more immediate impacts on agricultural productivity. Among the most important in the Asian context are likely policies related to emissions of short-lived climate pollutants, such as particulate matter and nitrogen dioxide. The aggregate impact of poor air quality on crop productivity has been estimated to be as much as 30% for some crops in Asia (e.g., Lin et al. 2018). Progress in local air quality, driven for instance by energy and transportation policies, could thus have important mitigation benefits by reducing LUC and associated emissions.

7.6.2 Storing Carbon on Farms

Policies to encourage carbon uptake on farms appear attractive both in terms of potential scale and cost-effectiveness. Moreover, substantial co-benefits are likely to accrue from greater soil organic matter and establishment of trees in croplands. For example, planting trees in croplands is often encouraged as a strategy for managing climate risk (Lasco et al. 2014) and is prominent in many national climate adaptation plans. These other benefits increase the attractiveness and thus feasibility of these actions.

The main policy challenge in this area appears to be ensuring that compliance protocols are sufficiently robust to result in meaningful mitigation. Investing in research to improve low-cost measurement and modeling of soil carbon and the associated key practices will help to facilitate the effective markets needed to realize the potential of this set of activities.

7.6.3 Reducing Animal and Rice Emissions

Animals produce the bulk of CH_4 emissions from agriculture (Figure 7.2) and animal manure also contributes a significant fraction of N_2O (Figure 7.3). In much of the world, including much of Asia, animal systems are too dispersed for cost-effective mitigation measures to be feasible. This difficulty underlies the small fraction of mitigation potential estimated for these measures (Table 7.1). Nonetheless, a global trend toward centralization of animal production systems is occurring, not least of all in the PRC (Bai et al. 2018). At the same time, the emergence of satellite systems capable of monitoring CH_4 emissions from large point sources should greatly aid efforts to reduce emissions from these centralized facilities, such as through alternative feeds and methane capture systems. The combined effect of these centralization and measurement trends is that an ever-growing share of animal emissions are trackable. Moreover, as discussed in section 7.2, CH_4 can be especially important in shaping near-term warming rates. While modest in potential relative to the first two priorities, efforts related to reducing CH_4 from animal systems thus appear to be a good bet.

Similarly, methane emissions from rice systems, as well as practices that help to shape emissions, are increasingly verifiable at low-cost. For countries in East Asia and Southeast Asia, where rice emissions are a considerable portion of overall CH_4, a policy emphasis on reducing these emissions is warranted.

7.6.4 Improve Technologies for CH_4 and N_2O Mitigation

Given the high costs of most current measures for CH_4 and N_2O reduction, policy makers should redouble efforts to develop a new generation of technologies that provide lower-cost options. For CH_4, breeding and vaccination offer large potential benefits across a wide range of systems, and novel feed supplements and CH_4 inhibitors could also play an important role, especially in feedlot operations (Reisinger et al. 2021). For N_2O, low-cost technologies are needed to better match the quantity and timing of fertilizer application to crop needs, as these mismatches are the primary drivers of N_2O loss. Rapid diagnostics of canopy and soil nitrogen status, as well as unmanned vehicles to deliver fertilizer in small doses, could help drive cost reductions. More research is also needed to understand the potentially significant N_2O effects of additives designed to increase soil carbon, namely biochar and crushed basalt.

7.6.5 Demand-Side Policies

While this chapter has emphasized supply-side measures, policy makers should also consider demand-side interventions as part of their mitigation portfolio. In part, this could emphasize reducing demand for GHG-intensive food products, for example by encouraging behavior changes related to waste or consumption of animal products, or by directly subsidizing climate-friendly alternatives such as plant-based dairy and meat substitutes. These measures are, in my view, unlikely to be as effective in aggregate as supply-side measures, but nonetheless can play an important role. Equally important could be policies that reduce demand for non-food uses of crops or cropland. For example, policies that promote electrification of vehicles can reduce demand for ethanol and biodiesel.

7.7 Conclusions and Policy Recommendations

The prospects for a carbon-neutral food system are real. Estimates of mitigation opportunities at $100 per ton CO_2 are equal to the magnitude of total current food-related emissions, with on-farm carbon storage able to balance residual emissions of CH_4 and N_2O. Nonetheless, achieving carbon neutrality will be difficult and many approaches that at first glance appear promising will struggle to deliver large-scale, low-cost mitigation.

This chapter argues that the single best bet for achieving carbon-neutrality is to ensure sufficient investment in agricultural productivity, which is critical for determining land use change in Asia and throughout the world. History has shown that public investments in productivity have had large-scale impact and are very cost-effective as a mitigation strategy. The most critical challenge for policy makers is that much, or sometimes all, of the impact occurs outside of the country where the productivity improvement occurs, and thus a global mitigation framework that is centered around domestic commitments will tend to greatly underinvest in this pathway. Policy makers, both in and outside

Asia, must find ways to make sure that these R&D investments do not fall through the cracks of the emerging mitigation policy framework, which has tended to focus solely on domestic emissions.

A second critical task facing policy makers is to help establish both the rules and the measurement systems that can facilitate investments in CH_4 and N_2O reduction and on-farm carbon storage. Even solutions that are otherwise scalable and low-cost will fail to take hold without low-cost and accurate verification technologies. For the foreseeable future, public institutions will play a pivotal role in overcoming the verification challenges that are key to unlocking the potential of agricultural mitigation.

In this effort, policy makers in Asia should be able to leverage lessons and data from the recent and ongoing efforts being made in other regions. For example, the protocols for rice and manure management systems established by California's Air Resources Board, as part of the state's Cap-and-Trade Program, illustrate the power of clear protocols to foster investment in agricultural mitigation. Similarly, the recent and pending launch of multiple satellites—the result of investments by multiple governments, nonprofit organizations, and businesses—will drastically improve measurement of CH_4 emissions and set the stage for low-cost monitoring and verification. Policy makers in Asia should build off this recent progress to quickly establish similar protocols and emissions markets in the region.

In summary, the Asian region will play a pivotal role in determining whether a carbon-neutral food system becomes reality, as it is currently the source of 40% of global food-related emissions. Policy makers should play at least two important roles in this effort. First, they must ensure a sufficient level of investment in new technologies that are relevant to emissions, taking care to not only focus on technologies that reduce CH_4 and NO_2 emissions or enhance soil carbon storage, but also to invest in improving agricultural productivity that is a key determinant of land use change emissions. Second, they should establish clear targets for reducing overall emissions and provide the necessary protocols and monitoring systems to ensure that actions that reduce emissions can be properly incentivized. In both efforts, coordination with policy makers in other regions will likely help to magnify and speed up the impact of their actions.

References

Acemoglu, D., P. Aghion, L. Bursztyn, and D. Hemous. 2012. The Environment and Directed Technical Change. *American Economic Review* 102(1): 131–166.

Allen, M. R. et al. 2016. New Use of Global Warming Potentials to Compare Cumulative and Short-lived Climate Pollutants. *Nature Climate Change* 68(6): 773–6. https://www.nature.com/articles/nclimate2998

Azzari, G., P. Grassini, J. I. R. Edreira, S. Conley, S. Mourtzinis, and D. B. Lobell. 2019 Satellite Mapping of Tillage Practices in the North Central US Region from 2005 to 2016. *Remote Sensing of Environment* 221: 417–429.

Bai, Z. et al. 2018. China's Livestock Transition: Driving Forces, Impacts, and Consequences. *Science Adv*ances 4: 1–12.

Beerling, D. J. et al. 2018. Farming with Crops and Rocks to Address Global Climate, Food and Soil Security. *Nature Plants* 4: 138–147.

———. 2020. Potential for Large-scale CO2 Removal via Enhanced Rock Weathering with Croplands. *Nature* 583: 242–8. http://dx.doi.org/10.1038/s41586-020-2448-9

Blanc-Betes, E. et al. 2021. In Silico Assessment of the Potential of Basalt Amendments to Reduce N2O Emissions from Bioenergy Crops. *GCB Bioenergy* 13: 224–41. https://onlinelibrary.wiley.com/doi/full/10.1111/gcbb.12757

Borchard, N. et al. 2019. Biochar, Soil and Land-use Interactions that Reduce Nitrate Leaching and N2O Emissions: A Meta-analysis. *Science of the Total Environment* 651: 2354–64.

Bossio, D. A. 2020. The Role of Soil Carbon in Natural Climate Solutions. *Nature Sustainability* 3: 391–8. http://dx.doi.org/10.1038/s41893-020-0491-z

Burney, J. A., S. J. Davis, and D. B. Lobell. 2010a. Greenhouse Gas Mitigation by Agricultural Intensification. *Proceedings of National Academy of Science* 107(26): 12052–12057.

Cassman, K. G., and P. Grassini. 2020. A Global Perspective on Sustainable Intensification Research. *Nature Sustainability* 3: 262–8. http://dx.doi.org/10.1038/s41893-020-0507-8

Chapman, M. et al. 2020. Large Climate Mitigation Potential from Adding Trees to Agricultural Lands. *Global Change Biology* 26(8): 4357–4365.

COWI, Ecological Institute, and IIEP. 2021 *Setting Up and Implementing Result-based Carbon Farming Mechanisms in the EU.* Report to the European Commission, DG Climate Action. European Commission. https://op.europa.eu/en/publication-detail/-/publication/10acfd66-a740-11eb-9585-01aa75ed71a1/language-en

Crippa, M., E. Solazzo, D. Guizzardi, F. Monforti-Ferrario, F. N. Tubiello, and A. Leip. 2021. Food Systems are Responsible for a Third of Global Anthropogenic GHG Emissions. *Nature Food* 2: 198–209.

Cui, Z. et al. 2018. Pursuing Sustainable Productivity with Millions of Smallholder Farmers. *Nature* 555: 363–66.

Dubayah, R. et al. 2020. The Global Ecosystem Dynamics Investigation: High-resolution Laser Ranging of the Earth's Forests and Topography. *Science of Remote Sensing* 1: 100002.

Duren, R. M. et al. 2019. California's Methane Super-emitters. *Nature* 575: 180–4. https://www.nature.com/articles/s41586-019-1720-3

Eagle, A. J., L. P. Olander, K. L. Locklier, J. B. Heffernan, and E. S. Bernhardt. 2017. Fertilizer Management and Environmental Factors Drive N2O and NO3 Losses in Corn: A Meta-Analysis. *Soil Science Society of America Journal* 81(5): 1191–202. https://acsess.onlinelibrary.wiley.com/doi/full/10.2136/sssaj2016.09.0281

Fuglie, K. 2018. R&D Capital, R&D spillovers, and Productivity Growth in World Agriculture. *Applied Economic Perspectives Policy* 40(3): 421–444.

Fuglie, K., S. Ray, U. L. C. Baldos, and T. W. Hertel. 2022. The R&D Cost of Climate Mitigation in Agriculture. *Applied Economic Perspectives and Policy*. https://doi.org/10.1002/aepp.13245

Ganesan, A. L. et al. 2017. Atmospheric Observations Show Accurate Reporting and Little Growth in India's Methane Emissions. *Nature Communications* 81(8): 1–7. https://www.nature.com/articles/s41467-017-00994-7

Grassi, G., J. House, F. Dentener, S. Federici, M. den Elzen, and J. Penman. 2017. The Key Role of Forests in Meeting Climate Targets Requires Science for Credible Mitigation. *Nature Climate Change* 73(7): 220–6. https://www.nature.com/articles/nclimate3227

Grassini, P., and K. G. Cassman. 2012. High-yield Maize with Large Net Energy Yield and Small Global Warming Intensity. *Proceedings of the National Academy of Sciences* 109: 1074–9. http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3268318&tool=pmcentrez&rendertype=abstract

Griscom, B. W. et al. 2017. Natural Climate Solutions. *Proceedings of National Academy of Science* 114: 11645–50. https://www.pnas.org/content/114/44/11645

Gvakharia, A., E. A. Kort, M. L. Smith. and S. Conley. 2020. Evaluating Cropland N2O Emissions and Fertilizer Plant Greenhouse Gas Emissions With Airborne Observations. *Journal ofGeophysical Research: Atmospheres* 125(16): e2020JD032815.

Harris, N. L. et al. 2021. Global Maps of Twenty-first Century Forest Carbon Fluxes. *Nature Climate Change* 11: 234–240.

Hertel. T. W. 2018. Economic Perspectives on Land Use Change and Leakage. *Environmental Research Letters* 13: 075012.

Hong, C. et al. 2021. Global and Regional Drivers of Land-use Emissions in 1961–2017. *Nature* 589: 55–561.

Hosonuma, N. et al. 2012. An Assessment of Deforestation and Forest Degradation Drivers in Developing Countries. *Environmental Research Letters* 7: 044009.

Kritee, K. et al. 2018. High Nitrous Oxide Fluxes from Rice Indicate the Need to Manage Water for Both Long- and Short-term Climate Impacts. *Proceedings of the National Academy of Sciences* 115: 9720–5.

Lasco, R. D., R. J. P. Delfino, D. C. Catacutan, E. S. Simelton, and D. M. Wilson. 2014. Climate Risk Adaptation by Smallholder Farmers: The Roles of Trees and Agroforestry *Current Opinion in Environmental Sustainability* 6: 83–88.

Lin, Y. et al. 2018. Impacts of O3 on Premature Mortality and Crop Yield Loss across China. *Atmospheric Environment* 194: 41–7. https://doi.org/10.1016/j.atmosenv.2018.09.024

Lobell, D. B., U. L. C. Baldos, and T. W. Hertel. 2013. Climate Adaptation as Mitigation: The Case of Agricultural Investments. *Environmental Research Letters* 8: 15012. http://stacks.iop.org/1748-9326/8/i=1/a=015012

Lovell, R. J. 2019. Identifying Alternative Wetting and Drying (AWD) Adoption in the Vietnamese Mekong River Delta: A Change Detection Approach. *ISPRS International Journal of Geo-Information* 8(7): 312. https://www.mdpi.com/2220-9964/8/7/312/htm

Lynch. J., M. Cain, R. Pierrehumbert, and M. Allen. 2020. Demonstrating GWP*: A Means of Reporting Warming-equivalent Emissions that Captures the Contrasting Impacts of Short- and Long-lived Climate Pollutants. *Environmental Research Letters* 15(4): 044023. https://iopscience.iop.org/article/10.1088/1748-9326/ab6d7e

Nisbet, E. G. et al. 2020. Methane Mitigation: Methods to Reduce Emissions, on the Path to the Paris Agreement. *Review of Geophysics* 58(1): e2019RG000675. https://onlinelibrary.wiley.com/doi/full/10.1029/2019RG000675

Pardey, P. G. et al. 2018. The Shifting Structure of Agricultural R&D: Worldwide Investment Patterns and Payoffs. In N. Kalaitzandonakes, E. Carayannis, E. Grigoroudis, and S. Rozakis, eds. *From Agriscience to Agribusiness. Innovation, Technology, and Knowledge Management*. Cham: Springer. pp. 13–39. https://doi.org/10.1007/978-3-319-67958-7_2

Pendrill, F. et al. 2019. Agricultural and Forestry Trade Drives Large Share of Tropical Deforestation Emissions. *Global Environmental Change* 56: 1–10.

Phan, H., T. Le Toan, and A. Bouvet. 2021. Understanding Dense Time Series of Sentinel-1 Backscatter from Rice Fields: Case Study in a Province of the Mekong Delta, Vietnam. *Remote Sensing* 13(5): 921. https://www.mdpi.com/2072-4292/13/5/921/htm

Poore, J. and T. Nemecek. 2018. Reducing Food's Environmental Impacts through Producers and Consumers. *Science* 360(6392): 987–92.

Popp, D. 2010. Innovation and Climate Policy. *Annual Review of Resource Economics* 2: 275–98

Reisinger, A. et al. 2021. How Necessary and Feasible Are Reductions of Methane Emissions from Livestock to Support Stringent Temperature Goals? *Philosophical Transactions of the Royal Society A* 379: 20200452. https://royalsocietypublishing.org/doi/abs/10.1098/rsta.2020.0452

Roe. S. et al. 2019. Contribution of the Land Sector to a 1.5 °C World. *Nature Climate Change* 9(11).

Roe, S. et al. 2021. Land-based Measures to Mitigate Climate Change: Potential and Feasibility by Country. *Global Change Biology* 27(23): 6025–6058. https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.15873

Roque, B. M. et al. 2021. Red Seaweed (Asparagopsis Taxiformis) Supplementation Reduces Enteric Methane by over 80 percent in Beef Steers. *PLoS One* 16: e0247820. https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0247820

Seifert, C .A., G. Azzari, and D. B. Lobell. 2018. Satellite Detection of Cover Crops and their Effects on Crop Yield in the Midwestern United States. *Environmental Research Letters* 13: 064033.

Shang, Z., M. Abdalla, L. Xia, F. Zhou, W. Sun, and P. Smith. 2021. Can Cropland Management Practices Lower Net Greenhouse Emissions Without Compromising Yield? *Global Change Bioliogy* 27: 4657–70. https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.15796

Shcherbak, I., N. Millar, and G. P. Robertson. 2014. Global Metaanalysis of the Nonlinear Response of Soil Nitrous Oxide (N2O) Emissions to Fertilizer Nitrogen. *Proceedings of the National Academy of Sciences* 111: 199–204. https://www.pnas.org/content/111/25/9199

Smith, P., D. Reay, and J. Smith. 2021. Agricultural Methane Emissions and the Potential for Mitigation. *Philosophical Transactions of the Royal Society A* 379: 20200451. https://royalsocietypublishing.org/doi/abs/10.1098/rsta.2020.0451

Stevenson, J., D. Byerlee, N. Villoria, T. Kelley, and M. Maredia. Agricultural Technology, Global Land-use and Deforestation: A Review and New Estimates of the Impact of Crop Research. *Measuring the Environmental Impacts of Agricultural Research: Theory and Applications to CGIAR Research* (2011): 49–87.

Tian, H. et al. 2020. A Comprehensive Quantification of Global Nitrous Oxide Sources and Sinks. *Nature* 586: 248–56. http://www.ncbi.nlm.nih.gov/pubmed/33028999

Tubiello, F. N. 2018. Greenhouse Gas Emissions Due to Agriculture. *Encyclopedia of Food Security and Sustainability*. Volume 1. Amsterdam: Elsevier, pp. 196–205.

Villoria, N. B. 2019. Consequences of Agricultural Total Factor Productivity Growth for the Sustainability of Global Farming: Accounting for Direct and Indirect Land Use Effects. *Environmental Research Letters*.

