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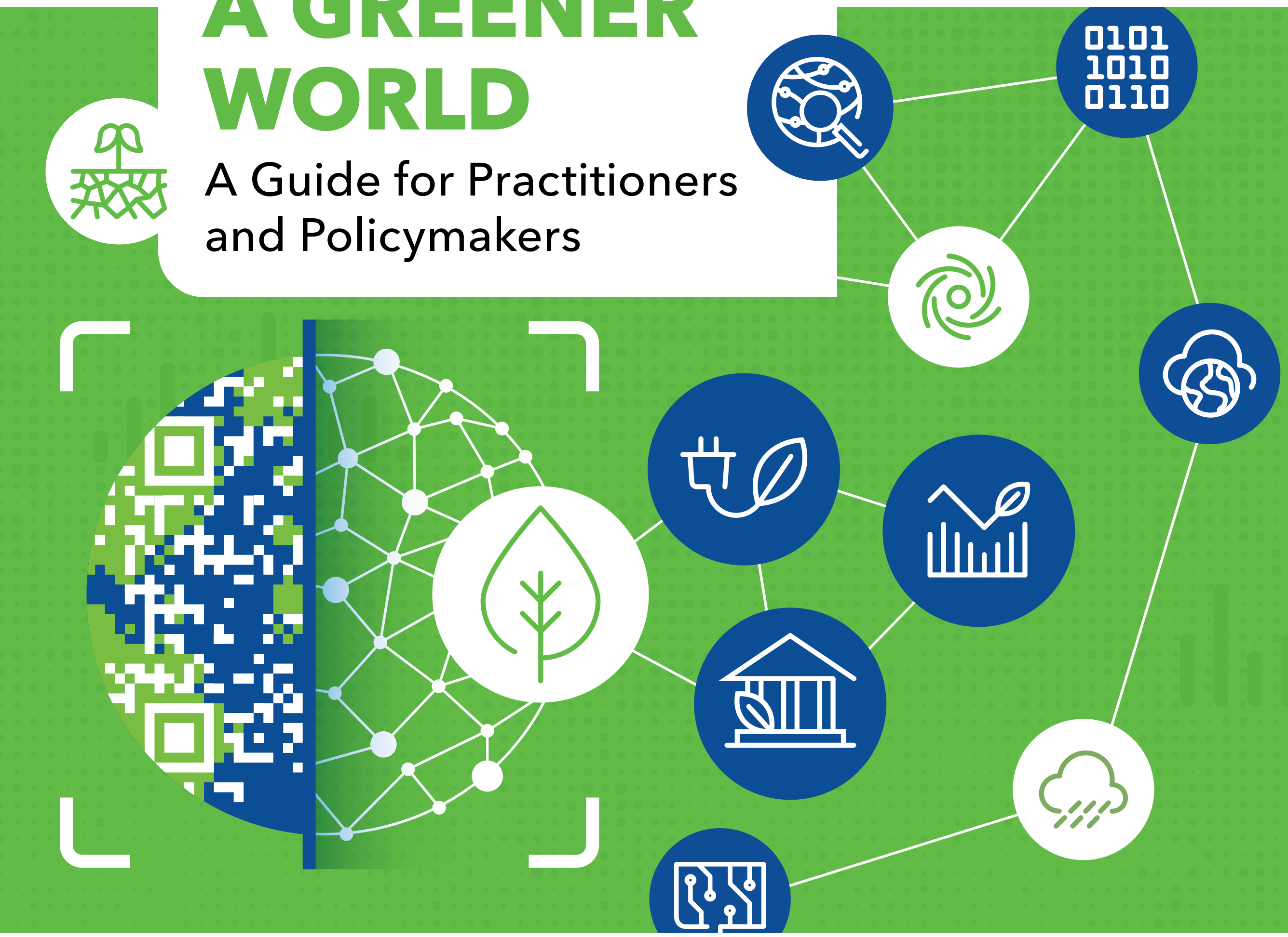
DATA FOR A GREENER WORLD

A Guide for Practitioners and Policymakers



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Foreword

Climate change is one of the biggest threats facing the world. We already see its effects on every continent and region—from an increasing number of wildfires and droughts to the melting ice caps and floodings. Policymakers everywhere are taking action to fight and adapt to climate change.

But designing effective policies requires accurate and reliable data—and these face serious limitations. We need to appropriately measure the consequences and causes of climate change to fight and manage it. This applies to global greenhouse gas emissions, carbon pricing, and many other social, economic, and financial aspects of climate change.

I am delighted that this book brings together recent research on how to better measure the economic, cross-border, and financial aspects of climate change. It is a joint effort by the IMF and six other international organizations—the European Central Bank, Eurostat, the International Energy Agency, the Organisation for Economic Co-operation and Development, the World Bank, and the World Trade Organization. It is anchored in the IMF *Climate Change Indicators Dashboard* launched in April 2021, benefited greatly from the discussions at the *9th IMF Statistical Forum on Measuring Climate Change* in November 2021, and is relevant for the new *G20 Data Gaps Initiative* launched in November 2022 with a module on climate data.

With its best practice examples, I hope that this book will inspire policymakers and practitioners to step up their efforts and provide them with the tools to deliver robust and comparable climate-relevant data toward transitioning to a greener and more resilient economy.

Kristalina Georgieva
Managing Director
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Preface

A famous physicist once said: “When you can measure what you are speaking about, and express it in numbers, you know something about it.” Nearly 140 years later, this maxim remains true and is particularly poignant for policymakers tasked with addressing climate mitigation and adaptation.

That is because policymakers and the public face major information gaps that impede their ability to understand the impact of policies—from measures to incentivize cuts in emissions, to regulations that reduce physical risks and boost resilience to climate shocks. And without comprehensive and internationally comparable data to monitor progress, it is impossible to know what works, and where course corrections are needed.

To accelerate cuts to emissions, policymakers need detailed statistics to monitor the path of the energy transition and assist them in devising effective mitigation measures that can deliver the fastest and least disruptive pathway toward net zero emissions. At the same time, countries need to monitor how mitigation and adaptation measures affect household incomes, consumption, and wealth. How, for example, will rising fossil fuel costs impact vulnerable households? And how should we prioritize investments to address new weather patterns and more frequent climate shocks?

This underscores the importance of the new Data Gaps Initiative for G20 economies, which calls for better climate data, together with indicators that cover income and wealth, financial innovation and inclusion, and access to private and administrative data. The initiative will draw on the collective expertise of the international agencies that are coordinating the work as well as on work undertaken by groups such as the Network for Greening the Financial System to develop a common understanding of climate-related financial instruments. It will also continue to build on the IMF *Climate Change Indicators Dashboard*, launched in April 2021 at the Spring Meetings of the IMF and the World Bank Group, which provides relevant climate-related indicators for economic analysis, providing comparable data for all countries.

This book is closely linked to these initiatives and has benefited greatly from the discussions at the *9th IMF Statistical Forum on Measuring Climate Change* in November 2021. It is a joint international effort that brings together renowned experts from seven international organizations to distill lessons for measuring key economic, cross-border, and financial aspects of climate change. In doing so, it presents practical approaches to close climate data gaps with existing data and provides future avenues for further enhancements.

As countries pursue reforms to facilitate the transition to a greener economy, we hope they will find this book to be a useful companion. The IMF will remain their steadfast partner in making sure they have the means to track their progress with accurate, reliable, and comparable data.

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This book has been a joint effort involving seven international organizations—European Central Bank, Eurostat, International Energy Agency, International Monetary Fund, Organisation for Economic Co-operation and Development, World Bank, and World Trade Organization. Anchored in the IMF *Climate Change Indicators Dashboard* launched in April 2021, it benefited greatly from the discussions at the *9th IMF Statistical Forum on Measuring Climate Change* in November 2021. Many colleagues have inspired and supported us in our journey to see the book come to fruition. First and foremost, we are grateful to the authors of the various chapters; they are renowned experts in their fields and we appreciate the time and care they spent on their contributions. We want to thank, in particular, Louis Marc Ducharme for his strong support, as well as Albert Kroese, Jim Tebrake, Andrea Richter Hume, Roberto Rosales, Carlos Sánchez-Muñoz, Artak Harutyunyan, Dragana Ostojic, and Linda Griffin Kean for their backing and encouragement. We also thank Lorraine Coffey and Patricia Loo of the IMF Communications Department for their excellent work managing the production of this book, and TDI Digital Solutions, Inc., for copyediting, typesetting, proofreading, and indexing. We hope that our efforts will provide policymakers and practitioners with practical tools to measure and facilitate the transition to a greener economy.

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Abbreviations

ADS-B	Automatic Dependent Surveillance–Broadcast
AE	Advanced economy
AMNE	OECD Activities of Multinational Enterprises
AnaCredit	Analytical credit data set
APEC	Asia-Pacific Economic Cooperation
AR	Assessment Report
BACI	Base pour l'Analyse du Commerce International
BDG	Bridging data gaps
BEA	US Bureau of Economic Analysis
BIMTS	Balanced International Merchandise Trade Statistics
BIS	Bank for International Settlements
BP	British Petroleum
BPM6	Balance of Payments and International Investment Position Manual, Sixth Edition
CCrS	Carbon-critical sectors
CEF	Carbon emissions factors
CEPAL	Economic Commission for Latin America and the Caribbean
CEPII	Centre d-Etudes Prospective et d'Informations Internationales
CET1	Common Equity Tier 1
CFALTL	Carbon footprint adjusted loans to total loans
CFBL	Carbon Footprint of Bank Loans
CGE	Computable general equilibrium
CH_4	Methane
CI	Carbon inefficiency
CID	*Climate Change Indicators Dashboard*
CIL	Carbon Intensity of Loans
CI	Critical infrastructure
CFMB	Committee on Monetary, Financial and Balance of Payments Statistics
CMIP6	Coupled Model Intercomparison Project Phase 6
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
COFOG	Classification of Functions of Government
COOLR	Cooperative Open Online Landslide Repository
COP	Conference of the Parties

CPAT	Climate Policy Assessment
CPEIRs	Climate Public Expenditure and Institutional Reviews
CPI	Carbon price instruments
CPS	Carbon Pricing Score
CSDB	Centralised Securities Database
CSRD	Corporate Sustainability Reporting Directive
DAC	Development Assistance Committee
DFO	Dartmouth Flood Observatory
DGI	Data Gaps Initiative
DNB	De Nederlandsche Bank
DOE	Domestically owned enterprise
DOTS	IMF Direction of Trade Statistics
DRMKC	European Commission Disaster Risk Management Knowledge Centre
ECB	European Central Bank
ECMWF	European Centre of Medium-Range Weather Forecasts
ECP	Emissions-weighted carbon price
ECR	Effective carbon rates
EDB	WTO Environmental Database
EDDI	European Drought Impact Report Inventory
EDGAR	Emissions Database for Global Atmospheric Research
EDR	European Drought Reference
EFAS	European Flood Awareness System
EFFIS	European Forest Fires Information System
EGs	Environmental goods
EGS	Environmental goods and services
EIA	US Energy Information Administration
EIOPA	European Insurance and Occupational Pensions Authority
EM-DAT	Emergency Events Database
EMDEs	Emerging markets and developing economies
EMS	Copernicus Emergency Management Service
EPA	US Environmental Protection Agency
E-PRTR	European Pollutant Release and Transfer Register
EPSGG	European Petroleum Survey Group Geodesy
ERTR	Emergency Response and Transitional Recovery
ESA	European Space Agency
ESCB	European System of Central Banks
ESDAC	European Soil Database
ESG	Environmental, Social, and Corporate Governance
ESM	European Settlement Map

ESRB	European Systemic Risk Board
ESS	European Statistical System
ETS	Emissions trading systems
EU	European Union
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
EUR	Euro
ECMWF	European Centre for Medium-Range Weather Forecasts
Eurostat	European Statistical Office
EV	Electric vehicle
FD	Final demand
FDI	Foreign direct investment
F-gas	Fluorinated gas
FMIS	Financial Management Information Systems
FSAP	Financial Sector Assessment Program
FSB	Financial Stability Board
G20	Group of Twenty
GADM	Global Administrative Areas
GAINS	Greenhouse Gas–Air Pollution Interactions and Synergies
GBD	Global Burden of Disease
GBS	Green Bond Standard
GDP	Gross domestic product
GFCF	Gross fixed capital formation
GFSM	Government Finance Statistics Manual
GHGs	Greenhouse gases
GHL	Global Human Settlement
GIS	Geographic Information System
GJ	Gigajoule
GLC	Global Landslide Catalog
GPP	Global Petrol Prices
GWP	Global warming potential
HANZE	Historical Analysis of Natural Hazards in Europe
HARCI-EU	HARmonized grids of Critical Infrastructures in EUrope
HS	Harmonized Commodity Description and Coding Systems
IAG	Inter-Agency Group on Economic and Financial Statistics
IAMs	Integrated assessment models
IASB	International Accounting Standards Board
IBFD	International Bureau of Fiscal Documentation
ICAO	International Civil Aviation Organisation
ICAP	International Carbon Action Partnership

ICE	Internal combustion engine
ICIO	Inter-country input–output
IEA	International Energy Agency
IFC	International Finance Corporation
IFRS	International Financial Reporting Standards
IHME	Institute for Health Metrics and Evaluation
IIASA	International Institute for Applied Systems Analysis
IMF	International Monetary Fund
ISIN	International Securities Identification Number
IO	Input-Output
IPCC	International Panel on Climate Change
IPSAS	International Public Sector Accounting Standards
IPSF	International Platform for Sustainable Finance
IQR	Interquartile range
IRF	International Road Federation
ISC	International Science Council
ISIC	International Standard Industrial Classification of All Economic Activities
ISSB	International Sustainability Standards Board
JRC	Joint Research Centre
KBDI	Keetch-Byram Drought Index
Km	Kilometer
LAU	Local administrative unit
LCI	Loan carbon intensity
LCT	Low-carbon technology
LEI	Legal Entity Identifier
LNG	Liquefied natural gas
LRC	Landslide Reporter Catalog
LULUCF	Land use, land use change, and forestry
MAPE	Mean absolute percentage error
MAST	Multi-Agency Support Team
MFN	Most favored nation
MNE	Multinational enterprise
NACE	Nomenclature statistique des activités économiques dans la Communauté européenne
NAMEA	National Accounting Matrix including Environmental Accounts
NASA	National Aeronautics and Space Administration
NDC	Nationally determined contribution
NEX-GDDP	NASA Earth Exchange Global Daily Downscaled Projections
NFC	Nonfinancial corporation
NGFS	Network on the Greening of the Financial Sector

NOx	Nitrogen oxide
NPL	Nonperforming loan
NSO	National statistics office
NTM	Nontariff measure
NUTS	Nomenclature of territorial units for statistics
NZE	IEA net-zero energy scenario
OECD	Organisation for Economic Co-operation and Development
OSM	Open street map
PCAF	Partnership for Carbon Accounting Financials
PFM	Public financial management
PINE	Policy Instruments for the Environment
PGA	Peak ground acceleration
$PM_{2.5}$	Particulate matter with diameter less than 2.5 micrometers
POI	Point of interests
PPP	Purchasing power parity
PWC	PricewaterhouseCoopers
QGIS	Quantum Geographic Information System
RCP	Representative concentration pathways
RDH	Risk Data Hub
RGGI	Regional Greenhouse Gas Initiative
ROE	Return on equity
SC	Statistics Committee
SCM	Subsidies and Countervailing Measures
SCN	IMF Staff Climate Note
SEEA	System of Environmental-Economic Accounts
SEEA-CF	System of Environmental-Economic Accounts–Central Framework
SFWG	Sustainable Finance Working Group
SHS	Securities Holdings Statistics
SNA	System of National Accounts
SPEs	Special purpose entities
SPS	Sanitary and phytosanitary measures
SSM	Single supervisory mechanism
Stats NZ	Statistics New Zealand
STCs	Specific trade concerns
SO_2	Sulfur dioxide
TBT	Technical Barriers to Trade
TCFD	Task Force on Climate-related Financial Disclosures
tCO_2e	Tonnes of carbon dioxide equivalent
TCP	Total carbon price
T&D	Transportation and distribution

$TECO_2$	OECD trade in embodied CO_2 database
TEU	Taxing Energy Use
TRAINS	Trade Analysis Information System
TVF	Transition Vulnerability Factors
UNCTAD	United Nations Conference on Trade and Development
UNDP	United National Development Programme
UNDRR	United Nations Office for Disaster Risk Reduction
UNFCCC	UN Framework Convention on Climate Change
UNIDO	United National Industrial Development Organization
UNSD	United Nations Statistics Division
USD	US dollar
USDA	US Department of Agriculture
USGS	US Geological Survey
VAT	Value-added tax
VOC	Volatile organic compound
WEO	*World Economic Outlook*
WITS	World Integrated Trade Solutions
WRI	World Resources Institute
WTO	World Trade Organization

Introduction

Serkan Arslanalp, Kristina Kostial, and Gabriel Quirós-Romero

Climate change is confronting us all and will be increasingly impactful in the coming years and decades. Global warming is bound to affect basic living conditions, productivity and growth, fiscal positions and debt trajectories, and asset valuations. It will raise financial stability risks, redistribute income across the globe, and influence trade patterns and exchange rate valuations.

We need to get ahead of these challenges. But policymakers and investors alike face a lack of reliable and comparable data for researching the specifics of damaging economic activity and tracking the transition to a low-carbon economy. More than 200 frameworks, standards, and other forms of guidance on sustainability reporting and climate-related disclosures are active across 40 countries. However, they lack consistency and comparability.

Harmonized and reliable data are necessary to enhance analyses and could also help unlock action by both the public and private sectors. Policymakers could then better monitor the transition and design appropriate macro policies. In turn, the private sector could better assess climate exposures and facilitate the flow of capital toward climate-sustainable investments.

Extensive work is underway to fill data gaps on both macro and micro levels. On the macro side, the IMF launched the *Climate Change Indicators Dashboard* in April 2021, which provides timely and standardized climate change-related experimental indicators. It improves the frequency and timeliness of climate change data, bringing their publication at par with the general pattern in macroeconomic statistics. Equally important, it aims to ensure a common methodology to make data comparable across countries. On the micro side, the *Network for Greening the Financial System* has identified and prioritized data needs, which also serve as a framework for the new *G20 Data Gaps Initiative,* which sets climate data as priority.

This book builds on these and other initiatives and efforts worldwide. It marks the first attempt to present a structured discussion of measurement issues related to key macroeconomic, financial, and cross-border dimensions of climate change. Involving seven international organizations—the European Central Bank (ECB), Eurostat, the International Energy Agency (IEA), International Monetary Fund (IMF), the Organisation for Economic Co-operation and Development (OECD), the World Bank, and the World Trade Organization—the books aims to leverages each institution's leadership in relevant statistical methodologies.

The book is aimed at informing policymakers, economists, statisticians, academics, and private sector actors for whom climate data have become a critical need. It combines theory and analysis with real-world examples, explained by leading practitioners and experts. We hope the readers will find the book to be an inspiration for further analysis.

Chapter 1 presents estimates of quarterly greenhouse gas emissions by economic activity, developed in a partnership between Eurostat, IEA, IMF, OECD, and the United Nations Statistics Division. It outlines the underlying methodology used to prepare the estimates, presents possible applications, and explores avenues for future work.

Chapter 2 shifts the focus from emissions by production to emissions by consumption—with international trade being the missing link. Based on work pioneered by the OECD, it describes the sources and methods used to estimate the carbon dioxide emissions embodied in international trade, and then final domestic demand. The estimates are based on global input–output tables to account for global production networks and value chains and can be used for structural decomposition analysis to reveal the drivers of emissions in final demand.

Chapter 3 turns to fiscal policies geared toward protecting the environment. It reviews the definitions and measurement of environmental taxes and expenditures, shows how they have changed in recent decades, and discusses ways to improve their measurement, including through green budget tagging.

Chapter 4 is aimed at central banks, based on work by the ECB. It discusses physical risk indicators that could be used for analyses and climate stress testing and highlights new data sources and methodologies borrowed from geographers, climate scientists, and disaster management experts at the intersection of climate and financial analysis.

Chapters 5, 6, and 7 turn to transition risks, particularly for tracking the impact of mitigation policies. Chapter 5 provides an overview of approaches for measuring carbon pricing. It summarizes the World Bank's indicators for direct carbon pricing, as outlined in its *Carbon Pricing Dashboard*, and outlines underlying methodologies and limitations. The chapter also presents the World Bank's framework for combining direct and indirect carbon pricing into a single metric of total carbon pricing.

Chapter 6 describes the IMF's methodology for measuring fossil fuel subsidies at the global and country levels and quantifies the impacts of reform. It involves an extensive compilation of country-level data on sectoral fuel consumption; fuel prices; supply costs; climate, local air pollution, and broader externalities associated with fuel use; and general consumer taxes. A spreadsheet tool for estimating the environmental, fiscal, and economic impacts of fuel-price reform is also briefly discussed.

Chapter 7 presents an experimental indicator—the carbon footprint of bank loans—to quantify the exposure of a country's banking sector to climate transition risks. It presents the results of the indicator for a range of emerging and advanced economies and discusses how to overcome data limitations related to the indicator in the context of the broader climate information architecture.

Chapters 8 and 9 turn to cross-border aspects of climate data. Chapter 8 presents two measures of carbon emissions associated with foreign direct investment (FDI) in host economies from capital formation financed by FDI (for example, constructing new plants and equipment), and from direct and indirect carbon emissions from the production of foreign-owned firms.

Finally, Chapter 9 discusses how to estimate trade in low-carbon technology (LCT) products, such as solar panels and wind turbines. It discusses recent trends in LCT trade, provides an overview of barriers to trade in LCTs, and discusses policy uses and applications of the experimental indicators, which could inform international negotiations on trade policy and climate finance.

The common thread running throughout the book: practical approaches are available that can close climate data gaps using already existing data sources, and close cooperation across institutions and fields of expertise is of the essence. Many indicators presented in this book are available on the IMF *Climate Change Indicators Dashboard* and can be replicated by other countries, including emerging and developing economies. We thus hope that our book will help policymakers and practitioners improve their understanding of the impact of climate change on their economies and ultimately accelerate policy action toward a greener world.

CHAPTER 1

Quarterly Greenhouse Gas Emissions by Economic Activity

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The urgency of abating climate change highlights the need to monitor progress toward nationally determined contributions on a timely basis. This chapter presents estimates of quarterly greenhouse gas (GHG) emissions by industry and households, developed in a partnership between staff of Eurostat, the International Energy Agency (IEA), the International Monetary Fund (IMF), the Organisation for Economic Co-operation and Development (OECD), and the United Nations Statistics Division (UNSD). The chapter outlines the underlying methodology used to prepare these accounts, presents possible applications, and explores avenues for future work with the aim to inspire practitioners in all countries to publish quarterly GHG emissions accounts.

INTRODUCTION

Countries regularly update their Paris Agreement climate action plans for reducing their greenhouse gas (GHG) emissions.[1] Yet, official data on GHG emissions are usually published with low frequency and much delay—annually, with a lag of 12 to 24 months—if published at all. The urgency of abating climate change and the need to communicate it properly highlight the importance of tracking progress toward these targets on a regular and timely basis, including at a higher quarterly frequency.

Recognizing the need for a close review of the structural trends of GHG emissions, Eurostat, the International Energy Agency (IEA), the International Monetary Fund (IMF), the Organisation for Economic Co-operation and Development (OECD), and the United Nations Statistics Division (UNSD) partnered to establish a dedicated Task Team. The Task Team was mandated to design a consistent methodological approach—based on source data availability—that can be used to develop country-level quarterly GHG emissions accounts by industry and households.

The objective of the Task Team is to produce quarterly GHG emissions data consistent with GDP statistics in as timely a manner as possible and with the widest country coverage possible. For consistency and comparability with national accounts statistics, particularly GDP, the Task Team has adopted the framework endorsed by the UN Statistical Commission for air emissions accounts. This framework prescribes recording emissions arising from the activities of all resident units (the same economic activities covered in GDP), regardless of where these emissions occur geographically. Air emissions accounts have the same system boundaries as national accounts (the framework for GDP statistics). The partnership between the international organizations in the Task Team has already led to the regular publication by Eurostat and the IMF of quarterly GHG emissions accounts for European Union (EU) countries and others, respectively. The data are available with a lag of

[1] GHGs include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases (F-gases). F-gases are hydrofluorocarbons, perfluorocarbons, sulfur hexafluoride, and nitrogen trifluoride.

approximately four to five months, starting with the first quarter of 2010.[2] The OECD will also soon publish quarterly GHG emissions accounts for its members. To streamline the process and have a consistent set of estimates among international organizations, it is envisioned that these data will be produced without duplicating efforts.

This chapter discusses the estimation method used by the Task Team in developing quarterly GHG emissions accounts. The next section discusses the conceptual underpinnings of these accounts and explains the main differences between emissions inventories and accounts. The following section dives into data and compilation issues and the selection of predictors on a quarterly basis. The final section concludes by providing avenues for future improvements.

CONCEPTUAL BACKGROUND

Quarterly air emissions accounts adopt the same principles, definitions, and structure as the annual air emissions accounts. The latter is one type of account developed in the System of Environmental-Economic Accounts (SEEA) to record anthropogenic,[3] that is, human-induced, emissions by resident economic units as classified by the International Standard Industrial Classification of All Economic Activities (ISIC) and by households.

The SEEA is the international statistical framework used to record and present internationally comparable environmental accounts and their link to economic activity. The SEEA Central Framework (United Nations and others 2012) is consistent with the System of National Accounts (SNA; United Nations and others 2008), following well-established underlying concepts such as the resident recording principle. The residency principle is crucial when defining the economic activities belonging to a specific country's economy.

The ISIC is the international reference classification of productive activities. Its main purpose is to provide a set of activity categories that can be utilized for the collection and reporting of statistics relating to such activities. The use of the ISIC ensures that statistics on GHG emissions follow the same classification of activities as GDP statistics follow, allowing for comparability. In other words, SEEA-based air emissions accounts are directly comparable to the economic information on production and consumption, as obtained from the SNA. By following the SEEA standard, the emissions accounts are readily used for environmental-economic analyses, such as environmental intensity calculations and consumption-based carbon footprint analysis.

The UN Framework Convention on Climate Change's (UNFCCC) inventory for GHG emissions is another framework to collect and structure data on anthropogenic GHG emissions as reported by countries. It takes stock of emissions generated within the territory of a country by different sources (for example, electricity production, manufacturing, transport) and follows the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories.[4] International aviation and shipping are excluded from the country inventory totals, given their international nature, but are available as separate memo items. There are two types of parties under the UNFCCC, with the industrialized countries (referred to as Annex I reporters in the UNFCCC) committed to producing annual GHG emissions inventories, while others report data on a best-effort basis, usually with longer lags.[5]

The Emissions Database for Global Atmospheric Research (EDGAR; Crippa and others 2021) also provides an estimated inventory of GHG emissions. Instead of countries directly reporting,

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[2] The countries without subannual data (energy statistics, indices of industrial production, and gross value-added) are grossed based on estimates for countries in their region. The IMF's Climate Change Indicators Dashboard at this point provides data at the regional level even though they are estimated at the country level. Country-level data might be added as the methodology is further refined.

[3] Natural flows of GHG emissions, for example from volcanoes and forest fires, are excluded.

[4] For more information, see https://www.ipcc.ch/report/2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/.

[5] There are 43 Annex I reporters (42 countries, plus the EU). See https://unfccc.int/parties-observers.

EDGAR relies on primary sources of sectoral data, collected and made comparable by international organizations such as the IEA for energy and the Food and Agriculture Organization (FAO) for agriculture. As in the UNFCCC inventory, EDGAR classifies GHG emissions by source and thus needs to be mapped to the ISIC classification of economic activities. Overall, the annual data set contains 232 economies, which are used in calculating the world and regional (sub) aggregates.

In contrast to the UNFCCC or EDGAR inventories, the SEEA classifies the emissions generated by all residents of a country, irrespective of where the emissions take place. This accounting principle means that all emissions from international transportation are assigned to the countries in which the operators of these transport services are domiciled. As a reference, international shipping and aviation account for around 700 (1.8 percent of worldwide emissions) and 600 (1.6 percent of worldwide emissions) metric tons of CO_2 emissions, respectively. Another difference is that the inventories capture changes in carbon stocks originating from land use, land use change, and forestry, which are not included in the SEEA accounts.

The UNFCCC/EDGAR inventories and the SEEA follow a *direct recording principle*, which means emissions are recorded at the level of those processes or industries where they are released. For example, emissions generated by power plants are not attributed to the electricity consumers in the accounts. The SEEA-based emissions accounts can be used for input–output analysis, through which such emissions can be attributed to final users.

The UNFCCC/EDGAR inventories and SEEA rely on various techniques to estimate emissions. Emissions can be estimated directly through emissions monitoring (for example, CO_2 released via the smokestacks of larger emitters). They can also be measured indirectly. A common approach is the use of emissions factors: a coefficient that converts activity data into GHG emissions. For example, an industry that uses 10,000 liters of diesel has 26.8 metric tons of carbon emissions, based on an emissions factor of 2.68 kg per liter of combusted diesel. Although in practice the estimation is often performed at a more detailed level, a simplified model would take the following form:

Emissions (*e*) = Activity Data (*ad*) × Emissions Factor (*ef*)

The Eurostat (2015) Manual for Air Emissions Accounts explains that there are at least two approaches used by countries to produce SEEA emissions accounts:

1. The *inventory-first* approach takes the UNFCCC emissions inventory as the starting point. Two adjustments are needed to (1) move from a territory-based to a residency-based recording and the inclusion of international transportation in total emissions, and (2) break down the emissions sources into production activities and households.
2. The *energy-first* approach can be applied when energy accounts, or energy supply and use tables, measured in quantity units, are available. These can be used to transform the combustion-related energy inputs for each of the different fossil energy products into emissions. However, this approach will only produce energy-related emissions, thus other sources must be used to derive the non-energy-related GHG emissions.

The *inventory-first* method provides an easier bridging between UNFCCC inventory and SEEA data (see Box 1.1). Statistical discrepancies may occur between the UNFCCC inventory and the SEEA emissions accounts derived from the *energy-first* approach when different sets of energy data and emissions factors are used. Another potential source of statistical differences is having only partial coordination between national statistical offices, which often compile emissions accounts, and environmental agencies, which are responsible for producing inventories.

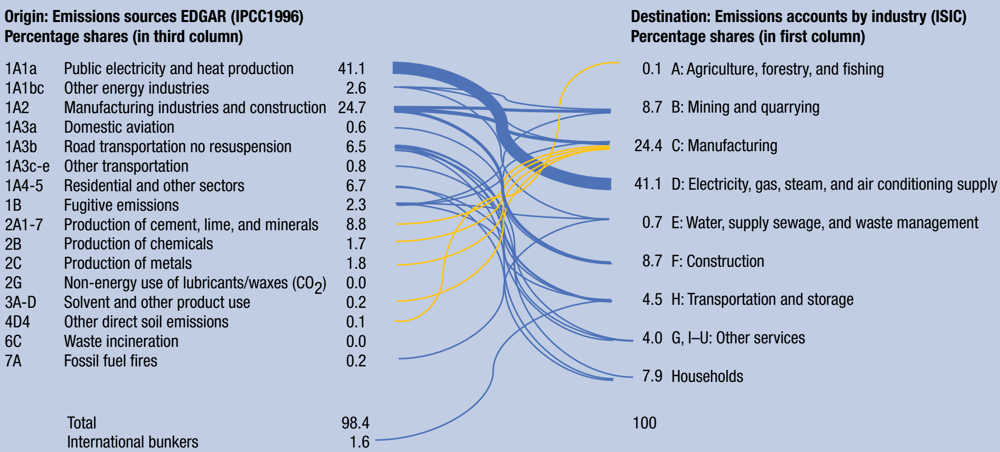
Despite the slight conceptual and institutional differences between the inventory and energy accounts frameworks, usually the majority of national GHG emissions are from resident units' activities in the territory of their country, implying that conceptual differences are generally negligible. However, especially for small economies, the emissions-relevant activities of nonresidents in the territory and the emissions-relevant activities of residents abroad may be significant in relation to the national totals.

Box 1.1. Assigning the CO_2 Emissions to Industries and Households: The Example of China

For China, the Emissions Database for Global Atmospheric Research (EDGAR) is used to obtain the annual emissions data. Before starting the temporal disaggregation and compiling the quarterly estimates, the classification of emissions sources is aligned to the industries and households as identified in the emissions accounts.

Figure 1.1.1 visualizes how the classifications of emissions sources in EDGAR, on the left side, and activities (International Standard Industrial Classification of All Economic Activities [ISIC] and households), on the right, are matched. The blue lines refer to emissions from fuel combustion. The orange lines refer to emissions from other processes, such as production of cement and metals. The figure shows that the larger part of the CO_2 emissions (84 percent) originates from fossil energy use. China is not unique in this respect in that for most countries fossil energy use is the largest contributor to greenhouse gas (GHG) emissions.

Figure 1.1.1. China, CO_2 Emissions, 2018



Sources: Emissions Database for Global Atmospheric Research (EDGAR); and IMF estimates.
Note: CO_2 = carbon dioxide; IPCC 1996 = 1996 version of the Guidelines for national greenhouse gas inventories of the Intergovernmental Panel on Climate Change; ISIC = International Standard Industrial Classification of All Economic Activities.

Various methods can be applied to convert emissions inventory-based data to an industry-based recording. Not all the mappings are one-to-one, and some of the emissions sources must be allocated to various industries. For example, transport is carried out by a wider range of activities than the transport sector alone. The IMF derived a concordance between emissions sources and the various industries using Eurostat data for all European Union (EU) member states. With the help of EU emissions inventories and System of Environmental-Economic Accounts (SEEA) accounts, the two data sets were analyzed to assign (portions of) a certain source to a certain industry. This information was used to compile a transformation matrix. The preceding figure shows that only a limited number of emissions sources in this matrix are critical, such as *Public electricity and heat production* (41.1 percent) and *Manufacturing industries and construction* (24.7 percent).

If the emissions from international bunkers (shipping and aviation) are added to the transportation sector (the lowest blue line not assigned to any of the EDGAR emissions sources for China), the emissions accounts are 1.6 percent higher than the EDGAR data. In EDGAR, similar to the UN Framework Convention on Climate Change (UNFCCC) inventory, the emissions from international bunkers are separately recorded as a memo item and are not included in the total country GHG emissions estimates. In IMF estimated accounts, these emissions are assigned to individual countries based on information on the relative sizes of the transport industries.

Lastly, both frameworks report GHG emissions in metric tons of CO_2 equivalents, which is the amount of CO_2 emissions with the same global warming potential as one metric ton of another GHG.[6] For example, one metric ton of CH_4 (methane) released has 25 times the global warming potential of CO_2 released in the atmosphere. Thus, one metric ton of CH_4 is equivalent to 25 metric tons of CO_2 equivalent.

ESTIMATIONS: FROM ANNUAL TO QUARTERLY ACCOUNTS

Annual Accounts

As the goal is to estimate timely GHG emissions consistent with GDP, the annual SEEA-based emissions accounts serve as the benchmark for the quarterly estimates. Since the SEEA Central Framework's endorsement by the United Nations Statistical Commission in 2012[7] (and in some cases prior to its endorsement), EU members have been publishing environmental accounts, as required by EU Regulation No. 691/2011,[8] no later than 21 months after the reference year. The harmonized EU reporting template provides detailed information on 64 Nomenclature Statistique des Activités Économiques dans la Communauté Européenne (NACE)/ISIC activities and three household activities (heating/cooling, transport, and other). The IMF's Climate Change Indicators Dashboard includes these Eurostat-collected data as well as emissions accounts for seven non-EU OECD economies (though not necessarily at the same level of detail as found in the EU reporting template).