Wang, Y. et al. 2021 .Potential Benefits of Liming to Acid Soils on Climate Change Mitigation and Food Security. *Global Change Bioliogy* 27(12): 2807–21. https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.15607

Yagi, K. et al. 2019. Potential and Promisingness of Technical Options for Mitigating Greenhouse Gas Emissions from Rice Cultivation in Southeast Asian Countries. *Soil Science and Plant Nutrition* 66(1): 37–49. https://doi.org/10.1080/00380768.2019.1683890

Zhang, G. et al. 2020. Fingerprint of Rice Paddies in Spatial–Temporal Dynamics of Atmospheric Methane Concentration in Monsoon Asia *Nature Communications* 11: Article 554. https://www.nature.com/articles/s41467-019-14155-5

PART V

Carbon Pricing

8

Exploiting Complementarity of Carbon Pricing Instruments for Low-Carbon Development in the People's Republic of China

Jie Wu, Ying Fan, Govinda Timilsina, and Yan Xia

8.1 Introduction

As global emissions have been increasing steadily, there is an urgent need to speed up the process of reducing emissions for all countries around the world. After setting a series of energy and climate policy targets, the Government of the People's Republic of China (PRC) pledged in the Paris Agreement that its carbon emissions would peak around 2030, while further committing to reach carbon neutrality before 2060 in the 2020 United Nations General Assembly (Ministry of Ecology and Environment of the People's Republic of China 2021). To achieve these goals, two key targets of reducing carbon dioxide (CO_2) emissions and fossil energy consumption for 2030 were introduced at the Climate Ambition Summit in 2020: a 65% reduction in CO_2 intensity compared to the 2005 level and 25% of the total primary energy supply coming from nonfossil fuels. In addition, in the 14th Five-Year Plan announced in 2021, there is also a goal regarding air quality: The share of days with good air quality in cities at the prefecture level and above should be more than 87.5% by 2025 (State Council of the People's Republic of China 2021). While these targets are interrelated, it seems that it will be difficult to achieve all of them with a single climate policy (Mo et al. 2018; Duan et al. 2021).

Carbon pricing has been considered the first-best policy worldwide to combat climate change, with a carbon tax (CT) and an emissions trading scheme (ETS) being the most common forms. While CT is a tax levied on the carbon emissions required to produce goods and services, an ETS sets a quantitative cap on the total emissions by all participating emitters and provides a market for emission permit trade. Under emissions trading, emitters with high marginal abatement costs could choose to purchase permits from those with low marginal abatement costs, thereby reducing the total abatement cost (Montgomery 1972; Tietenberg 1985). As a market-based instrument, carbon pricing could lead to effective emissions abatement at the lowest possible costs, and therefore is being increasingly implemented by regional, national, and subnational jurisdictions (Borenstein 2012; Mo et al. 2021). According to the World Bank (2021), 67 carbon pricing initiatives were already in place or are scheduled for implementation in the world by 2021. In the PRC, the emissions trading scheme has been adopted as the most important carbon pricing instrument for emissions reduction domestically. Based on a trial run of seven pilot projects at the provincial and city levels since 2013, a nationwide carbon market was announced at the end of 2017. After 3 years of capacity building, which included the construction of a system for reporting, registration, and trading, the nationwide carbon market started operating in July 2021. The nationwide carbon market is planned to cover the following sectors: power generation, petrochemicals, chemicals, building materials, steel and iron, nonferrous metals, paper making, and domestic civil aviation. The average carbon price is CNY47/tCO_2, and the accumulated trade volume is 23.44 million tons until November 2021.

The most important purpose of emissions trading is to encourage institutions to reduce their greenhouse gas emissions through a market-based mechanism to optimize resources allocation and achieve maximum ecological and economic benefits at the lowest possible social cost (Coase 1960; Marshall 1998; Kuika and Mulder 2004). Moreover, providing incentives for utilizing low-carbon technologies and improving energy efficiency has been considered a "second aim" of the nationwide carbon market in the PRC. However, there is great uncertainty regarding this additional aim, as the emissions trading scheme is expected to improve energy efficiency and trigger the innovation of low-carbon technologies in an indirect way. In fact, the emissions trading scheme will not always capture all potential emission sources due to high market operation costs, such as emissions from households and some service sectors. For example, the nationwide carbon market in the PRC only includes the electricity sector in the initial phase and will cover eight energy-intensive sectors as planned. Furthermore, imperfect market conditions may make the ETS, which is usually a cap-and-trade scheme, fail in terms of the optimal output and social welfare (Geng and Fan 2021).

Some empirical studies of the European Union Emissions Trading Scheme (EU ETS) have shown that the impact of the ETS on low-carbon technology innovation and energy efficiency has not been that significant. For example, it has been found that demand-pull policies like the EU ETS can fail to achieve multiple targets unless they are combined with complementary policies (Fischer and Newell 2008; Acemoglu et al. 2012; Gawel, Strunz, and Lehmann 2014; Borghesi, Cainelli, and Mazzanti 2015; Río 2017). In addition, Rogge, Schneider, and Hoffmann (2011) found that the impact of the EU ETS on renewables and demand-side energy savings has been limited and that the EU ETS may not provide sufficient incentives for low-carbon technology innovation. Schmidt et al. (2012) evaluated the impact of the EU ETS on technological change using novel survey data from the electricity sector in seven EU countries and found that the EU ETS has had limited and even controversial effects. They therefore suggested that other technology policies should be adopted to complement the ETS policy. Calel and Dechezleprêtre (2012) provided a comprehensive empirical assessment of the impact of the EU ETS on low-carbon technological change in both regulated and unregulated companies. Their results showed no evidence of technological change from the EU ETS in non-ETS companies, indicating that a single carbon price by itself is not enough to have a substantial impact on bringing about low-carbon technological change.

In the context of the PRC, there have been a lot of analysis and discussions focusing on the two types of carbon pricing policies—ETS and CT (Cui et al. 2014; Zhang et al. 2014; Zhang 2015; Jiang et al. 2016; Guo et al. 2020; Yu et al. 2020). Guo et al. (2014) applied a computable general equilibrium (CGE) model to investigate the impacts of a carbon tax on the PRC's economy and carbon emissions and suggested that a carbon tax would be an effective means of reducing carbon emissions. The empirical results in their study indicate that a moderate carbon tax would significantly reduce carbon emissions and fossil fuel energy consumption in the PRC, while it would slightly reduce the pace of economic growth. In order to evaluate the economic impacts of the national ETS on different regions, Pang and Timilsina (2021) developed a multiregional CGE model and found that emission-intensive regions experience higher gross domestic product (GDP) loss in attempting to achieve the PRC's nationally determined contributions in 2030 through an ETS. Based on the comparison of carbon tax and carbon trading under the same GDP effect using a CGE model, Jia and Lin (2020) suggested rethinking the choice of CT and carbon trading in the PRC. They found that the emissions reduction efficiency of the CT is higher than that of carbon trading, and this advantage increases over time. From an environmental regulation perspective, Yang, Jiang, and Pan (2020) investigated the employment double-dividend effect of carbon trading policy in the PRC and suggested that the PRC needs to form a complete set of strict ecological environment protection policies and administrative measures to achieve sustainable development of the economy.

Given the uncertainties surrounding the implementation of a single carbon pricing, complementary policies may provide a hedge against the failure to achieve multiple climate targets (Pizer 1999; Newell and Pizer 2003). For example, a mixture of carbon market and renewable energy policies is necessary in order to achieve both targets of emissions reduction and renewable energy development (Tu and Mo 2017; Fan 2018; Wu et al. 2020; Gugler, Haxhimusa, and Liebensteiner 2021). Lecuyer and Quirion (2013) argued that the risk of the CO_2 price dropping to zero cannot be excluded from the ETS and that it could be socially beneficial to implement an additional instrument to encourage emissions reduction. Hoel (2012) investigated the impact of uncertainty when a subsidy is combined with a CT; he pointed out that regulatory failures may lead to a carbon price that is too low, and additional instruments, such as subsidies, may be required in some cases. While carbon pricing is usually considered to be the first-best option, Hepburn, Stern, and Stiglitz (2020) and Rosenbloom et al. (2020) suggested that a mix of policies may best lead to a deep decarbonization at an accelerated pace. An earlier study by Mandell (2008) analyzed whether it is preferable to regulate a portion of the economy through a cap-and-trade program while subjecting the rest to a CT rather than subjecting the entire economy to either a cap-and-trade program or a CT, and he suggested that mixed regulation can be superior in some conditions.

Although a nationwide carbon market is already operating, the most ambitious policy would cover only 50% of the total emissions in the PRC (Cao et al. 2019). For that reason, it is of great importance to assess whether a single cost-effective instrument is enough for developing a low-carbon economy or whether a policy portfolio would be more effective (Duan et al. 2018). There are few studies trying to consider a mixed carbon pricing portfolio in the PRC (Shi et al. 2013; Sun 2014; Bi, Xiao, and Sun 2018; Cao et al. 2019). Using a national CGE model that incorporates short-run unemployment effects, Bi, Xiao, and Sun (2018) compared the impacts of a single ETS, a single CT, and a combination of an ETS and a CT. Assuming that an ETS will stimulate increased energy-saving innovation while a CT will not, their results showed that a mixed system will lead to lower GDP losses than a single carbon pricing, which is similar to the finding in Zhang et al. (2022). While most studies use a fixed CT in the analysis, Cao et al. (2019) compared the impacts of implementing an ETS and a hybrid system including an ETS and a CT on the national economic costs under the same emissions reduction target at a national level, and the results indicated that the hybrid system would achieve the same CO_2 goals with lower permit prices and GDP losses.

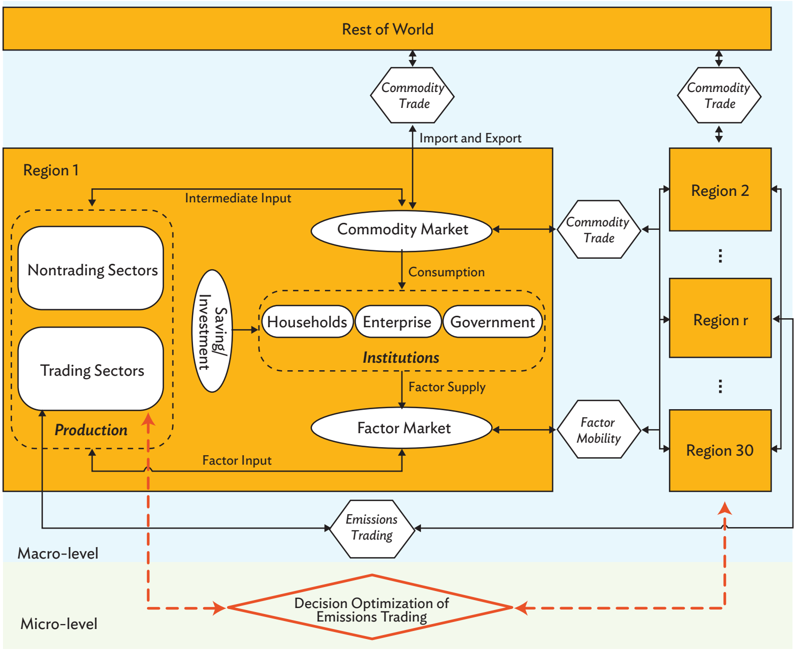
While the above studies explore the impacts of a mixed carbon pricing portfolio in the PRC using a national CGE model, some existing studies have developed multiregional CGE models to discuss the impact of carbon pricing (an ETS or a CT) on regional economies (Zhang et al. 2013; Zhang et al. 2020; Pang and Timilsina 2021; Zhao, Wang, and Cai 2022). However, there is a lack of discussion on the complementarity of different carbon pricing instruments at the regional level. This chapter contributes to previous research by investigating the impacts of different carbon pricing portfolios on regional CO_2 emissions, social costs, interregional factor mobility, sectoral outputs, and export and import in the PRC. Using a multiregional CGE model in the PRC, we not only evaluate the ETS and CT policies separately, but we also simulate the combination of an ETS and a CT. Another contribution of this chapter is that we further discuss two possible policy portfolios by combining carbon pricing with a subsidy for energy-efficient vehicles, to present the promotion of new energy vehicles in the PRC.

Our chapter is organized as follows. Section 8.2 describes the PRC multiregional CGE model used in this research, section 8.3 presents the policy scenarios, section 8.4 displays and discusses the numerical results, and our conclusions are presented in section 8.5.

8.2 Methodology

In this chapter we adopt the Center for Energy and Environmental Policy Research (CEEP) Multi-Regional Energy-Environment-Economy Modelling System (CE^3MS) to analyze the economic impacts of different policies, which is based on a PRC multiregional CGE model. The CE^3MS was first introduced by Wu, Fan, and Xia (2016a) and has been used in various climate policy analyses (e.g., ETS, renewable energy policy, etc.) (Fan et al. 2016; Wu et al. 2016b; Wu et al. 2020). The overall framework of the proposed model is described in section 8.2.1, and the modeling of an ETS and CT will be introduced in section 8.2.2. Section 8.2.3 presents the recycling of auction revenues in an ETS and CT revenues under the CT policy, and section 8.2.4 explains how we can implement subsidies for energy-efficient vehicles in the model.

Figure 8.1: Framework for CE³MS



CE³MS = CEEP Multi-Regional Energy-Environment-Economy Modelling System, CEEP = Center for Energy and Environmental Policy Research.

Sources: Fan et al. (2016).

8.2.1 Framework of the CGE Model

The CE³MS includes 30 regions in accordance with the administrative structure of the PRC (excluding the Tibet Autonomous Region due to a lack of data). Each region consists of production sectors, rural and urban households, a representative enterprise, and a local government. The production sectors are aggregated as 17 representative sectors: one agriculture sector, five energy sectors, seven nonenergy industrial sectors, and four service sectors (Table 8.1). The model includes six modules: production module, emissions trading module, commodity trading module, institution module, labor and capital mobility module, and macro closure. Details of the different modules are provided in one of our earlier papers that was published as a World Bank Policy Research Working Paper (Fan et al. 2017).

Table 8.1: Sector Declarations and Descriptions

Sector	Description
Agriculture	Agriculture, forestry, animal husbandry, and fishery
Coal	Coal
Oil and natural gas	Crude oil and natural gas
Mining	Mining
Food	Manufacture of foods, beverages, tobacco, textiles, wearing apparel, leather, wood, paper, and publishing
Petroleum	Coking, gas, and processing of petroleum
Chemical	Chemical industry
Nonmetallic	Manufacture of nonmetallic mineral products
Metal	Manufacture and processing of metals and metal products
Other manufacturing	Other manufacturing
Electricity	Production and supply of electricity, heat power
Gas	Production and supply of gas, water
Construction	Construction
Transport	Transport, storage, post, information transmission, computer services, and software
Wholesale	Wholesale and retail trades, hotels, and catering services
Real estate	Real estate, leasing, business services, and financial intermediation
Other services	Other services

Sources: Wu, Fan, and Xia (2016a); Fan et al. (2016).

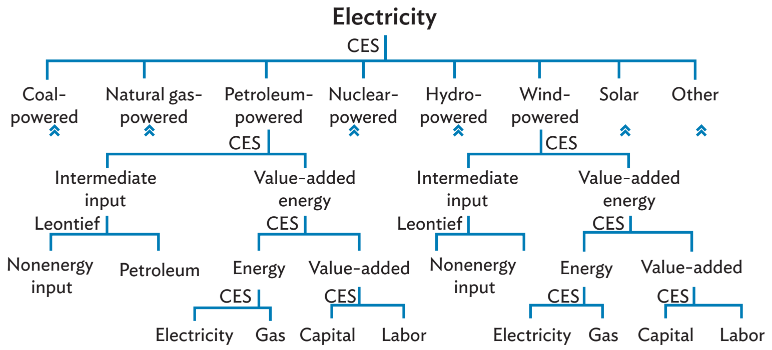
The production module describes the production activities of different sectors under the assumption of cost minimization. We use a nested structure of the constant elasticity substitution (CES) function to formulate the production structure. Generally, the total output of sectors (excluding electricity) is composed of nonenergy intermediate inputs and capital-labor-energy inputs.

$$QA_{j,r} = \alpha_{j,r}\left[\delta_{j,r} QVAE_{j,r}{}^{\rho_{j,r}} + \left(1 - \delta_{j,r}\right) QINTA_{j,r}{}^{\rho_{j,r}}\right]^{\frac{1}{\rho_{j,r}}}, \quad j \notin ele, \quad (1)$$

where $PA_{j,r}$ and $QA_{j,r}$ are the producer price and output of sector j in region r, $QINTA_{j,r}$ and $QVAE_{j,r}$ are the quantity of intermediate input and the value added and energy input, respectively, $\alpha_{j,r}$ and $\delta_{j,r}$ are the efficiency parameter and share parameter of the CES function, and $\rho_{j,r}$ is the substitution elasticity parameter.

The structure of electricity production is given in Figure 8.2, which shows that power generation is represented by eight generation technologies: coal (*Coa*), natural gas (*Ngs*), petroleum (*Pet*), nuclear (*Nuc*), hydropower (*Hyd*), wind (*Win*), solar (*Sol*), and other renewable technologies (*Oth*). Coal, natural gas, and petroleum are raw material inputs of coal-, natural gas-, and petroleum-powered generation and thus are considered to be intermediate inputs rather than value-added or energy inputs for coal-, natural gas-, and petroleum-powered generation.

Figure 8.2: Production Structure of Electricity Sector in CE³MS



CE³MS = CEEP Multi-Regional Energy-Environment-Economy Modelling System, CEEP = Center for Energy and Environmental Policy Research, CES = constant elasticity of substitution.

Source: Fan et al. (2017).

In the commodity trading module, we adopt the Armington assumption to describe the imperfect substitutions between domestic commodities (including local commodities and commodities from other regions) and foreign commodities. With regard to exports, we use the constant elasticity transformation function to distribute the domestic products between exports and domestic sales.

$$QA_{j,r} = \alpha^{cet}_{j,r}\left[\delta^{cet}_{j,r} QDS_{j,r}^{\rho^{cet}_{j,r}} + \left(1-\delta^{cet}_{j,r}\right) QE_{j,r}^{\rho^{cet}_{j,r}}\right]^{\frac{1}{\rho^{cet}_{j,r}}}, \quad \rho^{cet}_{j,r} > 1 \qquad (2)$$

$$QDS_{j,r} = \alpha^{ds}_{j,r}\left[\delta^{ds}_{j,r} QRRE_{j,r}^{\rho^{ds}_{j,r}} + \left(1-\delta^{ds}_{j,r}\right) QRD_{j,r}^{\rho^{ds}_{j,r}}\right]^{\frac{1}{\rho^{ds}_{j,r}}}, \quad \rho^{ds}_{j,r} > 1 \qquad (3)$$

$$QQ_{j,r} = \alpha_{j,r}^{am}\left[\delta_{j,r}^{am} QDC_{j,r}^{\rho_{j,r}^{am}} + \left(1 - \delta_{j,r}^{am}\right) QM_{j,r}^{\rho_{j,r}^{am}}\right]^{\frac{1}{\rho_{j,r}^{am}}} \tag{4}$$

$$QDC_{j,r} = \alpha_{j,r}^{dc}\left[\delta_{j,r}^{dc} QRRM_{j,r}^{\rho_{j,r}^{dc}} + \left(1 - \delta_{j,r}^{dc}\right) QRD_{j,r}^{\rho_{j,r}^{dc}}\right]^{\frac{1}{\rho_{j,r}^{dc}}} \tag{5}$$

Equations (2) and (3) describe the allocation of the total output of commodity j between domestic market ($QDS_{j,r}$) and export ($QE_{j,r}$), where$QRD_{j,r}$ and $QRRE_{j,r}$ are the supply of commodity j in region r and the total supply to other regions, respectively. Equations (4) and (5) describe the total supply of commodity j, which is from domestic market ($QDC_{j,r}$) and import ($QM_{j,r}$). And the supply from the domestic market includes the supply of local production ($QRD_{j,r}$) and production in other regions of the PRC ($QRRM_{j,r}$).

The institution module describes the income, expenditures, and savings of institutions—such as rural and urban households, a representative enterprise, and the local government—in each region. The utility functions of households and local government are assumed as Cobb-Douglas functions in this model. The income of the central government is partly from tax revenue from the various regions, and its expenditures are fixed transfers to the regional governments.