For those countries that do not produce SEEA-based accounts, the annual data are obtained from other sources. For 10 countries in the data set, the country-reported UNFCCC inventory data (Annex I countries only) are used as the starting point.[9] For another 188 countries and territories ("economies"),[10] estimates are obtained from the EDGAR database. Table 1.1 provides a summary of the annual source data used.

The UNFCCC Annex I data provides a breakdown of the sources of GHG emissions, generally allowing for a one-to-one correspondence to the ISIC classification at the level at which the quarterly GHG estimates take place (discussed further later). For Japan, Kazakhstan, Russia, Ukraine, and the United States, the OECD methodology (Flachenecker, Guidetti, and Pionnier 2018) and corresponding OECD database are used to map the generation of GHG emissions to industries or households. For other countries, similar but streamlined approaches are used. For example, rather than

[6] The Global Warming Potential is the extent to which a gas contributes to the greenhouse effect. The Intergovernmental Panel on Climate Change (IPCC) prescribes which Global Warming Potential should be used per gas. The IPCC Fourth Assessment Report recommends a Global Warming Potential for CH_4 equal to 25, while the Fifth Report recommends a value of 28. See the values used to calculate the CO_2 equivalent at https://unfccc.int/process-and-meetings/transparency-and-reporting/greenhouse-gas-data/frequently-asked-questions#eq-10.

[7] The SEEA Central Framework (SEEA-CF) was adopted by the United Nations Statistical Commission (UNSC) at its 43rd Session, in 2012, as the first international standard for environmental-economic accounting. At the 52nd session, in 2021, the UNSC adopted the SEEA Ecosystem Accounting (SEEA-EA). The SEEA-EA takes a spatial approach to accounting, as the benefits a society receives from ecosystems depend on where those assets are in the landscape in relation to the beneficiaries. In contrast, the SEEA-CF looks at individual environmental assets (resources), such as water or energy resources. It comprises a number of different accounts for measuring the environment and its relationship with the economy.

[8] https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1416221752426&uri=CELEX:02011R0691-20140616.

[9] Including for Australia and Canada, because the SEEA accounts are not available for individual GHGs, but on an aggregated basis only.

[10] For example, Puerto Rico and Guam are US territories but their GHG emissions are separately recorded from the GHG emissions of the United States.

TABLE 1.1.

Annual Source Data	
Sources	**Countries**
SEEA EU (27)	Austria, Belgium, Bulgaria, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden
SEEA Non-EU (7)	Colombia, Iceland, New Zealand, Norway, Switzerland, Turkey, United Kingdom
UNFCCC (10)	Australia, Belarus, Canada, Japan, Kazakhstan, Liechtenstein, Monaco, Russia, Ukraine, United States
EDGAR (188)	Remaining economies

Sources: Emissions Database for Global Atmospheric Research (EDGAR) database; Eurostat air emissions accounts; Organisation for Economic Co-operation and Development air emissions account; and UN Framework Convention on Climate Change (UNFCCC) database.
Note: Number in brackets represents the number of countries. EU = European Union; SEEA = System of Environmental-Economic Accounts.

trying to split the sources of emissions as being from cars or motorcycles, they are entirely mapped to households, as most of these vehicles are used for consumption. Similarly, other transportation sources (for example, trucks, buses, domestic aviation) are mapped entirely to the transportation industry.

The EDGAR data provide less detail on emissions sources. For example, instead of a breakdown of emissions from cars and motorcycles (allowing them to be allocated to households) and trucks and buses (allowing them to be allocated to the transportation industry), a more aggregated "road transportation" category is provided. Consequently, instead of many one-to-one mappings, more redistributions are required from EDGAR sources to ISIC industries, and thus are less precise than a more refined mapping that could be done by national statistical offices for the SEEA-based emissions accounts.

Quarterly Accounts

Since annual data on GHG emissions serve as a benchmark, the quarterly estimation technique follows an approach that is commonly applied in the compilation of quarterly statistics.[11] The basic principle of temporal disaggregation is to distribute the annual time series into quarterly values (backward series) and to extrapolate those quarters for which annual accounts are not yet available (forward series). Both steps, distribution and extrapolation, are performed with auxiliary information, that is, subannual (monthly or quarterly) "predictors" or "indicators," which are considered sufficiently suited to approximate the quarterly developments of GHG emissions.

The GHG emissions accounts can best be described as a four-dimensional data cube consisting of geography, GHG, activity (industries and households), and time. Since the level of detail by activity and GHG varies considerably across countries, an estimation plan (see following section) is required to reduce all categories of these dimensions to a manageable number of time series.

Creating the Quarterly Estimation Structure

The first step in developing an estimation plan is to identify the target variables; that is, the level of detail to which quarterly GHG emissions accounts are to be estimated. In countries that regularly produce annual air emissions accounts, the annual level of detail varies. For the EU members, the annual GHG emissions accounts data set contains 402 time series for each country (67 economic activities times 6 GHGs). When the level of detail is significant, it is practical to identify a more aggregated estimation structure for the quarterly estimates. Several considerations are relevant to determine the aggregation, as follows:

- *Identify the economic activities that contributed most significantly to air emissions.* Since CO_2 emissions make up the bulk of GHG emissions, the focus is on estimating them at a more detailed level by industry. For example, if annual GHG emissions data for the manufacture of

[11] For information on temporal disaggregation techniques, see IMF (2017) and Eurostat (2018).

other nonmetallic mineral products (ISIC division 23, which includes cement manufacturing) and manufacture of basic metals (ISIC division 24, which includes steel manufacturing) are available, as well as subannual data (for example, index of industrial production), then the estimation of quarterly GHG emissions is performed at this level of detail.

- *Consider the range of subannual predictors available in a timely manner* (that is, less than 90 days after the reference quarter). For countries that do not produce annual emissions accounts, the UNFCCC and EDGAR data are converted into emissions accounts, as described previously.
- *Review the level of detail at which the results will be disseminated*. Since the level of detail varies widely across countries, the publication level of economic activities at the quarterly frequency follows those countries with the lowest level of detail.

Review of Subannual Data

A review of international organizations' databases was performed to obtain possible indicators that could be used for compiling quarterly emissions estimates. In particular, annual emissions statistics may be measured directly through systems that monitor GHGs and be supplemented by estimated emissions that are calculated from detailed energy statistics, for which data are usually not available at a subannual level. The review was done to reduce the burden on authorities of any new data collections and to ensure widespread country coverage by utilizing similar concepts, classifications, and data formats. In some limited cases, given a country's importance in contributing to GHG emissions, certain subannual data are sourced directly from that country's websites (for example, subannual data obtained for the United States).

Two approaches were considered for selecting indicators:

- A *qualitative approach* utilizing assumptions about the relationship between the subannual data and the annual benchmark. It assumes the existence of a correlation between the estimated variable and its predictor; for instance, predicting CO_2 emissions from combustion using fossil energy use data.
- A *purely statistical approach* that considers all subannual input data provided for a particular economy and picks the "best" predictor utilizing correlations.

The rationale for thoroughly checking statistical correlations is twofold. First, the basket of predictors is in many cases sparse, especially for less advanced statistical systems. If so, a selection based on the best possible correlation seems reasonable. Second, temporal disaggregation requires a certain level of correlation between the annual and quarterly series for acceptable results.

As soon as the annual accounts become available, the previously compiled quarterly accounts are made consistent with the annual accounts. These revisions should ideally be small and unbiased. They should also be carefully examined to evaluate the validity of the quarterly estimation process and to readjust the measurement process where needed.

Differences between the Eurostat and IMF Approaches

Eurostat and the IMF follow slightly different approaches in their estimations, mainly due to differences in the availability of data for the larger set of economies that the IMF estimates. Both approaches are discussed.

The Eurostat Quarterly Estimation Process

Eurostat condenses the annual level of detail for the quarterly estimation, which consists of 46 time series (NACE/ISIC industries and household activities by GHG combinations). For the majority of economic activities, it applies a standard method to produce quarterly GHG emissions estimates. Table 1.2 provides a summary of the list of subannual predictors utilized for the standard method

TABLE 1.2.

Eurostat's List of Subannual Predictors for the Standard Method Cases

Predictor Label	Provider	Data Set Name
Gross value added in agriculture, forestry, and fishing	Eurostat	Gross value added and income A*10 industry breakdowns
Gross value added in industry	Eurostat	Gross value added and income A*10 industry breakdowns
Index of industrial production in other nonmetallic mineral products	UNIDO	UNIDO Quarterly Index of Industrial Production
Index of industrial production in basic metals	UNIDO	UNIDO Quarterly Index of Industrial Production
Net electricity generation from combustible fuels	Eurostat	Net electricity generation by type of fuel
Gross inland deliveries—observed—of motor gasoline and road diesel	Eurostat	Supply and transformation of oil and petroleum products—monthly data
International marine bunkers and final consumption transport sector of oil products (EU27 aggregate)	Eurostat	Supply and transformation of oil and petroleum products—monthly data
CO_2 emissions air transport	OECD	Air transport CO_2 emissions
Gross value added in service industries	Eurostat	Gross value added and income A*10 industry breakdowns
Heating degree days	IEA	Heating degree days (reference temperature 18°C and threshold temperature 15°C)
Gross value added in all NACE activities (excluding NACE A)	Eurostat	Gross value added and income A*10 industry breakdowns
Index of turnover in wholesale and retail trade	Eurostat	Turnover and volume of sales in wholesale and retail trade—quarterly data
GDP at market prices, in current prices, million euro	Eurostat	GDP and main components (output, expenditure, and income)

Source: Eurostat (2022).
Note: CO^2 = carbon dioxide; IEA = International Energy Agency; NACE = Nomenclature Statistique des Activités Économiques dans la Communauté Européenne; OECD = Organisation for Economic Co-operation and Development; UNIDO = United National Industrial Development Organization.

cases (Eurostat 2022). In each quarterly estimation cycle, the complete time series starting from the first quarter of 2010 is recalculated and is therefore subject to revision. The data are not seasonally adjusted.

The standard method utilizes the subannual indicators to temporally disaggregate the annual target and then extrapolate the most recent quarters for which the annual estimate is not yet available, all in one estimation procedure. It includes the following techniques:

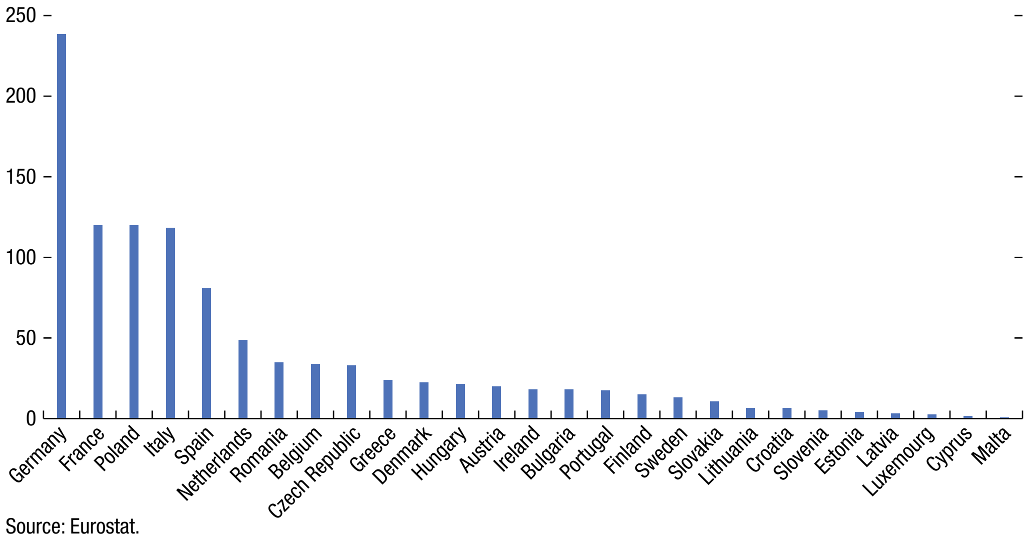
- The *Denton proportional first difference variant method* aims at preserving the movement of the subannual series, while respecting the benchmarking constraint (that is, the sum of the four quarters is equal to the annual value) (Eurostat 2013, 2018).
- Static regression methods, such as in *Chow-Lin, Fernandez, and Litterman* (Eurostat 2013, 2018).

The selection of the technique is based on (1) the plausibility of the quarterly estimates as computed by each of these techniques, such as avoiding any negative values, and (2) the quality of forecasts achieved by assessing simulated historical annual emissions accounts with the published time series. In general, the Denton method is the default method.

Eurostat performs the calculations at the EU country level but publishes only total GHG emissions at that level. Figure 1.1 shows that the top five countries in the EU for GHG emissions in the fourth quarter of 2021 were Germany, France, Poland, Italy, and Spain.

The EU aggregate is calculated as follows. First, the various GHGs, expressed in CO_2 equivalents, are summed up to a total GHG aggregate. Second, the EU aggregate is calculated bottom-up from the quarterly accounts of the 27 EU members. Third, the estimation level of detail (that is, the

Figure 1.1. Total GHG Emissions for All NACE Activities and Households, Fourth Quarter, 2021
(Millions of metric tons of CO_2 equivalents)



Source: Eurostat.
Note: CO_2 = carbon dioxide; GHG = greenhouse gas; NACE = Nomenclature Statistique des Activités Économiques dans la Communauté Européenne.

46 time series) is aggregated to nine groupings of economic activities (eight industries and total activities by households), which are disseminated for the EU total, as shown in Figure 1.2.

Eurostat selects the subannual predictors mainly based on their relationship with the respective emissions sources.[12] For a few target variables, where predictors are not available, specific estimation methods are used.

- *Methane emissions from waste management*

Methane emissions from waste management in the EU show a stable downward trend from 1990 to 2017, and it seems reasonable to simply extrapolate this trend (Petrescu and others 2021). These entries in the annual air emissions accounts are temporally disaggregated by using the Boot, Feibes, and Lisman (1967) method.[13] In other words, the annual rate of change is proportionally adopted for the quarterly estimates as well. The quarters beyond the available annual air emissions accounts (forward quarterly series) are estimated by a weighted moving average of the three latest quarterly observations.

- *Emissions of methane and nitrous oxide from agriculture*

There is no suitable subannual predictor for the emissions of methane and nitrous oxide from agriculture. When annual data are not yet available, the annual emissions are extrapolated using annual rates of change for livestock. The Boot, Feibes, and Lisman technique is applied to temporally disaggregate the annual emissions.

- *Emissions of CO_2 from air transport*

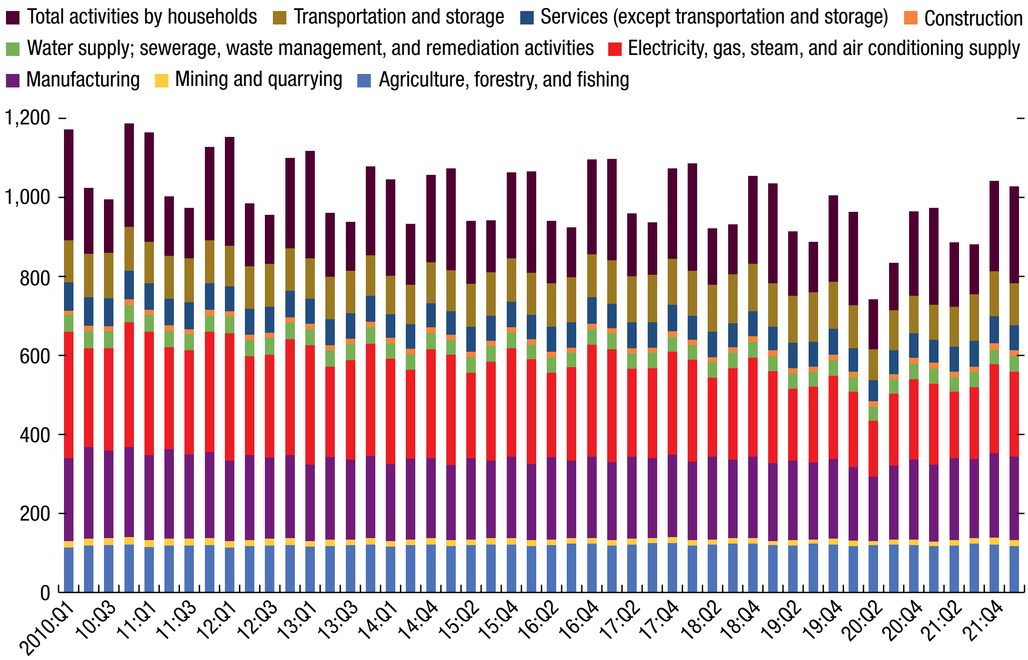
The Denton method is applied, and the quarterly time series of the predictor is spliced together using two data sources:

1. For the period 2010–18, the annual air emissions accounts, whereby the annual estimate is simply divided by four quarters of equal size.
2. From 2019 onward, the monthly OECD data on CO_2 emissions by air transport, aggregated to arrive at quarterly time series.

[12] Annex 3, "Assignment of predictors to 46 AEA data points of greenhouse gas emissions," in Eurostat (2022) contains more information.

[13] This method corresponds to Denton's proportional first variant method with a constant as a predictor (IMF 2017).

Figure 1.2. Total Greenhouse Gas Emissions by Economic Activity for the European Union
(Millions of metric tons of CO_2 equivalents)



Source: Eurostat.
Note: CO_2 = carbon dioxide.

- *Emissions of CO_2 from water transport*

Unlike other time series, emissions of CO_2 from water transport do not have a country-specific predictor for the EU countries. Instead, the EU aggregate for fuel delivered to international marine bunkers is used, reflecting the overall activity levels of marine transport in seaports.

The IMF Quarterly Estimation Process

The IMF quarterly measurement system for non-EU countries is sufficiently flexible to adapt to the specific data structures of individual countries as well as to handle large data sets with wide country coverage. To produce estimates within four to five months of the reference quarter, the estimation process is more general in scope and less able to deal with specific estimation issues than is Eurostat's.

Because the IMF constructs the annual emissions accounts, a uniform classification structure can be applied. For non-EU economies producing annual emissions accounts, the first step is to create a common structure for the quarterly estimation, which requires careful database management in terms of data consistency, aligning variations in data frequency (months, quarters, years), structure (a variety of classifications), and content.

The IMF estimation process uses similar source data as Eurostat:

- IEA electricity statistics, oil statistics, and weather for energy tracker (IEA, 2021, 2022a, 2022b).
- Gross value-added in constant prices (IMF and OECD, quarterly).
- Index of industrial production (United National Industrial Development Organization [UNIDO], quarterly; IMF and Australian Bureau of Statistics, monthly).
- Data for the United States on carbon dioxide emissions (U.S. Energy Information Administration [EIA], monthly); on value-added by industry (U.S. Bureau of Economic

Analysis [BEA], quarterly); on construction spending (U.S. Census Bureau, monthly); and on meat production (U.S. Department of Agriculture [USDA], quarterly).

- External trade (IMF and World Trade Organization [WTO], monthly).
- Transportation data (OECD, quarterly).
- Labor force (IMF, monthly).

Table 1.3 shows the use of subannual predictors for the temporal disaggregation of the economic activities by region. It provides an indication of how often the predictor is used and its corresponding impact on constructing the quarterly aggregate for total GHG emissions. Table 1.3 highlights that indices of industrial production are the most used predictors (representing 49 percent of the weighted share of total GHG emissions). Furthermore, subannual energy data are also frequently used (representing 21 percent of the weighted share of total GHG emissions). Table 1.3 highlights also that there is a lack of energy statistics for certain (sub)regions of the world, such as in Africa or parts of Asia, which are important for monitoring the energy transition. Because suitable subannual data are not available for all countries/territories, the quarterly air accounts estimates are available for only 110 economies, representing 92 percent of the world's GHG emissions. For annual world GHG emissions, the IMF constructs an aggregate using 232 economies/territories.

The IMF's estimation plan has a clustering of activities and gases. It targets the breakdown by industries and households, taking into consideration the relevance and availability of subannual predictors. The plan has three country groups that divide countries based on the availability of source data and the structure of their annual emissions accounts (see Annex 1.1).

Because the first and second groups of countries contain a highly aggregated estimation structure for certain GHGs, the IMF breaks down quarterly emissions into more industries to facilitate aggregation by industry across all types of GHGs. For the backward series, it uses as the allocation factor the structure of annual air emissions accounts for each year. And for the forward series, it uses as the allocation factor the structure of the latest available annual air emissions accounts. This generates results at various levels of aggregation: countries, (sub)regions, and the world.

Subannual data are seasonally adjusted, either by the source or, if not, by the IMF. Compared to the Eurostat method, this is a significant methodological difference. One important argument to support seasonally adjusting predictors prior to their use is that their quarterly patterns may not necessarily correspond to the quarterly patterns of emissions (further pros and cons of seasonal adjustment are discussed later in this chapter).

The IMF selects most quarterly predictors based on their highest correlation. Therefore, while the Eurostat method follows mostly a predetermined selection of predictors, the IMF method selects for each quarterly estimate the best-performing predictors based on historic correlations.[14] Annex 1.2 shows the results of the analysis.

Box 1.2 provides an idea of how well the IMF estimation process performs when compared to the quarterly estimates as published by the country's statistical offices.

The IMF disseminates data for the same nine groupings of economic activities (eight industries and total activities by households) as Eurostat. While Eurostat disseminates total GHG emissions for these groupings, the IMF disseminates them by four types of GHGs (CO_2, CH_4, N_2O, and fluorinated gases). The IMF derives regional and subregional quarterly estimates by aggregating the economies when there is full coverage of a (sub)region or otherwise by benchmarking. Figure 1.3 shows that the dominant economic activities that emit GHGs emissions are the electric, manufacturing, and agricultural industries. Households are also a major source of emissions.

[14] For China and India, a more prescriptive approach is followed that restricts the selection of indicators based on an assumed relationship (for example, energy data for CO_2 emissions). A future refinement would be to combine correlation and choose the indicator that is similar to the indicator used to prepare the annual emissions accounts.

TABLE 1.3.

Subannual Predictors by Region for the 110 Economies Used in the Quarterly Estimation of the IMF
(Percentage, weighted shares of total world greenhouse gas emissions, average, 2010–20)

Regions	Crops and Livestock	Degree Day	Emissions	Energy	External Trade	Gross Value Added	Index of Industrial Production	Labor Force	Meat Production	Transport	Grand Total
Africa						0.02	4.53				4.55
Northern Africa							1.64				1.64
Sub-Saharan Africa						0.02	2.89				2.91
Americas			7.97	0.78	0.04	9.6	4.08	0.03	0.06	0.89	23.46
Latin America and the Caribbean				0.73	0.04	2.91	3.5	0.03		0.33	7.53
North America			7.97	0.06	0	6.69	0.59		0.06	0.56	15.93
Asia				16.36	0.93	3.89	32.35	0.3		0.75	54.57
Central Asia							0.7	0.16		0.34	1.21
Eastern Asia				13.73	0.85	0.1	20.67	0.01		0.21	35.57
Southeastern Asia						1.12	4.11	0.13			5.35
Southern Asia				2.32		1.45	5.4				9.17
Western Asia				0.3	0.07	1.23	1.47	0		0.2	3.27
Europe	0.01	0		4.08	0.04	2.66	7.47	0.48		1.26	16
Eastern Europe				0.54		1.53	5	0.01		0.3	7.38
Northern Europe				0.47		0.44	0.6	0.43		0.28	2.22
Southern Europe		0		0.77	0	0.37	1.01	0		0.14	2.3
Western Europe	0.01			2.3	0.04	0.32	0.86	0.04		0.54	4.11
Oceania				0.03		0.69	0.7			0	1.42
Oceania subregions				0.03		0.69	0.7			0	1.42
Total	0.01	0	7.97	21.25	1.01	16.86	49.13	0.81	0.06	2.9	100

Source: IMF estimates.

Note: There could be differences between the Eurostat estimates and the IMF estimates due to the selection of different subannual predictor variables. Eurostat and the IMF will further align their efforts in the course of 2023.

Box 1.2. Comparing the IMF Quarterly Estimates with Those Published by Statistics New Zealand

New Zealand is one of only a handful of countries that publishes quarterly greenhouse gas (GHG) emissions accounts. This provides an opportunity to compare the estimation method described in this chapter and results with those published by Statistics New Zealand (Stats NZ).

The experimental quarterly account, as published by Stats NZ, uses annual estimates of emissions by industry and households and, based on subannual data, provides more timely emissions estimates. The annual GHG emissions by industry and households account uses the latest UN Framework Convention on Climate Change (UNFCCC) GHG inventory for New Zealand and a range of economic data sources to measure emissions from industry and households. Stats NZ's emissions accounts series are compiled using the System of Environmental-Economic Accounts (SEEA).

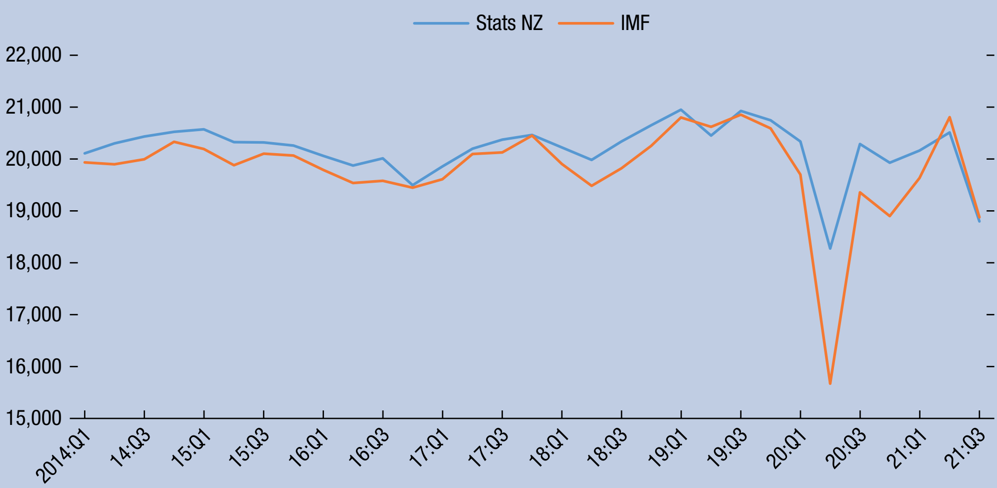
Stats NZ's quarterly estimates are available for seven industry groups (which are aggregations of industries based on the Australian and New Zealand Standard Industrial Classification 2006), along with household direct emissions. The quarterly accounts cover carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), F-gases, and the sum of these four gases based on CO_2 equivalents.

The following data sources are used as input data: (1) annual GHG emissions; (2) quarterly energy statistics; (3) quarterly GDP; and (4) additional data sources, including electricity use, card transaction data, prices, and transport statistics.

The accounts are seasonally adjusted, which allows for showing quarter-on-quarter movements. The accounts become available five months after the reference quarter.

Figure 1.2.1 shows that the IMF-estimated quarterly GHG emissions approximate the quarterly movements as measured by Stats NZ quite well. However, during specific events, such as the COVID-19 lockdown, the two estimates are less strongly correlated, with the IMF projecting a much stronger decline than Stats New Zealand.

Figure 1.2.1. Quarterly Greenhouse Gases in New Zealand (CO_2 + CH_4 + N_2O)
(Thousands of metric tons of CO_2 equivalents)

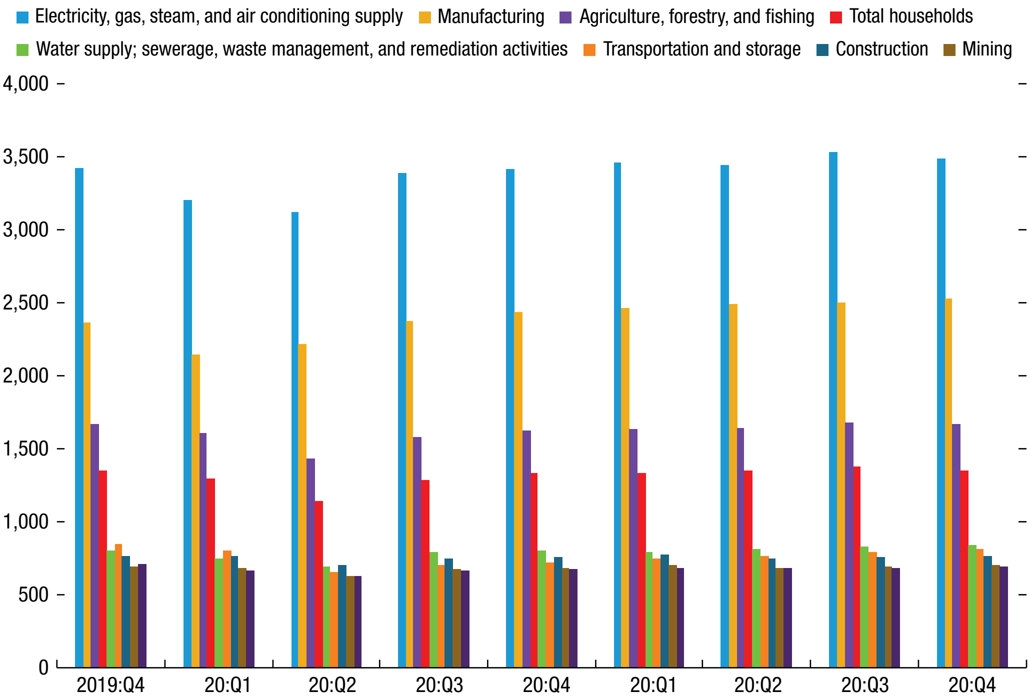


Source: Statistics New Zealand (Stats NZ); and IMF estimates.
Note: CH_4 = methane; CO_2 = carbon dioxide; N_2O = nitrous oxide.

Seasonal Adjustment and Weather-Related Effects

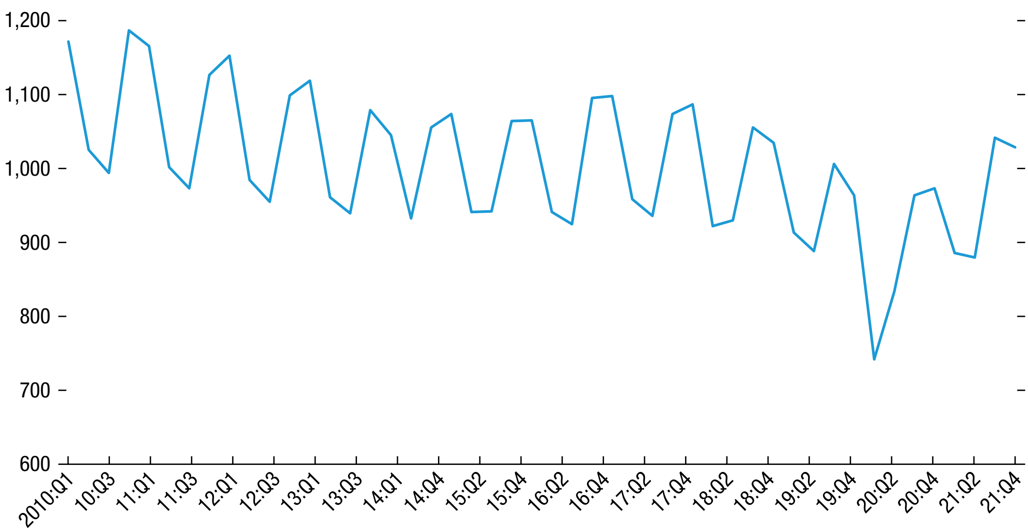
Emissions normally fluctuate strongly across seasons, since demand for electricity, heating, and air conditioning varies depending on temperature and weather. They may also fluctuate from quarter to quarter based on the underlying economic activity. For instance, the estimates produced by Eurostat for the EU aggregate clearly show a pattern of higher emissions in the first and fourth quarters and lower emissions in the second and third (Figure 1.4), largely reflecting colder temperatures in European autumn and winter. The question then becomes: Should GHG emissions be adjusted, and if so, how?

Figure 1.3. Total Greenhouse Gas Emissions by Economic Activity for the World
(Millions of metric tons of CO_2 equivalents)



Source: IMF Climate Change Indicators Dashboard.
Note: CO_2 = carbon dioxide.

Figure 1.4. EU Greenhouse Gas Emissions, All Activities and Households
(Millions of metric tons of CO_2 equivalents)



Source: Eurostat.
Note: CO_2 = carbon dioxide.

Seasonal adjustment aims to strengthen the interpretation of subannual statistics by separating out individual elements that contribute to the overall movement. The seasonal patterns are often a dominant feature of subannual unadjusted data, masking the underlying signal. By removing seasonal patterns, seasonal adjustment not only helps to identify recent trends but also allows doing so in as close to real time as possible. In particular, seasonally adjusted data allow for trend identification in advance of the year-over-year change. Seasonally adjusted emissions series can help to isolate and identify the structural development of GHG emissions over time.

The standard seasonal adjustment accounts for three components: (1) weather-related, (2) institutional, and (3) calendar effects. The recurring weather effects due to seasonal changes reflect the change in anthropomorphic activities resulting from weather changes of the four seasons. The institutional component reflects statutory holidays or industry-specific norms, such as the effects of regular annual vacations and scheduled shutdowns. And the calendar effect results from quarters having different numbers of working weekdays, from one year to another.

This adjustment process does not exclude all weather-related effects. It only removes the predictable seasonal fluctuations from the unadjusted data, whereas any divergence from the normal seasonal fluctuations as part of the irregular component still influence the seasonally adjusted data. Thus, seasonal adjustment does not eliminate the effects on energy consumption and emissions of prolonged heat waves or extremely cold winters.

To isolate the long-term trends in GHG emissions, some statistical institutes have also started implementing weather normalization from average conditions.[15] This potentially provides a clearer indication of the underlying trends, particularly for emissions data. The adjustment assumes that any excesses in demand for electricity for heating and cooling (air conditioning) are likely to reflect deviations from normal weather conditions. With electricity generation and gas consumption representing a large portion of total GHG emissions, these temperature fluctuations can have a significant impact on the seasonally adjusted emissions. For example, the Australian Department of Climate Change and Energy Efficiency (2012) has implemented such a correction to their Quarterly National Greenhouse Gas Inventory Data. Australia uses Demetra, a standard seasonal adjustment tool, to remove the effects of seasonal components. The seasonally adjusted estimates are further adjusted to correct for the effects of variations around average seasonal temperatures based on the concept of "heating and cooling degree days," and this adjustment is applied to total emissions (excluding land use, land use change, and forestry) and the electricity sector. The Netherlands applies a similar weather adjustment based on heating degree days but does not apply any seasonal adjustment.

As there is not any established international best practice, the Task Team is discussing what type of adjustments to apply for the quarterly GHG emissions accounts.

CONCLUSION AND FUTURE WORK AND RESEARCH

The quality of the quarterly GHG accounts depends on the subannual data series that are used to construct the accounts. It has been shown that it is possible to produce global and regional estimates for a handful of industries using publicly available data. National statistical offices could build on the work presented in this chapter by using more precise and granular subannual indicators.

Importance of Primary Source Data

Subannual (monthly) IEA energy statistics already are an important subset of predictors for the quarterly emissions accounts. Still, further research seems warranted to explore how subannual energy use data, as it concerns the dominant source of CO_2 emissions, can be further introduced into

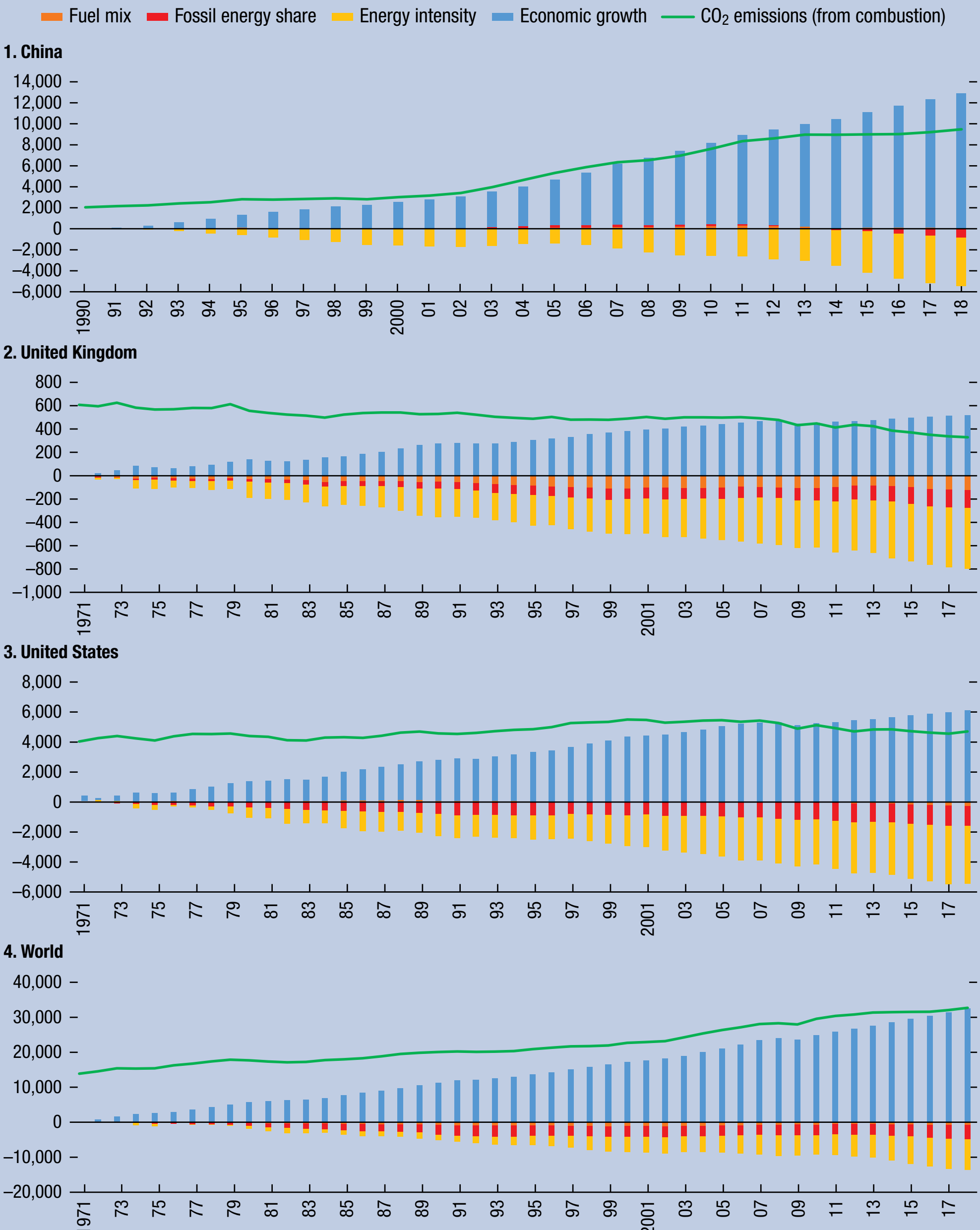
[15] While seasonal adjustment does not affect the annual sum, weather normalization can affect the annual sum (as do calendar adjustments).

Box 1.3. Applications: Tying the Emissions Accounts to Energy Accounts

Both emissions inventories and accounts heavily rely on energy statistics, using fossil energy–based predictors such as fossil energy used in electricity production. Thus, energy data are essential for monitoring greenhouse gases (GHGs). To quantify the dynamics in carbon dioxide (CO_2) emissions over time, Figure 1.3.1 provides examples that bring together annual emissions statistics from the Emissions Database for Global Atmospheric Research

Figure 1.3.1. Decomposition Analyses of the Annual Changes in CO_2 Emissions from Combustion

(Millions of metric tons of CO_2)



Sources: Emissions Database for Global Atmospheric Research; International Energy Agency; World Bank; and authors' estimates.
Note: CO_2 = carbon dioxide.

Box 1.3. (*continued*)

(EDGAR), energy statistics from the International Energy Agency (IEA), and GDP volume growth data as collected by the World Bank. Using the methodology discussed in De Haan (2001), the three data sets are used in a decomposition analysis in which the annual changes in emissions are broken down into four change components:

1. *Fossil fuel mix*. For example, when power plants replace coal with gas, this will lead to lower emissions.
2. *Fossil energy share* of total energy use. For example, the substitution of fossil energy with renewable energy will lead to lower emissions.
3. *Energy intensities*. Obviously, lower energy use from higher efficiency will lead to lower emissions.
4. *Economic growth* as measured by real GDP change. Everything else unchanged, economic growth will lead to increased energy consumption and thus to rising GHG emissions.

Developments in countries can be quite different as abatement measures may not have been able to compensate for the overall impact of economic growth on emissions. For instance, in China (1990–2018), the growth component substantially surpassed emissions abatements, leading to an overall increase in CO_2 emissions. The opposite is seen in the United Kingdom (1971–2018), where the impact of fuel mix, fossil energy share, and energy intensity changes contributed significantly to the downward trend in CO_2 emissions.

the quarterly estimations. One way to do so could be to introduce indicators on the use of energy by the largest energy consumers, such as power plants, or fuel consumption as a predictor, which may better capture energy transitions. Another option may be to refine or expand the current use of fossil energy–based predictors to introduce more granular information on the type of oil products instead of using aggregate oil supply. Given the variation in the emissions factors across the different activities, introduction of such granularity may help to improve the robustness of the estimates.

It is therefore essential that the primary source data at the national level be available at a high frequency, globally. Resources allocated to national statistical offices to collect primary data are not always at the level required as not all countries have the subannual energy statistics required to monitor the trends in a timely fashion.

Strengthening International Cooperation

National statistical offices, especially in the top 20 GHG emitters, could begin by adapting the IMF and Eurostat methods to their circumstances. Techniques could be refined by using more detailed source data, especially on energy statistics that may be available at the individual country level.[16] Along with making the case for high-frequency and timely GHG emissions statistics through peer workshops, capacity development might also be needed. To this end, the IMF is in the process of designing a course on climate change statistics.

In the meantime, international organizations will be further aligning their dissemination strategies in the course of 2023. A *three-stage rocket* strategy is foreseen in which Eurostat will release GHG emissions accounts data for the EU members, followed by the OECD for OECD countries, and then the IMF for the remaining countries as well as the world and (sub)regional aggregates. The OECD will adopt the results published by Eurostat, and the IMF will do the same with respect to the OECD and Eurostat releases. This three-stage dissemination strategy will ensure consistency and eliminate duplication of efforts.

Emissions from International Transport at the Country Level

The transformation of the annual UNFCCC and EDGAR data to emissions accounts requires further work on including the territory-resident adjustment. On the CO_2 emissions from aviation, the OECD publishes a comprehensive monthly data set, which could help in the transition of a

[16] The IEA publication "World Energy Balances Highlights 2021" provides full-world coverage and includes the production and use data of 45 individual countries. The IEA also publishes monthly energy statistics, but these data do not provide all details needed for our analysis.

territory-based to a resident-based recording of emissions (Clarke and others 2022). Its main source is the International Civil Aviation Organization (ICAO), which covers all commercial passenger and freight flights around the world.[17] In addition to comprehensive information on the emissions from domestic and international flights, it provides a breakdown of whether these flights are operated by resident or nonresident operators. The database is also a valuable source for the calculation of subannual CO_2 emissions. The OECD is working on a similar data set on international shipping.

ANNEX 1.1.
IMF ESTIMATION PLAN

The IMF's estimation plan divides economies into three broad groups.

The *first group* of 31 countries is more aggregated than the Eurostat mapping (see Annex Table 1.1.1). It consists of 11 industry classes plus a class for households. For this group, the contributions of potentially high pollutive activities can be measured, such as manufacture of nonmetallic mineral products (including cement production), basic metals (including steel production), and three types of transport.

The *second group* applies to Colombia, New Zealand, and Turkey, which have subannual data sets, though not with sufficient detail. It includes nine classes that are similar to the first group, except for transportation, which is combined in a single category (Annex Table 1.1.2).

ANNEX TABLE 1.1.1.

IMF Estimation Plan for the First Group

Industry Classes Considered
Agriculture, forestry, and fishing
Mining, manufacturing, water and waste, construction excluding nonmetallic mineral products and basic metals
Manufacture of other nonmetallic mineral products
Manufacture of basic metals
Electricity, gas, steam, and air conditioning supply
Water supply; sewerage, waste management, and remediation activities
Wholesale and retail trade; repair of motor vehicles and motorcycles
Road transport
Water transport
Air transport
Other services excluding transport
Household excluding transport

Source: Authors.

ANNEX TABLE 1.1.2.

IMF Estimation Plan for the Second Group

Industry Classes Considered
Agriculture, forestry, and fishing
Mining, manufacturing, water and waste, construction excluding nonmetallic mineral products basic metals and metal products
Manufacture of basic metals and fabricated metal products, except machinery and equipment
Electricity, gas, steam, and air conditioning supply
Water supply; sewerage, waste management, and remediation activities
Wholesale and retail trade; repair of motor vehicles and motorcycles
Transportation and storage
Other services
Households

Source: Authors.

[17] For each flight, this database includes information on the departure and arrival airports, the operating airline, and the type of aircraft used. From 2019 onward, the International Civil Aviation Organization (ICAO) data source is an Automatic Dependent Surveillance-Broadcast (ADS-B) system, and for years prior to 2019 the estimates are based on a database of scheduled flight information.

The *third group* of 76 countries represents those economies with limited subannual data. Its estimation plan consists of nine classes—eight for industries and one for households (Annex Table 1.1.3).

ANNEX TABLE 1.1.3.

IMF Estimation Plan for the Third Group
Industry Classes Considered
Agriculture, forestry, and fishing
Mining and quarrying
Manufacturing
Electricity, gas, steam, and air conditioning supply
Water supply; sewerage, waste management, and remediation activities
Construction
Transportation and storage
Other services
Households

Source: Authors.

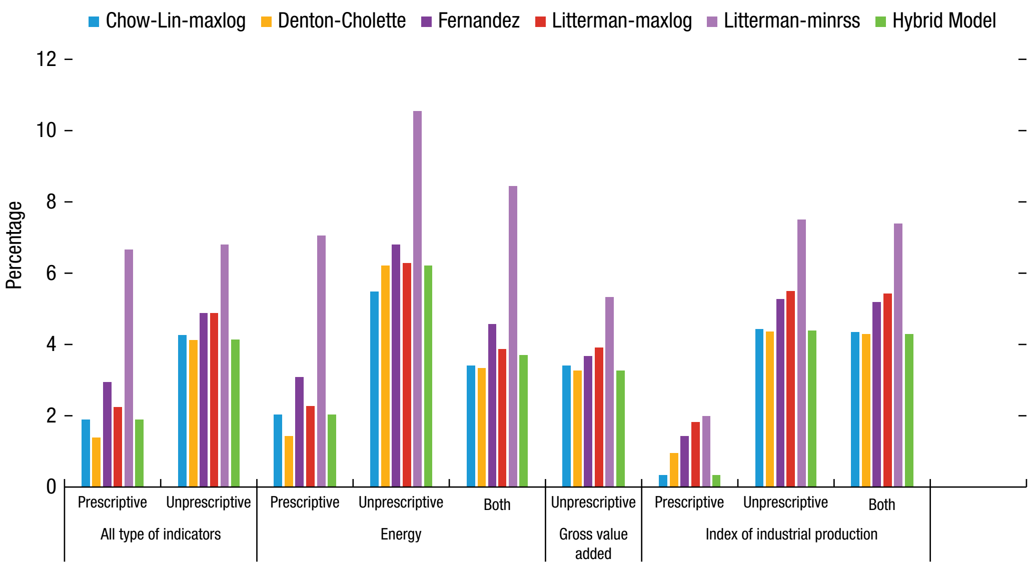
ANNEX 1.2.
IMF MANUAL SELECTION OF PREDICTORS

As discussed in the chapter, given the large set of economies that the IMF estimates, most selections of quarterly predictors are based on the highest time-series correlations ("Unprescriptive" category in Annex Figure 1.2.1). In case of unexpected or unlikely results, some of the predictors or temporal disaggregation models may in a subsequent step be manually selected using assumptions about the relationship between the predictor and the annual target ("Prescriptive" category in the figure). In the analysis, several temporal disaggregation models (*Denton*, *Chow-Lin*, *Fernandez,* and *Litterman*) are reviewed to determine which method(s) should be utilized. Annex Figure 1.2.1 shows the weighted mean absolute percentage errors of the various models.

In the end, a "hybrid" approach was chosen where prescribed and unprescribed mappings were utilized with the Denton and Chow-Lin temporal disaggregation techniques, which provided a lower weighted mean absolute percentage error. If the calculation of the extrapolation error were based only on total emissions it would mislead the analysis as errors might cancel out during the aggregation of gases, industries, and countries. The mean absolute percentage error uses a bottom-up approach from the estimation of clusters to the aggregation for a country.

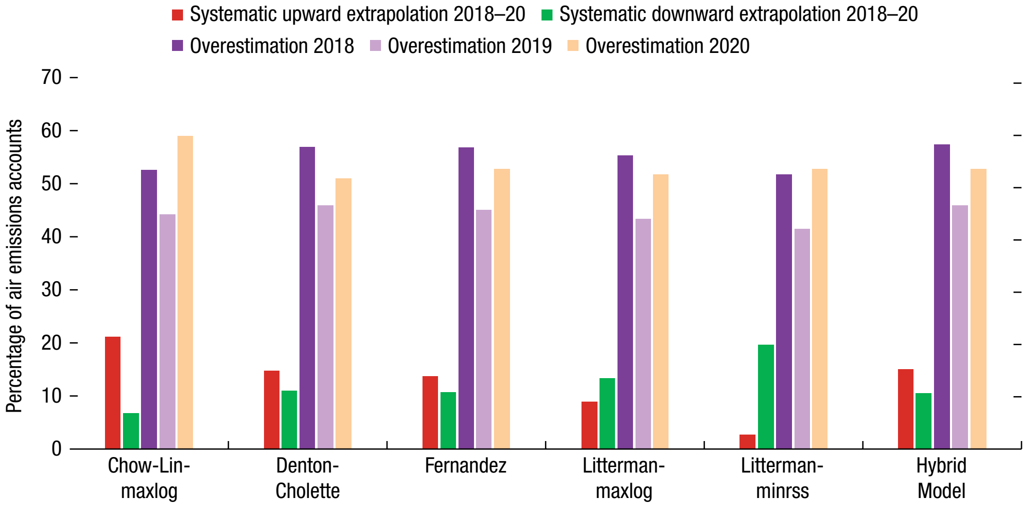
The IMF carries out another sensitivity analysis. This is the persistence of extrapolation bias for forward series from 2018 to 2020. When a model is well calibrated, lower systematic extrapolation bias is a desirable property to reflect that the difference between estimated and actual or the residual is randomly distributed. Annex Figure 1.2.2 shows that the IMF hybrid model that combines both the Denton and the Chow-Lin methods has only 15 percent of clusters displaying a systematic upward extrapolation bias and 10 percent of clusters with a systematic downward extrapolation bias. Meanwhile, using only the Chow-Lin method with the current indicator-selection strategy would result in 20 percent of clusters having a systematic upward extrapolation bias.

Annex Figure 1.2.1. Weighted Mean Absolute Percentage Error for Temporal Disaggregation Model by Indicator Type and Selection Method, 2018



Source: IMF estimates.
Note: Maxlog is the maximization of the likelihood function. Minrss is the minimization of the residual sum of square. For gross value added, there is no prescriptive mapping.

Annex Figure 1.2.2. Systematic Bias of Temporal Disaggregation Methods



Source: IMF estimates.
Note: Maxlog is the maximization of the likelihood function. Minrss is the minimization of the residual sum of square.

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CHAPTER 2

Measuring CO_2 Emissions Embodied in International Trade and Domestic Final Demand

Norihiko Yamano, Joaquim Guilhoto,[1] Xue Han, Colin Webb, Nathalie Girouard, and José-Antonio Monteiro

This chapter describes the sources and methods used to estimate the carbon dioxide (CO_2) emissions embodied in international trade and final demand, based on work pioneered by the Organisation for Economic Co-operation and Development (OECD). Understanding the differences between production-based and final demand–based CO_2 emissions helps governments to better monitor and evaluate climate mitigation policies. When trade volumes are high and production is relocated abroad, reductions in domestic emissions may be offset by increased emissions elsewhere in the world. To support policy discussions, the OECD maintains and updates a set of trade-in-embodied CO_2 indicators that highlight countries or regions that are net exporters or importers of emissions and the origins of emissions in final demand for goods and services. These data are based on global input–output tables to account for global production networks and value chains, and can be used for structural decomposition analysis to reveal the drivers of emissions in final demand.

INTRODUCTION[2]

Designing effective and appropriate policies and measures to reduce carbon dioxide (CO_2) emissions is at the core of climate policies. Given that international trade connects supply and demand, CO_2 emissions not only can be analyzed from a production or consumption perspective, but also can provide a more complete view of the effects of economic activities on CO_2 emissions by taking into account both the direct and indirect impacts of consumption on emissions.[3]

International trade has complex effects on CO_2 emissions, which go beyond the emissions released during the production of the exported goods and services and during international transportation. Trade can affect where production takes place and the associated level of emissions, given the differences in carbon intensity between industries and countries. Importantly, trade also plays a critical role in developing and deploying low-carbon technologies (see Chapter 9 of this book). Whether a country is a net exporter or net importer of CO_2 emissions depends on a number of factors, such as the structure of its economy and domestic demand (as well as its human, natural, and technological resources—in particular, energy sources) and the types of goods traded.

[1] The contribution of this author reflects his work at the OECD prior to joining the IMF.

[2] The authors would like to express sincere gratitude for comments and advice received from our colleagues Serkan Arslanalp, Kristina Kostial, and Gabriel Quiros, which helped to improve the quality and clarity of the chapter.

[3] The OECD's work on emissions embodied in final demand has mainly focused on CO_2 emissions from fuel combustion, as this is the primary greenhouse gas (GHG) (making up about two-thirds of all GHG emissions). Efforts to develop demand-based indicators for other GHGs are ongoing (see "Way Forward" section).

The indicators described in this chapter can contribute to measuring progress in GHG emissions reduction and guiding policy action toward a low-carbon economy.[4] Assessing final demand–based CO_2 emissions and distinguishing the embodied emissions in international trade can help governments to better monitor whether climate change mitigation policies have led to actual domestic emissions reduction by improving energy efficiency and conservation or by outsourcing, or in some cases offshoring, emissions-intensive activities to other countries with less stringent climate policies. This risk of carbon leakage depends on many factors, including the level of stringency of climate policies and the carbon intensity of sectors, and could result in a situation where reductions in domestic emissions are partially or more than fully offset by increased emissions elsewhere due to the outsourcing or offshoring of carbon-intensive production. Carbon leakage and competitiveness concerns associated with ambitious climate change policies might lead to calls for border carbon adjustment measures to ensure that foreign competitors are subject to the same carbon costs as domestic producers. Measuring the CO_2 emissions embodied in international trade can allow the identification of products that are more carbon intensive, accounting for the embedded emissions in domestic and foreign inputs.

This chapter describes the sources and methods used to estimate CO_2 emissions embodied in international trade and final demand, based on work pioneered by the OECD on the measurement of carbon footprints (for instance, Ahmad and Wyckoff 2003; Nakano and others 2009).[5] The measure accounts for global production networks and value chains and highlights divergences between territory and residence principles, and between production- and consumption-based carbon emissions.

The chapter is structured as follows. The first section presents the methodology and data sources. The following section presents global carbon emissions estimates, while the next section sheds some light on potential avenues for refining the estimates further, and the final section presents key conclusions.

METHODOLOGY AND DATA SOURCES

There has been increased focus on the use of input–output (IO) analysis to measure emissions embodied in international trade and final demand, particularly *global* IO tables. Recent studies based on a range of global IO databases include Nakano and others (2009), Peters, Andrew, and Lenox (2011), OECD (2011), Arto, Rueda-Cantuche, and Peters (2014), Owen and others (2014), Moran and Wood (2014), Wiebe and Yamano (2016), and Yamano and Guilhoto (2020).

An important aspect of the measurement of emissions embodied in final demand is the application of the *territory principle* versus the *residence principle*. As explained in Chapter 1 of this book, the *territory principle*, used in the scope of emissions inventories, assigns emissions to the country where they take place, while under the *residence principle*, used in the scope of emissions accounts, emissions are assigned to the country where the economic operator is resident. The production-based and final demand–based emissions discussed in this chapter follow the *residence principle*.

To obtain production emissions based on the *residence principle*, the OECD's methodology (based on Yamano and Guilhoto 2020) allocates territorial emissions (emissions from fuel sales in each country) to production-based emissions (industries and households of each country) using the

[4] The indicators described in this chapter are available from the OECD's Trade in Embodied CO_2 ($TECO_2$) database: http://oe.cd/io-co2. Some indicators are also featured in the OECD Green Growth Indicators (https://www.oecd.org/greengrowth/green-growth-indicators/) and OECD Climate Dashboard (https://www.oecd.org/climate-action/ipac/dashboard). Greenhouse gases include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases, including hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphurhexafluoride (SF_6).

[5] The carbon footprint is the total CO_2 emissions resulting from the activities of households and the consumption of goods and services in a given year.

OECD Inter-Country Input-Output (ICIO) tables (http://oe.cd/icio), the International Energy Agency (IEA) GHG Emissions from Energy database,[6] the OECD Air Emissions Accounts,[7] and the OECD's Air Transport CO_2 Emissions database.[8]

In particular, the methodology introduces (1) explicit distinctions between the territory and residence principles, economic output and final demand–based emissions, and emissions embodied in gross imports and exports; (2) estimates by major fuel combustion sources; and (3) fuel purchases by nonresident industries and households, considering fuels for road transportation, international aviation, and marine bunkers.

Based on the ICIO tables and the production-based emissions, the OECD maintains and develops a set of indicators, which it publishes in the Trade in Embodied CO_2 ($TECO_2$) database (http://oe.cd/io-co2). The latest edition (2022) covers the period from 1995 to 2019; 45 industries, and 76 economies, "rest of the world," and several regional groups. All 38 OECD, all G20, and all European Union and ASEAN members are included.

A country's total *production-based emissions* is the sum of industry emissions[9] and household emissions:

$$\textit{Production-based emissions} = \textit{Industry emissions} + \textit{Households emissions} \tag{2.1}$$

Industry emissions factors, in metric tons of CO_2 per million US$ of output, are defined as the ratio between emissions and associated output:

$$\textit{Industry emissions factors (e)} = \textit{Industry emissions / Industry output} \tag{2.2}$$

To estimate emissions embodied in the consumption of final goods and services, as well as in traded products, one needs to take into consideration not only the *direct* emissions necessary for production but also the *indirect* emissions; that is, the upstream emissions included in the inputs used in production process. For example, to manufacture cars, direct emissions are produced by the automotive industry while indirect emissions are produced by the upstream industries (both domestic and foreign) that supply the inputs required for car production, such as metals, tires, and glass. Thus, emissions incorporated in a final good are the sum of direct and indirect emissions. Given the complexity and global fragmentation of production processes, this estimation requires the use of models based on IO analysis. In brief, this methodology requires the estimation and use of a "total requirements matrix," which shows in a given column the direct and indirect inputs needed from the different industries to produce one unit of the final good, known as the Leontief inverse matrix of total requirements.

From the emissions factors estimated in Equation 2.2 and the use of the Leontief inverse matrix it is possible to obtain the *demand-based industry emissions*, as is shown in Guilhoto (2021) and Yamano and Guilhoto (2020) and detailed in Annex 2.1.

Demand-based industry emissions are defined by matrix M, which links final demand with the input requirements and the associated industry emissions factors:

$$\boldsymbol{M} = \hat{e}\mathrm{B}y \tag{2.3}$$

Where $\hat{e}$ is a diagonal matrix with the industries' emissions factors (as defined in Equation 2.2) in the main diagonal; B is the Leontief inverse matrix; and y is the vector of final demand, which shows for each industry the value of final goods and services. As can be seen in Equation 2.3, the independent variable on the right side is the final demand (y), and the dependent variable is emissions (M),

[6] See https://www.iea.org/data-and-statistics/data-product/greenhouse-gas-emissions-from-energy.

[7] See https://stats.oecd.org/Index.aspx?DataSetCode=AEA.

[8] See http://stats.oecd.org/Index.aspx?DataSetCode=AIRTRANS_CO2.

[9] Includes emissions by government activities; for example, "*Public administration and defense.*"

so it is possible to estimate for a basket of final goods and services what the total emissions (footprint) are and what the source industries are of these emissions.

The total *demand-based emissions* of a country are then defined as the sum of the *demand-based industry emissions* (***M***) and the direct household emissions:

$$\textit{Demand-based emissions} = \textit{Demand-based industry emissions} + \textit{Household emissions} \qquad (2.4)$$

GLOBAL CARBON EMISSIONS

Given the integration of the world economies and the fragmentation of production, the emissions incorporated in the final and traded goods are associated not only with the emissions of the country where the consumption takes place, but also with the world structure of production. Table 2.1 summarizes the evolution of some key indicators to underscore the importance of consumption and trade for world emissions and the role played by advanced economies and emerging market and developing economies:[10] (1) per capita CO_2 emissions in consumption; (2) foreign carbon intensity, defined as imported CO_2 emissions as a share of total CO_2 emissions embodied in domestic final demand; and (3) capital emissions intensity, defined as CO_2 emissions embodied in capital goods as a share of total demand-based emissions.[11] In 2019, average CO_2 consumption per capita in advanced economies was 3.7 times greater than that in emerging market and developing economies—11.7 metric tons per capita (down from a peak of 15.0 in 2005) and 3.2 metric tons per capita (up from 2.2 in 2005), respectively. In aggregate, advanced economies are more dependent on foreign carbon-intensive activities than are emerging market and developing economies. Imported emissions are predominantly due to final household and government consumption. Also, emerging market and developing economies use more emissions for capital formation (for example, public infrastructure, machinery, and equipment) than do advanced economies.

Carbon Emissions Balances

Carbon emissions balances show the difference between production-based and demand-based emissions. If a country or a region produces more CO_2 emissions than it consumes in final demand for goods and services, it is considered a net exporter of CO_2. Similarly, a country or a region is a net importer if it consumes more CO_2 emissions than it produces.

In aggregate, advanced economies are net importers, while emerging market and developing economies are net exporters of embodied carbon dioxide emissions (see Figure 2.1). For advanced economies, the solid blue line (demand-based emissions) is above the dashed blue line (production-based emissions). For emerging market and developing economies, the solid green line (demand-based emissions) is below the dashed green line. The balanced structure of the OECD's TECO$_2$ database (Yamano and Guilhoto 2020) ensures that the negative emissions balances of advanced economies are the same as the positive emissions balances for emerging market and developing economies. Advanced economies' net imports grew since 1995 to reach a peak in 2006 and have since been gradually declining.

Although most advanced economies are net importers of CO_2 emissions, some, for instance Canada and Korea, are net exporters (Figure 2.2). Many emerging market and developing economies are also net importers, particularly those with relatively low CO_2 emissions per capita. China, India, and the Russian Federation are significant net exporters.

[10] The country groups are based on the IMF's World Economic Outlook: www.imf.org/external/pubs/ft/weo/2022/01/weodata/groups.htm. The OECD calculations do not include Andorra, Macao SAR, Puerto Rico, and San Marino.

[11] CO_2 consumption per capita corresponds to the indicator FD_PCCO2 in the OECD's Trade in Embodied CO_2 (TECO$_2$) database (http://oe.cd/io-co2), while foreign carbon intensity refers to imported CO_2 emissions as a share of total CO_2 emissions embodied in domestic final demand, expressed as (DFD_FCO2 / FD_CO2), and capital emissions intensity refers to the CO_2 emissions embodied in gross fixed capital formation as a share of demand-based emissions (GFCF_CO2/ FD_CO2).

TABLE 2.1.

Key Results

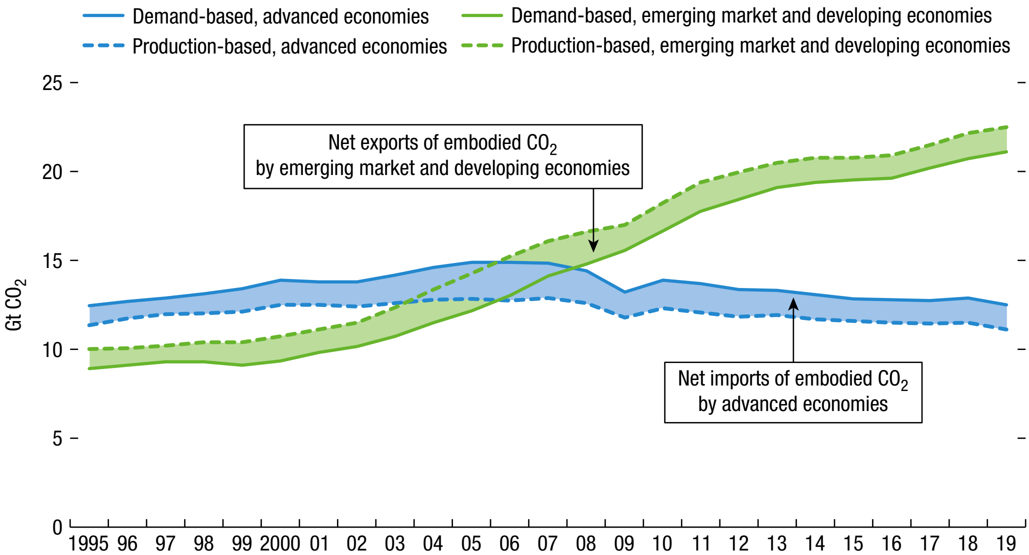
	Advanced Economies					Emerging Market and Developing Economies				
	1995	**2019**	**Peak**	**Average**	**Trend**	**1995**	**2019**	**Peak**	**Average**	**Trend**
Demand-based CO_2 intensity (metric tons of CO_2 per capita)	13.3	11.7	15.0	13.5		1.85	3.18	3.18	2.47	
Foreign carbon intensity (on average, %)	24.4	31.5	31.5	28.5		11.2	14.9	16.6	14.3	
Capital emissions intensity (on average, %)	18.5	18.5	19.3	18.3		24.4	35.9	36.7	30.9	

	Demand-based CO_2 Intensity		Production-based CO_2 Intensity		Foreign Carbon Intensity			Capital Emissions Intensity		
	Metric Tons of CO_2 per Capita		Metric Tons of CO_2 per Capita		Percent (%)			Percent (%)		
	AE	**EMDE**	**AE**	**EMDE**		**AE**	**EMDE**		**AE**	**EMDE**
1995	13.34	1.85	12.18	2.08	1995	0.24	0.11	1995	0.18	0.24
1996	13.53	1.86	12.49	2.06	1996	0.24	0.12	1996	0.19	0.25
1997	13.65	1.88	12.69	2.06	1997	0.24	0.12	1997	0.18	0.24
1998	13.78	1.84	12.63	2.06	1998	0.25	0.12	1998	0.18	0.25
1999	14.03	1.78	12.68	2.03	1999	0.26	0.13	1999	0.19	0.24
2000	14.43	1.80	12.97	2.07	2000	0.27	0.14	2000	0.19	0.25
2001	14.23	1.87	12.89	2.11	2001	0.26	0.13	2001	0.19	0.26
2002	14.14	1.90	12.74	2.16	2002	0.26	0.13	2002	0.18	0.25
2003	14.48	1.99	12.84	2.29	2003	0.27	0.13	2003	0.18	0.27
2004	14.80	2.10	12.93	2.44	2004	0.29	0.14	2004	0.18	0.28
2005	14.99	2.20	12.90	2.57	2005	0.30	0.15	2005	0.19	0.30
2006	14.91	2.32	12.74	2.70	2006	0.31	0.15	2006	0.19	0.31
2007	14.77	2.48	12.81	2.83	2007	0.31	0.16	2007	0.19	0.32
2008	14.24	2.56	12.43	2.88	2008	0.31	0.17	2008	0.19	0.33
2009	12.98	2.66	11.57	2.90	2009	0.28	0.14	2009	0.18	0.35
2010	13.55	2.81	12.00	3.08	2010	0.30	0.15	2010	0.17	0.34
2011	13.26	2.96	11.70	3.23	2011	0.31	0.16	2011	0.18	0.35
2012	12.88	3.03	11.41	3.28	2012	0.31	0.16	2012	0.18	0.36
2013	12.77	3.10	11.42	3.32	2013	0.30	0.15	2013	0.18	0.37
2014	12.47	3.10	11.16	3.33	2014	0.31	0.16	2014	0.18	0.36
2015	12.19	3.09	11.00	3.29	2015	0.30	0.15	2015	0.18	0.36
2016	12.09	3.06	10.86	3.26	2016	0.30	0.14	2016	0.18	0.35
2017	12.00	3.11	10.77	3.31	2017	0.31	0.15	2017	0.18	0.35
2018	12.11	3.16	10.79	3.37	2018	0.31	0.15	2018	0.18	0.35
2019	11.69	3.18	10.38	3.39	2019	0.32	0.15	2019	0.19	0.36
Max	14.99	3.18	12.97	3.39	**Max**	0.32	0.17	**Max**	0.19	0.37
Avg	13.49	2.47	12.04	2.72	**Avg**	0.29	0.14	**Avg**	0.18	0.31

Sources: Organisation for Economic Co-operation and Development's TECO_2 database, 2022 edition; and authors' estimates.
Note: *Foreign carbon intensity* refers to imported carbon dioxide (CO_2) emissions as a share of total CO_2 emissions embodied in domestic final demand. *Capital emissions intensity* refers to the CO_2 emissions embodied in gross fixed capital formation as a share of demand-based emissions. AE = advanced economies; EMDE = emerging market and developing economies.

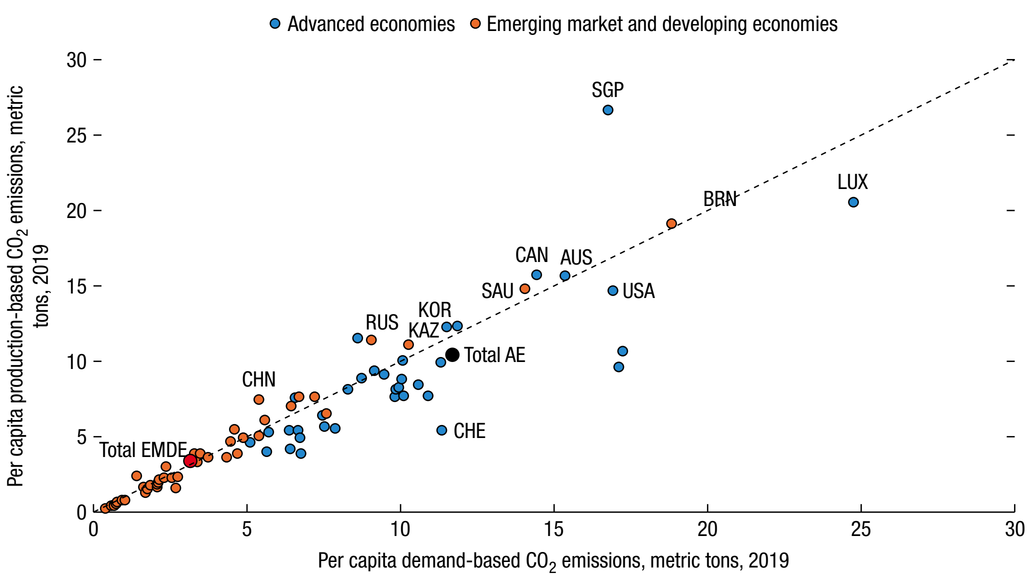
Since the mid-2000s total emissions by advanced economies, both production- and consumption-based, have fallen, while for emerging market and developing economies they have increased. For the advanced economies, this reflects the efforts being made in many of these countries to reduce total emissions. For emerging market and developing economies, the increases are a consequence of economic development; that is, on one hand emissions related to a significant increase in exports to meet demand in advanced economies, and on the other hand, the growth of these economies to meet basic needs and improve the quality of life of their population. However, as can be seen in Figure 2.2,

Figure 2.1. Production-based and Demand-based CO_2 Emissions from Fuel Combustion, Advanced Economies versus Emerging Market and Developing Economies



Sources: Organisation for Economic Co-operation and Development's $TECO_2$ database, 2022 edition; and authors' estimates.
Note: CO_2 = carbon dioxide; Gt = metric gigatons, equivalent to 10^9 metric tons.