In the labor and capital mobility module, labor and capital are assumed to flow across sectors and regions due to changes in relative wages and returns on capital. Finally, the neoclassical closure is adopted in the macro-closure of CE^{3}MS.

8.2.2 Modeling of ETS and CT

The costs of carbon pricing, either via an ETS or a CT, would directly affect production in the sectors covered by the policy by increasing their total production costs. As shown in Equation (6), the production costs of ETS sectors or CT sectors include not only intermediate input costs and costs of energy and value added, but also the costs of carbon pricing ($TC_{j,r}$).

$$\begin{aligned} PA_{j,r}QA_{j,r} &= PVAE_{j,r}QVAE_{j,r} + PINTA_{j,r}QINTA_{j,r} \\ &+ TC_{j,r}, j \in ETS\ or\ CT \end{aligned} \tag{6}$$

$PVAE_{j,r}$ and $PINTA_{j,r}$ are the price of value added and energy input and the intermediate input, respectively.

When there is an ETS, $TC_{j,r}$ is the total costs of abatement cost and permit trading cost in ETS sectors. Equation (7) shows that by comparing its marginal abatement cost and carbon price, each trading sector can determine its actual emissions reduction and trading volume under the objective of total cost minimization. A decision to reduce emissions will directly affect the production of trading sectors through changes in production costs (Eq. (6)). In the ETS setting of this study, eight energy and energy-intensive sectors in all regions are regulated as trading sectors.

$$Min\, TC_{j,r} = AC_{j,r}(\overline{COE}_{j,r} - COEE_{j,r}) + CP_1 \times (COEE_{j,r} - \overline{COQ}_{j,r}) \tag{7}$$

$$s.t. \sum_{j,r} COEE_{j,r} = \sum_{j,r} \overline{COQ}_{j,r} \tag{8}$$

where $TC_{j,r}$ is the total cost, which includes the abatement cost and trading cost of trading sector j in region r. $COEE_{j,r}$ is the actual emissions under the ETS policy, while $\overline{COE}_{j,r}$ is the emissions in the benchmark. $\overline{COQ}_{j,r}$ is the initial emission quota allocated to sector j in region r, and the "grandfathering" approach is adopted in this study, which means that initial quotas are distributed across sectors based on historic emission levels. CP_1 is the CO_2 price of the nationwide carbon market.

When there is a CT, $TC_{j,r}$ in Equation (6) is the costs of a CT for the sectors on which the CT is imposed.

8.2.3 Recycling of Auction and CT Revenues

So that we can compare the different policies, we recycle the auction revenues and CT revenues in the same way in this chapter. In an ETS, we assume a perfect auction, such that the auction price is equal to the carbon price. To maintain government revenue neutrality, we assume that the auction revenues or CT revenues are returned to households under both the ETS and CT policies. When we adopt an additional subsidy for energy-efficient vehicles, we assume that the auction revenues or CT revenues will be used as subsidies rather than being returned to households.

8.2.4 Subsidies for Energy-Efficient Vehicles

In this chapter, we also consider scenarios that include subsidies for energy-efficient vehicles as a way to encourage emissions reduction in the transport sector. Similarly to Imhof (2011), we implement a subsidy on capital that is used to provide transportation services. The purpose of this subsidy is to encourage consumers to substitute capital for fuel in transportation services, as a way of representing subsidies for energy-efficient vehicles.

8.3 Scenarios

This study utilizes five policy scenarios to assess the impact of different climate policy portfolios in the PRC (Table 8.2), and we set the national CO_2 emissions reduction target at 10%.[1] An ETS scenario refers to a nationwide carbon market covering energy and energy-intensive sectors. A CT scenario refers to a unified CT for all sectors. In the ETS_CT scenario, both ETS and CT policies are adopted when the ETS refers to energy and energy-intensive sectors, and the CT policy refers to the rest of the sectors. A subsidy for energy-efficient vehicles is implemented in the ETS_SUB and CT_SUB scenarios in combination with the ETS and CT policies, respectively. As stated previously, we set the subsidy rate at 10%, which means that 10% of the capital price used in the transport sector is subsidized.

Table 8.2: Scenarios under Different Policies

Scenario	Scenario Description
Scenario S0	The base case without any policies
Scenario ETS	ETS policy for energy and energy-intensive sectors
Scenario CT	CT policy for all sectors
Scenario ETS_CT	ETS policy for energy and energy-intensive sectors and CT policy for the remaining sectors
Scenario ETS_SUB	ETS policy for energy and energy-intensive sectors combined with subsidies for energy-efficient vehicles
Scenario CT _SUB	CT policy for all sectors combined with subsidies for energy-efficient vehicles

CT = carbon tax, ETS = emissions trading scheme.

Source: Authors.

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[1] An earlier study by Cao, Ho, and Timilsina (2016) shows that achieving the PRC's Intended Nationally Determined Contribution would require a 9.8% reduction in emissions over the period 2015–2030. In order to evaluate the profound economic impacts that may be caused by carbon pricing, we simply adopt 10% as the emissions reduction target in this study.

In order to present the results clearly, we classified the 30 regions into three areas (eastern, central, and western) based on the regional divisions used by the National Bureau of Statistics of China (Table 8.3).

Table 8.3: Classification of Regions

Category	Regions
Eastern regions	Beijing (BJ), Tianjin (TJ), Hebei (HB), Liaoning (LN), Shanghai (SH), Jiangsu (JS), Zhejiang (ZJ), Fujian (FJ), Shandong (SD), Guangdong (GD), Hainan (HAN)
Central regions	Shanxi (SX), Jilin (JL), Heilongjiang (HLJ), Anhui (AH), Jiangxi (JX), Henan (HEN), Hubei (HUB), Hunan (HUN)
Western regions	Inner Mongolia (IM), Guangxi (GX), Chongqing (CQ), Sichuan (SC), Guizhou (GZ), Yunnan (YN), Shaanxi (SaX), Gansu (GS), Qinghai (QH), Ningxia (NX), Xinjiang (XJ)

Source: Fan et al. (2016).

8.4 Results

8.4.1 CO_2 Emissions

The total emissions rate is decreased in all scenarios, but the results show differences in the magnitudes of emissions reduction among the different scenarios (Table 8.4). The total emissions reduction under the ETS and ETS_SUB scenarios are a little more than we expected (10%) due to extra emissions reduction in sectors that are not covered by the ETS (non-ETS sectors). The main reason for this is that the non-ETS sectors are affected by the rising costs of energy and energy-intensive products, reduced final demand for goods under ETS, etc. Therefore, the output of these non-ETS sectors—or the intermediate input of energy and energy-intensive products in these sectors—is reduced, leading to a slight decline in emissions. On the other hand, total emissions decrease by 9.35% under the ETS_CT scenario, in which 90% of the emissions reduction target is allocated to the ETS and 10% is expected to be accomplished by the CT. However, our results show that while 90% of the target can be achieved by the ETS under a CO_2 price of CNY55.26/ton, it is still too difficult for non-ETS sectors to achieve the 10% target under a CT of CNY100/ton, as most of these non-ETS sectors are service sectors. Given that the CNY100/ton CT is already quite high for these non-ETS sectors, we have not imposed a further higher CT to force non-ETS sectors to achieve the 10% of the total emissions reduction target. For that reason, the emissions reduction rate under the ETS_CT scenario is 9.35%, which is less than 10%.

Table 8.4: Emissions Reduction Rate and CO_2 Prices

Scenario	Emissions Reduction Rate (%)	CO_2 Price (CNY/ton)	Carbon Tax (CNY/ton)
S1: ETS	10.25	64.81	–
S2: CT	10.00	–	77.18
S3: ETS _CT	9.35	55.26	100
S4: ETS _SUB	10.20	50.14	–
S5: CT _SUB	10.00	–	58.07

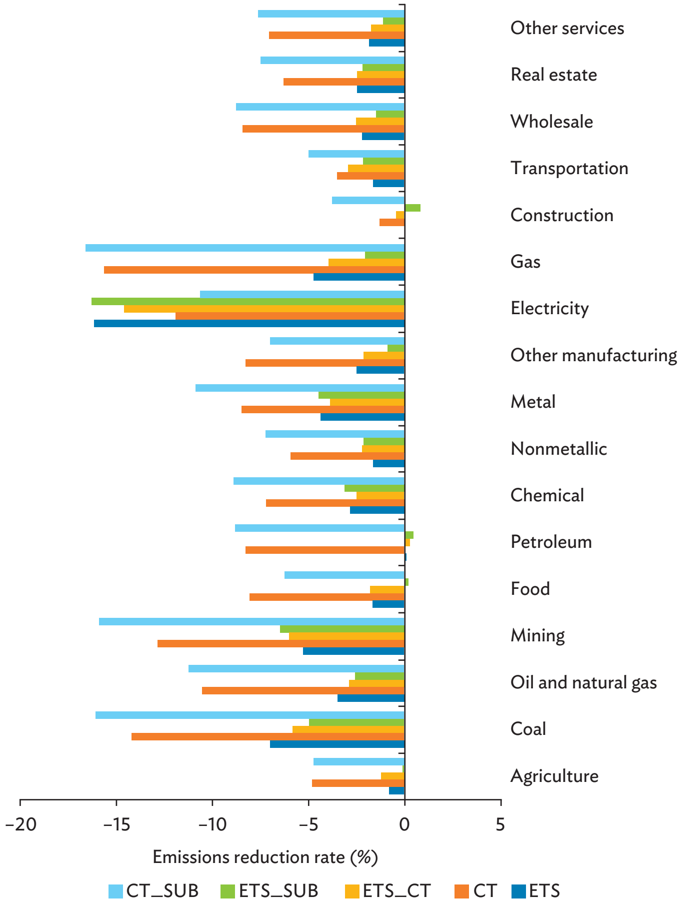
CT = carbon tax, ETS = emissions trading scheme.

Note: Due to differences in scenario settings, the CO_2 prices under the scenarios ETS and ETS_CT are quite different to that in the study by Cao et al. (2019). For example, all energy and energy-intensive sectors are covered by the ETS in this study, while only the electric power and cement sectors are included in the ETS in Cao et al. (2019).

Source: Authors.

By comparing emissions in different sectors, we find that the impact of the ETS policy on the energy sectors is more significant than on the other sectors. Our results show that the emissions in the coal and electricity sectors decrease by 7.0% and 16.2%, respectively, under the ETS scenario, while the service sectors only experience a 1.8% to 2.5% emissions reduction (Figure 8.3). However, the differences in the emissions reduction among the various sectors are relatively smaller under the CT policy than the ETS. These results show that the emissions in the energy and energy-intensive sectors decrease by 5.9% to 15.7% under the CT scenario and that the service sectors experience a 3.5% to 8.4% emissions reduction. The reason for this difference is that although both the ETS and CT are market-based instruments for emissions reduction, the quota allocation scheme of the ETS, which is based on sectoral historic emissions, takes into account the differences in the emissions reduction potential across sectors and allows for higher flexibility in the trading sectors in seeking to meet the emissions reduction targets through self-emissions reduction or quota purchases. Therefore, the energy and energy-intensive sectors have a higher degree of responsibility than the other sectors for reducing their rates of emission under the ETS and ETS_SUB scenarios.

Figure 8.3: Sectoral Emissions Reduction under Different Scenarios



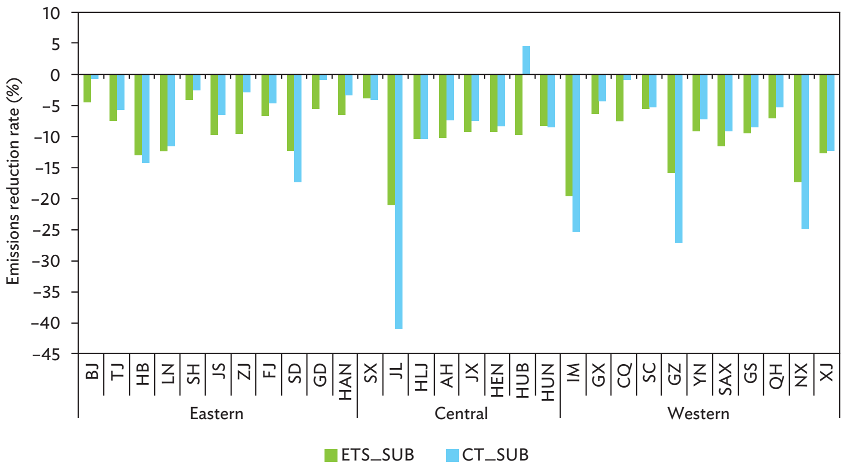
CT = carbon tax, ETS = emissions trading scheme.

Source: Authors.

We propose that an additional policy of providing subsidies for energy-efficient vehicles will lead to greater emissions reduction in the transport sector and energy-intensive industries. The results in Figure 8.3 show that the emissions from the chemical, nonmetallic, and metal sectors are reduced by 7.2%, 5.9%, and 8.5%, respectively, under the CT scenario, and they experience further reductions of 8.9%, 7.2%, and 10.9%, respectively, under the CT_SUB scenario. The results are similar under both ETS and ETS_SUB scenarios. The main reason for these results is that subsidies for energy-efficient vehicles reduce the demand for energy or energy-intensive products. On the other hand, the subsidies, which are from auction revenues or CTs, are returned to households under the ETS and CT scenarios and thus increase the consumption of energy-intensive products to some extent.

Figure 8.4 displays the differences in emissions reduction across regions under the ETS_SUB and CT_SUB scenarios. The results show significant differences between the two policies and that the emissions reduction present larger differences across regions under the CT_SUB scenario. Under the CT_SUB scenario, regions such as Jilin, Guizhou, Ningxia, and Inner Mongolia Autonomous Region need to reduce emissions much more in order to achieve the same emissions reduction target. As there is no emissions trading in the CT_SUB scenario, these regions will suffer from greater economic loss. Compared with CT_SUB, the emissions reduction under the ETS_SUB scenario is more evenly distributed across regions and seem to be more reasonable.

Figure 8.4: Regional Emissions Reduction under Different Scenarios



CT = carbon tax, ETS = emissions trading scheme.

Note: Refer to Table 8.3 for names of regions.

Source: Authors.

8.4.2 GDP and Welfare

Table 8.5 summarizes GDP and welfare changes under different scenarios. In the five different scenarios we present, the PRC would experience GDP losses of 0.07%, 0.13%, 0.05%, 0.13%, and 0.16%, respectively, compared with the base case scenario. As expected, the policies that include the ETS (except ETS_SUB) face lower economic costs than others. It is confirmed that the ETS is more cost-effective than the CT policy. In addition, the combination of ETS and CT policies has a lower GDP cost than the single ETS policy. When subsidies for energy-efficient vehicles are included in the plan, the distortion on consumption and investment increases, thus leading to higher social costs under the ETS_SUB scenario.

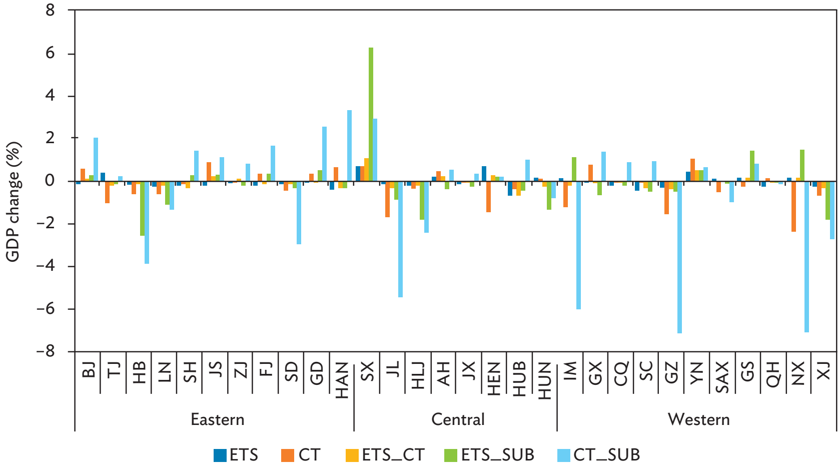
Table 8.5: GDP and Welfare Changes under Different Scenarios

Indicators	ETS	CT	ETS_CT	ETS_SUB	CT_SUB
National GDP Change (%)	−0.07	−0.13	−0.05	−0.13	−0.16
— Eastern Regions	−0.13	0.03	−0.04	−0.20	0.19
— Central Regions	0.09	−0.46	−0.04	−0.01	−0.33
— Western Regions	−0.08	−0.248	−0.11	−0.09	−1.12
Welfare Change (CNY billion)	36.7	147.2	56.9	−24.6	16.8
— Eastern Regions	8.0	80.9	26.2	−13.4	24.5
— Central Regions	18.6	30.5	17.0	−7.4	−2.7
— Western Regions	10.1	35.8	13.7	−3.8	−5.0

CT = carbon tax, ETS = emissions trading scheme, GDP = gross domestic product.
Source: Authors.

Figure 8.5 shows the GDP changes across regions under different scenarios. In regard to policy impacts at the regional level, four central and western regions—Jilin, Inner Mongolia Autonomous Region, Guizhou, and Ningxia—experience more significant GDP losses than other regions under the CT and CT_SUB scenarios. This indicates that the ETS policy could better reflect regional equity than the CT policy. The results in Figure 8.5 show that the GDP in all regions is affected less under the ETS and ETS_CT scenarios. Compared with a single ETS policy, the combination of subsidies for energy-efficient vehicles and the ETS has a larger impact on regional GDP, especially in Shanxi, Hebei, Heilongjiang, and Xinjiang.

Figure 8.5: Regional GDP Changes under Different Scenarios



CT = carbon tax, ETS = emissions trading scheme, GDP = gross domestic product.

Note: Refer to Table 8.3 for names of regions.

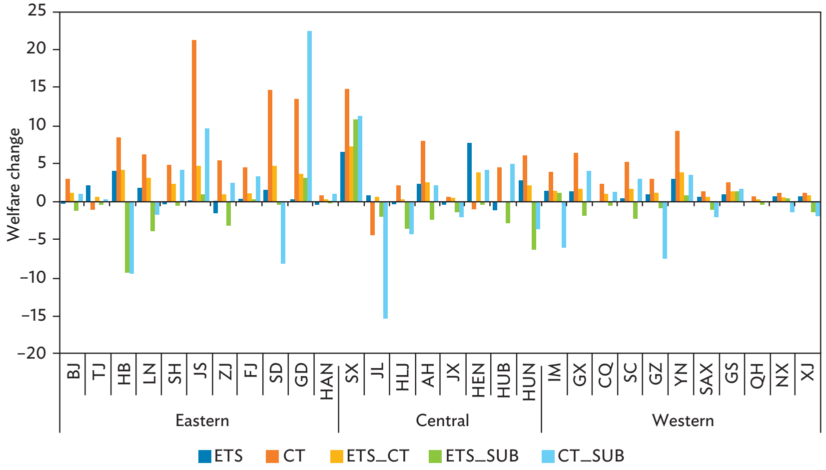
Source: Authors.