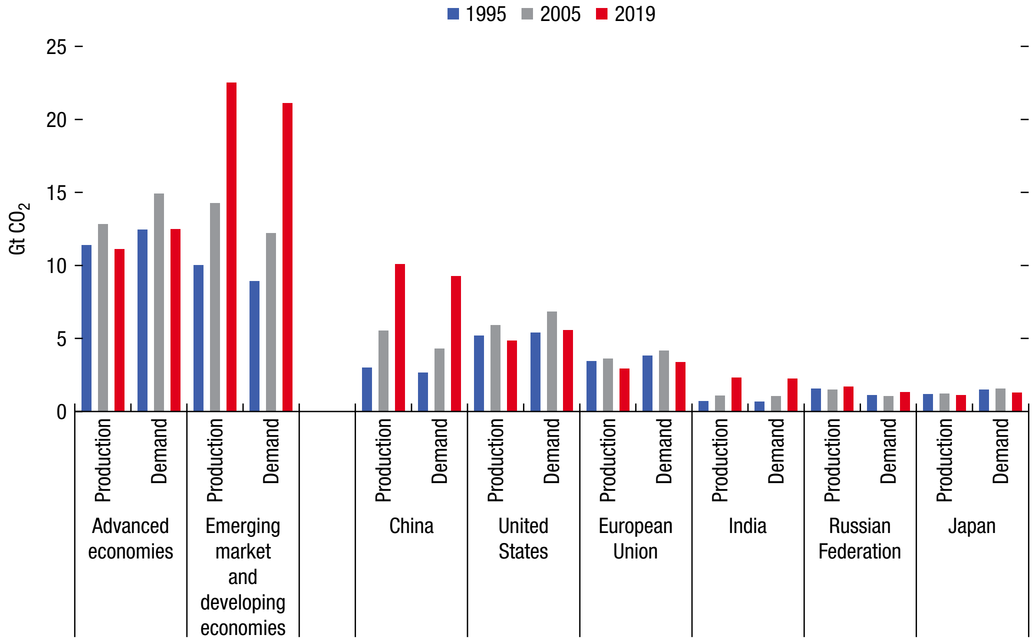
Figure 2.2. Per Capita Production-based and Demand-based CO_2 Emissions from Fuel Combustion, 2019



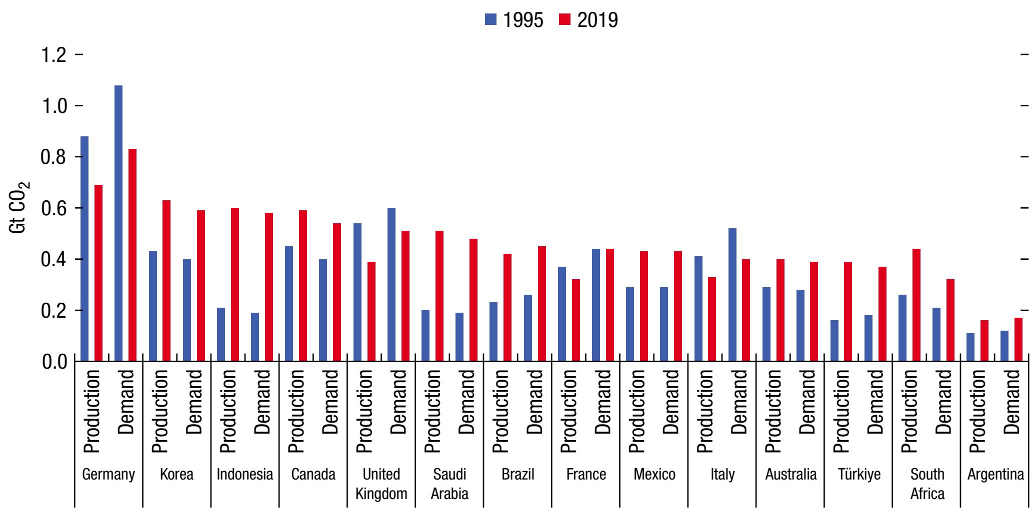
Sources: Organisation for Economic Co-operation and Development's $TECO_2$ database, 2022 edition; and authors' estimates.
Note: Economies above the diagonal line were net exporters of CO_2; those below the diagonal line were net importers. Data labels in the figure use International Organization for Standardization (ISO) country codes. CO_2 = carbon dioxide.

Figure 2.3. Total Production- and Demand-based CO_2 Emissions for G20 Economies

1. Top Six Emitters



2. G20 Economies Excluding the Top Six Emitters

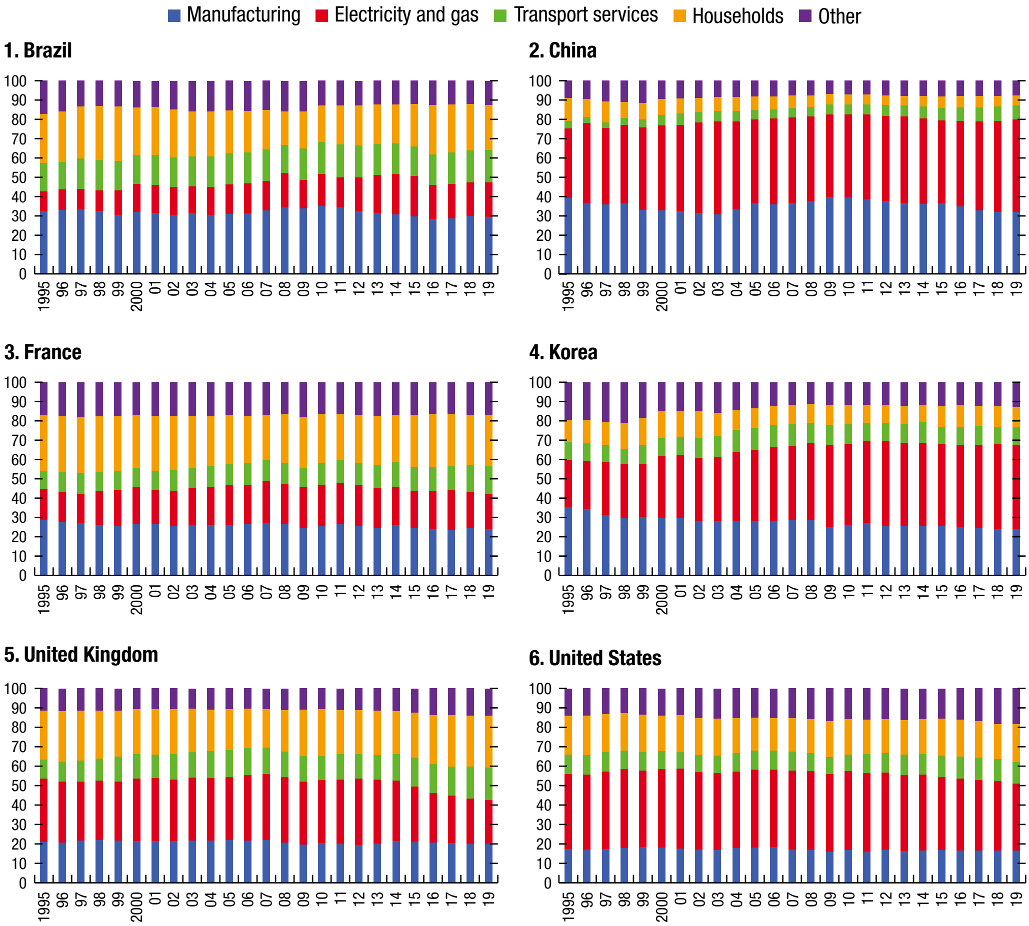


Sources: Organisation for Economic Co-operation and Development's $TECO_2$ database, 2022 edition; and authors' estimates.
Note: CO_2 = carbon dioxide; G20 = Group of Twenty; Gt = metric gigatons, equivalent to 10^9 metric tons.

advanced economies still have much higher per capita emissions than emerging market and developing economies.

Emissions balances for G20 economies have been relatively stable in recent years (Figure 2.3). Demand-based CO_2 emissions tend to follow similar trends as production-based CO_2 emissions. This is understandable in the sense that exports reflect the development of domestic economies and subsequently enhance the domestic consumption capacity.

Figure 2.4. Sources of Demand-based CO_2 Emissions for Selected G20 Countries
(Percent)



Sources: Organisation for Economic Co-operation and Development's TECO$_2$ database, 2022 edition; and authors' estimates.
Note: "Households" refers to resident households' use of fuel for motor vehicles, heating, cooking, etc.; "Other" includes agriculture, mining, construction, and other services. CO_2 = carbon dioxide; G20 = Group of Twenty.

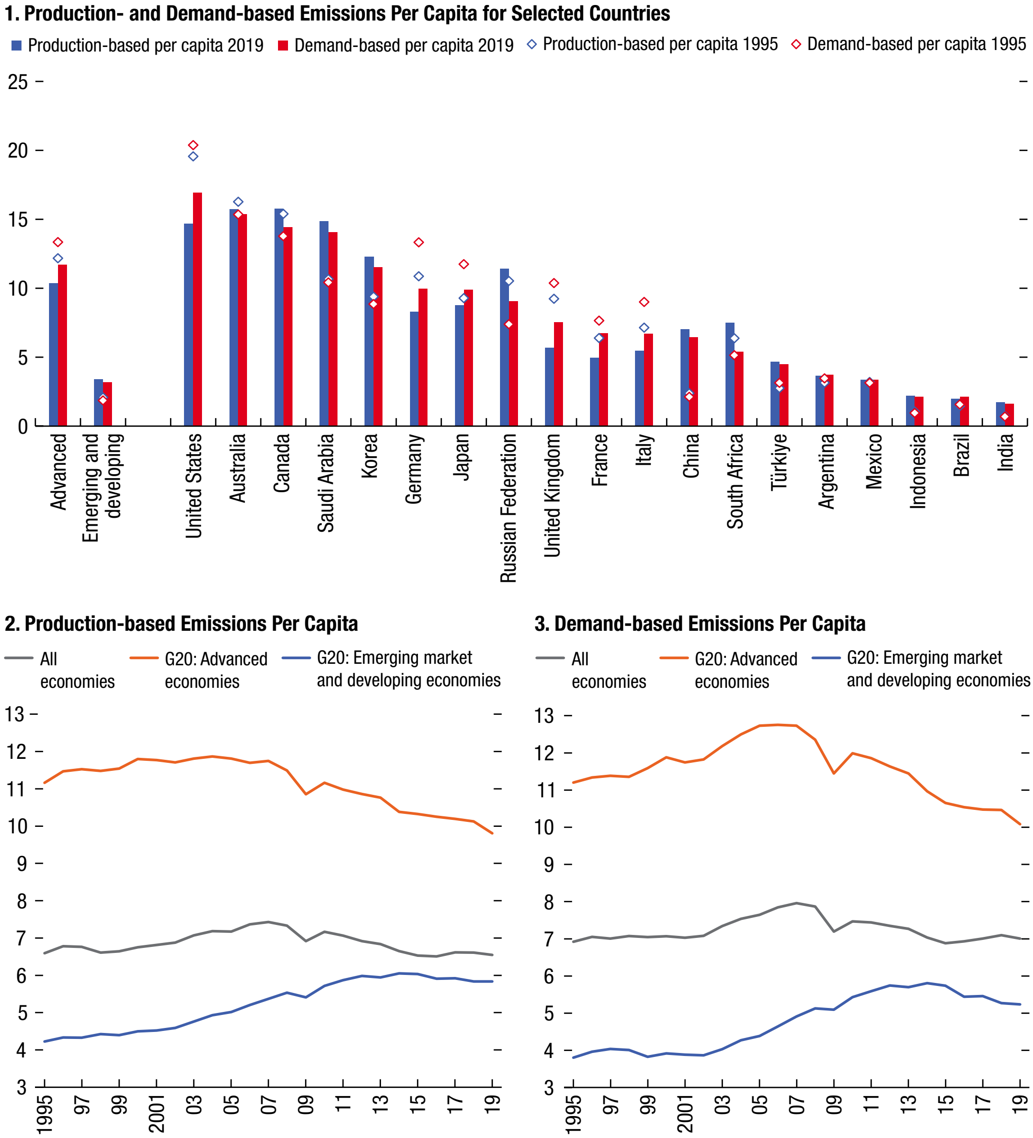
The six largest emitters, China, the United States, the European Union (EU), India, the Russian Federation, and Japan, accounted for over two-thirds of global CO_2 emissions in 2019—about 68 percent for both production-based and demand-based measures. This share has remained relatively stable over the past two decades. However, while the share of total world emissions embodied in final demand in the United States, EU, and Japan combined fell from 50 percent in 1995 to 30 percent in 2019, the share for China, India, and Russian Federation increased from 20 percent to 38 percent.

The sourcing structure of demand-based CO_2 emissions by broad industrial sectors has been relatively stable for most G20 countries (Figure 2.4). Emissions from manufacturing, electricity and gas, and transport services account for a significant share (52 percent to 88 percent for G20 economies) of demand-based emissions for many economies.

Electricity generation accounts for a large share of CO_2 emissions from the demand side, about one-third on average for G20 countries over the past 25 years, ranging from 10 percent to 61 percent of demand-based emissions. France and Brazil have the lowest demand-based emissions shares sourced from electricity generation; that is, less than 20 percent in 2019. France relies mainly on nuclear power (72 percent) and renewable energy (21 percent) for electricity production, making its

Figure 2.5. Per Capita Production- and Demand-based Emissions

(Metric tons of CO_2)



Sources: Organisation for Economic Co-operation and Development's $TECO_2$ database, 2022 edition; and authors' estimates.
Note: CO_2 = carbon dioxide; G20 = Group of Twenty.

electricity-generation activities among the cleanest in the world. Brazil's electricity sector is dominated by hydroelectric power (60 percent).

Advanced economies have much higher carbon emissions per capita than emerging market and developing economies (see Figure 2.5). This gap has narrowed. In 1995, production-based emissions per capita in advanced economies were about six times those of emerging market and developing economies. By 2019, production-based emissions per capita in advanced economies were only about three times higher.

There is a converging and declining trend in per capita emissions. China and India are big emitters because of their large populations, but they have the lowest per capita CO_2 emissions among G20 economies. In 2019, per capita emissions of the United States, Australia, Canada, and Saudi Arabia were more than double those of China and more than seven times those of India. Countries with high per capita emissions have reduced their emissions intensity in recent years, but still need to continue decarbonizing their production and consumption. Panel 2 in Figure 2.5 shows the average number of production-based and demand-based emissions per capita for advanced G20 economies (orange lines), emerging market and developing G20 economies (blue lines), and all 76 economies (grey lines). The converging trends are more evident during the early 2000s to late 2010s. Since the adoption of the Paris Agreement in 2016, downward trends in both groups of G20 economies are evident.

In terms of growth rates, China and India are the G20 economies with the highest growth in per capita consumption of CO_2 emissions. For China, they more than tripled (from 2.1 to 6.4 metric tons) between 1995 and 2019, while India's more than doubled (from 0.7 to 1.6 metric tons). Meanwhile, Germany, Italy, and the United Kingdom reduced their per capita consumption of CO_2 emissions by over 25 percent, although they still remain at relatively high levels. Specifically, in 2019, the consumption-based carbon emissions per capita for Germany, Italy, and the United Kingdom were 9.9, 6.7, and 7.5 metric tons of CO_2 per capita, respectively.

Production-based and demand-based per capita emissions are complementary to assessing the effectiveness of climate policies by helping to identify whether emissions reduction is due to the climate mitigation policies or to the outsourcing of some carbon-intensive production. For the United States, the United Kingdom, and France, production-based carbon emissions fell faster than demand-side emissions between 1995 and 2019, highlighting the role of outsourcing carbon-intensive production. Japan is the only G20 country where demand-based per capita emissions have fallen significantly faster (−16 percent) than production-based per capita emissions (−5.5 percent).

To better understand what is causing the changes in production- and demand-based emissions, Box 2.1 provides a case study for Australia, where the production-based emissions are decomposed into two factors (emissions intensity and output) and demand-based emissions are decomposed into six factors (direct households use intensity, emissions intensity, global production network, regional production network, domestic production network, and final demand).

Emissions on Consumption and Capital Goods

Measuring CO_2 emissions embodied in different types of final products—energy, consumer goods, and capital goods—is important in order to assess all direct and indirect emissions occurring along the value chain and to understand the role consumption and investment play in emissions.

Figure 2.6 plots six components of CO_2 emissions embodied in final products from 1995 to 2019 for selected countries,[12] that is, domestic and imported products directed to (1) capital formation, (2) energy and electricity consumption, and (3) nonenergy and nonelectricity products consumption.

Embodied emissions in nonenergy domestic products for consumption show to be the main component for the selected countries, representing in most cases around 40 percent of the demand-based emissions. This component also shows an overall stable share in the period being considered, except for a reduction of around 10 percentage points for India and the Russian Federation and 20 percentage points for China.

Domestic products for capital formation appear as the second largest component in demand-based emissions, with a share, on average, between 18 percent and 25 percent of the demand-based emissions for half of the select countries. At the same time, the United States shows the lowest share, of around 15 percent; Indonesia, India, and Korea show a share of around 30 percent; and China shows the highest share, around 50 percent.

Germany and Japan are the only countries that show a reduction of total demand-based emissions in 2019 when compared to emissions in 1995. Germany's reduction in demand-based emissions comes from the reduction of domestic products consumption (energy, nonenergy consumer goods,

[12] Additional country charts are presented in Annex 2.2.

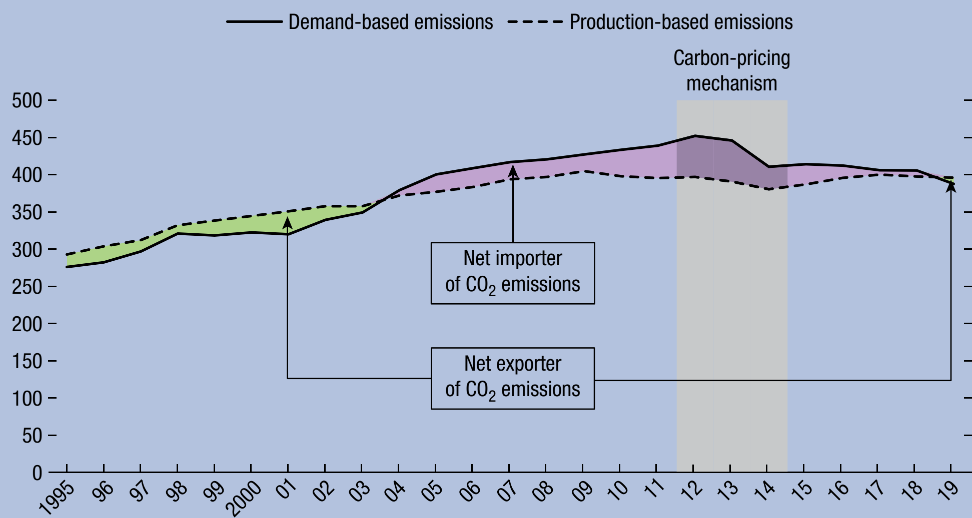
Box 2.1. Decomposition of CO_2 Emissions: A Case Study on Australia

This box presents a decomposition of Australia's carbon dioxide (CO_2) emissions during 1995–2019 from both a production and a demand perspective.

Australia's production-based and demand-based emissions generally follow similar trends (Figure 2.1.1). However, during 1995–2019, Australia switched from being a net exporter of CO_2 emissions to a net importer and then, most recently, back to a net exporter, mainly due to fluctuations in demand-based emissions. During 2004–18, Australia, like other advanced economies, was a net importer of CO_2 emissions, partly reflecting Australia's policies on demand-side emissions, including a carbon-pricing mechanism introduced in 2012.

Figure 2.1.1. Australian Production- and Demand-based CO_2 Emissions

(Millions of metric tons)



Sources: Organisation for Economic Co-operation and Development's $TECO_2$ database, 2022 edition; and authors' estimates.

Note: The carbon-pricing scheme in Australia was introduced in 2011 as part of the Clean Energy Act 2011 and came into effect on July 1, 2012. However, this scheme was repealed on July 17, 2014. CO_2 = carbon dioxide.

From 1995 to 2019, the most effective reduction in Australia's demand-based emissions happened for the period 2012–14, which may reflect the carbon-pricing mechanism. Australia's production-based emissions are shown to be less affected for the same period. To shed light on the factors causing these changes, a factor decomposition model based on Han and Yamano (2023) is applied, which is detailed in Annex 2.3.

Figure 2.1.2 displays the cumulative annual change in decomposition factors for Australia's emissions. As carbon-pricing policies were adopted in 2012 and there is a significant change from 2012 onward for demand-based emissions, the year 2012 was set as the base year to provide a view of Australia's emissions evolution.

From a production perspective, Australian total emissions are decomposed into two factors: (1) emissions intensity, measured as emissions per production, and (2) output. The decomposition changes for manufacturing, electricity, transport, and other service sectors are shown in Figure 2.1.2, panel 1. From 1995 to 2002, both components are relatively stable for those selected sectors, while there seem to be structural changes in Australia's production-based emissions from 2002 to 2012, when the emissions intensity in the manufacturing and transport sectors fell, respectively, by 78 percent and 65 percent.

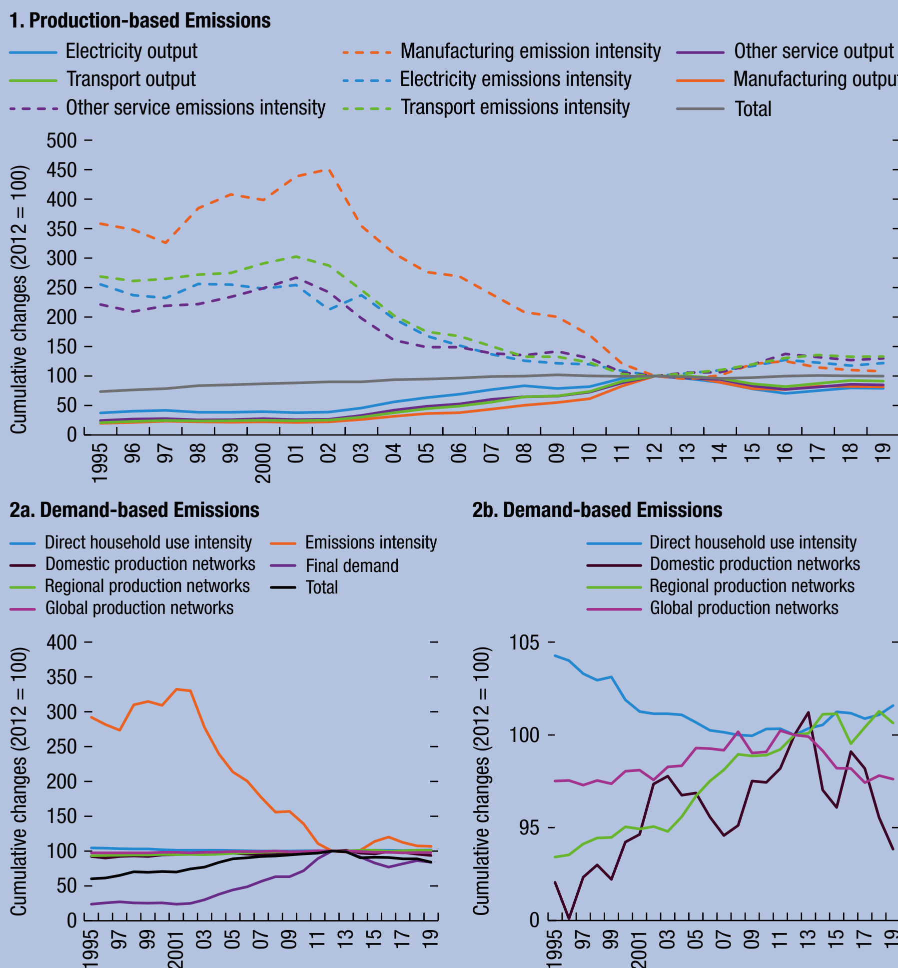
From a demand perspective, Figure 2.1.2, panel 2a, shows a structural decomposition analysis of Australia's demand-based emissions. This decomposition approach differentiates total emissions into six factors (direct households use intensity, emissions intensity, global production network, regional production network, domestic production network, and final demand) using input–output linkages. Emissions intensity and final demand are the strongest factors pushing total emissions, while final demand leads the aggregated emissions changes.

Box 2.1. *(continued)*

Figure 2.1.2, panel 2b, enlarges the structural changing lines for direct household use intensity and three production network factors. Direct household use intensity is the share of total emissions over industry activities–related emissions, representing the intensity of emissions that are directly used by households. Between 1995 and 2006, direct household use intensity is a negative driver for Australia's demand-based emissions. Since 2006, Australia's structure in demand-based emissions in terms of direct household use and industry applications has barely changed. Even though production networks have a relatively small impact on the overall trend of Australia's demand-based emissions, different drivers of domestic, regional, and global production networks can still be found.

Domestic and regional production networks have stronger impacts on Australia's demand-based emissions than do global production networks, which is related to Australia's geographic location and its close trade relationship with the Asia and Pacific region relative to the rest of the world. Before 2012, regional and global production networks were the main drivers of Australia's increasing demand-based emissions. After 2012, global production networks contributed to the reduction of Australia's demand-based emissions.

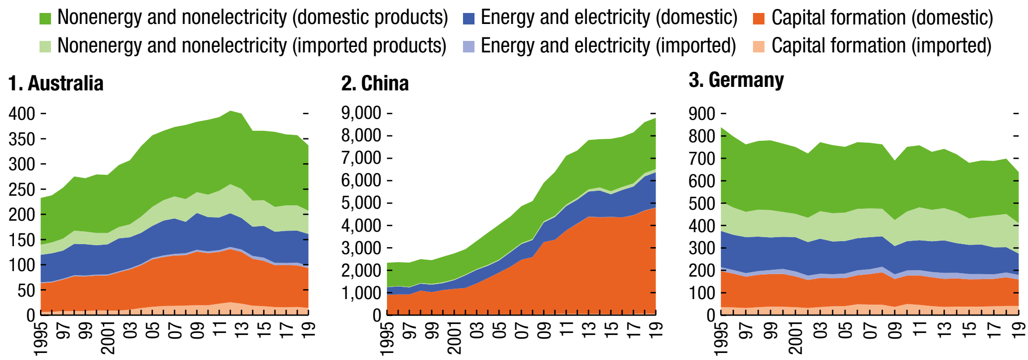
Figure 2.1.2. Factor Decomposition of Australian CO_2 Emissions



Sources: Organisation for Economic Co-operation and Development's $TECO_2$ database, 2022 edition; and authors' estimates. See Annex 2.3.

Note: CO_2 = carbon dioxide.

Figure 2.6. CO_2 Emissions Embodied in Final Products for Selected Countries
(Millions of metric tons)



Sources: Organisation for Economic Co-operation and Development's $TECO_2$ database, 2022 edition; and authors' estimates.
Note: "Energy products" refers to Coal (ISIC Rev. 4 / CPA Division 05), Oil (06), Petroleum and coke (19), and Electricity and gas (35). CO_2 = carbon dioxide.

and capital goods), while Japan's reduction comes mainly from the consumption of domestic capital goods and domestic and imported nonenergy consumer goods.

WAY FORWARD

Developing demand-based carbon measures is a complex and data-intensive approach (compared to the production-based approach) that builds on a number of assumptions mainly due to data limitations. This section outlines possible improvements and extensions to develop further indicators to better understand emissions and help policymakers to work toward more efficient policies to reduce emissions and attain net zero target emissions without compromising the benefits of living in an integrated world.

Expanding the Database

The OECD is frequently asked by researchers to expand the database of embodied CO_2 indicators—in particular, increasing country coverage, providing a more detailed industry breakdown, and going beyond CO_2 emissions from fuel combustion to include other sources of CO_2 emissions and other GHGs. Production of more timely estimates is another request.

Country coverage depends on the underlying ICIO tables, and there are minimum data requirements for inclusion—notably, availability and quality of national statistics such as supply and use tables, national accounts, and data on balance of payments and bilateral trade in goods and services. The OECD works with other international organizations (for example, the IMF, United Nations Economic Commission for Africa [UNECA], United Nations Industrial Development Organization [UNIDO], and World Trade Organization [WTO]) on statistical capacity-building exercises to enable countries to be included in the ICIO tables. As a result of recent exercises, the 2022 edition of ICIO covers 76 economies, 10 more than the 2021 edition. Efforts will continue to increase country coverage (especially for Africa and other under-represented regions).

While greater *industry detail* is highly desirable, compromises are necessary due to many countries' having a limited level of such detail in the national statistics required for ICIO construction. There are no plans to expand $TECO_2$ industry coverage in the near future. However, customized analysis targeting more-detailed industries in certain sectors is possible for selected countries, subject to the quality of the underlying detailed national data (for instance, splitting basic metals into steel and nonferrous metals).

A major enhancement would be to produce measures of emissions embodied in trade and in final demand, covering *all GHGs* rather than just CO_2 emissions from fuel combustion. This is envisaged for the 2023 edition.

Emissions by Fuel Type

Another possible extension would be the inclusion of the energy dimension in the emissions measures to shed light on which fuel type is contributing to emissions, allowing for a better understanding and planning of energy transitions within and across countries. For example, efforts to increase energy efficiency (for example, building's energy efficiency) may result in increased energy use in other parts of the economy (for instance, energy used in construction materials) or in different trading partners (such as embodied energy in imported construction materials).

Using information from the International Energy Agency's World Energy Balances (IEA 2022) and combining it with intercountry input-output tables can bring important elements to this discussion. The first step in this approach, *already accomplished*, is the estimation of energy physical supply and use tables (E-PSUTs) using the World Energy Balances (Guilhoto and others 2021). While the E-PSUTs themselves can be used to derive energy indicators in physical units, they are a key input into a "hybrid methodological approach," the Multi-Factor Input–Output (MF-IO) model (Guevara and Domingos 2017). The MF-IO, *under construction*, considers physical energy units and monetary units in the estimation of indicators that associate physical energy production and consumption with monetary production and consumption. The MF-IO model allows a richer understanding of the use of energy throughout the production and consumption processes as well as its link with the environment. The model has important methodological and analytical characteristics too, such as (1) considering energy-relative prices—that is, the price for the same fuel is not the same for all consumers; (2) respecting the energy conservation principle—that is, the conservation of embodied energy establishes that the energy embodied in the output of an industry is equal to the energy embodied in its intermediate inputs plus its direct energy inputs; (3) ensuring a consistent interconnection between the energy and nonenergy industries—that is, a consistent method to work with monetary and physical units, considering the monetary inputs necessary for the energy industries to produce physical energy and the physical energy necessary for the nonenergy industries to produce goods and services; and (4) allowing for the breakdown of the use of energy by different types of fuels and by direct and indirect energy use.

CONCLUSION

This chapter describes the methodology used to measure emissions embodied in final demand that complements the production-based emissions presented in the first chapter. Global CO_2 emissions balances show the difference between production-based and demand-based emissions and indicate whether economies are net importers or net exporters of CO_2 emissions.

Findings show that emissions balances have been relatively stable in recent decades. Advanced economies in aggregate are a net importer of embodied CO_2 emissions, while the major emerging market and developing economies are net exporters. There also is a converging trend in per capita emissions. Countries with high per capita emissions have reduced their emissions intensity in recent years, but still need to continue decarbonizing their production and consumption. Meanwhile more efforts are required in low per capita emissions countries to further reduce their carbon intensity.

From the demand perspective, six components of the emissions embodied in final products are decomposed. Nonenergy domestic products take up the largest part of the demand-based emissions. Domestic capital investments are generally the second largest components in demand-based emissions. Trade is a small part—less than 10 percent—of the demand-based emissions, except for some advanced economies.

While the availability of measures of embodied emissions has much improved in recent years, there is scope for further advances, which this chapter also discusses.

ANNEX 2.1

MEASURING CONSUMPTION-BASED EMISSIONS

This annex presents the mathematical estimation for demand-based emissions according to IO analysis.

The first step is to estimate the industry emissions factor (*e*),[13] which is obtained by dividing the total emissions of an industry by its output:

$$e = Industry\ emissions\,/\,Industry\ output \tag{2.1.1}$$

The industry emissions multiplier (***G***), showing the total emissions embodied in an industry per unit of final consumption, can be obtained by multiplying the Leontief inverse matrix ***B*** ($NK \times NK$) by the emissions factor diagonal matrix, $\hat{e}$ ($NK \times NK$), with the industries emissions factors in the main diagonal, where N is the number of countries and K the number of industries:

$$G = \begin{bmatrix} \hat{\mathbf{e}}^1 & \mathbf{0} & \dots & \mathbf{0} \\ \mathbf{0} & \hat{\mathbf{e}}^2 & \dots & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & \mathbf{0} & \dots & \hat{\mathbf{e}}^N \end{bmatrix} B = \hat{e}B \tag{2.1.2}$$

The global Leontief inverse matrix (***B***) comes from the ICIO system (see Guilhoto, Webb, and Yamano 2022) and considers the direct and indirect inputs needed to attend the demand of final consumers. The element b_{ij}^{rs} of this matrix shows the direct and indirect requirements of inputs from industry i in country r to produce one unit of output to meet final demand by industry j in country s.

The demand-based industry emissions (***M***) are obtained by multiplication of the emissions multiplier (***G***) and final demand matrix (***Y***):

$$M = \hat{e}BY = GY \tag{2.1.3}$$

The element y_i^{rs}, of the final demand matrix ***Y*** ($NK{\times}N$), shows the final demand of country s for goods and services produced by industry i in country r. The element m_i^{rs} of demand-based industry emissions matrix ***M*** ($NK \times N$) shows the CO_2 emissions emitted by industry i in country r to meet final demand in country s.

Demand-based emissions of country s are then calculated as the sum of column s in matrix ***M*** plus direct emissions from households in country s. Similarly, production-based emissions of country s are calculated as the sum of row s in matrix ***M*** plus direct emissions from households in country s.

Using the emissions multiplier matrix defined here, it is possible to estimate the emissions embodied in exports and imports as follows:

$$C = \hat{e}BT \tag{2.1.4}$$

where C is a vector of emissions by source industry and country, $\hat{\boldsymbol{e}}\boldsymbol{B}$ is the emissions multiplier matrix, and ***T*** is a matrix of trade flows, with each element being a bilateral trade flow.

As an example, emissions embodied in exports of industry p from country 1 to the rest of the world can be estimated as follows:

$$\begin{bmatrix} c_1^1 \\ c_1^2 \\ \vdots \\ c_K^N \end{bmatrix} = \hat{\mathrm{e}}\mathbf{B} \begin{bmatrix} 0 & 0 & \dots & 0 \\ 0 & t_{\mathrm{p}}^{12} & \dots & t_{\mathrm{p}}^{1,N} \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 0 \end{bmatrix} \mathrm{u} \tag{2.1.5}$$

where c_i^r is the emissions by industry i in country r, and $t_p^{r,s}$ are the exports of industry p from country r to country s (that is, imported by s), and u is an aggregation vector (row sum) with ones (NK x 1).

[13] In the chapter, the emissions factors refer to CO_2 emissions from fuel combustion; however, the same approach can be applied to other GHGs as well as to total GHG emissions.