As shown in Table 8.5, total welfare in the PRC increases by CNY36.7, CNY147.2, CNY56.9, and CNY16.8 billion under the ETS, CT, ETS_CT, and CT_SUB scenarios, respectively, while it decreases by CNY24.6 billion under the ETS_SUB scenario. As we have assumed in this chapter that either the auction revenues from the ETS or the revenues from the CT are all returned to households, the disposable incomes of households increase; thus, our results show welfare benefits in various regions, especially in the eastern regions. However, when the auction revenues and the CT are used as subsidies for energy-efficient vehicles, the disposable income of households is directly reduced. Therefore, the total welfare increases less under the CT_SUB scenario and even experiences a loss under the ETS_SUB scenario. By comparing the ETS, CT, and ETS_CT, we find that the ETS_CT improves the welfare in all regions. Shanxi, the province with the most coal resources in the PRC, experiences the biggest welfare increase compared to the other regions under the ETS_CT scenario.

Although we show that the welfare increase under the CT scenario is much higher that under the other scenarios, we find that there are wide gaps among the welfare increases across regions (Figure 8.6).

Regions with high emissions, such as Jiangsu, Shandong, Guangdong, and Shanxi, have much higher welfare increases than the other regions. The main reason is that these regions have more CT revenue if they implement a uniform CT, and this leads to a higher income for the local households. Regional coordinated development is an important focus in the PRC, and our results show that the CT policy might deepen gaps in the welfare of households across regions.

Figure 8.6: Regional Welfare Changes under Different Scenarios (CNY billion)



CT = carbon tax, ETS = emissions trading scheme.

Note: Refer to Table 8.3 for names of regions.

Source: Authors.

8.4.3 Interregional Labor and Capital Mobility

Different policy portfolios have different impacts on the reallocation of production factors—both labor and capital—across regions. Table 8.6 presents regional labor and capital changes under all scenarios. The results show that the ETS policy and CT policy have opposite effects on interregional labor and capital mobility. The ETS policy performs better in promoting the transfer of labor and capital from eastern regions to the central and western regions. For instance, labor decreases by 0.11% in the eastern regions and increases by 0.20% and 0.07% in the central and western regions under the ETS scenario. At the same time, labor in the central and western regions transfers to the eastern regions under the CT scenario. The results for capital are similar. The main reason is that the central and western regions usually have lower marginal abatement costs for emissions reduction than the eastern regions, and therefore they are major emission permit sale regions in the ETS. Compared with the eastern regions, which have high abatement costs, the central and western regions can choose to reduce emissions and get trading benefits through the ETS, which would increase their relatively higher rates of capital return and wages. This would cause interregional labor and capital mobility from the eastern regions to the central and western regions under the ETS policy.

The labor and capital both indicate mobility from the central and western regions to the eastern regions under the CT and CT_SUB scenarios. These findings indicate that the CT policy would probably exacerbate the imbalanced allocation of production factors between the eastern regions and the central and western regions. With the same cost per unit of emissions reduction under the CT policy, the rate of capital return and wages in the eastern regions are less affected than in the central or western regions due to higher levels of economic development in the eastern regions. For that reason, both labor and capital in the eastern regions show increases of 0.11% to 0.44%, compared with decreases of 0.02% to 1.50% in the central and western regions.

Table 8.6: Labor and Capital Changes under Different Scenarios

Indicators		ETS	CT	ETS_CT	ETS_SUB	CT_SUB
Labor changes (%)	Eastern	−0.11	0.17	0.00	0.04	0.26
	Central	0.20	−0.39	−0.01	−0.10	−0.24
	Western	0.07	−0.02	0.03	0.02	−0.45
Capital changes (%)	Eastern	−0.07	0.11	−0.02	−0.16	0.44
	Central	0.17	−0.29	0.08	0.40	−0.12
	Western	−0.12	−0.26	−0.16	0.05	−1.50

CT = carbon tax, ETS = emissions trading scheme.

Source: Authors.

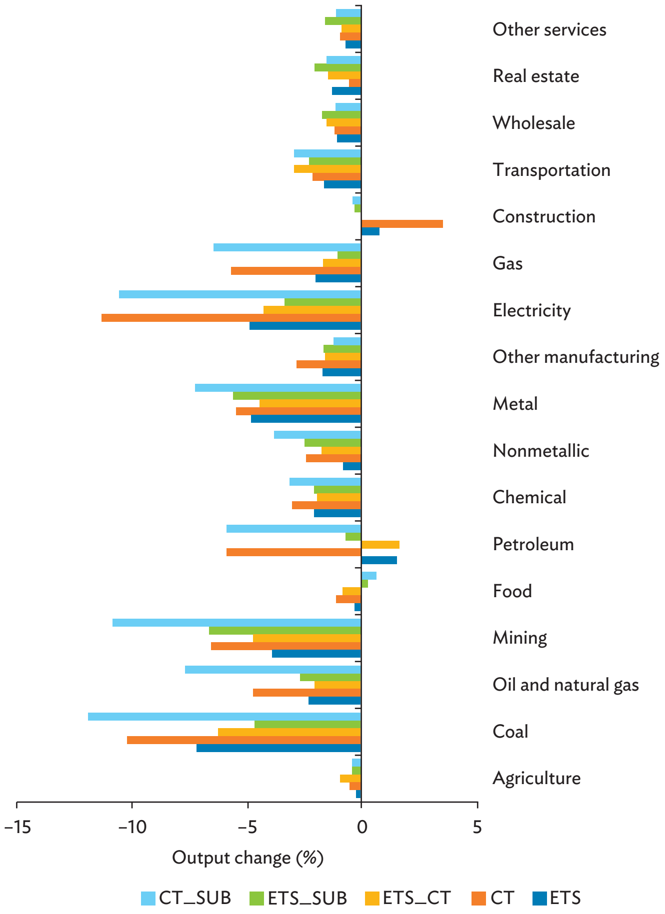
8.4.4 Sectoral Output and Industrial Structure

The total output of the PRC decreases under all policy scenarios, as the emissions reduction policies increase total production costs. Our estimation shows that the total output decreases by 1.53%, 2.38%, 1.77%, 1.84%, and 2.53%, respectively, under the ETS, CT, ETS_CT, ETS_SUB, and CT_SUB scenarios. When comparing ETS and CT policies, we can see that the CT policy leads to increased reduction in total output due to a higher price level for all sectors. Figure 8.7 displays the sectoral output changes under the different scenarios. It shows significant differences in the impacts of the ETS and CT policies on sectoral outputs, with most sectors experiencing more reduction in outputs under the CT and CT_SUB scenarios.

When an ETS policy is included in a scenario, the energy and energy-intensive sectors (except for petroleum) have higher rates of reduction in output than other sectors. As energy and energy-intensive sectors are the targeted industries for emissions reduction in the PRC and are also the main sectors included in the carbon market, these sectors are assigned clear emissions reduction targets and are thus facing more output reduction. By comparing the ETS, ETS_CT, and ETS_SUB scenarios, the electricity industry, which is the largest CO_2 emitter, experiences the biggest reduction in output under the ETS scenario. The main reason is that the adoption of a CT or subsidies for energy-efficient vehicles will reduce the CO_2 emissions from nontrading sectors, especially the transport sector, leading to a reduction in the demand for emission permits in the carbon market. Therefore, the electricity industry will struggle to reduce their excessive output under the ETS_CT and ETS_SUB scenarios. The output of the petroleum sector experiences increases of 1.50% and 1.63% under the ETS and ETS_SUB scenarios, which could be explained by the substitution of petroleum and coal. Another explanation for this is the slight increase in the demand of households as the auction revenues are returned to households. Our results show that the household consumption of petroleum slightly increases (0.47% and 0.79%, respectively) under the ETS and ETS_SUB scenarios.

Table 8.7 presents the industrial structure under the base case scenario and all policy scenarios. As expected, the percentage of energy and energy-intensive products in the total output experiences declines of 0.34% to 1.10% under all scenarios compared to the base case. This indicates that all policy portfolios are effective in reducing the output of high-emission industries. When comparing the ETS and CT policies, the industrial structure adjustment is more significant due to its implementation of a CT. One reason for this is that to reduce emissions,

Figure 8.7: Sectoral Output Changes under Different Scenarios



CT = carbon tax, ETS = emissions trading scheme.

Source: Authors.

the industries with high rates of emission usually choose to change their energy input structures or reduce their output under a CT policy. However, they have more flexibility in achieving reduction targets by purchasing emission permits under an ETS policy, thus avoiding having to reduce their output. Therefore, the ETS, ETS_CT, and ETS_SUB policies are less effective than the CT and CT_SUB policies in promoting changes to the industrial structure.

Table 8.7: Industrial Structures under Different Scenarios

	S0	ETS	CT	ETS_CT	ETS_SUB	CT_SUB
Agriculture	6.20%	6.28%	6.32%	6.26%	6.29%	6.34%
Energy	8.57%	8.44%	8.03%	8.50%	8.50%	8.01%
Energy-intensive	19.63%	19.30%	19.28%	19.36%	19.24%	19.09%
Other	40.39%	40.66%	40.85%	40.64%	40.77%	41.12%
Service	25.21%	25.32%	25.52%	25.25%	25.20%	25.44%

CT = carbon tax, ETS = emissions trading scheme.
Source: Authors.

8.4.5 Exports and Imports

Table 8.8 presents the impacts of different policy portfolios on the total export of goods and services. The total export of goods and services decreases compared to the base case. The results show that the export of energy-intensive goods (i.e., nonmetallic mineral products, metals, and chemicals) significantly decreases under all scenarios. Compared with the ETS and CT scenarios, however, the decline in total exports is more significant under the ETS_SUB and CT_SUB scenarios. This indicates that while the implementation of an ETS or CT decreases the export of energy-intensive goods, subsidies for energy-efficient vehicles cause further drops in the export of energy-intensive goods. In contrast to energy-intensive goods, the export of coal increases by 11.82% to 29.80% under all scenarios. This could be explained by the decreased domestic demand for coal, as most industries would reduce their coal input to control their CO_2 emissions during production.

Table 8.9 presents the impacts of different policy portfolios on the total import of goods and services. This also experiences a decrease, which is mainly caused by the decreased domestic demand. As expected, the import of fossil fuels also experiences a decline, which is conducive to reducing the PRC's energy dependence. The results show that the import of coal and crude oil would decrease by 4.23% to 6.74% and 1.70% to 10.09%, respectively, under all scenarios. As compared with the CT policy, the import of coal decreases more under the ETS, ETS_CT, and ETS_SUB scenarios. However, the import of crude oil has a much more significant decrease under the CT and CT_SUB scenarios.

Table 8.8: Sectoral Export Changes under Different Scenarios (%)

	ETS	CT	ETS_CT	ETS_SUB	CT_SUB
Total	–0.96	–3.31	–1.02	–0.42	–0.09
Agriculture	1.35	0.20	1.69	5.85	5.20
Coal	21.32	29.80	19.90	15.97	11.82
Oil and natural gas	2.49	5.72	3.22	–1.12	–2.68
Mining	23.91	19.54	17.75	1.42	–6.53
Food	0.08	–1.99	–0.57	2.85	4.31
Petroleum	10.75	–6.46	12.95	1.66	–6.54
Chemical	–2.95	–5.84	–1.08	–3.25	–8.01
Nonmetallic	–3.54	–9.55	–2.79	–6.89	–16.49
Metal	–9.25	–12.72	–7.43	–10.08	–13.01
Other manufacturing	–1.08	–3.04	–1.01	–0.98	0.22
Electricity	–3.87	–16.39	–2.98	1.95	6.46
Gas	–3.65	–11.57	–2.63	–0.99	–10.55
Construction	–3.17	–12.34	–4.37	–3.91	–11.54
Transport	0.80	–1.48	–6.57	4.53	2.95
Wholesale	1.33	1.12	1.01	2.15	7.64
Real estate	1.11	10.80	3.05	0.80	14.88
Other services	1.98	4.03	2.62	5.41	10.84

CT = carbon tax, ETS = emissions trading scheme.

Source: Authors.

Table 8.9: Sectoral Import Changes under Different Scenarios (%)

	ETS	CT	ETS_CT	ETS_SUB	CT_SUB
Total	–1.57	–1.43	–1.68	–1.55	–1.13
Agriculture	–0.35	–0.09	–0.79	–0.73	–0.33
Coal	–6.74	–4.90	–6.00	–6.61	–4.23
Oil and natural gas	–2.71	–10.09	–2.69	–1.70	–6.43
Mining	–9.66	–8.28	–9.67	–12.20	–14.31
Food	–0.46	0.22	–0.78	–1.04	–0.55

continued on next page

Table 8.9 *continued*

	ETS	CT	ETS_CT	ETS_SUB	CT_SUB
Petroleum	−2.29	−4.18	−2.45	−1.81	−3.36
Chemical	−1.17	−1.09	−1.65	−1.20	−0.16
Nonmetallic	1.82	4.77	0.08	−0.18	1.29
Metal	−0.30	0.46	−0.95	0.01	1.34
Other manufacturing	−1.38	−1.00	−1.30	−1.05	−0.40
Electricity	1.83	12.45	1.07	−2.03	11.38
Gas	−1.43	−2.21	−1.45	−1.36	−2.83
Construction	−0.50	7.41	−0.30	−0.18	−0.06
Transport	−1.18	−1.11	−0.86	−2.67	−2.35
Wholesale	−1.55	−1.56	−1.90	−1.94	−2.13
Real estate	−0.90	0.06	−1.00	−1.13	−2.04
Other services	−0.55	−1.01	−1.02	−2.10	−1.14

CT = carbon tax, ETS = emissions trading scheme.
Source: Authors.

8.4.6 Comparison of Results with Previous Research

It is important to compare the results in this study with those of previous studies, as it helps to check the robustness of our findings. We find that due to differences in the model structure, database, and setting of policy scenarios, the values of results vary across existing studies. For example, Pang and Timilsina (2021) developed a multiregional CGE model and found that an ETS would cause a national GDP loss of 0.3% to 0.5% in 2030 under a reduction target of 13%, in which all the production sectors are included in the ETS. With a sectoral coverage of seven energy and energy-intensive industries in the national ETS, Jia and Lin (2020) found that the national GDP would decrease by 0.08% to 0.13% in 2030. In this study, eight energy and energy-intensive industries are included in an ETS, and we find that the national GDP experiences a 0.05% to 0.13% reduction under the ETS, ETS_CT, and ETS_SUB scenarios under a 10% reduction target. However, both Pang and Timilsina (2021) and this study have found that from a regional perspective, some regions would benefit from a national ETS whereas other regions would lose out. In terms of the existing studies on a hybrid policy of carbon pricing that are national-level analyses, the findings in Cao et al. (2019) and Zhang et al. (2022) show that a hybrid policy including emissions trading and carbon tax may be the most efficient way to reduce emissions with lower economic cost than a single ETS or CT. This finding is comparable to that of this study.

8.5 Conclusion and Policy Recommendations

To achieve its climate change mitigation targets by 2030 and 2060, the PRC is seeking to implement a variety of measures to reduce emissions. The emissions trading scheme has been adopted by the government as the most important emissions reduction policy in the PRC, and a nationwide carbon market was established in 2017. However, a single policy instrument such as an emissions trading scheme might not be sufficient to reduce all emissions, as it does not encompass all greenhouse gas sources. Therefore, to improve the efficiency of emissions reduction in the PRC, it is necessary to examine whether a single policy could work well or whether it would be better to adopt a policy portfolio.

From regional and industry perspectives, we have compared the impacts of a separate emissions trading scheme, a carbon tax, and the combination of an emissions trading scheme and a carbon tax. We have further evaluated the economic impacts of two policy portfolios by combining these two instruments with subsidies for energy-efficient vehicles.

Our analysis shows that under the emissions reduction target of 10% from the base case, the actual total emissions will be slightly reduced by more than 10% with a nationwide emissions trading scheme due to the additional emissions reduction in sectors that are excluded from the carbon market. Compared with a separate carbon tax, the GDP losses caused by a separate emissions trading scheme, or the policy portfolio of an emissions trading scheme and a carbon tax are lower, especially in some central and western regions. The adoption of subsidies for energy-efficient vehicles on top of an emissions trading scheme or a carbon tax will lead to greater GDP loss. In terms of regional welfare, our analysis shows that although the total welfare increase under a separate carbon tax is much higher than with other policy portfolios, there are wider gaps in welfare increases across regions.

As regards interregional labor and capital mobility, the separate carbon tax policy or the policy mix of a carbon tax and subsidies for energy-efficient vehicles will probably exacerbate the imbalanced allocation of production factors between the eastern regions and the central and western regions. Our analysis shows that a separate emissions trading scheme performs better in promoting the transfer of labor and capital from the eastern regions to central and western regions. When a carbon tax or subsidies for energy-efficient vehicles are implemented, the labor and capital both follow the opposite trend of transferring from the central and western regions to the eastern regions.

While implementing a carbon tax increases social costs in the PRC, it also causes a higher decrease in total output compared with the emissions trading scheme. In addition, although all policy portfolios are effective in reducing the output of high-emission industries, the industrial structure adjustment is more significant when a carbon tax is put in place, especially when combined with subsidies for energy-efficient vehicles. We saw a similar situation in the export of goods and services. While the implementation of an emissions trading scheme or a carbon tax decreases the export of energy-intensive goods, the subsidies for energy-efficient vehicles cause further drops in the export of energy-intensive goods.

In conclusion, as the most important emissions reduction policy in the PRC, a nationwide emissions trading scheme certainly has its advantages compared with a carbon tax, such as cost-effectiveness and regional equity. However, compared to other policies, such as a policy portfolio of a carbon tax and subsidies for energy-efficient vehicles, it is less effective in regard to industrial structure adjustment and emissions reduction in sectors that are excluded from the emissions trading scheme, such as the transport sector. For that reason, policy portfolios could be adopted to improve the efficiency of emissions reduction in the PRC. In terms of social costs, a carbon tax for sectors that are excluded from the emissions trading scheme or subsidies for energy-efficient vehicles could be seen as a supplementary policy for the emissions trading scheme in the PRC. As more countries in Asia and beyond have developed and are developing carbon pricing mechanisms, the findings of this chapter represent an important reference.

The limitations of this study should be noted when interpreting our findings. Due to the limitation of industry classification in the database, the sectors covered by the emissions trading scheme in this chapter are not completely consistent with the sectors included in the national carbon market of the PRC. For example, domestic civil aviation is included in the transport sector in this study rather than as a trading sector in the emissions trading scheme. In addition, this chapter lacks a discussion on the long-term impact of carbon pricing because of the static model. These should be considered for future research.

References

Acemoglu, D., P. Aghion, L. Bursztyn, and D. Hemous. 2012. The Environment and Directed Technical Change. *American Economic Review* 102(1): 131–166.

Bi, H. M., H. Xiao, and K. J. Sun. 2018. The Impact of Carbon Market and Carbon Tax on Green Growth Pathway in China: A Dynamic CGE Model Approach. *Emerging Markets Finance and Trade* 55 (6): 1312–1325.

Borenstein, S. 2012. The Private and Public Economics of Renewable Electricity Generation. *Journal of Economic Perspectives* 26(1): 67–92.

Borghesi, S., G. Cainelli, and M. Mazzanti. 2015. Linking Emission Trading to Environmental Innovation: Evidence from the Italian Manufacturing Industry. *Research Policy* 44(3): 669–683.

Calel, R., and A. Dechezleprêtre. 2012. Environmental Policy and Directed Technological Change: Evidence from the European Carbon Market. *Review of Economics and Statistics* 42(1): 551–574.

Cao, J., M. S. Ho, D. W. Jorgenson, and C. P. Nielsen. 2019. China's Emissions Trading System and an ETS-carbon Tax Hybrid. *Energy Economics* 81: 741–753.