In the same way, the emissions embodied in imports from all trade partners by country 2 of products from industry p can be estimated as follows:

$$\begin{bmatrix} c_1^1 \\ c_1^2 \\ \vdots \\ c_K^N \end{bmatrix} = \hat{\mathbf{e}}\mathbf{B} \begin{bmatrix} 0 & 0 & \dots & 0 \\ 0 & t_p^{12} & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & t_p^{22} & \vdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & t_p^{N2} & \dots & 0 \end{bmatrix} \mathrm{u} \qquad (2.1.6)$$

where c_i^r is the vector of emissions from industry i in country r embodied in imports from industry p by country 2.

The $TECO_2$ database shows a vast set of emissions indicators that are obtained by using different configurations for the final demand (Y) and the trade (T) matrices. Details on the possible configurations of these matrices, estimation procedures, and interpretations of the results can be found in Guilhoto, Webb, and Yamano (2022) [14]

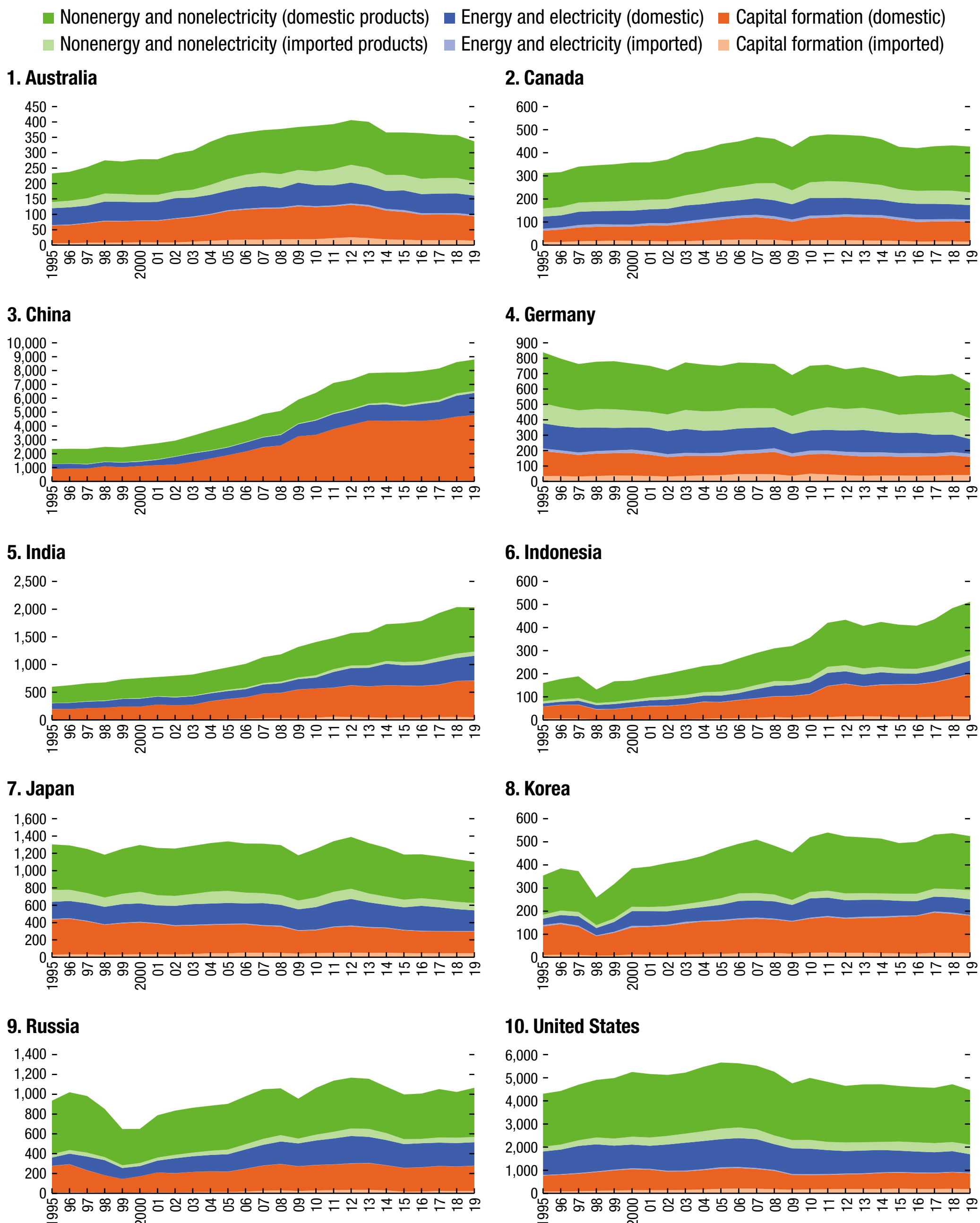
[14] The focus of this work is on the OECD Trade-in Value Added (TiVA) indicators, but the same idea and approaches can be applied to the $TECO_2$ indicators.

ANNEX 2.2

EMISSIONS EMBODIED IN FINAL DEMAND, BY BROAD TYPE OF PRODUCT GROUP AND FOR 10 SELECTED COUNTRIES, MILLION METRIC TONS

Annex Figure 2.2.1. CO_2 Emissions Embodied in Final Demand, by Broad Type of Product Group and for 10 Selected Countries

(Millions of metric tons)



Sources: Organisation for Economic Co-operation and Development's $TECO_2$ database, 2022 edition; and authors' estimates.
Note: Energy products refers to Coal (ISIC Rev. 4 / CPA Division 05), Oil (06), Petroleum and coke (19), and Electricity and gas (35). CO_2 = carbon dioxide.

ANNEX 2.3

FACTOR DECOMPOSITION OF AUSTRALIA'S PRODUCTION-AND DEMAND-BASED EMISSIONS[15]

Factor Decomposition of Australia's Production-based Emissions

Australia's production-based emissions amount in industry *i* is the product of the emissions intensity of industry *i* in Australia and the output of industry *i* in Australia:

$$Prod\_CO2_i^{Aus} = e_i^{AUS} * X_i^{AUS} \tag{2.3.1}$$

The focus is put on four aggregate sectors, namely manufacturing industries, electricity generation, transportation services, and other services. The annual decomposition changes from 1995 to 2019 are expressed as follows:

$$\begin{aligned}
\Delta ProdCO2^{Aus,i}_{1995,2019} &= Prod_CO2^{Aus,i}_{2019} \,/\, Prod_CO2^{Aus,i}_{1995} \\
&= \frac{ProdCO2^{Aus,i}_{1996}}{ProdCO2^{Aus,i}_{1995}} * \frac{ProdCO2^{Aus,i}_{1997}}{ProdCO2^{Aus,i}_{1996}} * \ldots * \frac{ProdCO2^{A}_{20}}{ProdCO2^{A}_{20}} \\
&= \frac{e^{AUS,i}_{1996} * X^{AUS,i}_{1996}}{e^{AUS,i}_{1995} * X^{AUS,i}_{1995}} * \frac{e^{AUS,i}_{1997} * X^{AUS,i}_{1997}}{e^{AUS,i}_{1996} * X^{AUS,i}_{1996}} * \ldots * \frac{e^{AUS,i}_{2019} * X^{AUS,i}_{2019}}{e^{AUS,i}_{2018} * X^{AUS,i}_{2018}} \\
&= \underbrace{\frac{e^{AUS,i}_{1996}}{e^{AUS,i}_{1995}} * \frac{e^{AUS,i}_{1997}}{e^{AUS,i}_{1996}} * \ldots * \frac{e^{AUS,i}_{2019}}{e^{AUS,i}_{2018}}}_{\text{emission intensity}} \times \underbrace{\frac{X^{AUS,i}_{1996}}{X^{AUS,i}_{1995}} * \frac{X^{AUS,i}_{1997}}{X^{AUS,i}_{1996}} * \ldots * \frac{X^{AUS,i}_{2019}}{X^{AUS,i}_{2018}}}_{\text{output}}
\end{aligned} \tag{2.3.2}$$

Thus, the total changes in Australia's production-based emissions in industry *i* is decomposed into the annual changes of two factors: emissions intensity and output.

Structural Decomposition Analysis (SDA) of Australia's Demand-based Emissions

For SDA, the demand-based industry emissions $FDCO2 = FDCO2.IND + HC = e * B * Y + HC$ is expressed as:

$$\begin{aligned}
FDCO2 &= FDCO2 = \frac{FDCO2}{FDCO2.ind} * FDCO2.ind \\
&= sh * e * B * Y = sh * e * G * R * L * Y
\end{aligned} \tag{2.3.3}$$

Where *sh* is the share of total emissions over industry activities–related emissions, *B* is Leontief matrix (Leontief 1956), *Y* is final demand; and *G, R,* and *L* are global, regional, and domestic production network matrix (Han and Yamano 2023). Three specific regions are considered—Europe, Asia and Pacific, and the Western Hemisphere—with "rest of the world" being the fourth region.

Thus, Australia's demand-based emissions is written as follows:

$$FDCO2_{AUS} = \sum_{s}^{M}\sum_{i}^{N}\sum_{j}^{N} CO2^{s,AUS}_{i,j} = \sum_{s}^{M} sh_s \sum_{i}^{N} e_i^s \sum_{c1,c2}^{M}\sum_{j1,j2,j}^{N} G^{s,c1}_{i,j1} R^{c1,c2}_{j1,j2} L^{c2,c2}_{j2,j} Y^{c2,AUS}_{j} \tag{2.3.4}$$

[15] In this chapter, the methodology is applied to CO_2 emissions from fuel combustion. However the same approach can be applied to other GHGs as well as to total GHG emissions.

The annual changes of these IO-linked equations apply the polar SDA approach (Dietzenbacher and Los 1998; Xu and Dietzenbacher 2014; Jiborn, Kulionis, and Kander 2020) to decompose Australia's demand-based emissions from 1995 to 2019 into six factors:

$$\Delta FDCO2^{AUS}_{1995,2019} = \frac{FDCO2^{AUS}_{2019}}{FDCO2^{AUS}_{1995}}$$

$$= \frac{FDCO2^{AUS}_{1996}}{FDCO2^{AUS}_{1995}} * \frac{FDCO2^{AUS}_{1997}}{FDCO2^{AUS}_{1996}} * \cdots * \frac{FDCO2^{AUS}_{2019}}{FDCO2^{AUS}_{2018}}$$

$$= \underbrace{\frac{sh_{1996}}{sh_{1995}} * \cdots \frac{sh_{2019}}{sh_{2018}}}_{\text{direct household use}} \times \underbrace{\frac{e_{1996}}{e_{1995}} * \cdots \frac{e_{2019}}{e_{2018}}}_{\text{emission intensity}} \times \underbrace{\frac{G_{1996}}{G_{1995}} * \cdots \frac{G_{2019}}{G_{2018}}}_{\text{global production}} \times \underbrace{\frac{R_{1996}}{R_{1995}} * \cdots \frac{R_{2019}}{R_{2018}}}_{\text{regional production}}$$

$$\times \underbrace{\frac{L_{1996}}{L_{1995}} * \cdots \frac{L_{2019}}{L_{2018}}}_{\text{domestic production}} \times \underbrace{\frac{Y_{1996}}{Y_{1995}} * \cdots \frac{Y_{2019}}{Y_{2018}}}_{\text{final demand}} \quad (2.3.5)$$

Therefore, the total changes of Australia's demand-based emissions is decomposed into the annual changes of six factors: direct household use, emissions intensity, global production network, regional production network, domestic production network, and final demand.

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CHAPTER 3

Environmental Taxes and Government Expenditures on Environmental Protection

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Tax and expenditure policies are an important part of a government's toolkit to address environmental issues, including climate change. Environmental taxation can help reduce environmentally harmful behavior, while generating revenue at all levels of government. Government spending can enable governments to take direct action related to climate change, for instance, by providing subsidies to households and businesses, or capital spending, for the use of renewable energy. This chapter reviews the definitions and measurement of environmental taxes and expenditures, shows how they have changed in recent decades, and discusses priorities for further statistical development. Data on environmental taxes and expenditures can be found at climatedata.imf.org; and more granular data at stats.oecd.org and in the IMF Government Finance Statistics Database, respectively.

INTRODUCTION

Tax and expenditure policies are an important part of a government's toolkit to address environmental issues in general, including climate change:

- Taxes are one of the most effective tools to change the behavior of businesses and households. Many governments levy taxes on goods or activities that are harmful to the environment, including excise taxes on gasoline and other fuels. Increasingly, governments are also recognizing the need to tax greenhouse gas (GHG) emissions, for example through establishing emissions trading systems.
- Government spending can also influence economic and technological decisions that impact the environment, for instance, through spending on public transport to reduce the use of private vehicles, or by providing subsidies and capital grants to businesses and households to encourage the use of renewable energy. Governments can also help control GHG emissions through their capital investment. For example, as new schools, hospitals, or other public buildings are built, refurbished, or upgraded, governments can invest in an environmentally friendly way. They can also engage in adaptation spending, for instance, by investing in stronger flood defenses.

This chapter is organized as follows. The first section discusses the definition of environmentally related taxes,[2] in line with international statistical standards, and provides related guidance for practitioners. It also examines the revenue raised by these instruments and their trends. The next section discusses the measurement of government expenditures on environmental protection, also in line with international statistical standards. It also discusses spending patterns and how to improve data going forward. The last section draws conclusions and next steps for improving measurement of government interventions to protect the environment or combat climate change.

[1] The section on taxes was contributed by Organisation for Economic Co-operation and Development (OECD) coauthors Ivan Haščič, Florian Mante, and Miguel Cárdenas Rodríguez. The views expressed here are the authors' own and do not necessarily reflect those of the OECD or its member countries.

[2] The terms *environmentally related taxes* and *environmental taxes* are used interchangeably.

ENVIRONMENTAL TAXES TO ADDRESS ENVIROMENTAL CHALLENGES

Methodology and Data Sources

Taxes are defined as compulsory, unrequited payments, made in kind or in cash, receivable by government units from institutional units. This concept is well established at the international level (OECD 2001, 2018a; United Nations 2009; IMF 2014).[3]

An *environmentally related tax* is a tax whose base is a physical unit (or a proxy of it) of something that has a proven, specific, negative impact on the environment (United Nations and others 2014). Environmental taxes may be designed to internalize externalities, and as such the tax rate should equal the marginal external costs. Nonetheless, while the tax base is relevant for the environment, the tax itself might be motivated in the first place to raise revenue—for example, excise taxes on gasoline—with little or no consideration of their environmental effects (OECD 2017a). Permit schemes, such as emissions trading systems, are considered nonrecurrent taxes on goods and services in international tax classifications and statistical standards. Consequently, the government revenue generated from the auctioning or selling of permits or certificates is included as environmental tax revenue.

To determine whether a tax is environmentally related, the tax base needs to be identified. Table 3.1 lists the most commonly used tax bases (OECD 2020). Although the list is comprehensive in the scope of possible environmental taxes, it does not aspire to be exhaustive. The list is likely to evolve over time to reflect new technological developments, new uses of environmental assets, improved measurement of ecosystem services, and better understanding of human impacts on ecosystems.

The definition of an environmental tax cuts across commonly applied tax classification systems. In practice, common tax classifications in macroeconomic statistics follow the economic function of taxes and as such do not generally allow the identification of specific tax bases. More concretely, international tax classifications categorize taxes into the following five groups (IMF 2014, Table 5.1; OECD 2017b, Annex A.1):

1. Taxes on income, profits, and capital gains
2. Taxes on payroll and workforce
3. Taxes on property
4. Taxes on goods and services
5. Taxes on international trade and transactions

Most environmental taxes are established on goods and services, typically taking the form of excise taxes, taxes on specific services, and taxes on the use of goods and on permission to use goods or perform activities. Taxes on income, profits and capital gains, payroll, and property are, in general, not related to the environment, and will in general contain few environmentally related taxes. At the same time, as the general understanding of the links between the environment and the economy evolves over time, the scope of what is considered environmentally related may also change. Property taxes, for example, are a rarely used yet potentially suitable instrument to support environmental policy objectives (OECD 2018b; Oueslati and others 2016), as they can help increase the density of land use and curb urban sprawl (Brandt 2014; Blöchliger 2015).

[3] Governments also collect revenue via various fees and charges that target environmental tax (or fee) bases, but do not feature as tax revenue. Similar to taxes, fees and charges seek to internalize (at least some of) the external costs. But, unlike taxes, they are required; that is, they tend to be paid in proportion to a quantity in return for a service received. Common examples of environmentally related fees or charges include charges on drinking water supply, wastewater treatment, and municipal solid waste collection and management. While environmentally related fees and charges can have important fiscal and environmental implications, they are out of the scope of this chapter.

TABLE 3.1.

Main Tax Bases for Environmental Taxes

Tax Base Category	Specifics	Environmentally Related Tax Base (consumption, production, and trade, as well as measured and estimated values, if appropriate)
Energy, including fuel for transport	Energy products for transport purposes	Unleaded gas, leaded gas, diesel, other energy products for transport purposes (for example, liquified petroleum gas, natural gas, kerosene, or fuel oil)
	Energy products for stationary purposes	Fossil fuels (light fuel oil, heavy fuel oil, natural gas, coal, coke), biofuels, electricity, district heat, other energy products for stationary use
	Energy-related (GHG) emissions	Energy-related carbon content, energy-related emissions of CO_2 and other GHGs (including proceeds from permit schemes)
Transport, excluding fuel for transport	Ownership of motor vehicle	Motor vehicles: production, trade or sale (one-off taxes), registration or use (recurrent, for example, annual taxes), vehicle insurance (excludes general insurance taxes)
	Road usage	Road: use (for example, motorway taxes)
	Congestion	Congestion (for example, congestion charges and city tolls)
	Other transport tax	Other means of transport: railways, waterways (for example, taxes on ships), air (for example, flights and flight tickets)
Pollution	Non-energy-related GHG emissions	Non-energy-related carbon content (such as peat), emissions of CO_2 and other GHGs not related to energy (for example, cattle breeding, rice cultivation, synthetic fertilizer application, meat diets, cement); including proceeds from permit schemes
	Pollutant emissions to air	Nitrogen or sulfur oxide emissions, other air pollutants (excluding GHGs)
	Ozone-depleting substances	Ozone-depleting substances (for example, chlorofluorocarbons, halons, hydrochlorofluorocarbons)
	Effluents to water	Effluents of oxidizable matter, other effluents to water, effluent collection and treatment (fixed annual taxes)
	Nonpoint sources of water pollution	Pesticides (based on, for example, chemical content, price, or volume), artificial fertilizers (based on, for instance, phosphorus or nitrogen content or price), manure (based on nitrogen released)
	Waste management	Waste collection, treatment or disposal, individual products (for example, batteries, tires, lubricants), packaging (for example, beverage containers, plastic bags)
	Noise	Noise (for example, aircraft takeoffs and landings)
	Radiation	Radiation, radioactive substances
Resources	Extraction	Extraction of raw materials (excluding oil and natural gas, including exploration activity)
	Abstraction	Freshwater abstraction
	Harvesting	Harvesting of biological resources (for example, timber, meat, hunted and fished species, wild plants and animals)
	Landscape change	Landscape changes (for example, cutting of trees)

Source: Organisation for Economic Co-operation and Development (2020).
Note: CO_2 = carbon dioxide; GHG = greenhouse gas.

Environmental taxes are typically grouped into four mutually exclusive categories that relate to energy, transport, pollution, and resources (Table 3.1). Each tax base is allocated to a single category. For example, a congestion tax levied on cars is categorized as a "transport tax" because the tax base is the vehicle and possibly the hour and duration of driving. The categorization is thus independent of any motivation or purpose of the tax, such as to diminish local air pollution and noise. Only tax bases relating to the quantity of pollutant (for example, particulate matter emitted or noise produced) would be included in the "pollution tax" category.[4]

[4] A well-known example is the Swedish tax on nitrogen oxide emissions applied to the quantity of emissions of nitric oxide (NO) and nitrogen dioxide (NO_2). The Swedish regulation introducing the tax targeted large combustion sources (for example, power plants, industrial plants, waste incinerators) and mandated continuous monitoring of the emissions at the plant level, making it possible to tax polluters based on the quantity of NOx emissions (OECD 2013). As another example, waste taxes can be based on the weight and composition of waste (recyclable versus mixed household waste), and alternatively on waste collection frequency or waste bin volume.

Current definitions of environmental taxes do not include any revenue from general taxes on goods and services, such as the value-added tax (VAT).[5] This is because these taxes do not change relative prices, provided they are the same for all and therefore will not modify the environmental pressure originally identified.[6] However, VATs with higher rates levied on environmentally related tax bases are interesting to consider. For example, Norway has introduced a full exemption of 25 percent VAT on electric vehicles since 2001 (OECD 2022a). The exemption generates a forgone revenue (tax expenditure). However, since electric car sales exceed 50 percent since 2019, the 25 percent VAT rate on fossil fuel cars can be considered an elevated tax rate, and the revenue coming from this elevated tax rate could be considered an environmental tax. Since 2019, the OECD has expanded its data collection to also record higher VAT rates that address environmental concerns.

There are various databases on revenue collected through environmental taxes. The Organisation for Economic Co-operation and Development (OECD) collects and publishes the most comprehensive international data through its Policy Instruments for the Environment (PINE) database, with data provided by government officials and country experts. Eurostat also publishes data on environmental taxes for its Member States and some surrounding countries, drawing on the data reporting of national tax lists. Moreover, both Eurostat and OECD collect data on environmental tax revenue *accounts*, that is, revenue by economic activity. The *IMF Climate Change Dashboard* (CID) draws upon the OECD database to publish headline environmental tax revenue, supplemented by additional data collections by the IMF to fill data gaps for some countries.

TRENDS IN ENVIRONMENTAL TAX REVENUE

Environmentally related tax revenue is small compared to GDP and total tax revenue. In most countries, the predominant forms of tax revenue are general sales taxes, such as VATs, and taxes on income, profits, and capital gains paid by individuals (personal income taxes) and businesses (corporate income taxes). Most countries also raise tax revenue from other types of taxes that are not environmentally related, such as taxes on property and excise taxes on goods such as tobacco and alcohol.

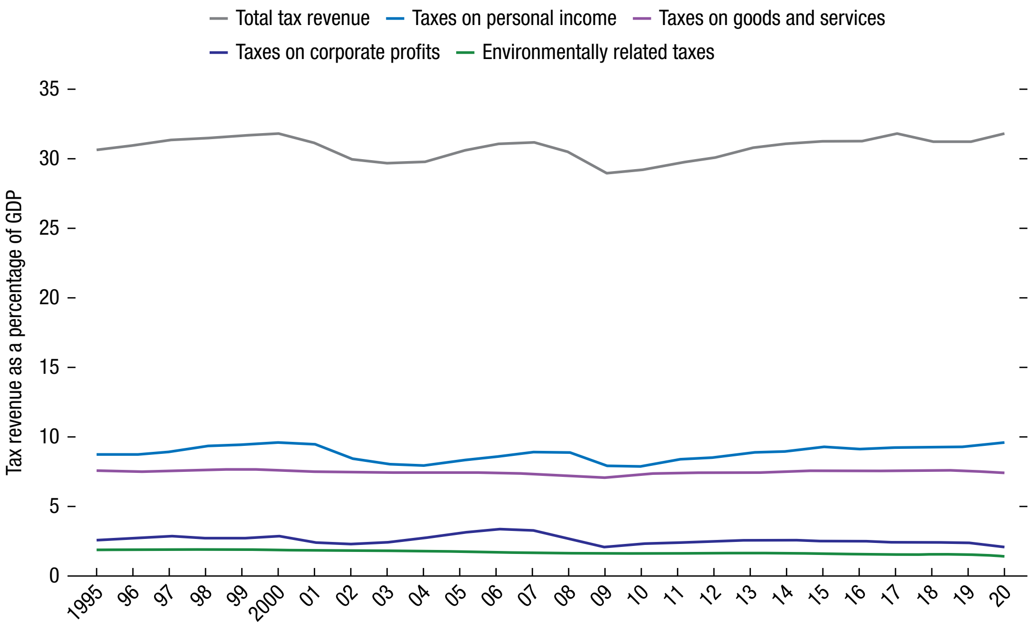
In advanced economies, environmental tax revenue represented on average just 1.7 percent of GDP during 1995–2020 (Figure 3.1). In comparison, tax revenue from income, profit, and capital gains of individuals is close to six times higher, and that on goods and services is five times higher. The low level of revenue raised by environmental taxes combined with the economic efficiency of these instruments to address environmental issues (See "Limitations and Priorities for Further Statistical Development") indicate that there is room for them to play a bigger role in addressing environmental challenges at the domestic and international levels.

Revenue from environmental taxes is only a few basis points higher in advanced economies compared to emerging market and developing economies. The gap between the two country groupings has narrowed over time, partly because the tax base, such as water abstraction, quantity of energy consumed, or pollution emitted, tends to diminish per unit of GDP in advanced economies, whereas it increases in emerging market and developing economies.

[5] For instance, when buying gasoline at a UK gas station, the price paid by the consumer includes a significant amount of both UK Fuel Duty at 52.95 pence per liter (as of June 2022), but also a substantial amount of value-added tax (VAT). VAT is charged at 20 percent on both the price of the underlying gasoline and the UK Fuel Duty. In June 2022, when buying gasoline in the UK, a consumer might pay around 85 pence per liter in combined Fuel Duty and VAT, but while the 52.95 pence per liter Fuel Duty is included in environmental tax revenue for the UK, the 32 pence per liter VAT is not.

[6] For a more complete methodology to retrieve environmental tax revenue from common tax classifications, see OECD (2020).

Figure 3.1. Tax Revenue as a Percentage of GDP in Advanced Economies, GDP-Weighted Average[7]



Source: Organisation for Economic Co-operation and Development (2022b, 2022c).
Note: This figure is based on a subset of advanced economies and emerging market and developing economies, as data for some of these countries are currently not available.

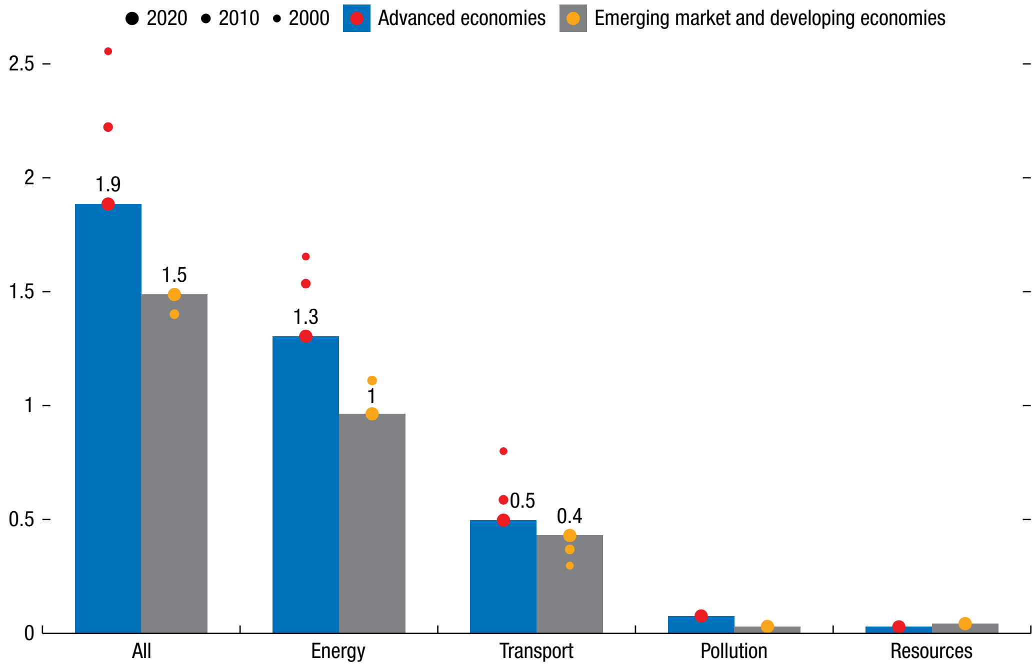
Revenue from environmental taxes increased in real terms during 1995–2018.[8] However, it has been on a declining trend compared to GDP since 1995. Over the past 25 years, these taxes have fallen by 0.4 percentage points and now represent only 1.3 percent of GDP (2020 average) (Figure 3.1). In contrast, taxes on goods and services represent 10.7 percent of GDP in OECD countries, and this share has remained steady over the period 2000–20 (OECD 2021a). The decline can be explained by three main factors:

- Most environmental taxes are levied on tax bases that are defined in *physical units* that do not change over time. This contrasts with income or product taxes, which are levied on tax bases defined in monetary units and hence tend to increase over time due to rising producer and consumer prices. If environmental tax rates remain fixed, the share of environmental tax revenue will fall over time. For example, the US federal gas tax has remained at 18.4 cents per liter of gasoline since 1993 and thus has significantly declined in value in real terms. Automatic adjustments of nominal tax rates for the rate of inflation, or similar adjustment mechanisms, are needed to avoid an erosion of the stringency of environmental taxation over time.
- Eroding tax bases, meaning a decrease in their physical quantity, can also explain the drop in revenue. Such erosion can be considered good news if it reflects diminishing environmental pressures. However, the decline is observed mostly per capita or per unit of GDP in advanced economies; if the population and GDP grow in absolute terms, the overall pressure will not necessarily diminish. Moreover, in emerging market and developing economies, emissions and pollution have been rising in both relative and absolute terms. Enlarging the tax base can help

[7] This chart and subsequent charts on environmental tax revenue are based on a subset of advanced economies and emerging market and developing economies, as data for some of these countries are currently not available.

[8] A decrease is observed in 2020, following the restrictions due the COVID-19 pandemic. Environmentally related tax revenue is based on the physical quantity of energy used or pollution emitted (see “Methodology and Data Sources”), and in 2020 energy and transport usage as well as pollution mostly decreased due to the restrictions.

Figure 3.2. Environmental Tax Revenue as a Percentage of GDP in Emerging Market and Developing Economies versus Advanced Economies, 2000, 2010, and 2020
(By tax base category, GDP per capita-weighted average)



Source: Authors' calculations using Organisation for Economic Co-operation and Development (2022c).

address these trends. In the case of transportation taxes, differentiating personal and commercial vehicles or introducing recurrent car taxes (ownership) and road taxes (distance traveled) are ways to tackle declining revenue. In the case of resource taxes, land as well as other natural resources remain a large untapped revenue stream.

- Tax leakage, involving relocation of economic activities to jurisdictions with laxer environmental regulation, can also play a role. This is why, for instance, the proposed European Union (EU) Carbon Border Adjustment Mechanism targets carbon-intensive sectors by taxing imports in the same way as the EU does domestic production. Enlarging the tax base by considering taxing the imports of environmentally harmful goods would also help mitigate environmental tax leakage.[9]

The composition of environmental tax revenue has also changed over time, slowly increasing in emerging market and developing economies as a percentage of GDP, while decreasing in advanced economies (Figure 3.2). Revenue from taxing energy use represents the biggest share, although it has continuously decreased from 1995 to 2020. Energy taxes, especially taxes on gasoline and similar fuels, are some of the oldest taxes on environmentally related goods and services. In countries that managed to maintain high levels of gasoline excise taxes in real terms, such taxes have incentivized improvements in fuel efficiency and a shift toward electric vehicles, thus reducing revenue from these taxes. Therefore, other types of environmental taxes are becoming relatively more important.

[9] The use of consumption-based, as opposed to production-based, environmental footprint information can help policymakers design such instruments (Yamano and Guilhoto 2020). Corporate sustainability due diligence systems that require the identification of actual or potential adverse effects of operations on the environment, including through supply chains, and the public communication of this information, can also help governments address potential tax leakage.

There have been significant increases in revenue from resource taxes, possibly due to governments' growing concerns about finding more sustainable uses of natural resources, such as abstracting freshwater and harvesting timber and fish. Revenue generated from taxing transport use has remained constant in relative terms, but the nature of the taxes has shifted over time. Although the basis is still composed of a car registration tax, the incentives to shift from conventional cars to hybrid and, more recently, electric cars have translated into tax reductions for these vehicles, resulting in less revenue for the government, everything else equal. Additional revenue has been generated by the introduction of congestion taxes.

Environmental taxes that are common in advanced economies differ from those in emerging market and developing economies. Advanced economies mostly tax energy use, and carbon taxes form a larger proportion of environmental tax revenue, while for emerging market and developing economies taxes on resources are relatively more important. Also, the comparatively higher weight of the value added of agriculture, forestry, and fishing in emerging market and developing economies' GDPs can explain why taxes on resources represent a more significant share of overall revenue.

Another way to compare environmental taxes across countries is to consider cross-country differences in total tax revenue (Figure 3.2). The share of environmental taxes in total tax revenue has declined since 2010 in many countries, both advanced economies and emerging market and developing economies. Yet some countries such as the Solomon Islands and India, Turkey, and Uganda made progress on the path toward "greening" their taxation systems. Reforming and phasing out fossil fuel subsidies and a progressive increase in taxation of such fuels as well as other environmental pressures, following the polluter-pays principle, would generate additional revenue for government budgets while addressing negative environmental externalities.

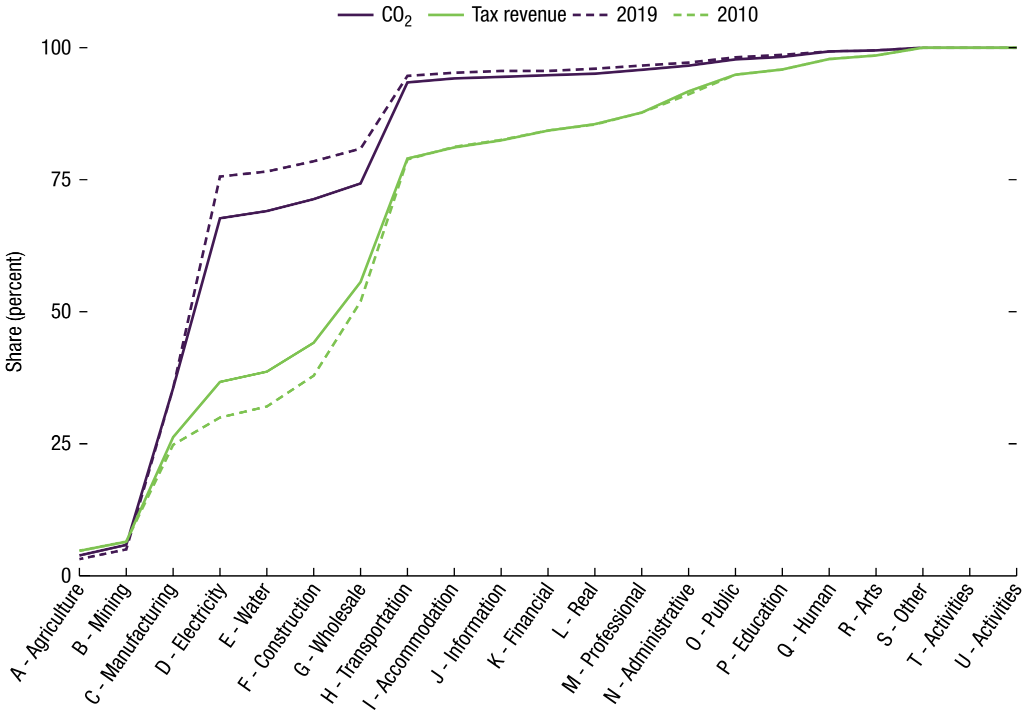
More generally, environmental tax reforms can be used to decrease the distortionary effects of other taxes (Pearce 1991). Several countries have done so, in turn improving environmental outcomes. A study that included 27 EU Member States examined the effects of gradually shifting taxes from labor toward environmental pollution, increasing taxes on fossil fuels, electricity, and water use (Groothuis 2016). The results suggest that employment would increase by 3 percent and GDP by 2 percent over a five-year period, while water use, energy use, and carbon emissions would decline by over 5 percent (OECD 2017a; IMF 2021a).

LIMITATIONS AND PRIORITIES FOR FURTHER STATISTICAL DEVELOPMENT

Scaling up efforts for all countries and all environmental taxes is key. Methods to identify environmental tax revenue are well established. They make use of fine-grained data at the level of individual tax instruments to assess their environmental relevance. But current data reporting efforts focus largely on energy taxes and are concentrated primarily in OECD countries.