Cao, J., M. S. Ho, and G. R. Timilsina. 2016. Impacts of Carbon Pricing in Reducing the Carbon Intensity of China's GDP. World Bank Policy Research Working Paper WPS 7735. World Bank, 589 Washington, DC. https://ssrn.com/abstract=2811383 (accessed 18 February 2022).

Coase, R. H. 1960. The Problem of Social Cost. *Journal of Law and Economics* 3: 1–44.

Cui, L. B., Y. Fan, L. Zhu, and Q. H. Bi. 2014. How Will the Emissions Trading Scheme Save Cost for Achieving China's 2020 Carbon Intensity Reduction Target? *Applied Energy* 136: 1043–1052.

Duan, H. B., J. L. Mo, Y. Fan, and S.Y. Wang. 2018. Achieving China's Energy and Climate Policy Targets in 2030 under Multiple Uncertainties. *Energy Economics* 70: 45–60.

Duan, H. B. et al. 2021. Assessing China's Efforts to Pursue the 1.5 °C Warming Limit. *Science* 372(6540): 378–385.

Fan, Y. 2018. Optimizing Low-carbon Path by Strengthening Top-Level Design of Carbon Market. *Journal of Environmental Economics* 3(1): 1–7. In Chinese

Fan, Y., J. Wu, Y. Xia, and J. Y. Liu. 2016. How Will a Nationwide Carbon Market Affect Regional Economies and Efficiency of CO2 Emission Reduction in China? *China Economic Review* 38: 151–166.

Fan, Y., J. Wu, G. R. Timilsina, and Y. Xia. 2017. Understanding the Interactions Between Emissions Trading Systems and Renewable Energy Standards Using a Multi-regional CGE Model of China. In:

World Bank Policy Research Working Paper No. 8159. Washington, DC: World Bank.

Fischer, C., and R. G. Newell. 2008. Environmental and Technology Policies for Climate Mitigation. *Journal of Environmental Economics and Management* 55(2): 142–162.

Gawel, E., S. Strunz, and P. Lehmann. 2014. A Public Choice View on the Climate and Energy Policy Mix in the EU — How Do the Emissions Trading Scheme and Support for Renewable Energies Interact? *Energy Policy* 64(6): 175–182.

Geng, W., and Y. Fan. 2021. Emission Trading in an Imperfectly Competitive Product Market: A Comparison of Social Welfare under Mass- and Rate-Based Schemes. *Computers and Industrial Engineering* 162: 107761.

Gugler, K., A. Haxhimusa, and M. Liebensteiner. 2021. Effectiveness of Climate Policies: Carbon Pricing vs. Subsidizing Renewables. *Journal of Environmental Economics and Management* 106(1): 102405.

Guo, J. F., F. Gu, Y. P. Liu, X. Liang, J. L. Mo, and Y. Fan. 2020. Assessing the Impact of ETS Trading Profit on Emission Abatements Based on Firm-level Transactions. *Nature Communications* 11: 2078.

Guo, Z., X. Zhang, Y. Zheng, and R. Rao. 2014. Exploring the Impacts of a Carbon Tax on the Chinese Economy Using a CGE Model with a Detailed Disaggregation of Energy Sectors. *Energy Economics* 45: 455–462.

Hepburn, C., N. Stern, and J. E. Stiglitz. 2020. Carbon Pricing. Special Issue in the European Economic Review. *European Economic Review* 127: 103440.

Hoel, M. 2012. Second-best Climate Policy. Working Paper. Oslo: Oslo University, Department of Economics.

Imhof, J. 2011. Subsidies, Standards and Energy Efficiency. *Energy Journal* 32: 129–152.

Jia, Z., and B. Lin. 2020. Rethinking the Choice of Carbon Tax and Carbon Trading in China. *Technological Forecasting and Social Change* 159: 120187.

Jiang, J., D. Xie, B. Ye, B. Shen, and Z. Chen. 2016. Research on China's Cap-and-trade Carbon Emission Trading Scheme: Overview and Outlook. *Applied Energy* 178: 902–917.

Kuika, O., and M. Mulder. 2004. Emissions Trading and Competitiveness: Pros and Cons of Relative and Absolute Schemes. *Energy Policy* 32: 737–745.

Lecuyer, O., and P. Quirion. 2013. Can Uncertainty Justify Overlapping Policy Instruments to Mitigate Emissions? *Ecological Economics* 93(3): 177–191.

Mandell, S. 2008. Optimal Mix of Emissions Taxes and Cap-and-trade. *Journal of Environmental Economics and Management* 56(2): 131–140.

Marshall, C. 1998. Economic Instruments and the Business Use of Energy. Report to Chancellor of the Exchequer. London: H.M. Treasury.

Ministry of Ecology and Environment of the People's Republic of China. 2021. Responding to Climate Change: China's Policies and Actions. https://www.mee.gov.cn/ywgz/ydqhbh/syqhbh/202107/W020210713306911348109.pdf (accessed 25 March 2022). In Chinese

Mo, J. L., H. B. Duan, Y. Fan, and S. Y. Wang. 2018. China's Energy and Climate Targets in the Paris Agreement: Integrated Assessment and Policy Options. *Economic Research Journal* 53(9): 168–181. In Chinese

Mo, J. L., W. Zhang, Q. Tu, J. Yuan, and Z. Meng. 2021. The Role of National Carbon Pricing in Phasing Out China's Coal Power. *iScience* 24(6): 102655.

Montgomery, W. D. 1972. Markets in Licenses and Efficient Pollution Control Programs. *Journal of Economic Theory* 5(3): 395–418.

Newell, R. G., and W. A. Pizer. 2003. Regulating Stock Externalities under Uncertainty. *Journal of Environmental Economics & Management* 45(2): 416–432.

Pang, J., and G. R. Timilsina. 2021. How Would an Emissions Trading Scheme Affect Provincial Economies in China: Insights from a Computable General Equilibrium Model. *Renewable and Sustainable Energy Reviews* 145(37): 111034.

Pizer, W. A. 1999. The Optimal Choice of Climate Change Policy in the Presence of Uncertainty. *Resource and Energy Economics* 21(3–4): 255–287.

Río, P. D. 2017. Why Does the Combination of the European Union Emissions Trading Scheme and a Renewable Energy Target Make Economic Sense? *Renewable and Sustainable Energy Reviews* 74: 824–834.

Rogge, K. S., M. Schneider, and V. H. Hoffmann, 2011. The Innovation Impact of the EU Emission Trading System: Findings of Company Case Studies in the German Power Sector. *Ecological Economics* 70(3): 513–523.

Rosenbloom, D., J. Markard, F. W. Geels, and L. Fuenfschilling. 2020. Opinion: Why Carbon Pricing Is Not Sufficient to Mitigate Climate Change – and How "Sustainability Transition Policy" Can Help. *Proceedings of the National Academy of Sciences* 117 (16): 8664–8668.

Schmidt, T. S., M. Schneider, K. S. Rogge, M. J. A. Schuetz, and V. H. Hoffmann. 2012. The Effects of Climate Policy on the Rate and Direction of Innovation: A Survey of the EU ETS and the Electricity Sector. *Environmental Innovation and Societal Transitions* 2(2): 23–48.

Shi, M. J., Y. N. Yuan, S. L. Zhou, and N. Li. 2013. Carbon Tax, Cap-and-trade and or Mixed Policy: Which Is Better for Carbon Mitigation? *Journal of Management Sciences in China* 16 (9): 9–19. In Chinese

State Council of the People's Republic of China. 2021. Outline of the 14th Five-Year Plan 2021-2025 for National Economic and Social Development and the Long-range Objectives Through the Year 2035. http://www.gov.cn/xinwen/2021-03/13/content_5592681.htm (accessed 25 March 2022). In Chinese

Sun, Y. N. 2014. Carbon Tax Policy in the Carbon Market. *China Population, Resources and Environment* 24 (3): 32–40. In Chinese

Tietenberg, T. H. 1985. Emissions Trading: An Exercise in Reforming Pollution Policy. Washington, DC: Resources for the Future.

Tu, Q., and J. L. Mo. 2017. Coordinating Carbon Pricing Policy and Renewable Energy Policy with a Case Study in China. *Computers and Industrial Engineering* 113: 294–304.

World Bank. 2021. *State and Trends of Carbon Pricing 2021*. Washington, DC: World Bank.

Wu, J., J. Albrecht, Y. Fan, and Y. Xia. 2016b. The Design of Renewable Support Schemes and CO2 Emissions in China. *Energy Policy* 99: 4–11.

Wu, J., Y. Fan, G. R. Timilsina, Y. Xia, and R. Y. Guo. 2020. Understanding the Economic Impact of Interacting Carbon Pricing and Renewable Energy Policy in China. *Regional Environmental Change* 20: 74.

Wu, J., Y. Fan, and Y. Xia. 2016a. The Economic Effects of Initial Quota Allocations on Carbon Emissions Trading in China. *Energy Journal* 37(SI1): 129–151.

Yang, X., P. Jiang, and Y. Pan. 2020. Does China's Carbon Emission Trading Policy Have an Employment Double Dividend and a Porter Effect? *Energy Policy* 142: 111492.

Yu, S. M., Y. Fan, L. Zhu, and W. Eichhammer. 2020. Modeling the Emission Trading Scheme from an Agent-based Perspective: System Dynamics Emerging from Firms' Coordination Among Abatement Options. *European Journal of Operational Research* 286(3): 1113–1128.

Zhao, Y. B., C. Wang, and W. J. Cai. 2022. Carbon pricing Policy, Revenue Recycling Schemes, and Income Inequality: A Multi-regional Dynamic CGE Assessment for China. *Resources, Conservation and Recycling* 181: 106246.

Zhang, D., S. Rausch, V. J. Karplus, and X. L. Zhang. 2013. Quantifying Regional Economic Impacts of CO_2 Intensity Targets in China. *Energy Economics* 40: 687–701.

Zhang, D., V. J. Karplus, C. Cassisa, and X. L. Zhang. 2014. Emissions Trading in China: Progress and Prospects. *Energy Policy* 75: 9–16.

Zhang, W. W., B. Zhao, Y. Gu, B. Sharp, S. C. Xu, and K. N. Liou. 2020. Environmental Impact of National and Subnational Carbon Policies in China Based on a Multi-regional Dynamic CGE Model. *Journal of Environmental Management* 270: 110901.

Zhang, Y. Q., L. L. Qi, X. Y. Lin, H. R. Pan, and B. Sharp. 2022. Synergistic Effect of Carbon ETS and Carbon Tax Under China's Peak Emission Target: A Dynamic CGE Analysis. *Science of the Total Environment* 825: 154076.

Zhang, Z. X. 2015. Carbon Emissions Trading in China: The Evolution from Pilots to a Nationwide Scheme. *Climate Policy* 15: S104–S126.

9

What Role for Carbon Taxes and Emissions Trading in a Portfolio of Policies to Reduce Greenhouse Gas Emissions?

Frank Jotzo and Dina Azhgaliyeva

9.1 Introduction

Carbon pricing is becoming a mature policy instrument. The first emissions trading system was implemented by the European Union (EU) in 2005. Since then, 46 national jurisdictions (e.g., the United Kingdom, Australia, Singapore, Kazakhstan, Japan, the People's Republic of China [PRC], and the Republic of Korea) and 36 subnational jurisdictions (e.g., Tokyo, Saitama, and California) have implemented some form of carbon tax or emissions trading scheme (ETS) for greenhouse gas (GHG) emissions, collectively referred to as carbon pricing. Other jurisdictions have scheduled the implementation of carbon pricing in the future (e.g., Indonesia and Washington), and others are considering its introduction (e.g., Thailand, Viet Nam, Pakistan, Malaysia, and Türkiye) (World Bank 2022a). ETS and carbon taxes now cover more than 20% of total global emissions (World Bank 2022a). The experiences made in some jurisdictions where carbon pricing has been in place for a long time—have provided important practical lessons and have allowed policy design to evolve in line with experience (Dubash et al. 2002).

However, carbon pricing is practically never the only policy instrument aimed at GHG emissions reduction in jurisdictions where policy effort is made to reduce emissions, and in many instances various kinds of non-pricing policies are the dominant or exclusive form of climate change mitigation policy. In some cases, there is a theoretical case for non-pricing policies on the basis of effectiveness or efficiency, while in other cases the preference for them over or alongside carbon pricing may stem from political or institutional factors.

In practice, there are widespread policy overlaps and extensive interactions between different policy instruments, some aimed fully or primarily at emissions reduction and others that impact emissions as a side effect. Increasingly, policies for emissions reduction come in packages aimed at providing a more comprehensive basis for climate policy, and to allow achievement of policy objectives other than only reducing emissions, such as social or regional economic objectives, or industrial development goals. Carbon pricing often plays a role in these, but that role can differ greatly.

With net-zero carbon emissions goals by around 2050–2060 having been adopted by many countries (including the PRC, Indonesia, Kazakhstan, Viet Nam from developing Asia), alongside stronger medium-term emissions targets in some jurisdictions, policy makers increasingly need to consider climate policy as a tool to facilitate non-marginal change. What is the possible, desirable, or likely role for carbon pricing in portfolios of policies aimed at decarbonization over the coming decades? This chapter approaches this question by drawing inferences from a review of some aspects of policy theory and evidence from implementation in practice.

Section 9.2 reviews the respective roles for carbon pricing and non-pricing instruments. Section 9.3 examines the implementation of policy packages for multiple policy objectives. Section 9.4 reviews some aspects of evolution of design of carbon pricing. Section 9.5 draws some inferences with policy implications for Asia and concludes.

9.2 Roles for Carbon Pricing and Non-Pricing Instruments in Reducing Greenhouse Gas Emissions

9.2.1 Principles of and Role for Carbon Pricing

The theoretically most efficient approach to greenhouse gas emissions across an economy is to implement policy instruments that put an explicit or implicit cost on emitting GHGs, with that cost equal across all sources of emissions. For global efficiency, the marginal cost of emitting (or marginal cost of abatement) should be equal across all jurisdictions.

Further conditions for overall theoretical optimality of emissions reduction policy are that an expectation of future costs of emissions is created in the marketplace so that investment decisions are taken based on the expected future costs of emissions.

Carbon pricing is the most direct, and generally theoretically preferred, policy instrument to achieve this outcome. Nevertheless, carbon pricing in practice needs to be combined with regulatory policy instruments and selected other approaches, in order to variously achieve comprehensiveness, robustness, distributional objectives, or societal acceptance.

An *emissions tax* (usually referred to as a carbon tax although it may also apply to other GHGs), directly sets a price on emissions. The tax rate can be varied over time to adjust for changes in desired emissions reductions, or for changes in costs of reducing emissions. Conversely, an *emissions trading scheme* (or cap-and-trade system) creates an emissions price by way of a government requiring the acquittal of permits to cover each unit of emissions by covered entities, providing permits into the market according to the required maximum amount of emissions, and allowing trading (and possibly banking and borrowing) of permits.

There are variants of carbon pricing systems, for example baseline-and-credit systems where a price for emissions permits is created in the market, but the government is not (or not to a significant extent) an issuer of permits and therefore does not take in (or not to a significant extent) revenue from carbon pricing. Further, there are emissions reduction crediting and credit trading schemes that also create a uniform price on emissions within activities that are part of the scheme, typically on a voluntary basis.

Carbon pricing has a range of design options that governments can use to tailor the instruments to the specific requirements or objectives. These include whether and on what basis to provide free permits under emissions trading or exemptions under carbon taxes, provisions for minimum or maximum market prices under emissions trading, provisions for adjustment of carbon tax rates over time, linkage between emissions trading schemes with other jurisdictions or with emissions offset schemes, decisions about which emitters are covered, and more. These design choices can have consequences for the effectiveness, political acceptability, distributional impacts, and fiscal effects of carbon pricing. Section 9.4 elaborates on some aspects that have been of relevance in practice.

9.2.3 Principles and Roles for Non-pricing Policy Instruments

Types of Non-pricing Policy Instruments

Non-pricing policy instruments for GHG reductions include various regulatory policies that do not involve a direct price levied on emissions content and that usually involve setting emissions standards, subsidies for mitigation action including support research and development (R&D), government procurement of low-emissions goods, services, and infrastructure, and policies that support voluntary action (e.g., through information provisions).

Regulatory measures include technology standards that prescribe the use of certain low-emissions or emissions-reducing technologies (e.g., insulation in buildings, green construction material,[1] or carbon capture-and-storage in gas extraction) or rule out the use of certain high-emissions technologies (e.g., a ban on incandescent light bulbs and appliances with low energy efficiency performance) (Azhgaliyeva, Shen, and Leal forthcoming) or in the future on internal combustion engine cars.[2]

They also, and importantly, include performance standards that prescribe a maximum emissions intensity (or energy intensity) of different products or services, for example, emissions intensity of power stations, fuel use of cars, or energy use of appliances. These performance standards can be tradable, that is many producers or users of specific products can fulfill average performance benchmarks collectively (across a portfolio) and trade the individual overshoot or undershoot with each other. Widely used forms of portfolio standards include renewable energy provision in electricity grids, involving the trade of renewable energy certificates between power producers or distributors; and fuel efficiency standards for car fleets in a jurisdiction, allowing trading of efficiency certificates between different manufacturers.

Governments can also subsidize low-emissions investments and activities (including renewable energy, energy efficiency, carbon capture utilization and storage, clean transportation, green buildings, green hydrogen), including through tax credits, subsidized loans, or direct subsidy programs. Governments further have important levers through their own purchasing decisions, especially in procuring infrastructure, as well as buildings, equipment, and transport facilities, the military and so forth. Subsidies for research, technology development, and development adaptation to specific circumstances are also important areas for

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[1] Five countries—the United Kingdom, India, Germany, Canada, and the United Arab Emirates—pledged to support demand for low-carbon steel, cement, and concrete at the 26th United Nations Climate Conference of the Parties (COP26) in Glasgow.

[2] A declaration to sell only zero-emissions transport vehicles globally by 2040, and by no later than 2035 in leading markets, was signed at COP26 by many governments, local and regional authorities, and automotive companies and investors. These new targets aim to accelerate the transition to zero-emissions transport vehicles in a bid to achieve the Paris Agreement's goals.

government intervention to support low-emissions technologies and practices.

Governments also have a traditional role in providing information that helps in the adoption of low-emissions technologies, for example through mandatory energy efficiency labelling of appliances or buildings (for more information see Chapter 3). Governments can also initiate or support voluntary emissions savings programs, for businesses as well as for individuals, typically by providing an institutional framework for the harmonization and monitoring of voluntary emissions saving activities.

Theoretical Reasons for the Use of Non-pricing Instruments

While economic theory suggests a primary role for carbon pricing, there are several in-principle reasons why non-pricing policy instruments may be required as the sole or primary policy instruments instead of carbon pricing, or in addition to carbon pricing.

These can include the following situations.

Carbon pricing cannot be effectively applied to specific emissions sources when transaction costs are too high. This includes situations where there many small (or "non-point") emissions sources, and/or where the measurement of emissions from specific sources is difficult or costly. A typical example are direct emissions from agricultural activities,[3] which need to be estimated and typically arise from a large number of dispersed sources, making the attribution of precise amounts of emissions to individual companies difficult and costly. Usually, such small emitters are excluded from a carbon pricing policy.

Carbon pricing cannot be effectively applied when the incentive created by carbon pricing is not effective in achieving emissions reductions or split incentives. This can include situations where cognitive or perception issues preclude effective emissions saving investment or activities. A typical example is energy efficiency at the consumer or small business level, where those in charge of making investment decisions may not be aware of energy costs and the additional costs imposed by carbon pricing (and opportunities to save on those costs). Carbon pricing can also be ineffective where there are split incentives, e.g., the cost savings from lower emissions equipment do not flow to the company or individual making the investment—this is often the case in rented buildings (Kapoor et al. 2021).

Carbon pricing cannot be effectively applied when there are externalities or market failures that mean that the optimal marginal cost of emissions in specific applications is higher than the average optimal carbon price, and/or that other policy instruments are required. A typical

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[3] For decarbonization strategies in the agriculture sector, see chapters 6 and 7.

case is when there are positive spillovers from emissions reductions actions in particular activities. The most prominent example of this is low-emissions innovation. The benefits from innovation are to a large extent a public good, and consequently individual companies under invest in innovation. Further, accelerated deployment of novel technologies can result in dynamic cost reductions through learning-by-doing, justifying investment in new emissions saving technologies at higher marginal costs.

In this situation, dynamically optimal policies may require a marginal cost of abatement for the specific activity that is far higher than the average (optimal) marginal cost of abatement across the economy; the dynamic benefit arises from the cost reductions that are achieved by investment into the new technology at initially high unit costs. This can involve technology "push" policies such as R&D subsidies, and technology "pull" policies such as subsidies or performance standards that result in greater deployment. These policies are often used partly in parallel, shifting from an emphasis on push policies toward an emphasis on pull policies as technologies mature and costs fall. Once costs have fallen sufficiently, carbon pricing or other policy instruments applied at the average marginal cost will be sufficient to make the deployment of the emissions saving technology economically efficient. A standout example is solar photovoltaic technology that reduced greatly in production costs as a result of R&D and then policy-driven deployment at relatively high marginal costs of abatement.

Carbon pricing cannot be effectively applied when other existing policies interact with carbon pricing in a way that requires the application of other policy instruments. Existing policy instruments of any kind may either promote emissions savings or the use of high emissions practices and technologies, requiring correction even in the presence of a carbon price. A typical example is subsidies for fossil fuels, which result in an incentive to use a greater amount of fossil fuels and therefore emissions than would be the case without policy. Although many countries pledged to remove fossil fuel subsidies, which are usually not effectively targeted toward the most vulnerable groups (ADB 2016), if subsidies cannot be removed, other measures would be needed to counter the incentive to increase emissions that stems from the subsidies.

One or more of these factors apply to many areas of emissions reductions. Non-pricing policy instruments (also referred to as regulatory policy instruments, although carbon pricing also has its basis in governments' regulatory action) then are needed, whether as sole, primary, or additional policy instruments.

In some cases, the boundary between carbon pricing and non-pricing instruments is blurred, especially where the requirements of a regulation can be achieved through a market-based trading system.

Examples are trading of certificates for renewable energy generation or energy efficiency improvements, which create a market price for these outcomes (e.g., the amount of renewable energy generated) that is not a price on emissions, but that creates broadly similar incentives to a carbon price in the application.

9.2.4 Political Acceptability and Institutional Feasibility of Different Policy Instruments

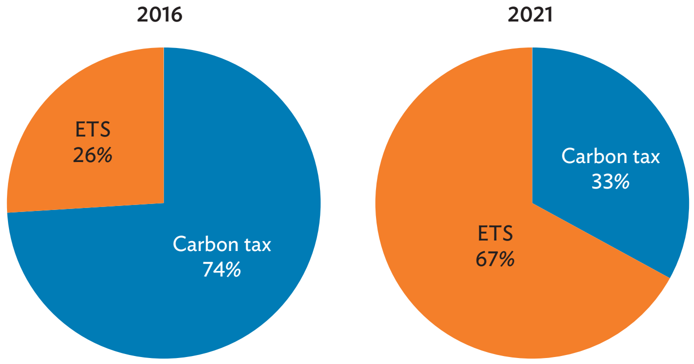
An important factor—and on occasion overriding consideration—in policy choice and design in practice is whether and to what extent different policy instruments are politically acceptable and institutionally feasible, including for implementation.

These factors tend to be strongly context specific. However, it is frequently observed that carbon pricing faces hurdles of acceptability, in particular at the stage of initial implementation. Carbon pricing has faced political difficulties, especially in democracies where one or more parties are positioned politically against climate change policy. Prominent examples of these political dynamics include the federal level of the United States where proposed carbon pricing legislation has never succeeded, and Australia where carbon pricing was at the heart of a political contest over climate policy for many years and where a comprehensive carbon pricing system was legislated and implemented, only to be abolished after 2 years.

In these and other cases, opponents of effective climate policy (or of carbon pricing in particular) created a narrative of carbon pricing as an economically detrimental policy instrument that results in higher costs to industry and thus diminished competitiveness, and higher costs to consumers and thus diminished standards of living. Such narratives usually omit the fact that the revenue from carbon pricing is used to reduce other taxes, provide more government services, or is recycled to emitters; and usually obscure the fact that non-pricing policy instruments tend to have similar effects in terms of rising costs of emissions-intensive processes and products and thus increase production costs and consumer prices. Global carbon pricing revenues have increased sharply. In 2021, revenues reached a record high of $84 billion, which is a 60% increase from 2020 levels (World Bank 2022a). In 2021, revenues from emissions trading schemes exceeded carbon tax revenues for the first time.

With carbon pricing, policy makers and politicians have a difficult task communicating the rationale and relatively complex effects of the policy. It can also be difficult to identify specific examples of where a carbon tax or emissions trading scheme results in emissions reductions,

Figure 9.1: Revenues from Carbon Tax and Emissions Trading Schemes



ETS = emissions trading scheme.

Source: Authors using data from World Bank (2022b).

because of the diffuse and pervasive nature of the price incentive that results in economy-wide marginal changes in investment, production, and consumption decisions.

The practical experience with carbon pricing schemes has shown that the gradual implementation of such policy instruments can be advantageous, for example through “pilot” ETS that apply only in some subnational jurisdictions and where relatively low carbon prices prevail at first, such as in the case of the PRC’s pilot ETS schemes. A gradual approach also allows continuous refinement of policy design and implementation, as was the case with the EU ETS.

Carbon pricing has been shown to be strongly effective in reducing overall emissions, for example one large ex post study suggests that in jurisdictions that had a carbon price in place, average annual growth of covered emissions was 2 percentage points lower than in jurisdictions without a carbon price, after accounting for a multitude of other factors.

However, the solid theory and empirical evidence does not necessarily translate into political feasibility, even in cases where the use of revenue from carbon pricing was broadly designed to maximize voter appeal, as was the case in the Australian carbon pricing system (through income tax reform and changes in social security payments that left a large majority of people better off).

By contrast, non-pricing instruments are typically specific to identifiable activities, processes, and products, and their effect on emissions is more readily apparent and more easily explained to the public, that they can be readily tailored to specific sectors and purposes, and that they may more readily be designed to achieve (or avoid) specific distributional outcomes. For example, support policies for renewable energy deployment typically find relatively strong public support, as the purpose of the policy intervention is clearly defined, and the proximate purpose of the policy (increased supply of renewable energy) is in line with most people's preferences. The framing of a policy as "support" tends to de-emphasize additional costs that are imposed on producers and/or consumers, or consumers are more willing to bear the additional costs because they understand (better than in the case of carbon pricing) what is being achieved.

Institutional feasibility can also be a hindrance to the implementation of broad-based carbon pricing, and instead favor more narrowly focused regulatory policies. This can be the case where emissions monitoring, reporting, and verification or systems for taxation are not uniformly of a high enough standard to base a system of payments on. Instead, it may be more feasible to implement regulatory policies in specific sectors where institutional prerequisites are given.

9.3 Policy Interactions and Packages for Multiple Policy Objectives

In the practice of climate policy making, an array of different policy instruments is used with the objective of reducing emissions. These operate alongside other policies and government measures that affect emissions, their effect being to either decrease or increase emissions. As a result, in practice there are multiple policy overlaps and policy interactions. For best overall effectiveness, policy overlaps and interactions should be recognized, and policies designed accordingly.

Increasingly, governments understand multiple policies as packages, which can be designed to achieve overall outcomes that cover both emissions reductions and other policy objectives. This is an expression of mainstreaming climate change policy into core economic and noneconomic policy making. In policy packages, focus tends to be not on the performance of each policy element in isolation, but on the package as a whole. The following subsections explore these themes both in principle and with reference to policy packages in practice.

9.3.1 Overlap and Interactions of Multiple Policy Instruments

In practice, there will inevitably be overlaps (as well as gaps) between policies that affect emissions, and interactions between different policy instruments. This applies both to new and existing policies and instruments, including ones whose intent is not to effect emissions, such as energy taxes or subsidies. Such interactions can make it complex to optimize any single policy instrument and could mean that individual policy instruments are most effective or efficient if their design deviates from what would be optimal if they operated as stand-alone instruments.

Policy interactions affecting GHG outcomes are often found between energy efficiency policies, and between carbon pricing and tax or subsidy policies, and carbon pricing and regulatory interventions. For example, a large majority of emissions covered by California's emissions trading scheme are also subject to other policy instruments (Mazmanian, Jurewitz, and Nelson 2020).

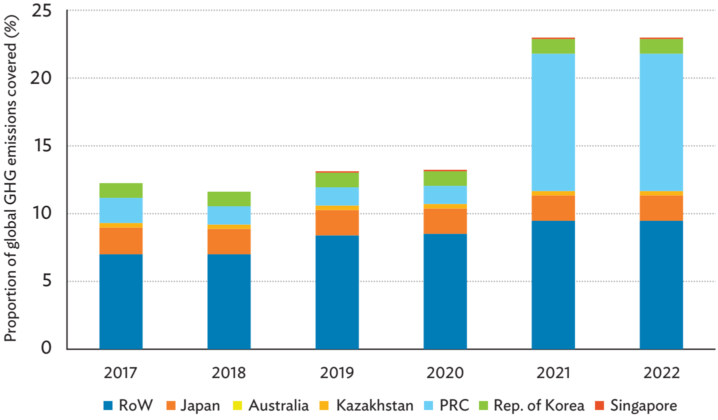
In the typical case of emissions policy interaction, two or more policies that affect the same emissions source will reinforce each other, for example an emitting activity is subject both to an emissions tax and an energy efficiency standard or an energy tax. In other, generally less frequent cases, the interaction is opposite, for example a carbon tax and a fossil fuel subsidy. In the specific case of an emissions trading scheme with a fixed cap (fixed total number of emissions allocations), the trading scheme can neutralize the effect of other existing policies, although these other policies still affect behavior. This is because other policies either reduce or increase the underlying level of emissions and thus the extent of reductions that need to be achieved through the trading scheme, but they do not change the overall outcome (this is referred to as the "waterbed effect").

The overall cost of achieving a given emissions reductions goal will typically be greater as a result of policy interactions. But it will often not be possible to avoid interactions—for example because existing policy instruments are geared toward other objectives, or because comprehensive policy reform is institutionally or politically impossible. Multiple policies can be justified in light of equity objectives and in some cases to achieve greater overall policy effectiveness (Stiglitz 2019), or to create greater robustness of the policy response.

9.3.2 Role of Carbon Pricing and Other Policy Instruments in Selected Jurisdictions from Asia

Globally, 46 national jurisdictions are covered by carbon pricing,[4] covering 23% of global GHG emissions (World Bank 2022a), half of which are covered by the Asia and Pacific region. This subsection provides a brief overview of carbon pricing policies (i.e., ETS and carbon tax) in several jurisdictions from Asia. The existing literature on the experience of carbon pricing in developed countries such as the EU, the United Kingdom, and Australia, is abundant. Although Asia and the Pacific contributes over 50% of global GHG emissions and is expected to contribute two-thirds of energy demand growth by 2040 (IEA 2019) there is a relative lack of literature on experience of carbon pricing in Asia (other than on the PRC pilot ETS).[5] In this section, we are focusing on experience with carbon pricing in Asia and mainly on ETS because carbon tax is less popular in Asia and the Pacific than ETS (Table 9.1).

Figure 9.2: Proportion of Global GHG Emissions in Asia and the Pacific



GHG = greenhouse gas, PRC= People's Republic of China, RoW = rest of the world.

Source: Authors using data from World Bank (2022b).

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[4] As of 16 September 2022.

[5] For carbon pricing in the PRC, see Chapter 8 of this book.

Table 9.1: Emissions Trading Schemes and Carbon Tax in Asia and the Pacific

Carbon Tax	Emissions Trading Schemes
Indonesia, Japan	Kazakhstan; People's Republic of China; Pakistan; Republic of Korea; Japan; Thailand; Viet Nam; Malaysia; Taipei,China; New Zealand

Note: This table includes implemented, scheduled, and under consideration emissions trading schemes and carbon tax.

Source: World Bank (2022a).

Kazakhstan's Emissions Trading Scheme

Kazakhstan's Nationally Determined Contribution (under the framework of the Paris Agreement) has set targets of GHG emissions reduction by 15% (unconditional target) and by 25% (conditional target) by 2030 relative to the 1990 GHG level of 386.3 metric tons of CO_2 equivalent. Kazakhstan has also pledged to net-zero carbon emissions target by 2060 announced at COP26 in Glasgow. Kazakhstan, the largest CO_2 emitter in Central Asia and 14th largest in the world (Marteau 2021), launched its ETS for monitoring, reporting, verification, setting of an emissions cap, and trading of CO_2 emissions in January 2013. Kazakhstan's ETS covers only CO_2 emissions and only entities from a list of covered sectors (Table 9.2). The emissions cap is calculated using a benchmark of CO_2 emissions per output over the 2013–2015 period (Zhasyl Damu 2022). Around half of all emissions were covered by the ETS in 2019 (Suleimenova 2021; KazEnergy 2022). Kazakhstan's ETS is being developed in phases (Table 9.2). Due to the challenges with implementing the ETS, the CO_2 emissions cap allocation and CO_2 emissions trading (but not emissions monitoring) in the ETS was suspended from April 2016 to 2018 (Kapsalyamova 2021; KazEnergy 2022; Zholdayakova et al. forthcoming). Kazakhstan's ETS was revised, particularly the CO_2 emissions cap allocation, and relaunched (Zhasyl Damu 2022). Currently, CO_2 prices in Kazakhstan are low (\$1.1/tCO_2 in 2021) to drive the implementation of decarbonization technologies, including hydrogen (Suleimenova 2021).

Table 9.2: Kazakhstan's Emissions Trading Scheme

Period	Phase	Emissions Cap, $MtCO_2$[a]	Sectors
2013	1st National Allocation Plan	147	Power sector, centralized heating extractive industries, manufacturing, oil and gas mining, metallurgy and chemical industry
2014–2015	2nd Allocation Plan	154.9–152.8	
2016–2017	Temporary suspension of Emissions Trading Scheme		
2018–2020	3rd National Allocation Plan	485.9	Power sector, centralized heating, extractive industries, manufacturing, oil and gas mining, metallurgy, chemical and processing industry (production of building materials: cement, lime, gypsum, and brick)
2021	4th National Allocation Plan	159.9	
2022–2025	5th National Allocation Plan	537.2	

CO_2 = carbon dioxide.

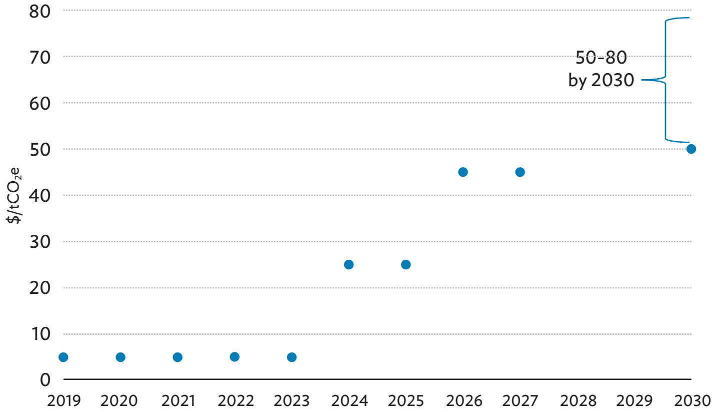
[a] Kazakhstan's ETS sets an emissions cap only on CO_2, other emissions are not covered.

Source: Authors using data from ICAP (2022).

Singapore's Carbon Tax

"Singapore is positioning itself as a hub for trading carbon credits generated from nature-based solutions, leveraging on existing advantages of having an ecosystem of services to engage in carbon finance and trading" (Low and Bea 2021, p.1). In 2020, Singapore set a target to peak GHG emissions at not more than 65 million tons of CO_2 equivalent ($MtCO_2e$) by 2030, halve emissions from its peak to 33 $MtCO_2e$ by 2050, and reach net-zero emissions as soon as viable in the second half of this century (National Climate Change Secretariat 2020). However, in February 2022, it was announced that the government would raise the emissions reduction target to achieve net-zero emissions "by or around mid-century" (National Climate Change Secretariat 2020, 2022; Lim 2022; Low, Ling, and Yi 2022). A carbon tax on large direct emitters was implemented in Singapore in 2019 with an initial tax of S\$5/tCO_2e until 2023 (Li and Su 2017). After that carbon tax will increase starting from 2024 to gradually reach S\$50–S\$80/tCO_2e by 2030 (National Climate Change Secretariat 2022; Lim 2022; Low, Ling, and Yi 2022). The government announced the gradual increase of carbon tax rates in 2024–2030 in advance (February 2022) in order to give businesses time to adjust and to plan accordingly. Plans for revenue from the carbon tax have been also clearly announced by the government to the public: for decarbonization efforts, and to support households and businesses (National Climate Change Secretariat 2022). Singapore's carbon

Figure 9.3: Singapore's Carbon Tax



tCO_2e = ton of carbon dioxide equivalent.

Source: Authors' data from the National Climate Change Secretariat (2022).

tax policy demonstrates the government's prioritization of advance announcement of future carbon tax rates and its revenue use to the public.

Japan's Carbon Tax and Emissions Trading Scheme

Given over 10 years of Japan's experience with carbon pricing in Asia, Japan's experience can provide valuable lessons to Asia. Japan has had a national carbon tax (called Climate Change Mitigation Tax) since 2012 (Box 9.1) and two province-level ETS: one in Tokyo (called Tokyo Cap-and-Trade Program)[6] since 2010 (which was the first ETS in Asia) and the other in Saitama (called Saitama Target-setting ETS)[7] since 2011 (Box 9.2).

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[6] https://www.kankyo.metro.tokyo.lg.jp/en/climate/cap_and_trade/index.html

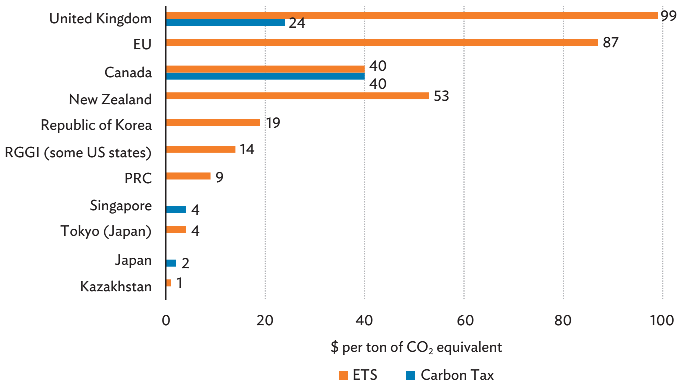
[7] https://www.pref.saitama.lg.jp/a0502/torihikiseido.html

Box 9.1: Japan’s Carbon Tax

This box is written by Wataru Kodama, research associate, Asian Development Bank Institute, and Dina Azhgaliyeva, research fellow, Asian Development Bank Institute.