All national statistical offices should also strengthen their efforts to compile accounts corresponding to environmental tax revenue and implement the System of Environmental-Economic Accounts (SEEA) more broadly. This would provide information on revenue by industries and households (see "Methodology and Data Sources"). The industry-level disaggregation provides more insights into the environmental and economic effectiveness of environmental taxes. For example, combining environmental tax accounts and CO_2 emissions accounts for a selection of advanced economies, Figure 3.3 shows that in the past decade the energy sector (D) has increased its relative contribution of environmental tax revenue while decreasing its share of CO_2 emissions. By 2019, the energy sector contributed up to 31 percent of CO_2 emissions but less so to environmental tax revenue (~10 percent). This could be explained partly by the tightening of the European Union's emissions trading system. Compared to aggregated *data* on environmental tax revenue, the

Figure 3.3. Cumulative Contribution of Industries to Environment Tax Revenue and Carbon Dioxide Emissions in Advanced Economies, 2010 and 2019



Source: Authors' calculations using Organisation for Economic Co-operation and Development (2022d, 2022e).
Note: On the *x*-axis, the letters are from the UN International Standard Industrial Classification (https://unstats.un.org/unsd/publication/seriesm/seriesm_4rev4e.pdf). The full name of section S is "Other service activities," Section T is "Activities of households as employers, undifferentiated goods- and services-producing activities of households for own use," and U is "Activities of extraterritorial organizations and bodies." CO_2 = carbon dioxide.

availability of environmental tax revenue *accounts* is even more limited, concentrated primarily in Europe.

ENVIRONMENTAL PROTECTION EXPENDITURES

Methodology and Data Sources

Government expenditure is a critical macroeconomic indicator. How much is the government spending, and on what? How much governments spend on environmental protection is a more recent question, one harder to answer due to data availability and at times a lack of transparency.

For most countries, government expenditure is defined in line with either national budgeting and accounting definitions or macroeconomic statistical manuals, such as the System of National Accounts 2008 (United Nations 2009) and the Government Finance Statistics Manual 2014 (IMF 2014), and in a few cases international public sector accounting standards. Fiscal data published following national standards or statistical manuals typically emphasize an economic classification of expenditure, breaking down spending into economic categories like compensation of employees (wages and salaries), purchases of goods and services, interest payments, subsidies, social benefits and other types of transfer, and investment by government in nonfinancial assets (capital projects). But this is not sufficient to understand government spending on climate change.

For that, we need data on expenditures categorized by the purpose or function of that spending. For many countries, the best currently available data are government expenditure data classified

TABLE 3.2.

Classification of Expenditure by Functions of Government

Divisions	Groups
General public services	
Defense	
Public order and safety	
Economic affairs	
Environmental protection	Waste management
	Wastewater management
	Pollution abatement
	Protection of biodiversity and landscape
	Research and development environmental protection
	Environmental protection not elsewhere classified
Housing and community amenities	
Health	
Recreation, culture, and religion	
Education	
Social protection	

Source: IMF (2014).

according to the Classification of Functions of Government (COFOG). COFOG is part of a family of classifications originally formulated by the OECD and published together with three other classifications in United Nations' Classifications of Expenditure According to Purpose (New York 2000). COFOG identifies 10 principal divisions of government expenditure, including defense, education, health, economic affairs, public order and safety, and *environmental protection* (see Table 3.2).

Each COFOG category also includes all expenditures on a particular function regardless of the economic nature of the expenditure. Consequently, government expenditures on environmental protection, under the COFOG classification, includes any compensation of employees, capital investment, purchases of goods and services, and transfers that have an environmental protection purpose. In some countries, COFOG data is cross-classified with economic classification expenditure data, but dissemination of this more detailed data is mostly limited to EU members and some other advanced economies.

Although the overall heading of "environmental protection" may sound highly relevant to the question of how much governments are spending in relation to climate change, the data is, at best, a proxy measure. To begin with, government spending on waste management (that is, refuse collection) and wastewater management (that is, sewerage systems), while important, is not necessarily related to climate change. Nor is protection of biodiversity and landscape, which covers, for instance, spending on national parks and nature reserves. While the definition of "pollution abatement" does include a direct reference to spending on "measures to control or prevent the emissions of GHGs," it also includes many other types of pollution that are not related to climate change, including noise pollution and protection against radiation.

COFOG is also compiled according to primary purpose, so government spending with a partial climate change–related motive is often recorded under the COFOG code that reflects the primary purpose of the spending. For example, spending on public transport, which can have a climate change motive, will typically be recorded under the COFOG code for transport. If a government builds new schools or hospitals with more environmentally friendly materials, or in an energy efficient way, or with on-site renewable power generation, it is likely that the spending will be recorded under the primary purpose of the school or hospital, as COFOG-classified spending on health or education. More precise alternatives to COFOG classifications in the form of green budget tagging or climate budget tagging are under development in many countries and are discussed later.

Government expenditures included within the COFOG-based definition are aligned with the concept of expenditure in the *Government Finance Statistics Manual* 2014 (IMF 2014). They

Box 3.1. Tax Expenditures

Government expenditures included within the Classification of Functions of Government (COFOG)–based definition are aligned with the concept of expenditure found in the *Government Finance Statistics Manual 2014* (IMF 2014). They include what are colloquially referred to as "current and capital" expenditures of the government. These concepts are more precisely defined in *Government Finance Statistics Manual 2014* as either *expenses* of government, transactions that reduce the net worth of the government, or *net acquisitions of nonfinancial assets,* transactions that involve acquisitions or disposals of nonfinancial assets, like land, equipment, or buildings (IMF 2014).

While these are the dominant ways that governments spend money, and the most typically tracked concepts of spending, there are other ways that governments can "spend" money that do not typically show up as government expenditures in the conventional measures of government expenditures, including expenditures classified using COFOG.

The most significant way that governments can spend money without it appearing as an expenditure is through the use of *tax expenditures*. Tax expenditures can be broadly defined as special provisions of the tax code, such as exclusions, deductions, deferrals, credits, and tax rates, that benefit specific activities or groups of taxpayers.

For some governments, tax expenditures that act as incentives to reduce tax liabilities can be an effective way to encourage economic agents to change their behavior. For example, since 2008 and 2009 the United States has provided federal tax credits to encourage purchases of electric vehicles, with further extensions to these credits included in the 2022 Inflation Reduction Act; other countries have adopted similar policies. The cumulative amounts of taxes forgone by this tax credit do not appear as part of US government expenditure, but have been an important policy driver for purchases of electric vehicles in the United States.

The amounts can be substantial. In 2020 the United Kingdom recorded expenditure on environmental protection of £15.4 billion, or 0.7 percent of GDP. In contrast, tax expenditures in 2018–19 were estimated by the UK National Audit Office (NAO 2020) to be worth some £426 billion, and while the vast majority of these are unrelated to climate change or environmental issues, tax expenditures can be an attractive way for governments to impact climate change without such expenditures appearing under conventional measures of expenditure.

While some countries compile tax expenditure reports, and the IMF encourages countries to compile reports on tax expenditures as part of the IMF Fiscal Transparency Code, most countries do not compile these reports, nor are these reports routinely added to other conventional measures of spending on policy areas like those captured in COFOG-based spending reports. Including data on tax expenditures alongside the more conventional measures of spending would provide a wider picture of the total size of government policy measures used to tackle environmental issues or climate change.

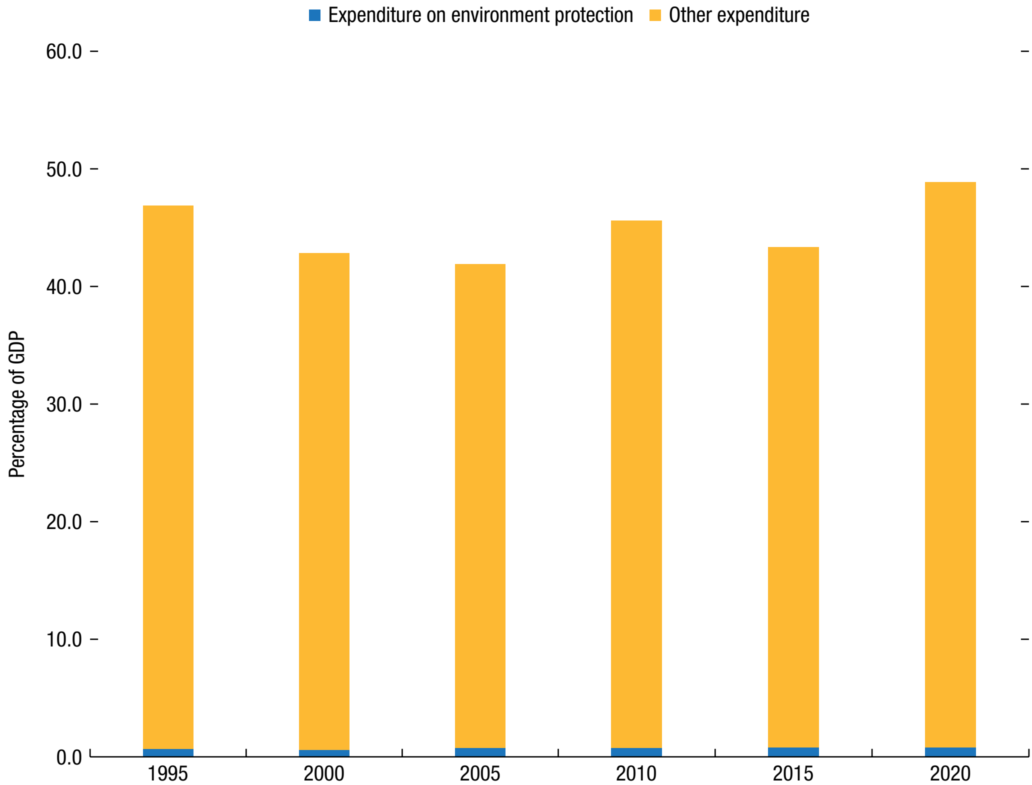
include what are referred to as "current and capital" expenditures of the government. However, there are forms of government "expenditure" that are not included in the conventional measures of government expenditure, most notably tax expenditures, discussed in more detail in Box 3.1.

COFOG data are compiled and reported by around 100 countries as part of the annual collection of data for the IMF's Government Finance Statistics Database. This database includes data for some countries back to the early 1990s, though shorter time series are more typical. Among EU members, detailed breakdowns of environmental protection expenditures, including for each of the subcategories, are available. In other countries, the more detailed breakdown is only available in recent years, or not at all, as prior to 2014 the IMF did not request that countries submit the full COFOG breakdown. Data in some countries, including most advanced economies, cover all government institutions (the general government). In other countries, data are limited to the central government or an even more limited set of institutions called the budgetary central government (which can exclude agencies and government entities that are engaged in environmental protection activities).

TRENDS IN ENVIRONMENTAL PROTECTION EXPENDITURE

Government spending on environmental protection is low as a percentage of GDP across countries and over time. For instance, average unweighted spending by the general government in advanced economies on environmental protection each year was only 0.7 percent of GDP during 2020. Across advanced economies and EU members, which have long time series of general government data,

Figure 3.4. Government Expenditure on Environmental Protection, as a Share of Total General Government Expenditure—Selected Advanced Economies and EU Member States



Source: Climatedata.imf.org.
Note: Data covers Australia, Austria, Belgium, Bulgaria, Canada, People's Republic of China, Hong Kong, Republic of Croatia, Cyprus, Czech Republic, Denmark, Republic of Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Latvia, Lithuania, Luxembourg, Malta, The Netherlands, Norway, Republic of Poland, Portugal, Romania, Slovak Republic, Republic of Slovenia, Spain, Sweden, Switzerland, and the United Kingdom.

total government expenditure on environmental protection has barely changed in two decades (Figure 3.4).

While the average is low, there are some countries with proportionally higher expenditures. In 2018 there were 13 countries where spending on environmental protection exceeded 1 percent of GDP, and within that group three countries where expenditure exceeded 2 percent of GDP—the Marshall Islands, Nauru, and Palau. The 13 countries with greater than 1 percent of spending on environmental protection included other island countries, such as Kiribati, Malta, and Samoa. It may be no coincidence that these island countries, facing the very real danger of rising sea levels, are spending proportionally more on environmental protection. Some advanced economies are also spending more than 1 percent of GDP on environmental protection, including Belgium, France, Greece, Japan, and the Netherlands.

LIMITATIONS AND PRIORITIES FOR FURTHER STATISTICAL DEVELOPMENT

COFOG data are at best a useful proxy measure of government spending related to climate change. For a better understanding, alternative measures are under development.

Several novel classifications and methodologies have been designed to better estimate and report activities on expenditures related to the environment or to climate change. The milestone initiative has been the "Rio markers," introduced by the Development Assistance Committee (DAC) of the OECD in 1998, with the aim to help "monitor development finance flows targeting the objectives of the Rio Conventions on biodiversity, climate change and desertification" (OECD 2011). Rio markers are not meant to help measure climate-specific finance flows, but rather provide a sense of how environmental and climate objectives are mainstreamed in donors' development agendas. Applied on a voluntary basis by OECD Member States, Rio markers assess whether each donor activity targets mitigation, adaptation, or both as either a principal objective or a significant objective. OECD's DAC is tasked with consolidating self-reported donor information.

The Rio markers have been used and adapted by multilateral development banks as a basis for their common principles adopted in 2015 to guide reporting on financial flows in support of climate change action. Both the World Bank and the United Nations Development Programme (UNDP) found inspiration in the Rio markers to develop methodologies for the identification of climate-related expenditures in the context of Climate Public Expenditure and Institutional Reviews (CPEIRs). In recent years, new methodologies have come to fruition, most notably the European Union Sustainable Finance Taxonomy (EU 2020), adopted in the context of the European Green Deal to help companies and investors better evaluate the environmental sustainability of their activities against six objectives.[10] Nonetheless, Weikmans and others (2017) look into more than 5,000 aid projects that were marked by donors as adaptation-relevant for year 2012 and found that in over 70 percent of the projects there was either no clear relation to adaptation or not enough information to make a call.

Finding inspiration in these frameworks, several governments have developed their own green budget tagging (GBT) or climate budget tagging (CBT) methodology in recent years as an alternative way to account for expenditures contributing to environmental objectives. Budget tagging is a public financial management process that allows one to identify, measure, and monitor spending attached to policy areas that cut across existing expenditure classifications. GBT is a decade-old practice that is still relatively rare among world governments. It is, however, considered a key entry point for the greening of public financial management (Gonguet and others 2021) and public investment management (IMF 2021b).

There are now about 20 governments applying (or planning to apply) a GBT methodology, most of which have started the process in the past half decade. CBT methodologies first appeared in emerging and developing Asian countries in the early 2010s (Nepal in 2012, Indonesia in 2014, Philippines in 2015, Bangladesh in 2018), often as a follow-up to CPEIRs carried out with the support and guidance of development partners such as the UNDP and the World Bank. Advanced economies are new to GBT practices, with Ireland being the first OECD country to implement them since 2018, followed by France in 2020 (see Box 3.2).

GBT transcends the administrative or functional classifications, but methodologies are largely country-specific, thus limiting data comparability. The focus of GBT is on environment- or climate-relevant expenditures, whatever the sector, function, or administrative entity. While COFOG or administrative classifications allow one to account for expenditures directly allocated to the environmental sector or ministry, GBT also considers expenditure items that contribute indirectly to environmental objectives, like investment in renewable energy or subsidies for carbon-efficient technologies. According to the OECD (2021b), governments planning to implement GBT face many critical design questions: defining what is green, deciding which budget measures to tag, developing a classification system, and identifying information needs. Yet, despite the

[10] Climate change mitigation, climate change adaptation, the sustainable use and protection of water and marine resources, the transition to a circular economy, pollution prevention and control, and the protection and restoration of biodiversity and ecosystems.

Box 3.2. Green Budget Tagging in France

Green budget tagging (GBT) was introduced in France as of the 2021 budget bill (September 2020), building on the Organisation for Economic Co-operation and Development (OECD)–led Paris Collaborative on Green Budgeting (which France joined in 2017) to integrate "green" tools into the budget process.

Following methodological work done by an interagency working group, including Ministry of Finance and Ministry of Environment agencies, France's green budget has four defining characteristics that make it the most comprehensive in the world to date. It (1) provides an assessment of the "green" impact of all state budget expenditures; (2) covers tax expenditures; (3) reflects not only concerns related to climate change, but also other environmental issues such as biodiversity and the fight against pollution, building on the European Union Sustainable Finance Taxonomy; and (4) rates not only expenditures favorable to the environment but also those with a negative impact.

In practical terms, the GBT exercise relies on extensive interactions between line ministries and the central budget authority as part of the budget preparation process. It examines, at a granular level, expenditures under the French performance budgeting framework to ascertain their contribution to environmental objectives. Actual "green" expenditures are tracked through the exploitation of budget execution reports but not through a specific tag in the financial management information system.

The second edition of France's "Green Budget," produced as part of the 2022 budget bill, highlights that €42.0 billion of expenditures (1.6 percent of 2022 GDP), or €53.4 billion including tax expenditures (2.0 percent of GDP), have an environmental impact, out of a total of €586.6 billion for state budget and tax expenditures. Out of this total, €38.2 billion are rated as favorable to the environment, €4.5 billion as having a mixed impact (positive on one or several elements of the European Union Sustainable Finance Taxonomy but negative on one or several other elements), and €10.8 billion as having a negative impact (mostly tax expenditures lowering the cost of energy for some specific uses).

The budget execution law for 2021 includes for the first time data on actual "green" expenditures. For the budget year 2021, it is noted that €38.9 billion of incurred expenditures have an environmental impact, out of which €31.9 billion have a positive impact, while €4.0 billion have a mixed impact and €3.0 billion have a negative impact.

The methodology used for France's green budget has a significantly broader scope than the Classification of Functions of Government definition of environmental protection expenditure, which highlights a total general government environmental protection public expenditure of 1.0 percent of GDP only for 2020 (Eurostat 2022).

Source: Authors, based on French Ministry of Finance documents (France 2021, 2022).

publication of detailed guidance by development partners (UNDP 2018; OECD 2021b; World Bank 2021), governments so far have opted for a wide range of solutions to these questions.

While Rio markers have often been a reference, governments implementing GBT have adopted diverse approaches to the definition of environmental or climate relevance, which requires making a judgment call, as many expenditure policies can contribute to several objectives at once.

Overall, there have been two broad approaches to assess the environmental or climate relevance of any expenditure item. A first group of countries considers the intended effect of the expenditure item to assess relevance, often based on existing markers and taxonomies. Most governments having made that choice rely at least partly on the Rio markers, but some have also opted for other frameworks and even set their own definitions or restrictions, depending on policy priorities.[11] A second approach has been to circumscribe relevance to a list of categories, programs, or activities explicitly identified in environmental and climate change strategies or policies. This is overall a more flexible approach, since that list can easily be modified or refined over time, but it might limit the comparability of data over time. Both approaches are often supported by explicit taxonomies in which governments list the environmental- or climate-relevant activities in a limitative or only indicative manner or, conversely, by lists of expenditure items explicitly excluded from the tagging exercise.

[11] For instance, Ireland has relied on the eligibility criteria set as part of the International Capital Market Group's Green Bond Principles, while France has set its definition to be consistent with the European Union Sustainable Finance Taxonomy. Colombia has set its own definitions based on those developed by a civil society organization, the Climate Finance Group of Latin America and the Caribbean.

Other important design choices include choosing the accounting method for environmental or climate-relevant expenditures and defining the scope to be covered by the tagging exercise. The estimation of environmental or climate-relevant expenditures is affected by the level of granularity at which the tag is applied—policies, programs, or activities—and by the scope of the tagging exercise. And there, too, solutions vary from one country to the next. Some governments only tag full programs for which the primary objective is explicitly environment- or climate-related, while others apply more granular weights that reflect the portion of the considered program or activity identified as relevant. As for the coverage of the tagging exercise, it can often be restricted to a predefined scope rather than being comprehensive. According to the World Bank (2021), out of the 19 governments already implementing a GBT framework at the time, eight governments focused on a few selected sectors or agencies, and five restricted tagging to the investment budget. Only four countries included transfers to state-owned enterprises as part of the exercise, and only one (France; see Box 3.2) included tax expenditures in the scope of its tagging exercise.

Contrary to COFOG, the implementation of a GBT methodology is usually driven by the agency in charge of running and facilitating the budget process—the Ministry of Finance or its equivalent. In most cases, tagging is integrated within the government's budget process. Most countries currently implementing GBT or CBT focus their effort on budget preparation, with the objective to estimate the share of the proposed budget allocation that would contribute to meeting green or climate objectives. This usually requires line ministries to apply the tags when they prepare their budget submissions, according to a tagging methodology set by the agency in charge of the budget, often with the collaboration of environmental/climate agencies. This is a significant undertaking for governments, and its success largely depends on political leadership by the ministries of finance and on the level of buy-in by other government stakeholders. Supporting public financial management practices has also proven critical to the effectiveness of GBT systems (Gonguet and others 2021). About half of governments rely on their financial management information systems to tag green/climate expenditures, while the rest achieve the tagging exercise manually, making accounting a somewhat painstaking task.

So far, national GBT exercises have often been more programmatic in nature than focused on the transparent accounting of actual expenditures. According to the World Bank (2021), only a handful of governments report on actual tagged allocations after the budget year is over (for example, Bangladesh, Cambodia, Nicaragua), with France doing so for the first time in 2022 for the 2021 budget outturn (Box 3.2).

Alternative classifications and methodologies, such as the Rio markers and the initiatives inspired by them, or national GBT exercises, have allowed countries to transcend the constraints of existing functional or administrative classifications for the purpose of accounting for environmental or climate expenditures. Yet there are limitations that prevent these alternatives from providing sound cross-country data on green expenditures. Despite significant guidance from development partners, there is no internationally agreed-upon approach to defining expenditures that are beneficial or detrimental to the environment. This has led to a wide range of methodological choices in terms of definitions, coverage, and accounting methods.

Furthermore, transparency on the outputs of GBT is not systematic among governments implementing it, with almost half of governments not even referencing climate change in their budget documents, and only a few countries reporting on actual expenditures. To unleash the potential of tagging exercises for accounting purposes, efforts are needed to (1) align definitions for environmental or climate relevance of expenditures, (2) monitor the tag during budget execution, and (3) systematically report on actual expenditures.

CONCLUSION

This chapter discusses two important policy tools and shows how revenue from environmental taxes and government expenditures on environmental protection have changed over the past 25 years. It explains how these tools are defined and how relevant data are compiled, presents recent trends, and describes their limitations. We find that while many countries already produce useful data on revenue from environmental taxes and government spending on environmental protection, care must be taken when using this data in the context of understanding government actions to combat climate change.

New initiatives, like GBT and CBT, and broader reporting of climate change–related tax expenditures or revisions to COFOG methodology could provide further useful information to help policymakers and stakeholders better understand how government policy is responding to climate change. Emerging work on GBT could be enhanced and more widely adopted. The OECD Paris Collaborative on Green Budgeting was launched in 2017 and aims to design innovative tools to assess and drive improvements in the alignment of national expenditure and revenue processes with climate and other environmental goals. To this end, the OECD is working on a project to measure climate-related expenditures. In line with recommendations of the IMF's Fiscal Transparency Code, more countries should also compile tax expenditure reports, ideally including some form of functional expenditure breakdown for each individual tax expenditure item. In the longer term, revisions to the COFOG standards should be considered to more easily identify climate change–related spending and to enable more comprehensive analysis by ensuring that analysis of spending, where the primary purpose is health or education, can nevertheless capture the secondary purpose of that spending when it relates to climate change.

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CHAPTER 4

Indicators of Granular Exposures to Climate-related Physical Risks for Central Banks' Analytical Purposes[1]

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Central banks worldwide are becoming increasingly aware of both the challenges posed by climate change and their role in fighting it. This chapter focuses on the derivation of physical risk indicators, which require the use of new data and methodologies borrowed from geographers, climate scientists, and disaster management experts. First, a conceptual framework is introduced that may be applied for climate impact assessment in economic and financial stability analysis, as well as for stress testing. It builds on different information layers corresponding to the three dimensions of physical risk assessment: (1) physical hazards, (2) assets exposures, and (3) vulnerability of the assets to those hazards. Second, experience in the processing of geospatial information is shared. Third, the analytical part focuses on granular indicators related to physical hazards and their various specifications, exploring the advantages provided by public data sets. The chapter also identifies remaining data gaps in the intersection of climate and financial analysis.

INTRODUCTION

Over the past few years, central banks have devoted increasing attention[2] to climate change in order to assess its economic consequences[3] and devise appropriate policy responses. While central bankers' knowledge of the topic has considerably expanded and they now have access to a broader set of tools to analyze this issue, the work is still at an early stage, and significant obstacles remain. A particularly challenging aspect is the availability of accurate and reliable climate-related data,[4] especially to

[1] This chapter draws on the European Central Bank's presentation at the 9th IMF Statistical Forum on measuring climate change. It should not be reported as representing the views of the European Central Bank (ECB). The views expressed are those of the authors and do not necessarily reflect those of the European Central Bank. The authors would like to thank Antofie Tiberiu Eugen from the Disaster Risk Management Knowledge Centre of the Joint Research Centre for the provision of the hazard data and clarification of underlying methodology, as well as useful comments and suggestions.

[2] The creation of the Network for Greening the Financial System (NGFS) in 2017 and its growth since then is a visible expression of the importance central banks attach to climate-related questions. The NGFS started with eight founding members consisting of central banks and supervisors. As of June 2022, it has 116 members and 19 observers.

[3] For instance, while most empirical studies based on historical data suggest that climate change is expected to have only a limited impact on the European economy in the next few decades, past experience may be a poor indication for future developments given the complex and nonlinear dynamics that characterize climate change. Analysis based on alternative scenarios for greenhouse gas emissions find larger economic effects, especially starting from the second half of the century (ECB 2021c).

[4] In addition to the issues related to data quality, other gaps relate to commonly agreed upon physical risk metrics, forward-looking and downstream emissions aspects, and the heterogeneity of climate-related disclosures among firms and financial institutions (ECB/ESRB 2021, 2022). For more details, see the NGFS progress report on bridging climate-related data gaps (NGFS 2022).

measure physical risks arising from extreme weather events, such as heat waves, landslides, floods, wildfires, and storms.[5]

The terms *hazard* and *risk* are often used interchangeably, but the climate literature distinguishes between the two concepts. Physical *hazard* refers to the intensity and frequency of natural phenomena, while physical *risk* is the expected impact, in monetary terms, stemming from the realisation of a physical hazard.[6] Figure 4.1 illustrates the mechanism through which physical hazards translate into physical risks.[7] A physical hazard can have direct effects on nonfinancial corporations if it impacts their fixed capital (for example, headquarters or plants), or indirect effects if, for example, it affects their supply chain. It may also lead to system-wide macroeconomic effects and induce, for example, a reduction in productivity. As a result, nonfinancial corporations may experience a deterioration of their business conditions, which in turn can affect the financial institutions exposed to them. If physical hazards reduce nonfinancial corporations' ability to repay debt, banks may have to write off the value of the loans granted and record a loss. In the same vein, insurance companies may face larger claims and be forced to liquidate assets at a loss to cover these costs.

To account for the economic and financial stability consequences of physical hazards, central banks have expanded their analytical frameworks to include physical risks. For example, the Bank of England (Bank of England 2017) and the Network for Greening the Financial System (NGFS; TCFD 2017) have developed macroeconomic modeling tools to better understand the effects of physical risk on inflation, economic activity, and financial markets. The Bank of Canada has adapted climate-economy models to examine possible macroeconomic and technological changes. Others, such as the De Nederlandsche Bank (DNB) and the Banque de France, have mapped climate scenarios obtained from climate models into a set of macroeconomic effects by using standard multicountry macroeconometric models.[8]

Central banks and policy institutions have also developed data sets and tools to help quantify and monitor the financial implications of physical risks. For example, the International Monetary Fund (IMF) has published the *Climate Change Indicators Dashboard* (CID), which allows one to visualize and compare the risk of crisis and disasters across countries, while the NGFS has developed a web-based interface that provides intuitive visualizations of physical risk scenarios. At the national level, for instance, the Bank of England has developed a score-based approach to measure current and expected future physical risk exposures of certain assets (Bank of England 2021). Similarly, the French supervisory authority has considered climate-related risks, including physical risks, and their impact on the French banking and insurance sector (Autorité de Contrôle Prudentiel et de Résolution 2021). Also the European Central Bank (ECB) has incorporated physical risk in its

[5] According to the definition of the Network on the Greening of the Financial Sector (NGFS 2020b), physical risk also arises from (1) *longer-term progressive shifts of climate* (such as changes in precipitation, extreme weather variability, ocean acidification, and rising sea levels and average temperatures); (2) *losses of ecosystem services* (for example, desertification, water shortage, degradation of soil quality or marine ecology); and (3) *environmental incidents* (for example, major chemical leakages or oil spills to air, soil, and water/ocean).

[6] Many factors enter into the calculations of physical risk (IPCC 2020): (1) *hazard location, frequency, and severity*; (2) *exposure*—total value of assets and socioeconomic elements (such as population, jobs) exposed to a hazard; and (3) *vulnerability*—degree of damage expected at different intensities of a hazard, including mitigation approaches aimed at lessening its adverse impact (for example, flood protection or insurance).

[7] The hazard classification developed within the Sendai Framework for Disaster Risk Reduction is used.

[8] See Chapter 3 of *Climate Change and Monetary Policy in the Euro Area* (ECB 2021c) for a detailed review. Notwithstanding progress, there is still a disconnect between the climate and economic "blocks" of existing models, as the feedback loops between economic and climate variables are still limited (ECB 2021c).

Figure 4.1. Transmission Mechanism of Physical Hazards into Physical Risk

Physical Hazards

- Hydrological: floods (river/coastal)
- Climatological: drought, wildfire, subsidence
- Geological: earthquake, landslide, volcano
- Meteorological: cold/heat wave, windstorm

Nonfinancial Corporations

Direct effects

- Real estate damage
- Other property damages

Indirect effects

- Business interruptions
- Supply chain disruptions
- Decreased demand for firm's products
- Infrastructure damage

Macroeconomic effects

- Lower productivity (e.g., from severe heat)
- Loss of household income (e.g., property damage, health impacts)
- Socioeconomic changes (e.g., migration, conflict)

Nonfinancial Corporations

- Impact on financial conditions: decreased revenues, repayment ability, refinancing and liquidity risk, increased insurance, repricing of equity/debt issuance

Financial Institutions

- Indicators: financial portfolios' exposure to vulnerable regions/sectors/type of assets
- Accounting for collateral type (physical collateral versus nonphysical) and its impairment
- Scenario analysis/stress test/financial modeling: estimation of probabilities and magnitude of financial losses

Financial System

- Indicators: risk concentration by size (total assets)/capital level (banks CET1 ratio)/profitability (ROE)
- Scenario analysis/stress test with systemwide spillovers

Sources: Adapted from NGFS (2020b) and ECB/ESRB (2021).
Note: CET1 = Common Equity Tier 1; ROE = return on equity.

stress-test exercise (ECB 2021b), preparing the ground for a regular analysis of the expected losses from extreme weather events at the European level.[9]

Assessing the physical risks of financial institutions requires the integration of three types of information: (1) the assets of financial institutions, (2) the physical location of those assets, and (3) the physical hazard associated with these locations. While the first two types of information are generally

[9] As a result of its monetary policy strategy review, the ECB in July 2021 also announced an action plan to include climate change considerations in its monetary policy decisions (ECB 2021a). This was followed in July 2022 by steps to incorporate climate change into the ECB's monetary policy framework, in particular the decision to adjust corporate bond holdings in the Eurosystem's monetary policy portfolios and its collateral framework, to introduce climate-related disclosure requirements, and to enhance risk management practices.

available to central banks, this is not the case for the third. For this reason, the focus is kept on the physical hazard dimension and a discussion of how to construct physical risk indicators at a granular geographic level. While the focus of this chapter will be on nonfinancial corporations, the indicators can be, in principle, used to analyze the risk stemming from households (through, for example, mortgages). Contrary to what is typically done, publicly available data sources are explored in place of commercial ones, allowing the extraction of hazard values at exact locations. This allows users to compile physical hazard indicators in a flexible and transparent manner (at both granular level and aggregated level) and to link them with other data sets. The physical hazard scores complied are then compared with the ones available from commercial data providers. Finally, experience in using geo-spatial data is shared—from both technical and methodological perspective—which might help other institutions to establish the technical infrastructure and analytical tools for physical risk analysis.

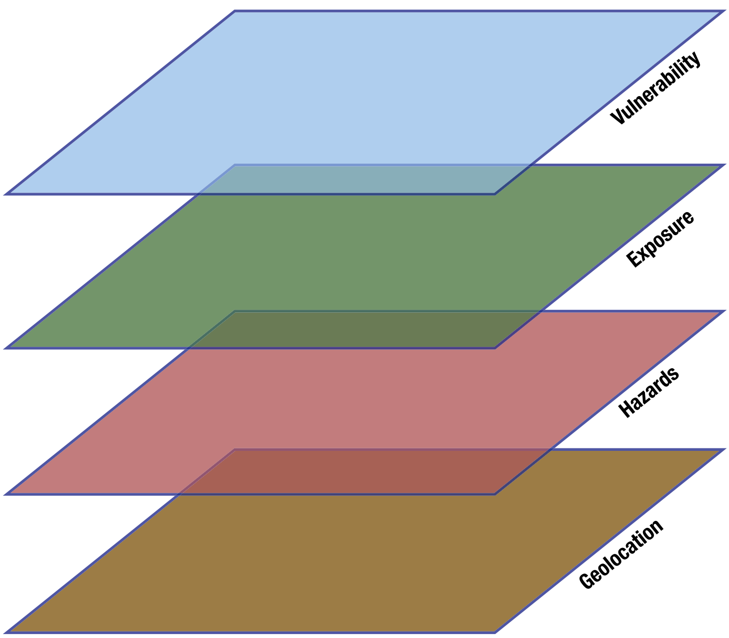
This chapter is structured as follows. The first section describes the data sources required for the analysis of physical risks, organized by analytical layers. The next section focuses on physical hazard indicators, tests various specifications, and compares them with risk metrics available from different sources. The final section concludes and discusses avenues for future work.

DATA LAYERS FOR PHYSICAL RISK ANALYSIS

Assessing physical risks requires location information, terrain characteristics, climate details, and atmospheric maps, as well as financial, economic, and socioeconomic variables, and combining these different types of data over a spatial dimension.

This analysis has drawn from Geographic Information System (GIS) science, arranging the information in analytical layers that reflect the three dimensions required for the physical risk analysis: hazards, exposure, and vulnerability. In addition, the sources are separated for location information, which is the basis for combining those dimensions (Figure 4.2).

Figure 4.2. Analytical Layers Required for Physical Risk Analysis



Physical risk = hazards × exposure × vulnerability

Source: Authors' adaptation based on the United Nations Office for Disaster Risk Reduction (UNDRR) terminology.

Physical Hazards

Physical hazard data are a prerequisite for doing an evaluation of the economic and financial risks posed by climate change. Meteorological and climate information is collected by weather observatories and used for disaster warning systems—by their nature, the data are in the hands of governmental agencies or scientific entities and constitute a public good. In turn, national and regional agencies, such as the National Aeronautics and Space Administration (NASA), the Copernicus Project in Europe, the IPCC (Intergovernmental Panel on Climate Change), and the data platform Resource Watch managed by the World Resources Institute (WRI) provide further input for global climate projections. Additional data sources for more refined analysis are often available within local jurisdictions. For instance, Europe-wide data are published in the form of high-resolution maps from the European Commission Disaster Risk Management Knowledge Centre (DRMKC) of the Joint Research Centre (JRC), as well as the Copernicus Project. Those institutions also offer global data sets for certain hazards.