In 2012, Japan introduced a national carbon tax, the Climate Change Mitigation Tax—one of the first Asian countries to do so (Gokhale 2021)[a]. It targets the carbon price of ¥286 (approximately $3.58)[b] per ton of carbon dioxide (CO_2) by imposing taxes on all fossil fuels such as crude oil, natural gas, and coal based on their CO_2 emissions intensity (e.g., ¥769 per kiloliter for crude oil and ¥670 per ton for coal).[c] Tax revenues are allocated to restraint measures for energy-oriented CO_2 emissions.[c] The petroleum and coal tax, which covers the main fossil fuels, functions as an important tax on fossil fuels. If one considers this tax as well as the Climate Change Mitigation Tax, Japan’s effective carbon price, which includes fossil fuel taxes, carbon taxes, and emissions trading schemes, for main fossil fuels results in about $5–$9 per ton of CO_2 (Table B9.1.1). This price is similar to that of the People’s Republic of China’s ETS but is still one of the lowest in developed economies (Figure B9.1.1). While Japan’s carbon tax has partially helped to reduce around 10% of greenhouse gas (GHG) emissions since 2014, its price needs to be higher to achieve Japan’s ambitious national target of 46% GHG emissions reduction by 2030, which was announced in 2021.[a]

Figure B9.1.1: Carbon Price in Selected Countries (as of April 2022)



ETS = emissions trading scheme, EU = European Union, PRC= People’s Republic of China, RGGI = Regional Greenhouse Gas Initiative, US = United States.

Source: Adapted from World Bank (2022a).

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Box 9.1 *continued*

Table B9.1.1: Effective Carbon Price, Japan

	Crude Oil and Petroleum Products	Gaseous Hydrocarbon (LPG/LNG)	Coal
Climate Change Mitigation Tax	¥779/tCO_2 (\$7.10/tCO_2)	¥400/tCO_2 (\$3.64/tCO_2)	¥301/tCO_2 (\$2.74/tCO_2)
Petroleum and Coal Tax		¥286/tCO_2 (\$2.60/tCO_2)	
Effective Carbon Price	¥1,065/tCO_2 (\$9.70/tCO_2)	¥686/tCO_2 (\$6.25/tCO_2)	¥687/tCO_2 (\$6.26/tCO_2)

Note: Annual average exchange rate of ¥109.795 to $1 in 2021.

Source: Authors' calculation based on Ministry of the Environment (2021).

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[a] Gokhale (2021)

[b] The exchange rate of ¥79.8075 to $1 in 2012 and ¥109.795 to $1 in 2021 is calculated using annual average interbank exchange rates from the Bank of Japan (2022).

[c] Ministry of the Environment (2021)

Box 9.2: Japan's Provincial Emissions Trading Schemes in Tokyo and Saitama

This box is written by Wataru Kodama, research associate, Asian Development Bank Institute, and Dina Azhgaliyeva, research fellow, Asian Development Bank Institute.

In Japan, the national-level carbon pricing has been a great concern to industries, and the government has been encouraging regional-level and voluntary mitigation measures. There are two regional ETS (as of September 2022) in Tokyo and Saitama.

Introduced in 2010, the Tokyo ETS, called the Tokyo Cap-and-Trade Program, regulates the manufacturing and commercial sectors, covering 1,000 offices and commercial facilities and 400 factories or around 40% of GHG emissions in Tokyo.[a] In March 2022, the Tokyo Metropolitan Government released results of the Tokyo Cap-and-Trade Program in the first year of the third compliance period, indicating that covered facility emissions were reduced by 33% (Figure B9.2.1) in 2020 compared to the base year (which is the average emissions of 3 consecutive fiscal years selected by facilities between fiscal years 2002 and 2007) due to energy-saving measures, low-carbon electricity and heat, and the coronavirus disease (COVID-19) pandemic.[b] However, there was no emissions reduction between 2016 and 2019 (Figure B9.2.1).

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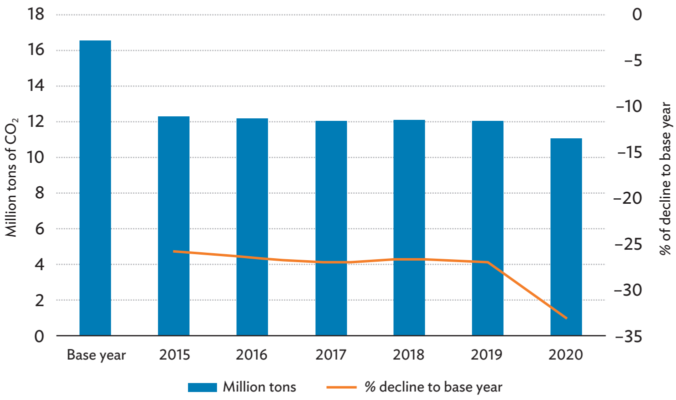
Box 9.2 *continued*

Figure B9.2.1: CO_2 Emissions of Facilities Covered by Tokyo's Emissions Trading Scheme



Note: Emissions in base year are the average emissions of 3 consecutive fiscal years selected by facilities between fiscal years 2002 and 2007.

Source: Authors, using data from Tokyo Metropolitan Government (2022).

Another prefecture, Saitama, introduced an ETS in 2011 with a similar design to Tokyo's ETS.[c] Saitama's ETS, called Saitama Target Setting Emissions Trading System, covers large emitters that have used 1,500 kiloliters or more of crude oil equivalent energy per year for 3 consecutive years.[d] Even though it has stimulated firms' efforts in GHG mitigations[a] and the program lacks penalties for noncompliance,[d] empirical research finds limited reduction impacts[c] due to the relatively low carbon price of around $4 per ton of CO_2 (Figure B9.2.1).

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[a] Wakabayashi and Kimura (2018)
[b] Tokyo Metropolitan Government (2022)
[c] Abe and Arimura (2020)
[d] Hamamoto (2021)

Indonesia's Emissions Trading Scheme and Carbon Tax

Indonesia has scheduled the implementation of a carbon tax sometime in 2022 (after postponing it twice—initial scheduled date was April 2022, with the first postponement until July 2022 and the second postponement's date is unknown) and considers implementing an

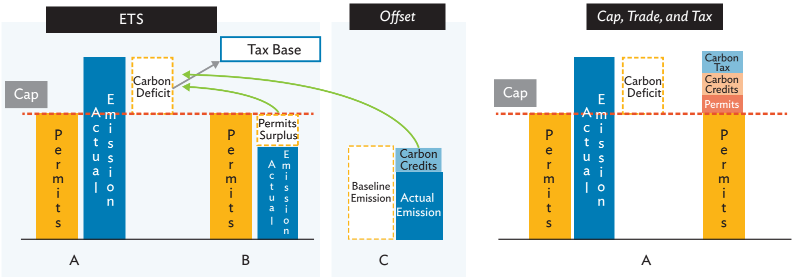
ETS in the future. Indonesia's experience of planning carbon pricing is interesting as a case of a country with heavy reliance on coal for power generation (Box 9.3). A carbon tax is planned to initially cover coal-fired power plants in order to incentivize investments in green technologies such as renewable energy, energy efficiency, and clean transport.

Box 9.3: Carbon Tax Policies in Indonesia

This box is written by Noor Syaifuddin, senior analyst, Fiscal Policy Office, Indonesian Ministry of Finance, and Riznaldi Akbar, senior capacity building and training economist, Asian Development Bank Institute.

The government has stipulated two regulations that mandate implementation of a carbon tax in 2021: President Regulation No. 98/2021 on carbon pricing, and Law No. 7/2021 (Article 13 on carbon tax) on Tax Regulation Harmonization. Carbon taxes are imposed on individual or corporations who buy goods containing carbon and/or emit carbon from their activities.

Figure B9.3.1: Implementation of Carbon Cap-Trade-and-Tax System in Indonesia



Source: Indonesian Ministry of Finance (2021).

Figure B9.3.1 shows that emitters can fulfill their carbon deficit by purchasing permits and/or carbon credits or paying the carbon tax. By the implementation of the cap-trade-and-tax system in Indonesia, the carbon tax price will tend to be the maximum price of both permits and carbon credit. The taxpayer may consider purchasing permits and/or carbon credit as it could be more favorable than the carbon tax with a higher rate. The carbon tax acts like a penalty in the cap-and-trade mechanism. The carbon tax, however, will be liable for the coal-fired power plants that are unable to fulfill their carbon deficit from permits and carbon credits.

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Box 9.3 *continued*

In 2021, the government was planning to implement a cap-trade-and-tax system for coal-fired power plants to come into force by 2022 with the potential ceiling price (i.e., carbon tax rate) of Rp30,000 (approximately $2.20) per tons of carbon dioxide equivalent (CO_2e). The revenues collected from this carbon tax can be used to support the mitigation and adaptation activities in the country. The carbon tax policy will consider the carbon tax and/or carbon market road map.

Table B9.3.1: Potential Carbon Deficit in 2022

Installed Capacity	Cap (tons CO_2e/MWh)	Surplus (million tons CO_2e)	Deficit (million tons CO_2e)	Net Deficit (million tons CO_2e)
MW >400	0,913	4.6	7.3	2.6
100 ≤ MW ≤ 400	1,013	3.6	6.3	2.7
MW ≤ 100	1.091	–	1.1	1.1
25 ≤ MW ≤ 100	1.300	–	–	–
Total				6.4

CO_2e = carbon dioxide equivalent, MW = megawatt.

Source: Indonesian Minister of Energy and Mineral Resources (2022).

On the carbon market of the coal-fired power plants, there is a potential of around 6.4 million tons CO_2e carbon deficit subject to the carbon tax in 2022. This amount remains a potential because it needs to consider how many carbon credits (e.g., from renewable energy etc.) could be used as the carbon tax reduction.

Table B9.3.2: Existing Carbon Related Levies

	Regulation	Object	Remark
Luxury Goods Tax on Motor Vehicles	Government Regulation No. 73/2019	Motor vehicles	The lower the amount of carbon dioxide emitted, the lower the tariff. Electric vehicle (EV): 0% Imposed one time (on import or production)
Regional Tax on Motor Vehicles	• Law No. 28/2009 on Regional Tax and Retribution • Tariff regulated by Regional Regulation	Ownership and/or mastery of motor vehicle	More vehicles owned the higher the tax rate Imposed annually

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Box 9.3 *continued*

	Regulation	Object	Remark
Registration Fee on Motor Vehicles	- Law No. 28/2009 on Regional Tax and Retribution - Tariff regulated by Regional Regulation	Transfer of ownership of motor vehicle	Tax payable for each transfer of ownership EV: 90% tariff reduction (national) and 0% tariff (DKI Jakarta and Bali)
Regional Tax on Fuel	- Law No. 28/2009 on Regional Tax and Retribution - Tariff regulated by Regional Regulation	Fuel of motor vehicle	

Source: Indonesian Ministry of Finance (2021).

Prior to the enactment of the carbon tax, there are various levies related to carbon. The most recent was Government Regulation No. 73/2019 imposing 0% tariff of luxury tax goods on electric vehicles. Even though the levies do not specifically entail a carbon levy, it has addressed environmental and carbon issues, while provided fiscal incentive to more green projects.

References

Regulation of the President of the Republic of Indonesia Number 98 of 2021 on the Implementation of Carbon Pricing

Law Number 7 of 2021 on Harmonization of Tax Regulation

Government Regulation Number 73 of 2019 on taxable goods classified as luxurious in the form of motor vehicles that are object to sales tax on luxury goods

Implementation of Carbon Economic Value (NEK) in Indonesia, Ministry of Finance, February 2022

Implementation of Carbon Economic Value in the Electricity Subsector, Minister of Energy and Mineral Resources, February 2022

The Republic of Korea’s Emissions Trading Scheme

The Republic of Korea has set a goal to reduce total national GHG emissions by 40% (727.6 $MtCO_2e$) from the 2018 level by 2030 and carbon neutrality by 2050. The Republic of Korea launched its national ETS in 2015 (Box 9.4). Unlike Kazakhstan’s ETS, the Republic of Korea’s ETS covers several GHG emissions, not only CO_2. It covers the following sectors: industry, power, building, domestic aviation, the public sector, and waste. About 73% of emissions are covered by the ETS (World Bank 2022a).

Box 9.4: The Republic of Korea's Emissions Trading Scheme

This box is written by Seung Jick Yoo, professor, Sookmyung Women's University, Seoul.

In 2015, the Republic of Korea launched its Emissions Trading Scheme (K-ETS). The government announced "Low Carbon Green Growth" in 2008 as the new national vision for the next 60 years and in 2009 set the greenhouse gas (GHG) emissions reduction target by 2020. As a legal framework of the K-ETS, the National Assembly of the Republic of Korea passed almost unanimously the Act on the Allocation and Trading of Greenhouse-Gas Emission Permits in May 2012. There have been extensive efforts by policy makers and regulated entities for the successful launch of the K-ETS. Starting in 2012, the GHG Target Management System (TMS) was implemented with the participation of the GHG-emitting entities. With the implementation of the TMS prior to the implementation of the K-ETS, the regulators developed and published guidelines for monitoring and reporting of GHGs at an entity level and to prepare an online reporting system managed by the Greenhouse Gas Inventory and Research Center (GIR). The annual inventory report of a regulated entity is subject to verification by the accredited verifiers before being submitted to the GIR. The information and experiences learned through the implementation of the TMS are valuable assets in monitoring GHG emissions and in allocating the allowances to the regulated entities.

There are some distinct characteristics in the K-ETS. First, the K-ETS covers all six GHGs (CO_2, CH_4, N_2O, hydrofluorocarbons, perfluorocarbons, SF_6) in the Kyoto Protocol and all sectors from the first implementation phase (2015 to 2017). The share of GHGs covered by the K-ETS compared to the national GHG emissions has been more than 70%. This makes the K-ETS the principal policy tool in achieving national GHG emissions reduction targets by pricing the emitted carbon. Other energy policies and measures have been implemented, such as voluntary agreements and renewable energy portfolio standards. However, the K-ETS is the most effective incentive tool to lower GHG emissions or improve the energy efficiency to the regulated entities. The aggregate cap for the K-ETS is determined by applying the average share of the K-ETS in the previous 3 years to the national GHG emissions to be aligned with the national emissions target (cap). The K-ETS started to allocate the allowance freely based on a "grandfathering" principle in the first implementation phase. The K-ETS gradually increases the share of the allocation by auction and the share of the benchmark allocation if allocated freely.

In the K-ETS, indirect emissions of the regulated entities are subject to cap-setting and allocation of allowances. It is due to the limited role of carbon prices in fuel choice in power generation due to the economic merit order dispatch system in which the carbon cost is not included and the regulated price of electricity in the retail market. Starting in 2022, the economic merit order dispatch system was replaced with the environmental merit order system to have the carbon cost included in determining the dispatching order. However, there is still limited pass-through of the carbon cost to the retail electricity price. Indirect emissions are subject to the allocation of the allowances to the regulated entities even in the third implementation phase (2021 to 2025).

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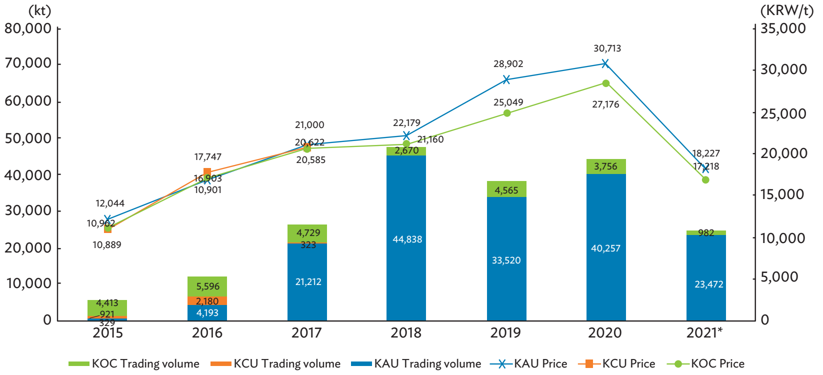
Box 9.4 *continued*

The K-ETS has been successful in its implementation as the principal policy tool to lower GHG emissions of the regulated entities since 2015. The market in the K-ETS has been stable and the allowance prices showed a steady upward trend before the impact of COVID-19 in 2020. The allowance prices in the K-ETS have been hovering around $35/ton CO_2eq (Figure B9.4.1). The compliance rates of the regulated entities have been almost 100%, and the regulated entities increase their investment in GHG emissions reduction technologies in addition to the increased participation in emissions trading (Figure B9.4.2). Well-designed implementation plans and measurement, reporting, and verification systems are prerequisites for the introduction of an emissions trading scheme. Given the limited role of the carbon price under the emissions trading scheme in the regulated electricity market, the inclusion of emissions is a good policy alternative to lower the inefficient use of electricity.

Figure B9.4.1: Trends in Total Trading Volume and Price by Emissions Permit



* Trading records are until the last trading day of KAU20 in 2021 (9 August 2021).

KAU = Korea Allowance Unit, KCU = Korea Credit Union, KOC = Korea Offset Credit, kt= kiloton.

Source: Adapted from GIR (2022).

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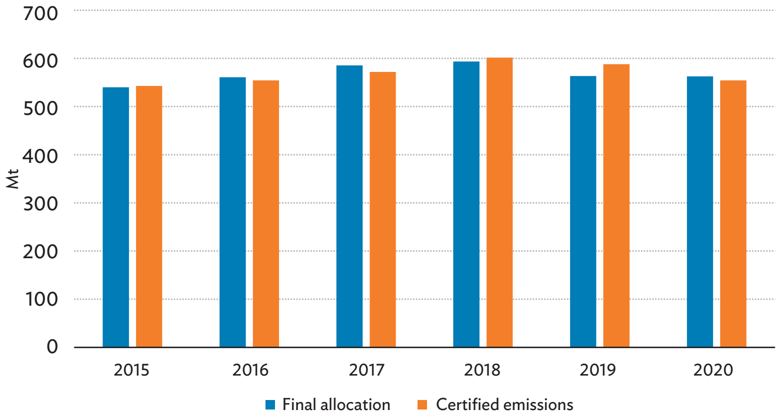
Box 9.4 *continued*

Figure B9.4.2: Final Allocation and Certified Emissions by Year



Mt = million tons.

Source: Adapted from GIR (2022).

9.3.3 Policy Packages for Greater Overall Effectiveness and Multiple Objectives

Deliberately designed policy packages (or policy mixes) allow interactions between different policy instruments, which can provide greater overall coverage of emissions with policy-based incentives or regulatory measures to reduce emissions. They can be used to gear emissions reduction policies toward achieving longer-term transition to more sustainable production and consumption systems, for example in transition to low-emissions energy systems (Rogge and Reichardt 2016).

Key goals of policy packages include comprehensiveness, balance, and consistency. Comprehensiveness can relate both to the extent that existing emissions sources are covered by policy instruments as well as using a suite of different policy instruments to address different pathways to impact—for example, emissions trading or taxes where investment and practices are price sensitive, minimum standards in areas where behavior is not responsive to price incentives (e.g., individual decisions on energy efficiency), and R&D support to achieve longer-term cost reductions of low-emissions technologies.