Commercial data providers also promptly reacted to the analytical needs for climate analysis. Several providers offer various indicators related to physical risk. Using as input public sources, and via statistical transformations, they build different types of risk-score indicators to recode hazard-intensity measures into scores ranging from low to high risk levels. Similar to the Environmental, Social, and Corporate Governance ratings applied in transitional risk analysis, these scores summarize complex multidimensional phenomena in a single number, which allows for a straightforward interpretation of the physical risk, even without any prior knowledge of climate science. However, ratings often lead to oversimplification[10] and mask highly nonlinear relationships between hazard measures and their impacts. Another challenge in understanding what a measure represents comes from there being limited documentation of methodological aspects and underlying sources.

More and more climate models and their output are published and freely downloadable, not only in aggregated format (for example, in the form of country results) but also in their original GIS format—a standard for encoding geographical information. While processing of the GIS data formats requires high computing power and new skills for central bank statisticians, it has the advantage of extracting information at the exact location, and also provides flexibility in building derived indicators, depending on analytical needs. The climate models also offer high transparency of methodology and replicability—key aspects of analytical work at public institutions. Because ready-to-go data sets offered by commercial providers have the advantage of providing input for a swift analysis, a commercial data provider is also mentioned. In the "Comparison of Hazard Measures from Different Sources" section, selected indicators are compared across sources to assess their consistency.

Exposure

Financial Exposure

To quantify the impact of physical hazards in economic terms, climate information needs to be combined with financial data. With respect to financial variables, different sources can be employed: credit, business, and securities registers.

Within the sources available to the European System of Central Banks (ESCB), the Analytical Credit data set (AnaCredit)[11] contains information on credit exposures, while the Centralised

[10] See, for example, Berg, Kölbel, and Rigobon (forthcoming).

[11] AnaCredit provides detailed, harmonized information on individual euro-area bank exposures above €25,000, providing an overview of the loan portfolio of financial institutions. It also contains information on the collateral type and region, which when linked to physical hazards in that location can provide valuable information on collateral impairment.

Securities Database (CSDB) and the Securities Holdings Statistics (SHS) cover securities[12] and are used to assess market risk stemming from potential repricing of equity and debt due to climate-related risks. The advantage of leveraging internal sources is having accessible, up-to-date, harmonized, granular information for European companies and financial institutions. However, data at such granularity are rarely available in other jurisdictions. Generally, access to public information at the firm level is limited, and available sources suffer from undercoverage and of lack of harmonization for cross-country comparison.

For the nonfinancial sector, Orbis, a commercial data set by Bureau van Dijk, contains financial statements and nonfinancial and contact information of around 400 million global listed and private companies. It contains several variables relevant from the physical risk perspective—fixed assets such as buildings as well as machinery, inventories, and financial information—which allow the assessment of liquidity and financial resilience of balance sheets in case of a natural catastrophe. However, the coverage differs by country and company characteristics (larger and older companies are better represented).

A common identifier—such as an international securities identification number (ISIN), legal entity identifier (LEI), or value-added tax (VAT) number—is crucial for linking information across databases and allows for broadening the analytical scope, for example, incorporating a transitional risk dimension. Expanding the inclusion of such standard identifiers in company mandatory and voluntary reporting would facilitate combining financial and sustainability information. To map the physical risk, the addresses of entities of interest (for example, borrowers) are also required, ideally not only for their headquarters but also for all plants, production sites, and other facilities exposed to physical hazards.

Socioeconomic Exposure

Socioeconomic data can further enhance the analysis of physical risk. Information on the population demographics of affected areas allows for capturing social impacts, for example, an increase in extreme temperature on health and productivity or job losses due to disruptions in company operations or bankruptcies. The European Statistical Office (Eurostat) provides detailed population information based on a census on a 1 km x 1 km grid.[13] Also, the IPCC accompanies its climate projections with population density estimates for each climate scenario.

Geospatial data, such as land cover, maps areas into different types, such as artificial surfaces, agricultural areas, forest and seminatural areas, wetlands, and water bodies. The European Corine Land Cover database contains 44 classes,[14] including categories for road and rail networks, ports, and airports—which can enhance the analysis by accounting for potential damages to company surroundings, such as critical public infrastructure. The snapshots of land cover are complemented by maps highlighting changes between the years, allowing for analysis related to climate and sustainability by indicating depletion of natural resources (for example, changes from forest to urban or agricultural area). A global land cover data set can be obtained from the Copernicus Land Monitoring Project.[15]

Another useful data set is the HARmonized grids of Critical Infrastructures in EUrope (HARCI-EU), which provides granular spatial data on major critical infrastructures in the transport, energy, industry, and social sectors. It is measured in economic units relevant for the sector, such as turnover, expenditure, freight transported, or energy produced.

[12] The CSDB is the reference database on individual securities information issued by European resident firms (for example, price, issuer name, and outstanding amount), while SHS gathers holding information on mutual funds shares, debt securities, and equities, with a focus on EU-issued instruments and internationally traded securities held by European investors.

[13] See Eurostat GEOSTAT project.

[14] See geospatial data at CORINE Land Cover and CORINE Land Cover nomenclature.

[15] See https://lcviewer.vito.be/2018.

Vulnerability

The most challenging data gaps in the physical risk assessment are related to vulnerability. Following the definitions[16] in the IPCC's Fifth Assessment Report (IPCC 2014), vulnerability depends on (1) *sensitivity*—"degree to which a system or species is affected . . . by climate variability or change," directly or indirectly, adversely or beneficially, and (2) *adaptive capacity*—"the ability . . . to adjust to potential damage, to take advantage of opportunities, or to respond to consequences." Vulnerability is the resulting final propensity to be adversely affected, which increases with higher sensitivity and lower adaptive capacity.

Vulnerability is usually hazard-specific, and different types of information are needed for different types of assets. For instance, year of construction can be a good indicator of the resilience of a building, given that building regulations are usually more stringent for newer buildings. However, to have a better assessment of a building's vulnerability, further parameters are required. For instance, for floods, information on elevation above the ground and flood barrier protection is required, while for earthquakes this is about the building's construction, such as flexible foundation and materials.

Damage functions link the exposure to a hazard with its possible damage, incorporating adaptation measures and providing an estimate of potential monetary loss. For instance, the building type, the construction type, and the material used would determine damages to a building from high gust speeds in a certain area.[17] For flooding, not only might the level and surface area of buildings matter but also implementation of mitigation measures (such as dikes), which all influence the shape of a damage cost curve.

Damage functions rely on detailed loss data, usually found in insurance-claim data—and mainly in the hands of private companies. The events themselves only happen rarely, so a long time span should be considered to get sufficient comparable data, especially for extreme events with large impacts. The JRC DRMKC has launched a project to harmonize the underlying data sources to make them comparable across Europe. For river and coastal flooding, damage costs are estimated for most European countries, while global damage curves are available for each continent.[18] The section "Accounting for Vulnerability: Illustrative Example" shows the application of the damage functions.

A main challenge is to obtain data on the building stock. One data source is Open Street Map (OSM), which is a community-built map (see Box 4.1 on geocoding). Its coverage varies across countries—for some countries, national institutions provide data of high accuracy for the entire area, while others rely on the contributions of volunteers. Even in countries that have almost full building coverage in OSM, information on specific characteristics such as the number of floors is usually available for only a small share of buildings.

OSM data could be augmented by linking them to other geospatial data. For instance, the European Settlement Map (ESM) is a spatial data set that maps human settlements in Europe and splits buildings into residential and nonresidential. Also the Global Human Settlement (GHL) database could provide information on population density and community borders. Lastly, census data or national registries could provide information on house type, number of floors, and house prices, but such data are not publicly available, and exist only in a few European countries.

The JRC, through the Projection of Economic Impacts of Climate Change in Sectors of the European Union Based on Bottom-up Analysis (PESETA) Project, conducts a comprehensive study of climate change impact and adaptation in Europe, providing comparable projections across sectors and EU regions. In the report (Feyen 2020), several impact categories are analyzed under three climate scenarios. The study combines projections of the individual hazards with socioeconomic impact models, allowing for estimations of welfare loss in monetary values, including damage to capital stock, sectoral productivity reduction, and changes in consumption. Adaptation measures to

[16] See Sharma and Ravindranath (2019).

[17] See Prahl (2012).

[18] https://publications.jrc.ec.europa.eu/repository/handle/JRC105688.

reduce the risks are also listed individually for each hazard (for example, cooling techniques, drought-resistant crops, early-warning systems), but the authors point to challenges in evaluating returns on such investments, and loss reduction attributed to adapting specific measures is estimated only for floods at a country level.

Insurance alleviates financial losses and helps to rebuild damages. Fache Rousová and others (2021) estimate that, if there is no insurance coverage, catastrophe damages of 1 percent of GDP translate to a 0.25 percentage point decrease in quarterly GDP growth. Conversely, an insurance coverage of 75 percent can lead to almost immediate recovery in growth. As there is only limited information on insurance against natural catastrophes, the European Insurance and Occupational Pensions Authority (EIOPA) launched a dashboard on the insurance protection gap; it covers historical data on insured and uninsured losses, the economic value of residential and commercial areas exposed to natural hazards, and vulnerability indicators of the building stock inventory to earthquakes and windstorms.

Location

Historically, macroeconomic data were available mainly only at a country level. In the area of sustainability, the IMF *Climate Change Dashboard* is an example of a data hub that contains cross-country indicators. Global coverage is a huge advantage of the IMF dashboard; however, more detailed analysis requires data at a subnational level, which, even when available, is rarely harmonized.

In Europe, more and more data sets include regional breakdowns. The Nomenclature of Territorial Units for Statistics (NUTS) is the statistical classification in Europe, dividing the EU into over 1,000 regions at three levels of detail, which are also presented by breakdowns indicating dominant terrain characteristics, such as urban–rural, metropolitan areas, islands, coastal, mountainous, and border regions.[19] Eurostat offers several statistical data sets with NUTS regional breakdowns, including, among others, GDP, business demography, health, tourism, labor market, energy statistics, crime, poverty, and social exclusion indicators.[20]

At a global level, the World Bank provides specifications for administrative boundaries, including national boundaries, disputed areas, and coastlines. The Global Administrative Areas (GADM), a project by the Food and Agriculture Organization (FAO) to map administrative units in the world, includes subnational divisions up to five levels.

Having data at exact locations allows for more flexibility in the analysis, which is not restricted to regional boundaries. While regional information is sufficient for the analysis of certain types of physical hazards (such as heat or cold waves), others (for instance, floods and landslides) require a higher level of granularity. Physical hazard data are already available in the form of high-resolution maps; however, potentially affected assets are often lacking location information.

Business registers contain the official address of a company's headquarters but not information on production sites, warehouses, or distribution centers, unless they are a separate legal entity. Asset location would enable adequate physical risk assessment—and would have much broader applications in economic analysis, allowing for the investigation of spillovers across value chains or of how proximity to certain markets, urban areas, or infrastructure affects productivity, trade, and the labor market. There are few data sets offering information on specific sectors,[21] and this remains one of the most pressing data gaps.

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[19] Vector files that include definitions of NUTS and LAU regions are available at the Eurostat GISCO website.

[20] See Eurostat regional data sets.

[21] For instance, the Geoasset database by the Spatial Finance Initiative covers global cement, iron, and steel production. The European Pollutant Release and Transfer Register (E-PRTR) contains data reported annually by more than 30,000 industrial facilities covering the largest polluters in the EU.

Box 4.1. Geocoding of Addresses: Technical Aspects

For integration with the physical hazards layer, the address needs to be converted to latitude and longitude—so-called geocoding. While there are many tools to facilitate this process, large-scale geocoding is computationally intensive. It is also particularly challenging for databases covering more than one country, with the outcome depending on the way the addresses are registered and the alphabet used. The geocoded data are the basis for further analysis, and correct coordinates are crucial for proper linking with hazards maps. For instance, the address "ECB, Sonnemannstrasse 22, 60134 Frankfurt am Main, Germany" is translated to a point (50.1105, 8.7024) in the projection EPSG:4326 (European Petroleum Survey Group Geodesy).

Several commercial cloud services, such as Google Maps and Bing Maps, allow one to query and geocode a limited number of addresses, but for larger-scale processing they can be slow and expensive, and the quality is difficult to assess. Hence, the European Central Bank implemented its own geocoding process suitable for millions of addresses and based it on a public and free-to-use Open Street Map (OSM) data set, which is a global inventory of geospatial objects, such as cities, streets, and buildings. In addition to its coverage of addresses, it also contains train tracks, highways, bridges, and millions of so-called points of interest, such as restaurants, banks, and factories, which could be relevant for economic analysis. It can be described as the "Wikipedia for map data," with hundreds of thousands of contributors—individual volunteers, governmental agencies, and nonprofit and commercial companies—who update it and add new information in a timely fashion.

One of the most challenging aspects is the heterogenous quality of addresses contained in economic data sets. The different postal code systems, alphabets, abbreviations, and ways of representing the same address pose difficulties in finding correct matches with the map data. Address information also might be incomplete, and often data fields have been manually filled with different degrees of precision. To address these challenges, dedicated tools[1] can be used that apply heuristics and machine learning approaches to clean and reformat the address information into a standardized set of variables (for example, street, house number, country, city, zip code) that are later converted into a canonical form suitable for matching with the OSM data.

[1] For example, the library *libpostal* (Barrentine 2018).

PHYSICAL HAZARD INDICATORS FOR THE EU: A DEEPER DIVE

Comparison of Hazard Measures from Different Sources

While physical risk indicators, which incorporate the financial dimension and potential impact on financial stability, have been analyzed in several studies, less attention has been dedicated to measures of the underlying physical hazards. Climate data sets, often available from commercial data providers, offer a wide range of measures; for example, mean or maximum temperatures, number of days with temperature over/under specific thresholds, number of consecutive days with precipitation over a threshold, or number of consecutive dry days. They could be expressed as absolute values or as changes with respect to a baseline period, given that impact and needed adjustments are often relative to the current situation.[22] Climate models and projections are also constantly updated. Economists might struggle to select a suitable measure or may have only a few indicators at hand from a single source. To illustrate the potential impact of using different sources and specifications of climate variables, data from a commercial provider Four Twenty Seven[23] is compared with best-aligned indicators from the JRC DRMKC, NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP), and the IPCC. The results are based on a Four Twenty Seven data sample, which was used in ECB reports that comprise over a million EU firms.[24]

The hazard data were processed in their original GIS format—a standard for encoding geographical information and representing location data. This has the advantage of extracting information at the exact location, as well as providing flexibility in building derived indicators depending on

[22] For instance, an increase in extreme temperatures might require installation of an air-conditioning system in regions where it was not needed before (for example, Germany), while regions exposed in the past to high temperatures do not require such adaptations (for example, Spain).

[23] Four Twenty Seven was acquired by Moody's ESG Solutions.

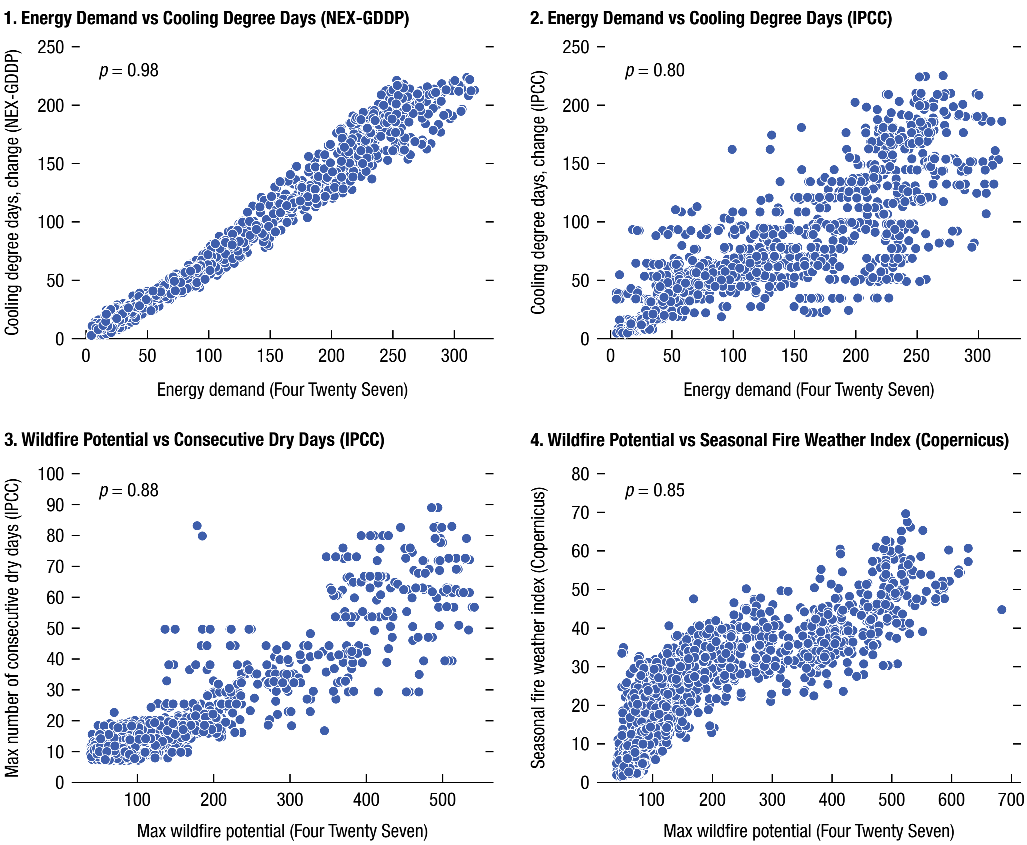
[24] See ECB/ESRB July 2021 and ECB 2021.

analytical needs. The exercise covered various sets of indicators related to temperature, precipitation, water stress, wildfires, earthquakes, and river and coastal flooding. Here, only heat stress indicators are presented—cooling degree days[25] and wildfires metrics—to illustrate the extent of divergence between sources, methodologies, and specifications.[26]

The measure for "energy demand' in Four Twenty Seven relies on the cooling-degree days metric and shows relatively high correlation with the IPCC data, even though Four Twenty Seven data are based on earlier climate models (Figure 4.3). When looking at the original source indicated by Four Twenty Seven (NEX-GDDP; Figure 4.3, panel 1), there is very high consistency between the two data sets. When a more up-to-date model is used from IPCC, the correlation decreases (Figure 4.3, panel 2), where application of different thresholds for defining cooling-degree days (18°C for NEX-GDDP and 22°C for the IPCC) could be a contributing factor for the divergence.

High temperature combined with lack of precipitation creates conditions for fire. Four Twenty Seven assesses wildfire risk using the Keetch-Byram Drought Index (KBDI),[27] a metric for forest fire

Figure 4.3. Heat Stress Indicators



Sources: European Central Bank (ECB); European Fire Weather Index (EFWI); Four Twenty Seven; IPCC (Intergovernmental Panel on Climate Change); and NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) calculations.
Note: Figures present correlations *p* computed between corresponding variables for the company. Sample covers companies located in the EU countries.

[25] Energy demand required for cooling depends on the excess of temperature above a given threshold. Cooling degree days is a useful measure that captures both the excess (in degrees) and duration (in days).

[26] Results for all other measures can be provided upon request.

[27] See Keetch and Byram (1968).

potential. The results combine NEX-GDDP projections on precipitation and temperature, adjusting for the burnable fuel availability, such as forest, based on land cover maps. This indicator is highly correlated with the number of consecutive dry days from IPCC (Figure 4.3, panel 3), as well as with the European Fire Weather Index from Copernicus (Figure 4.3, panel 4).

While this example shows a few comparable variables across data sets, public sources offer a wide range of information, and different climate scenarios and reference periods can be explored for a given category of risk, offering huge advantages for data users at public institutions.

Accounting for Vulnerability: Illustrative Example

Economic losses can arise due to disruptions along the value chain of a business or its surrounding infrastructure, even if the company itself is not directly affected by an extreme weather event.

In this section, a transportation data set and a river-flooding data set are examined to illustrate how the three layers of physical analysis—hazard, exposure, and vulnerability—are combined to assess potential damage to road infrastructure caused by flooding events.

For the **hazard layer**, the river-flooding data provided by JRC DRMKC are used. The maps encompass the flooded area and its intensity (water depth) for six return periods of 10 to 500 years for the entirety of Europe (Figure 4.4, panel 1).[28] In the next step, the hazard layer is combined with the **exposure layer**—a road network in Europe sourced from the HARCI project[29] that provides the location of critical infrastructure, including their economic importance, as measured by annually transported freight in kilotons (Figure 4.4, panel 2).

To estimate the **vulnerability dimension**, a damage function for transport in Europe[30] is applied to indicate the percentage loss of the affected part of a road, dependent on flood intensity (Figure 4.4, panel 3).[31] For instance, if the damage level is 20 percent for the water depth of 0.4 meters and the amount of freight is 80 kilotons, the expected loss in that flood event would be 16 kilotons. This value is then multiplied by the flooding probability, which can be derived from the return periods, and summed up over all return periods.[32]

In the last step, the expected annual losses are aggregated on the NUTS-2 level to obtain a picture of the most exposed regions (Figure 4.4, panel 4). For instance, the most affected region in this example is Hauts-de-Seine, a region located along the River Seine between Paris and Versailles, where 6.3 million tons of freight per year are expected to be impacted by river flooding.

The analysis could be expanded using more complex geospatial operations. First, annual freight is only an indicative measure of the economic importance of a road, flood damages might be repaired within days or weeks, and the reconstruction costs are not necessarily related to the volume of transported goods.[33] Second, in the computations, only the part of the road directly affected is included, while an entire section of the road might be blocked in the case of a natural disaster. However, the traffic could be directed to alternative routes, and looking at the entire road network and other transport infrastructure could further enhance the analysis.

[28] Also available with global coverage: https://data.jrc.ec.europa.eu/collection/id-0054.

[29] HARCI is only available for Europe. However, spatial data on roads can often be obtained from national geographic institutions, such as the IBGE for Brazil or universities such as Stanford University for South Africa or Mexico.

[30] Available at the JRC: https://publications.jrc.ec.europa.eu/repository/handle/JRC105688.

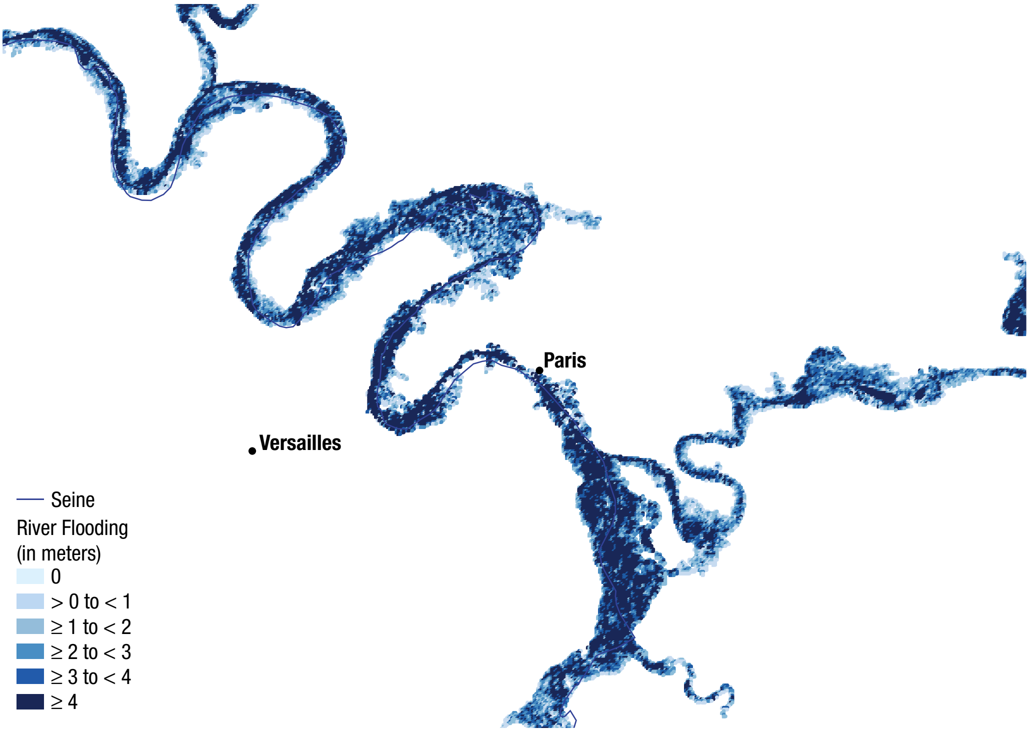
[31] The annual amount of freight in that road polygon is multiplied by the percentage level of damage.

[32] According to the formula EAL = transported freight * $\sum_{rp}$ *prob of occurrence*$_{rp}$ * *damage function* (*assets characteristics, hazard intensity*$_{rp}$), where rp = return period.

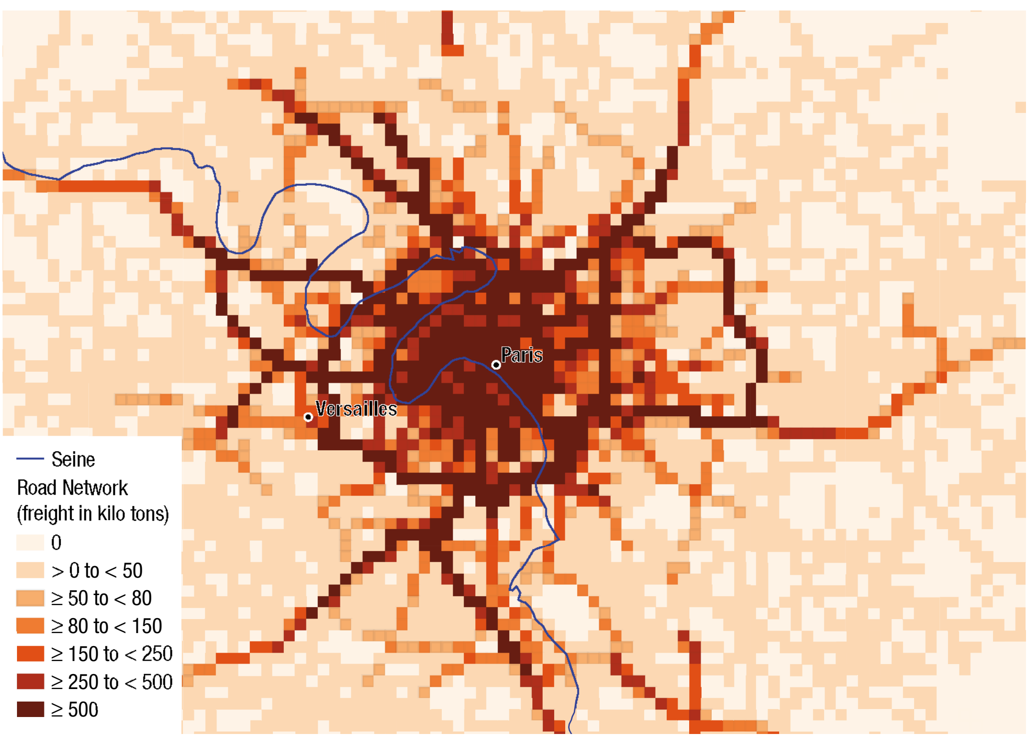
[33] For instance, Clarke and Acosta (2019) found in an analysis of flooding of transport networks in Ireland that a potential flooding event with a return period of 1,000 years would lead to costs of around 660 euro for a 1.27 km stretch of the main orbital motorway of Dublin.

Figure 4.4. Impact of River Flooding on Road Network in Europe—Illustrative Example

1. River Flooding 500-Year Return Period



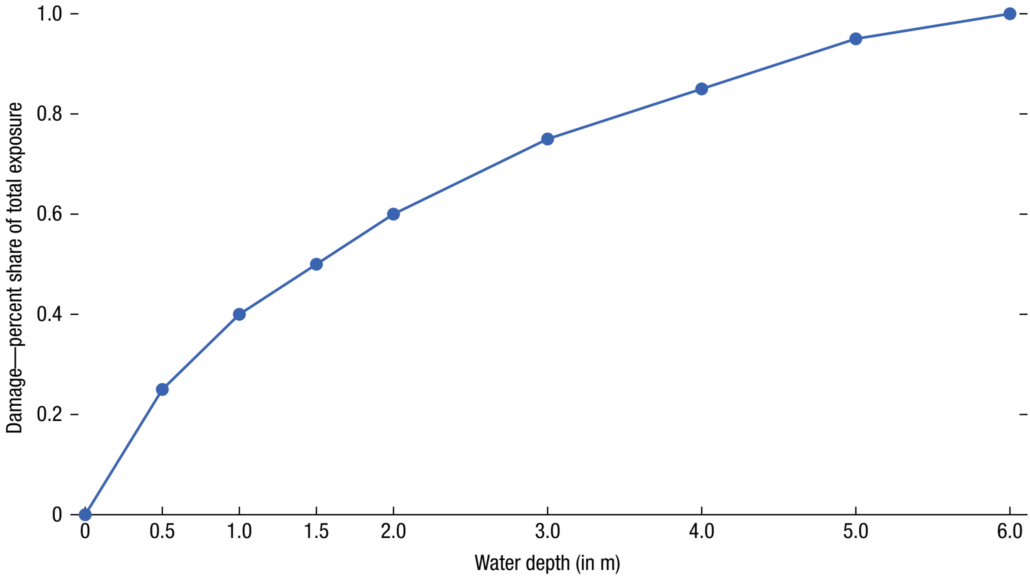
2. Road Network in Europe ***(Annually transported freight in kilotons)***



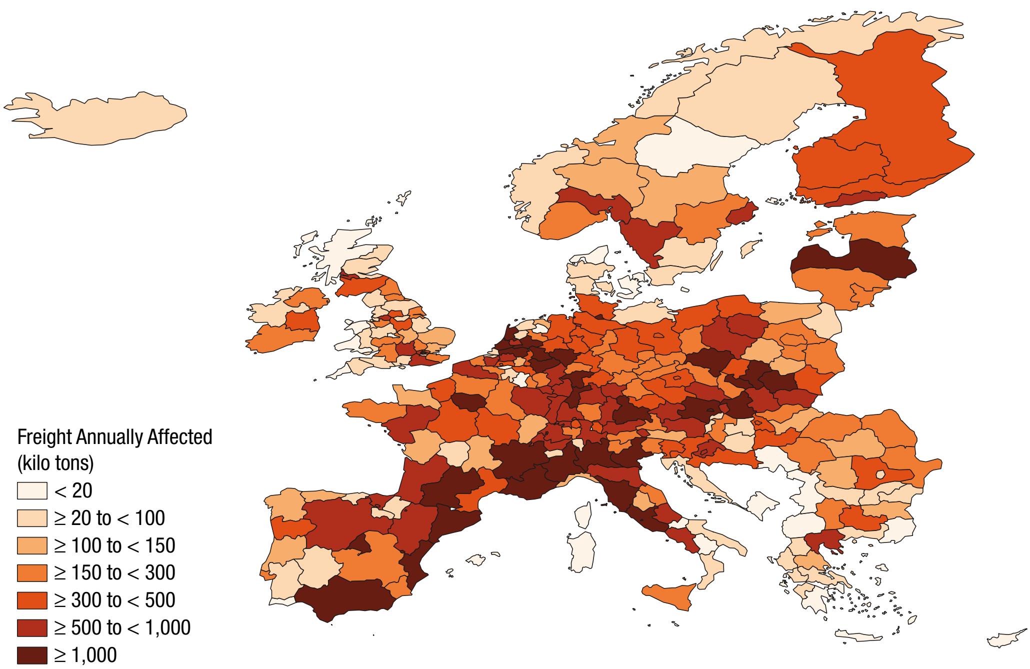
(Continued)

Figure 4.4. *(Continued)*

3. Transport Damage Function for River Flooding ***(Share of damage as a function of projected water depth)***



4. Expected Annual Loss in Terms of Impact on Annually Transported Freight ***(Aggregated to NUTS-2 regions)***



Sources: ECB calculations based on flooding data (Joint Research Center), transport data (HARCI, Copernicus), and damage function (Huizinga and others 2007).

CONCLUSION

This chapter presented the key aspects of compiling indicators of climate-related physical risk. The analysis of the consequences of physical hazards is still at an early stage, in particular at the level of individual business entities. Choices of data sources do have a potentially significant impact on results, and compilers need to be keenly aware of the methodology and approaches used by data providers. Large benefits are seen in using public data sources, which provide transparent documentation and ensure the replicability of results.

This chapter also illustrates the advantages of directly applying GIS tools. They allow for a flexible incorporation of new climate data sources and a link with financial information for any entity with address information. The ECB was able to apply the same procedure to over 10 million legal entities contained in the ESCB data sets, and the availability of firm identifiers allowed the addition of financial information from other data sets. Geospatial data can also be processed when new sources become available or updates are released. GIS files enable the compilation of physical hazard indicators at a chosen level of geospatial aggregation in a flexible and transparent manner, tailored to the relevant research questions.

In the areas of both climate and economic data, further enhancements are required.

Climate Data

Climate data often differ in their availability, consistency, and degree of harmonization across geographic areas, types of physical hazards, scenarios, and time horizons. The development of common reporting standards of climate information would help to improve the availability and quality of data.[34] Further development of the framework (Sendai Framework[7] and EU initiative[35]) on catastrophes would enable the creation of harmonized data on past disaster events. For governments and public institutions, the distinction between private and public losses, as well as the share of insured damages, would facilitate the design of appropriate policies, disaster response, and recovery. Finally, the alignment with standard statistical classifications of economic activity would allow one to combine disaster information with widely available economic variables, such as GDP.

With respect to future projections, climate models, especially those with global coverage, have low resolutions and need to be "downscaled"[36] to obtain finer regional details. They also rarely account for "tipping points" and cannot predict rare and extreme events, which might have high social and financial impact. While some variables can be modeled well (for instance, temperature), others pose challenges (for example, precipitation, wind), particularly at the local level. Two important areas still underexplored are accounting for multihazard risk and modeling of co-occurring events (for example, floods and landslides). Another blind spot is the vulnerability assessment for damages stemming from various hazards. As a result, caution should be exercised when drawing conclusions for individual entities (Fiedler and others 2021).

While companies are incentivized to report risks and opportunities stemming from climate change,[37] modeling its financial impact still poses many challenges, especially for smaller companies. The industry of climate-impact consultancy services is developing rapidly, however the reliability of

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[34] In Europe, there are several legislative initiatives that address various aspects of sustainability: (1) the EU Taxonomy defining sustainable activities; (2) the EU green bond standard, which builds on the taxonomy to classify sustainable financial instruments; and (3) the Corporate Sustainability Reporting Directive (CSRD), which covers the disclosure of environmental and social matters at the company level.

[35] See European Commission (2021).

[36] Downscaling is a procedure to obtain information at a smaller scale, starting from a more aggregated level. Two popular methods used for downscaling are (1) dynamical downscaling, which incorporates additional information such as detailed topography, vegetation, and land use to fine-tune global scale models; and (2) statistical downscaling, which uses the empirical statistical relationship between global and local variables (United States Agency for International Development 2014).

[37] Including the impact on their investment and supply chains (TCFD 2017).

the assessment is difficult to verify and it might take years before the level of the analysis reaches sufficiently high standards.

Economic Data

First, assets location information is key to achieving a better assessment of physical risk exposures of businesses' and subsequently of financial institutions' portfolios, especially if those assets serve as collateral. It is important to identify the location not only of a company's headquarters but also its facilities, production sites, distribution centers, and so forth. Currently, data sources with such information are limited and, if available, are only provided for select companies and sectors.[38] Further, requiring details on company operations and the network of suppliers and clients would enable assessing the climate impact on the entire value chain of the company.[39]

Second, companies should provide information on their specific climate adaptation measures, including insurance. Currently, such information is very limited and usually available only at the country level, while more detailed data are needed for proper calculations of financial impact and reconstruction capacity after a disaster.