Policy packages can also be geared to facilitate larger changes in economic systems, such as complementing emissions reductions policies with social adjustment policies to help smooth energy and industrial transition processes.

9.4 Evolution of Design of Carbon Pricing

Experience with carbon pricing has allowed the refinement of the design and implementation of carbon pricing, in particular emissions trading schemes, which by their nature allow a large range of modifications. Refinements have improved the effectiveness, efficiency, and political acceptability of carbon pricing instruments, and the interactions with other policy instruments as well as responsiveness to unanticipated economic or technological developments.

These experiences provide valuable insights to governments in jurisdictions that are considering or planning to implement carbon pricing. Here we review practical experiences in design and incremental refinement of three important aspects of carbon pricing. Examples include stabilization measures and permit allocation in emissions trading schemes, and use of fiscal revenue (revenue recycling).

The following sections provide an in-principle treatment of these issues with examples from specific emissions trading schemes.

9.4.1 Price and Allowance Stabilization Measures

In most GHG emissions trading schemes implemented so far, emissions fell or remained below the targeted amount (the predefined “cap” under the trading scheme), causing an accumulation of emissions permits or allowances over time (Haites 2018). This can indicate that underlying emissions trends were overestimated, that trading schemes were designed with little or no ambition, that emissions reduction was relatively easy to achieve, or that other policies were highly effective in cutting emissions. In most schemes, unused allowances can be retained for future use (“banked”), so a surplus in one year can mean lower scheme effectiveness in future years unless compensating measures are taken.

Policy makers have typically responded by adjustments to the cap trajectory, issuing fewer than planned emissions in future years; or withdrawing a defined number of allowances from the market under certain market conditions. The largest example of such a set-aside policy is the “market stability reserve” under the EU ETS (Hepburn et al. 2016). A relatively simple form of an automatic stabilizer is a price floor at auction, as it is, for example, implemented in California's ETS. The total number of permits issued is then automatically limited (below the predefined cap) if the price paid for newly issued permits does not exceed a defined minimum.

Such policy design features were often lacking from early emissions trading schemes but have become commonplace.

9.4.2 Permit Allocation

Another important area of design evolution of emissions trading schemes is how governments allocate allowances to emitters.

In the early phases of many ETS, including notably the EU ETS, a large share of the total emissions allowances was given for free to emitters, including on the basis of historical emissions levels ("grandfathering"). Providing free permits to existing emitters in this way will usually lead to windfall profits in industries where businesses tend to pass on increases in productions costs in the form of higher product prices. Providing such implicit subsidies, whether through free permits or other payments, is often used deliberately to achieve buy-in from high-emitting industries that might otherwise politically stymie the introduction of carbon pricing ("brown cushioning," Dorsch, Flachsland, and Kornek 2020).

Over time, however, free allocations to industries that do not need them to retain overall competitiveness or profitability are typically reduced or eliminated. For example, the EU ETS in its current form provides free allocations in the main only to industries that are emissions intensive and that operate in international competition, such as energy intensive commodity production. In these cases, free permits are provided based on the output of specific products, not the emissions in the process, using industry- or product-specific benchmarks. This disconnection between allocation of free permits and the actual emissions level retains the incentive to produce goods at lower emissions intensity. The rates of assistance to industry through permit allocation also tends to be lower over time.

9.4.3 Fiscal Revenue Use

The shift toward greater shares of auctioned emissions allowances, together with a general trend toward higher carbon prices, mean that a greater share of the overall amount of emissions allocation is available for governments to sell (usually at auction), creating greater fiscal revenue.

Where permit prices are high, and coverage of emissions is comprehensive, public revenue from emissions trading can be large. For example, the EU ETS created public revenue of €14 billion over the first half of 2021, which was available for member states to spend (Haase et al. 2022), while overall global carbon pricing revenue is estimated at $84 billion during 2021, of which around two-thirds were from emissions trading and one-third from carbon taxes (World Bank 2022a).

Public revenue from the sale of emissions allowances or from carbon taxes usually flows into consolidated government revenue. It thereby allows other taxes and levies to be lowered, potentially yielding an efficiency benefit (a “double dividend” of environmental and economic efficiency gains), public expenditure to be increased, or public debt to be reduced. These positive fiscal effects set carbon pricing apart from other climate policy instruments. They need to be considered in any economic evaluation of the overall effect of carbon pricing.

Revenue from carbon pricing can also be earmarked to support specific spending programs, either as direct earmarking or notionally as a justification for other fiscal policy changes. One typical application are social adjustment programs, for example increasing social security payments or lower taxes for low-income earners, in order to counteract any energy or product price increases that may come from the introduction of carbon prices. Another type of application is to fund climate change-related measures, for example subsidies for zero emissions technologies or spending programs on environmental protection.

Linking fiscal income from carbon pricing to such expenditure programs can increase public support for, and thereby the political viability and sustainability of, carbon pricing policies.

9.4.4 Cross-Jurisdictional Harmonization Including Linkages through Carbon Trading

Carbon Leakage

Due to risks of cross-border carbon leaking and impact on output price and competitiveness (as mentioned in section 9.2.3), the importance of regional and global cooperation in carbon pricing is widely recognized. The downside of carbon leakage is that it reduces the effectiveness of the carbon pricing policy. Cross-border leakage could lead to a reduction of emissions in a country by moving (leaking) carbon to other countries (with lower carbon prices), which will not have the expected impact on global GHG emissions reduction and investments in low-carbon technologies.

Carbon Border Adjustment Mechanism

Examples of regional cooperation in carbon pricing include the EU ETS. It was also proposed for the Association of Southeast Asian Nations (ASEAN). However, regional cooperation in carbon pricing is not an equivalent substitution to global cooperation in carbon pricing. That is why the Carbon Border Adjustment Mechanism was proposed by the European Commission (2021) in the EU, affecting imports of selected products to the EU. An alternative to global uniform carbon pricing is a border carbon tax adjustment mechanism proposed by the EU. The Carbon Border Adjustment Mechanism increases the price of selected imported products by adding a carbon price, tax, or duty to prevent carbon leakage and protect competitiveness. "The European Union (EU) moved closer to adopting its carbon border adjustment mechanism, and Canada and the United Kingdom are exploring options for similar mechanisms" (World Bank 2022a, p. 10).

International Carbon Price Floor

Several international organizations are discovering solutions for global cooperation on carbon pricing. Global uniform carbon pricing could eliminate the risk of cross-border carbon leaking. However, this is hard to implement. As a compromise, the International Carbon Price Floor was proposed by the International Monetary Fund (Parry, Black, and Roaf 2021) to be implemented simultaneously by large emitting countries with a minimum carbon price that depends on countries' income level ($75 per ton of carbon for developed economies, $50 per ton of carbon for higher-income emerging economies, and $25 per ton of carbon for lower-income emerging economies). The global carbon floor price could help to reduce GHG emissions without a large negative impact on countries' competitiveness, and thus economic growth.

9.5 Conclusions and Policy Recommendations for Asia

The review and synthesis presented in this chapter show that carbon pricing has a key role as part of an effective and efficient system of climate policy, alongside an array of other, non-pricing policies; that in practice, the role of carbon pricing differs greatly between different jurisdictions, including as part of broader policy packages; and that the design of existing carbon pricing systems has evolved to better meet multiple policy objectives.

On this basis, what is the role of carbon pricing in policy packages that aim to achieve deep reductions in GHG, in pursuit of net-zero emissions in the long term?

One plausible scenario is a continuation or intensification of present trends, which have carbon pricing in a key role or as the main climate policy instrument across many areas of the economy in some countries (or subnational and/or supranational jurisdictions). In many other countries, carbon pricing is a part of a policy package but limited in its breadth of application and/or limited strength of the carbon pricing signal; and other countries have no or very limited carbon pricing in other jurisdictions. Non-pricing policies would play an important role in many jurisdictions, depending on the overall strength of climate policy and the role of carbon pricing in the specific jurisdiction. Great heterogeneity of policy approaches would then persist, reflecting different political and institutional contexts; design features of carbon prices would continue to differ between countries. A corollary of this scenario would be that the impetus for international integration of carbon pricing systems (e.g., through international carbon trading), would remain limited.

In the pursuit of deeper emissions reduction, this scenario would typically miss out on opportunities for greatest efficiency and effectiveness by not making full possible use of carbon pricing. However, this may be the price to pay for achieving stronger climate policy under a multitude of practical constraints on policy instrument choice, and importance of other policy objectives that are best served through other policy instruments.

Another scenario is a gradual shift toward a more central role for carbon pricing. In typical jurisdictions, this would have carbon pricing being at the core of typical climate policy packages, covering a relatively high share of overall emissions, and operating at relatively high carbon price levels. Non-pricing policy instruments would then overall take a lesser role than in the first scenario, cover specific sectors or activities where carbon pricing does not apply, and fulfill an important adjunct role in sectors covered by carbon pricing. The high prevalence and central importance of carbon pricing may then engender a tendency toward harmonization of some design features across countries. International integration through cross-border carbon trading could provide greater benefits and thus become more attractive and widespread. However, not all national or subnational carbon pricing schemes would necessarily be harmonized, and non-pricing policies would continue playing different and important roles.

A scenario where carbon pricing becomes the overwhelming mainstay of climate change policy in most countries, without a significant role for non-pricing policies, appears unlikely. The manifold advantages and attractions of non-pricing policies for specific purposes are too great.

If an insight for policy makers can be distilled from this, it is that it pays to continuously examine the role that carbon pricing could play as part of an overall climate policy portfolio, and whether that role could beneficially be strengthened including through the adoption of improved design of carbon pricing.

References

Abe, T., and T. Arimura. 2020. An Empirical Study of the Tokyo Emissions Trading Scheme: An Ex Post Analysis of Emissions from University Buildings. In T. Arimura and S Matsumoto, eds. *Carbon Pricing in Japan*. Springer, Singapore, pp. 97–166.

Asian Development Bank (ADB). 2016. *Fossil Fuel Subsidies in Asia: Trends, Impacts, And Reforms Integrative Report*. Manila: ADB. https://www.adb.org/sites/default/files/publication/182255/fossil-fuel-subsidies-asia.pdf

Azhgaliyeva, D., B. She, and A. Leal. Forthcoming. *Low-Carbon Cooling. Tokyo*: ADBI Press.

Bank of Japan (BOJ). 2022. BOJ Time-Series Data. https://www.stat-search.boj.or.jp/ssi/cgi-bin/famecgi2?cgi=$nme_a000_en&lstSelection=FM08 (accessed 1 September 2022).

Dorsch, M. J., C. Flachsland, and U. Kornek. 2020. Building and Enhancing Climate Policy Ambition with Transfers: Allowance Allocation and Revenue Spending in the EU ETS. *Environmental Politics* 29(5): 781–803.

Dubash, N. et al. 2022. National and Sub-national Policies and Institutions. In J. Skea, et al. *Climate Change 2022: Mitigation of Climate Change*. IPCC 6th Assessment Report of Working Group III, Intergovernmental Panel on Climate Change.

European Commission. 2021. Proposal for a Regulation of The European Parliament and of The Council Establishing a Carbon Border Adjustment Mechanism. Brussels: European Commission. https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX:52021PC0564

Gokhale, H. 2021. Japan’s Carbon Tax Policy: Limitations and Policy Suggestions. *Current Research in Environmental Sustainability*. 3: 100082.

Greenhouse Gas Inventory and Research Center (GIR). 2022. 2020 Korean Emissions Trading System Report.

Haase, I, E. K. Velten, H. Branner, and A. Reyneri. 2022. The Use of Auctioning Revenues from the EU ETS for Climate Action – An Analysis Based on Eight Case Studies. Berlin: Ecologic Institute.

Haites, E. 2018. Carbon Taxes and Greenhouse Gas Emissions Trading Systems: What Have We Learned? *Climate Policy* 18(8): 955–966.

Hamamoto, M. 2021. Impact of the Saitama Prefecture Target-setting Emissions Trading Program on the Adoption of Low-carbon Technology. *Environmental Economics and Policy Studies* 23(3): 501–515.

Hepburn, C., K. Neuhoff, W. Acworth, D. Burtraw, and F. Jotzo. 2016. The Economics of the EU ETS Market Stability Reserve. *Journal of Environmental Economics and Management* 100(80):1 –5.

International Carbon Action Partnership (ICAP). 2021. Kazakhstan Emissions Trading System. https://icapcarbonaction.com/system/files/ets_pdfs/icap-etsmap-factsheet-46.pdf

International Energy Agency (IEA). 2019. *Energy Security in ASEAN+6*. IEA.

Kapoor, A., E.-Q. Teo, D. Azhgaliyeva, and Y. Liu. 2021. The Viability of Green Bonds as a Financing Mechanism for Energy-Efficient Green Buildings in ASEAN: Lessons from Malaysia and Singapore. In Y. Liu, F. Taghizadeh-Hesary, and N. Yoshino, eds. *Energy Efficiency Financing and Market-Based Instruments*. Springer, 263–286. https://link.springer.com/chapter/10.1007/978-981-16-3599-1_12

Kapsalyamova, Z. 2021. Implications of the Nationwide Carbon Dioxide Emission Targets: A Computable General Equilibrium (CGE) Model for Kazakhstan. Presentation at ADBI Virtual Workshop on Effective Greenhouse Gas Emission Control Policies, 25–27 August. https://www.adb.org/news/events/adbi-virtual-workshop-effective-greenhouse-gas-emission-control-policies

KazEnergy. 2022. *The National Energy Report 2021*. https://www.kazenergy.com/upload/document/energy-report/NationalReport21_en.pdf

Li, Y., and B. Su. 2017. The Impacts of Carbon Pricing on Coastal Megacities: A CGE Analysis of Singapore. *Journal of Cleaner Production* 165: 1239-1248.

Lim, V. 2022. Budget 2022: Singapore to Progressively Raise Carbon Tax to Reach Net-Zero Target “by or around Mid-Century”. Channel News Asia, 18 February. https://www.channelnewsasia.com/singapore/carbon-tax-net-zerotarget-emissions-singapore-green-plan-2506496 (accessed 1 April 2022).

Low, M., and E. Bea. 2021. Maximising Singapore’s Readiness as a Carbon Services Hub. *Energy Studies Institute Policy Brief* 47, 22 October. https://esi.nus.edu.sg/docs/default-source/esi-policy-briefs/maximising-singapore’s-readiness-as-a-carbon-service-hub.pdf

Low, M., T. J. Ling, and T. X. Yi. 2022. Singapore’s Carbon Tax Hike and Climate Ambition, *Energy Studies Institute Policy Brief* 52, 11 March. https://esi.nus.edu.sg/docs/default-source/esi-policy-briefs/singapores-carbon-tax-hike-and-climate-ambition.pdf?sfvrsn=295ec504_2

Marteau, J-F. 2021. From Paris to Glasgow and Beyond: Towards Kazakhstan’s Carbon Neutrality by 2060. World Bank Blog, 17 June.

https://blogs.worldbank.org/europeandcentralasia/paris-glasgow-and-beyond-towards-kazakhstans-carbon-neutrality-2060

Mazmanian, D. A., J. L. Jurewitz, and H. T. Nelson. 2020. State Leadership in US Climate Change and Energy Policy: The California Experience. *The Journal of Environment &* Development 29(1): 51–74.

Ministry of the Environment. 2021. Tax for Climate Change Mitigation. https://www.env.go.jp/policy/tax/about.html (in Japanese).

National Climate Change Secretariat. 2020. Singapore's Enhanced Nationally Determined Contribution and Long-Term Low-Emissions Development Strategy, Press Release, 28 February. https://www.nccs.gov.sg/media/press-release/singapores-enhanced-nationally-determined-contribution-and-long-term-low-emissions-development-strategy

____. 2022. Singapore Will Raise Climate Ambition to Achieve Net Zero Emissions by or Around Mid Century, and Revises Carbon Tax Levels from 2024. Press Release, 18 February. https://www.nccs.gov.sg/media/press-release/singapore-will-raise-climate-ambition

Parry, I., S. Black, and J. Roaf. 2021. Proposal for an International Carbon Price Floor Among Large Emitters. IMF Staff Climate Notes. 2021/001. Washington, DC: International Monetary Fund. https://www.imf.org/en/Publications/staff-climate-notes/Issues/2021/06/15/Proposal-for-an-International-Carbon-Price-Floor-Among-Large-Emitters-460468

Rogge, K. S., and K. Reichardt. 2016. Policy Mixes for Sustainability Transitions: An Extended Concept and Framework for Analysis. *Research Policy* 45(8): 1620–1635.

Stiglitz, J. E. 2019. Addressing Climate Change through Price and Non-price Interventions. *European Economic Review* 119: 594–612.

Suleimenova, Z. 2021. Kazakhstan's Climate Policy: Lessons Learned and the Way Forward. Presentation at the ADBI Virtual Workshop on Effective Greenhouse Gas Emission Control Policies, 25–27 August.

Tokyo Metropolitan Government. 2022. Results of Tokyo Cap-and-Trade Program in the First Year of the Third Compliance Period. https://www.kankyo.metro.tokyo.lg.jp/en/climate/cap_and_trade/index.files/resultfirstyearofthethird.pdf

Wakabayashi, M., and O. Kimura. 2021. The Impact of the Tokyo Metropolitan Emissions Trading Scheme on Reducing Greenhouse Gas Emissions: Findings from a Facility-based Study. *Climate Policy* 18(8): 1028–1043.

World Bank. 2022a. *State and Trends of Carbon Pricing 2022*. Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/37455

———. 2022b. Data: Carbon Pricing Dashboard. https://carbonpricingdashboard.worldbank.org/ (accessed 15 September 2022).

Zhasyl Damu. 2022. Emissions Trading System. https://recycle.kz/ru/parnikovye-gazy

Zholdayakova, S., Y. Abuov, D. Zhakupov, B. Suleimenova, and A.Kim. Forthcoming. Towards Hydrogen Economy in Kazakhstan. ADBI Working Paper. https://www.adb.org/publications/series/adbi-working-papers

Climate Change Mitigation

Policies and Lessons for Asia

Asia and the Pacific accounts for over 50% of the world's total greenhouse gas emissions, driven by rapid economic growth and energy consumption in developing countries. Far-reaching efforts are urgently needed to reduce the region's emissions and realize a 1.5°C temperature drop required to fight climate change and associated threats to sustainable development, particularly in highly polluted cities.

Many governments have pledged to meet net-zero carbon emissions by around mid-century, but action to transform energy markets alone will not be enough. Measures to promote the decarbonization of the transport, buildings, agriculture, and other sectors must also be taken forward to successfully achieve emissions reduction targets.

Climate Change Mitigation: Policies and Lessons for Asia highlights evidence-based approaches for advancing decarbonization across sectors. It offers timely insights for policy makers and scholars seeking to better understand the region's climate change mitigation challenges, policy approaches for fostering emissions breakthroughs, and the sustainable development implications.

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The Asian Development Bank Institute (ADBI) is the Tokyo-based think tank of the Asian Development Bank. ADBI provides demand-driven policy research, capacity building and training, and outreach to help developing countries in Asia and the Pacific practically address sustainability challenges, accelerate socioeconomic change, and realize more robust, inclusive, and sustainable growth.

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