Third, efforts are required to improve generally the coverage and availability of location information in granular databases, which is a prerequisite for the correct identification of physical risk. It is worth it to consider shifting to the reporting of addresses (or latitude/longitude information), where only regional information (postal code, NUTS regions) is provided.

Finally, this study covers firms, but could be expanded to the household sector. Households' exposure is rarely explored, and studies rely mostly on macro-level aggregates or surveys. To enable such analysis, access to credit registers covering loans to households, as well real estate registers including residential buildings, would be required; such data are currently available only in a few countries. Also, the government sector could be taken into consideration, in particular how damages to public infrastructure and state disaster relief impact government finances.

Closing the main data gaps listed here will considerably enhance climate risk analysis and allow for adequate policy responses. The European Central Bank is working, in cooperation with climate scientists, to further integrate climate and financial data sources to cover all three dimensions of physical risk—hazards, exposures, and vulnerability. More experience with geospatial tools and georeferencing the different internal databases would allow users to incorporate spatial aspects expanding economic analysis and research beyond climate statistics.

[38] For example, the European E-PRTR, or the Geoasset database by Spatial Finance Initiative.

[39] The need for additional information on foreign direct investment, multinational enterprises, and global value chains is mentioned in relation to carbon footprint reporting (for example, recommendation three of NGFS [2022]), but it is also relevant for the estimation of physical risk.

ANNEX 4.1

DESCRIPTION OF AVAILABLE DATA SOURCES

ANNEX TABLE 4.1.1.

Physical Hazard Data Sources			
Data Set	**Description**	**Hazards**	**Coverage**
IPCC	The Intergovernmental Panel on Climate Change (IPCC) provides information related to the evolution of the atmosphere (such as temperature and precipitation), oceans, and other variables, such as population density and anthropogenic carbon emissions. The projections are based on a set of simulation models and are available for different time horizons and scenarios on the possible developments of the anthropogenic drivers of climate change. The data collection is decentralized, involving various local climate institutions. Global IPCC data are also an input for more granular models.	Heat, precipitation, wind, frost, ocean, ozone, etc.	Global
WRI	The World Resources Institute (WRI) built the dynamic platform Resource Watch for historical, near-time, and projected climate- and natural resource–related data. To this end, a broad range of publicly accessible sources are employed. The platform includes not only temperature and weather data, but also data on forests, biodiversity, agriculture, and socioeconomics.	Numerous variables on natural hazards and resources, for example, water stress	Global
NASA/NCCS	NASA Center for Climate Services (NCCS) offers a large amount of climate model data and tools to visualize, analyze, and compare this data.	Atmospheric variables, fire data, etc.	USA/Global
JRC RDH	The Risk Data Hub (RDH) platform of the Disaster Risk Management Knowledge Centre (DRMKC) of the Joint Research Centre (JRC) gathers data on past natural disasters at different geographic levels (local, subnational, and national) and provides projections of their impact in terms of individual hazard intensities and frequency, economic damage, and human losses.	Flooding, subsidence, wildfire, landslides, earthquakes, etc.	Europe/Global
Copernicus	Copernicus is the European Union's Earth observation program. It offers information on land use and weather forecasts obtained by satellite information and in situ data. In the Climate Data Store, historical and predicted data on climate development is publicly available.	Climatic and weather data, windstorms, geospatial land use data, etc.	Europe
Four Twenty Seven/Moody's	The Four Twenty Seven data set available at the European Central Bank (ECB) covers climate hazard indicators for a sample of around 4 million companies worldwide from a global business register. The provider translated address information available in the sample to latitude and longitude, which were subsequently used to assign a hazard value from various climate models and climate projections, assuming the most pessimistic scenario of a model.	Earthquakes, floods, heat stress, hurricanes and typhoons, sea-level rise, water stress, wildfire	Global

ANNEX TABLE 4.1.2.

Public Data Sources Related to Vulnerability and Damages

Data Set	Description	Source	Coverage
DFO	The Dartmouth Flood Observatory (DFO) creates real-time maps of flooding events around the world. The lab, founded in 1993, uses satellite imagery to monitor changing water levels and is experimenting with other methods—such as using satellite-based microwave sensors—to track river levels.	Dartmouth Flood Observatory	Global
EDII/EDR	European Drought Reference (EDR) is a database designed to provide a single, publicly available site to disseminate detailed information about historical drought events in Europe. The European Drought Impact Report Inventory (EDII) was established for the purpose of cross-disciplinary research on drought vulnerability and risk. The information is obtained by reporting of countries, nongovernmental organizations, or personal observations.	European Drought Centre	Europe
EFFIS	The European Forest Fire Information System (EFFIS) supports the services in charge of the protection of forests against fires in the European Union and neighbor countries and provides services to the European Commission and the European Parliament, such as early fire warnings and reliable information on wildland fire extends in Europe.	Copernicus	Europe
EM-DAT	EM-DAT (Emergency Events Database) contains essential core data on the occurrence and effects of over 22,000 mass disasters in the world from 1900 to the present day. The database is compiled from various sources, including UN agencies, nongovernmental organizations, insurance companies, research institutes, and press agencies.	Centre for Research on the Epidemiology of Disasters (CRED)	Europe
EMSR	Information for emergency response and disaster risk management.	Copernicus	Europe
GLC	The Global Landslide Catalog (GLC) was developed with the goal of identifying rainfall-triggered landslide events around the world, regardless of size, impacts, or location. The GLC considers all types of mass movements triggered by rainfall, which have been reported in the media, disaster databases, scientific reports, or other sources. The GLC has been compiled since 2007 at NASA Goddard Space Flight Center.	NASA	Global
HANZE	The Historical Analysis of Natural Hazards in Europe (HANZE) database, contains two parts: (1) HANZE-Exposure with maps for 37 countries and territories from 1870 to 2020 in 100m resolution; and (2) HANZE-Events, a compilation of past disasters with information on dates, locations, and losses, currently limited to floods only.	Copernicus, Delft University of Technology	Europe
HARCI	The HARmonized grids of Critical Infrastructures in EUrope (HARCI-EU) data set represents major critical infrastructures in the transport, energy, industry, and social sectors expressed in sector-specific, economically relevant units. Critical infrastructures are assets, systems, or parts thereof that are essential for the maintenance of socioeconomic functions and the health, safety, and well-being of people.	Copernicus, JRC DRMKC	Europe
LRC	Landslide Reporter Catalog: The Cooperative Open Online Landslide Repository (COOLR) Project provides an open platform where scientists and citizen scientists around the world can share landslide reports to guide awareness of landslide hazards so as to improve scientific modeling and emergency response. All the data submitted is made available on the data portal Landslide Viewer, which shows referenced and imported landslide inventories from all over the world.	NASA	Global
NOAA	The National Centers for Environmental Information—with its divisions for tsunamis and earthquakes—is part of the National Oceanic and Atmospheric Administration (NOAA).	NASA	Global

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CHAPTER 5

Carbon Pricing Around the World

Joseph Pryor, Paolo Agnolucci, Carolyn Fischer, Dirk Heine, and Mariza Montes de Oca Leon

This chapter provides an overview of approaches for measuring carbon pricing. It summarizes World Bank indicators for tracking direct carbon pricing, including recent trends, as well as outlines the methodologies and limitations (https://carbonpricingdashboard.worldbank.org/). As direct carbon pricing is only a subset of what is needed for understanding the full incentives for consumption and production choices, the chapter also presents a framework and results for combining direct and indirect carbon pricing into a single metric of total carbon pricing. Preliminary analysis indicates that the scale of direct carbon pricing is dwarfed by that of indirect carbon pricing from energy taxes. Generally, direct and indirect carbon prices continue to fall short of what is required in terms of coverage and price, signaling the urgent need for more carbon pricing and higher prices globally.

INTRODUCTION

As the saying goes, "You can't manage what you don't measure." Managing the alignment of carbon pricing with the social costs of greenhouse gas (GHG) emissions requires the measurement and reporting of carbon pricing metrics. For almost two decades, the World Bank has measured and reported carbon prices applied by emissions trading systems and carbon taxes in its annual report on the State & Trends of Carbon Pricing ("State & Trends" hereafter).[1] This report emerged from the need to understand, collect, and standardize the measurement of carbon prices from the large number of emissions trading systems and carbon taxes following the introduction of the European Union Emissions Trading System in 2005.

Carbon pricing policy design differs significantly across jurisdictions, reflecting jurisdiction-specific characteristics and varied government policy objectives. This heterogeneity poses challenges for comparison and, therefore, requires methods for standardizing and aggregating carbon pricing efforts. Beyond facilitating the comparison and aggregation of jurisdiction data, a common framework is also necessary for understanding the extent to which economies are pricing the social cost of GHG emissions.[2] Such signals are critical to implement the *polluter pays principle*, leveling the playing field for clean alternatives and spurring conservation and innovation. Still, while these metrics are useful for tracking carbon pricing progress, they should not be interpreted as a measure of absolute ambition or mitigation efforts, and care should be taken when comparing across jurisdictions.

State & Trends has so far supported this by tracking three key metrics relating to carbon taxes and emissions trading systems: the carbon price in each jurisdiction, the amount of global carbon revenues collected, and the proportion of global GHG emissions covered by carbon taxes and emissions trading systems. Presently, this tracking effort involves collecting information on carbon pricing developments in almost 100 jurisdictions. The Carbon Pricing Dashboard, which has complemented the State & Trends since 2017, provides further data at the instrument level, which helps

[1] The predecessor of the current report, the States & Trends of the Carbon Market, had a stronger focus on market instruments under the United Nations Framework Convention on Climate Change.

[2] While this chapter focuses on GHG emissions, it is recognized that governments use pricing policies to address other (non-GHG) externalities, for example, road congestion and local air pollution.

assess the degree to which existing and emerging carbon taxes and emissions trading systems contribute to the alignment with the social cost of emissions.

However, a consensus is emerging that carbon taxes and emissions trading systems are only a fraction of the carbon costs imposed on carbon-intensive goods (Aldy and Pizer 2016; Carhart and others 2022; Dolphin, Pollitt, and Newbery 2020; OECD 2021). Other pricing policies, such as fuel taxes[3] and subsidies, can provide the same incentive delivered by emissions trading systems and carbon taxes, but in less direct ways. Accordingly, an exclusive focus on carbon taxes and emissions trading systems provides an incomplete picture of the broader price incentives within an economy. Further, failing to account for trends in these other pricing policies can result in arbitrary inclusions or exclusions, noting that governments may switch between policy instruments (for example, replacing existing "fuel taxes" with, or renaming as, "carbon taxes"). While broadening the scope of analysis poses challenges (for instance, information on the carbon price signal provided by these policy actions is more limited), it is critical to help understand and compare the carbon pricing incentives in place in different jurisdictions (such as for the use of carbon price floors).

Building on previous efforts (for example, Carhart and others 2022; Dolphin, Pollitt, and Newbery 2020; and OECD 2021), this chapter introduces a composite measure of carbon pricing called the total carbon price (TCP). The TCP is similar to, but broader than, the OECD's effective carbon rates. For example, the TCP accounts for the price signals provided by additional policies, such as fuel subsidies, and the impact of different value-added tax (VAT) rates within an economy (in addition to including carbon taxes, emissions trading, and fuel taxes). A key advantage of the TCP is that the methodology can deliver a TCP metric for a broader set of countries for every year since 1990.

This chapter is organized as follows. The next section summarizes a framework for categorizing climate mitigation policies and carbon pricing. The following section presents the World Bank's approach for tracking carbon pricing policies that offer a direct incentive to reduce GHG emissions. The subsequent section then explores the value of providing a more comprehensive carbon pricing metric by considering a broader set of carbon pricing instruments. The final section concludes.

A FRAMEWORK FOR CATEGORIZING CARBON PRICING

Pricing versus Nonpricing Policies

Identifying and understanding which climate policies should be categorized as carbon pricing is an important first step in trying to measure carbon pricing. A key feature of a "carbon pricing" policy is that it serves to align the costs of consuming carbon-intensive fuels or using carbon-intensive processes with the social costs of doing so. This chapter proposes a framework to categorize climate mitigation policies according to (1) whether the policy sets a pricing incentive, and (2) what market failure a policy is best suited to address.

Determining whether a policy sets a price incentive is based on whether it provides a continuous economic inducement not otherwise included in its market price that accounts for the social costs (or benefits) of a product or input. Nonpricing instruments fall into a broader category, which includes regulatory policies such as pollution control mandates, efficiency standards, public investment policies (where the government kickstarts the transformation via the provision of public goods), and policies addressing informational market failures, among others.[4]

Pricing policies can then be categorized based on the market failure they are primarily targeting. This chapter categorizes market failures into three groups: (1) unpriced carbon externalities; (2) information, behavioral, and financial barriers; and (3) technology market failures. When a pricing policy primarily addresses the unpriced carbon externality, it is referred to as a carbon pricing policy. However, while this chapter adopts this categorization, it is recognized that ultimately climate

[3] Fuel taxes are also referred to as energy taxes and fuel excise taxes.

[4] Additional detail is set out in Agnolucci and others (2022), including further dimensions.

policies sit on a continuum in how they contribute to the alignment with the social cost of emissions—from those primarily addressing the carbon externality (for example, emissions trading systems) to those primarily addressing technological, innovation, or behavior market failures (for instance, research and development subsidies), and also policies that from the outset address multiple market failures (for example, subsidies for electric vehicles).

Climate policies that do not provide a price incentive and do not primarily address the unpriced carbon externality do not easily translate into a clear carbon price and should not be categorized as carbon pricing. This classification is irrespective of the stated objective of the policy. Common examples are policies that subsidize or create markets for clean technologies; although they may be motivated in part by unpriced carbon externalities (for example, adjusting the *relative* costs of alternative technologies) they do not contribute to *absolute* carbon cost alignment for emitting technologies and behaviors, and they are better placed to address technology market failures and barriers.

These other policies are complementary to carbon pricing (Fischer and others 2012; Fischer and Newell 2008),[5] as they can address other market failures that carbon pricing is unable to address directly.[6] In fact, categorizing these policies as carbon pricing undervalues the critical role of complementary policies in decarbonization—they can unlock abatement options and improve the effectiveness and efficiency of carbon pricing. For example, the availability of good public transport systems can significantly increase the price elasticity of transport emissions (Avner, Rentschler, and Hallegatte 2014). Thus, they are required *in addition to* carbon pricing and are critical complements to decarbonize economies.[7] These may themselves be price-based policies (like feed-in tariffs or renewable subsidies) or nonprice policies (such as fuel efficiency standards, infrastructure investment for innovation, or mandates for the use or phase-out of specific technologies) (Acworth and others 2017; Jaffe, Newell, and Stavins 2004; Stern, Stiglitz, and Taylor 2022). Figure 5.1 provides a simplified representation of the classification approach.

Types of Carbon Pricing

Governments price carbon using a variety of instruments, which can be tailored to domestic circumstances. The climate impact of carbon pricing depends on a range of factors, including how broadly the price is applied, the price level and stability, the availability of abatement opportunities, and the extent to which the price signal is passed through the supply chain.

Direct Carbon Pricing

"Direct carbon pricing" refers to carbon pricing instruments that apply a price incentive directly in proportion to the GHG emissions generated by a given product or activity. By applying the same price per metric ton of carbon dioxide equivalent (CO_2e) across multiple sources, direct carbon pricing contributes to equalizing marginal abatement costs across emissions sources, resulting in cost-efficient climate change mitigation. In this chapter, direct carbon pricing includes carbon taxes and emissions trading systems (see World Bank [2022a] for more detailed descriptions).

Indirect Carbon Pricing

In line with the framework set out in the "Pricing versus Nonpricing Policies" section, this chapter defines indirect carbon pricing as instruments that change the price of carbon-intensive inputs[8] in ways

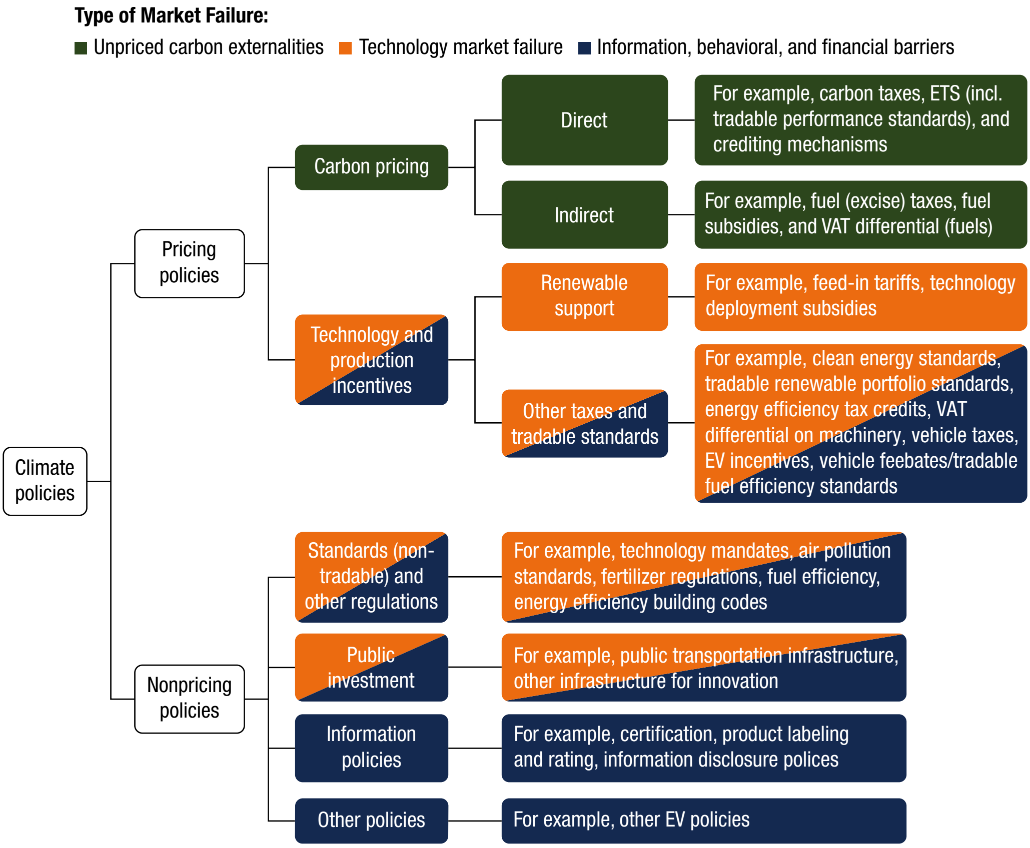
[5] Yet, in a second-best world of underpriced emissions, these policies are implemented as substitutes in many countries, which comes at an efficiency cost.

[6] While carbon pricing also creates incentives to adopt greener technologies, it is less able to directly address behavioral and financial barriers or deeper technology market failures.

[7] Depending on specific policy design, some policies might overlap and therefore be substitutes, rather than complements.

[8] While carbon-intensive inputs extend to a range of goods, this chapter focuses on fossil fuels, which are responsible for a large share of emissions and have a fixed relationship with GHG emissions (that is, proportional to the carbon content of the fuel).

Figure 5.1. Classification of Climate Mitigation Policies



Source: Authors.
Note: ETS = emissions trading system; EV = electric vehicle; VAT = value-added tax.

that may not be directly proportional to those emissions and thus vary across covered sources of GHGs, such as fuel type. Since these instruments change both the absolute and relative prices, they provide a carbon price signal, even though they are often (primarily) adopted for other socioeconomic objectives, such as raising revenue or addressing air pollution (Parry, Veung, and Heine 2015). The most important examples of indirect carbon pricing include consumption taxes and subsidies on fossil fuels.[9]

Even though the core difference between direct and indirect carbon prices relates to whether the price is proportional to emissions (Box 5.1), these differences have been less stark in practice. At one end of the spectrum would be a direct carbon pricing system that treats all emissions equally (that is, identical carbon price) across the entire economy. At the other end would be a set of fuel taxation systems that price fuels or activities at different rates (for example, combustion of fuel used for road transportation compared to industrial applications). Most jurisdictions with carbon prices sit in the middle of this spectrum. This includes jurisdictions with direct carbon pricing policies that apply different policy designs across different sectors or groups in the economy, such as in the coverage and/or price applied (for example, explicitly through different carbon tax rates or implicitly through differences in free allowance allocations). For example, Argentina and Mexico have introduced carbon taxes with varying carbon tax rates across fuels, independent of the carbon content of each fuel. This means that one ton of carbon dioxide (CO_2) is taxed at different rates if it originated from, say, gasoline rather

[9] Fuel taxes that apply a flat tax amount to gasoline per liter indirectly place a price on the carbon emissions from the gasoline's combustion. Inversely, fuel subsidies that reduce the price of fossil fuels create a "negative" indirect carbon price signal, which incentivizes higher consumption and therefore increases carbon emissions.

Box 5.1. The Case for Proportionality: Pricing Carbon-Intensive Goods in Proportion to Their Emissions

Carbon pricing aims to minimize abatement costs by internalizing the social cost of emissions. To achieve this, countries should aim to price goods in proportion to emissions.

Greenhouse gas (GHG) emissions' costs to society are largely independent of where and through which activity emissions are released into the atmosphere. This means that in theory all emissions within an economy should be priced the same. For economists, this principle is enshrined in the core of welfare economics, first proposed by Adam Smith (1759, section 2.2.2; 1776, section 1.4) and later formalized by Cecile Pigou (1932). For lawyers, the principle is enshrined in tort law—the idea that damages caused to third parties should be compensated proportionately is supported by most countries' legal systems and international law. In 1992, all countries agreed on the *polluter pays principle* to price goods for their environmental damage (Rio Declaration, Principle 16).

Abatement costs typically increase with higher levels of abatement and vary between market participants. Accordingly, the economy-wide cost of achieving a mitigation target can be minimized if each market participant undertakes mitigation actions until their marginal abatement costs (rather than the amount of abatement) equalize. Creating market incentives for this outcome requires setting the same carbon price for emissions from all market participants within the jurisdiction.

To promote consistency in how social costs are internalized and therefore to minimize abatement costs, countries should generally strive to price emissions equally across all emissions sources. Over time, countries should endeavor to transition to systems that price products and/or activities in proportion to the GHG emissions generated (that is, improve "proportionality")—in other words, move from indirect to direct carbon pricing and improve proportionality in direct carbon pricing instruments (for example, reduce exemptions to specific sectors or user groups).

than coal. While governments may call these policies carbon taxes, they are closer to the definition of indirect carbon pricing, due to the nonuniform carbon prices across fuels. In these cases, the overall carbon price is not directly proportional to emissions. This spectrum of how policies are designed and implemented underscores the need to include both direct and indirect pricing in a comprehensive framework (see "Total Carbon Pricing: Looking Beyond Direct Carbon Pricing" section).

MEASURING DIRECT CARBON PRICING

This section summarizes the methodologies used for the main indicators and metrics for direct carbon pricing instruments included in the World Bank's report State & Trends of Carbon Pricing 2022. Up-to-date information can be accessed through the Carbon Pricing Dashboard.

Key Indicators and Methods

Carbon Price

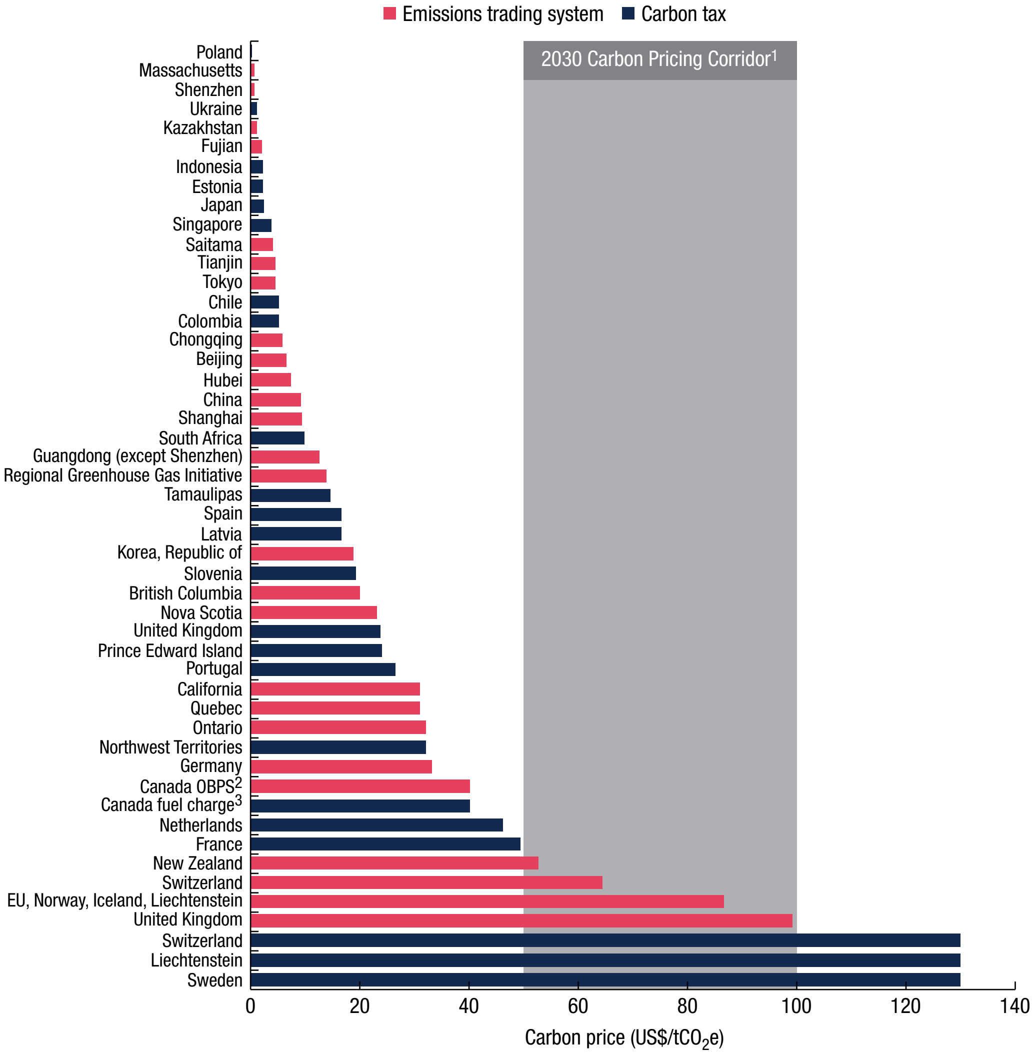
State & Trends reports annual nominal carbon prices for each carbon tax and emissions trading system in US dollars (US$) per metric ton of carbon dioxide equivalent. To promote consistency across years, the World Bank collects price data to reflect the nominal price applicable on April 1.[10] To allow comparability across jurisdictions, carbon prices are converted to US$ equivalents using market exchange rates, rather than purchasing power parities (PPPs).[11]

In 2021 and early 2022, carbon prices hit record highs in many jurisdictions, including California, Canada, the European Union (EU), New Zealand, and Switzerland. Several countries,

[10] Other analyses, such as International Carbon Action Partnership (ICAP 2022), estimate an average carbon price across a calendar year. This smooths out extremes, which has benefits and limitations. While there is no optimal date, April 1 provides advantages because it captures any rate changes that take effect from the beginning of a calendar year (January 1), as is the case in Europe and Latin America, as well as those commencing on April 1 (for example, Canada, Japan, Singapore, and South Africa).

[11] Market exchange rates are taken from the IMF exchange rates for April 1 (IMF 2022). While PPPs reflect actual income levels across countries (Blanchet 2017), market exchange rates allow for a transparent approach that is easily replicable and often preferred when trying to compare carbon prices across countries (Weil 2020).

Figure 5.2. Direct Carbon Prices per Jurisdiction and Instrument as of April 1, 2022



Source: World Bank (2022a).

Note: Includes nominal prices on April 1, 2022, for direct carbon pricing instruments with a positive value (that is, not zero). Only includes carbon taxes with a single carbon tax rate that is applied across multiple fuels. Prices are not necessarily comparable between instruments because of (for example) differences in the sectors covered and allocation methods applied, specific exemptions, and compensation methods. Carbon price on the *y*-axis is expressed in US$ per metric ton of carbon dioxide equivalent (tCO_2e).

[1] The 2030 carbon price corridor is based on the recommendations in the report of the High-Level Commission on Carbon Prices.

[2] Canada Output-Based Pricing System includes federal and provincial equivalent policies (Alerta, New Brunkswick, Newfoundland and Labrador, and Saskatchewan). The price reflects the excess emissions charge, which effectively acts as a price cap.

[3] Canada fuel charge includes federal and provincial equivalents (British Columbia, New Brunswick, and Newfoundland and Labrador).

including Canada, Ireland, Singapore, and South Africa, have also established more ambitious price trajectories for the coming years. However, less than 4 percent of global emissions are currently covered by a direct carbon price in the range needed by 2030, indicating a need for higher prices in addition to greater uptake of carbon pricing (see Figure 5.2).[12]

[12] The High-Level Commission on Carbon Prices (2017) identified a US$50–100/tons of CO_2e price range needed by 2030 to keep global warming to below 2°C.

During 2021, the EU emissions trading system—the largest such system by traded value—saw record trading activity and prices in both spot and futures markets. The year 2021 also saw China's National Emissions Trading System[13]—the largest such system by emissions coverage—complete its first compliance year.

Adopting ambitious carbon prices remains politically challenging, even more so following recent inflation and energy shocks. These developments have resulted in governments reconsidering the timing and ambition reflected in domestic carbon prices. For example, Indonesia announced a delay in the introduction of its carbon tax due to concerns over high energy prices (Yulismanm 2022), Mexico announced exemptions to the carbon tax applied to gasoline and diesel (Milenio 2022), and Austria suspended the application of its emissions trading system (Ministry of Finance 2022). But, as price pressures abate, opportunities should emerge to accelerate implementation of carbon pricing.

Direct Carbon Pricing Revenue

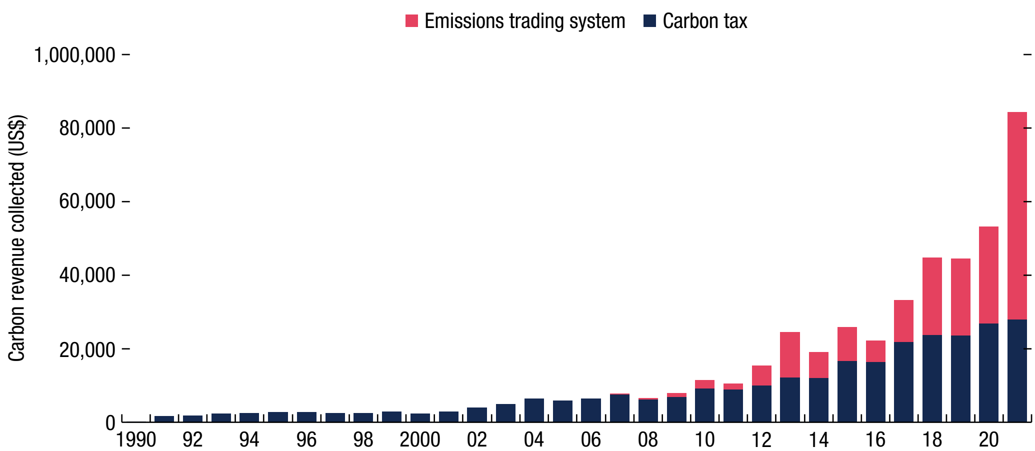
Carbon pricing revenue is defined as government proceeds from (direct) carbon tax collections and emissions trading system allowance auctions. It therefore does not include the value of exempted emissions or freely allocated emissions trading system allowances. In State & Trends, nominal carbon revenue estimates are collected and reported by calendar year, adjusting for jurisdictions with fiscal years that do not align with calendar years. Revenue is converted to US$ using market exchange rates on April 1.

Driven by higher carbon prices, global carbon pricing revenue in 2021 increased by almost 60 percent from 2020 levels, to around US$84 billion. Furthermore, for the first time, emissions trading system revenue surpassed carbon tax revenue, largely due to emissions trading system prices rising by more than carbon taxes, as well as the commencement of new such systems and increased auctioning in some jurisdictions (Figure 5.3).

Global Coverage

In addition to tracking jurisdiction-specific carbon pricing metrics (for example, price and revenue), State & Trends estimates the proportion of global GHG emissions covered by a carbon price. As of

Figure 5.3. Evolution of Global Direct Carbon Pricing Revenue



Source: World Bank (2022a).

[13] The China National Emissions Trading System is an emissions intensity–based system with ex post adjustments made to the emissions cap based on actual production levels; that is, it effectively operates as a tradeable performance standard, where each generation type has a separate standard or benchmark.

April 2022, approximately 23 percent of total global GHG emissions were covered by a direct carbon price. Global GHG coverage is estimated by taking the sum of emissions covered by each carbon tax or emissions trading system,[14] less the sum of emissions covered by multiple carbon price instruments, to account for overlapping instruments. The three underpinning components are as follows:

- **GHG emissions**: To promote consistency across countries, national GHG emissions are taken from the Emissions Database for Global Atmospheric Research (EDGAR) (Crippa and others 2021). GHG emissions estimates for subnational jurisdictions are taken from official sources. For example, GHG emissions values for Canadian provinces and territories are taken from Canada's submission to the UN Framework Convention on Climate Change (UNFCCC).
- **Coverage**: The proportion of a jurisdiction's GHG emissions covered by a carbon price reflects (in aggregate) how a carbon price is applied within an economy. For example, it reflects if a carbon price is applied to specific fuels, activities, or sectors, and/or if the carbon price has emissions participation thresholds (for example, obligations under the Korea Emissions Trading System apply to companies emitting more than 125,000 tCO_2/year, and facility emissions in excess of 25,000 tCO_2/year). Design aspects that reduce the carbon price applied to emissions from specific fuels or activities reduce the incentive applied within an economy but do not affect the global coverage assessment.[15]
- **Overlap**: Overlaps occur when multiple carbon pricing instruments apply to the same activities/fuels in the same jurisdiction. This can happen where a government introduces multiple instruments (see Box 5.2). It can also occur if regional (for example, multistate mechanisms such as the EU Emissions Trading System) or subnational governments introduce an instrument in addition to a national government's instrument. For example, the EU Emissions Trading System applies to fuels used at installations that are also covered by carbon taxes introduced by a subset of EU Member States. The amount of overlap is estimated by (or in consultation with) affected jurisdictions.

Box 5.2. Estimating Overlap for Mexico: A Simplified Example

Mexico has two national carbon pricing instruments.[1] Its carbon tax covers all fuels other than natural gas, equating to approximately 45 percent of national greenhouse gas (GHG) emissions.[2] Mexico also has a pilot emissions trading system,[3] which applies to carbon dioxide (CO_2) emissions from facilities with annual direct emissions greater than 100,000 tons of CO_2. This represents approximately 40 percent of national GHG emissions (ICAP 2022).

These two instruments overlap, in that solid and liquid fuels combusted at large facilities are covered by both the emissions trading system and the carbon tax. World Bank estimates that the proportion of emissions covered by both instruments (that is, the overlap) is around 22 percent of national GHG emissions.[2] Therefore, the proportion of Mexico's emissions covered by direct carbon prices is approximately 63 percent of national GHG emissions (45 percent plus 40 percent minus 22 percent). See the Carbon Pricing Dashboard for further information on Mexico's carbon pricing instruments.

[1] For simplicity, this example does not investigate overlap with subnational instruments.

[2] Based on GHG emissions contributions of specific fuels and sectors using data from International Energy Agency and Oak Ridge National Laboratory obtained from World Development Indicators (World Bank 2022b).

[3] While the emissions trading system pilot is currently in operation, its design does not impose economic costs on facilities (that is, the carbon price is US$0).

[14] The emissions covered by a carbon pricing instrument are based on official government estimates. Where this is not available, the World Bank estimates this value in consultation with government officials.

[15] To date, collected data do not encompass comprehensive estimates of GHG emissions covered by each specific carbon tax rate (for example, covered GHG emissions by each fuel).

Limitations of Direct Carbon Pricing Metrics

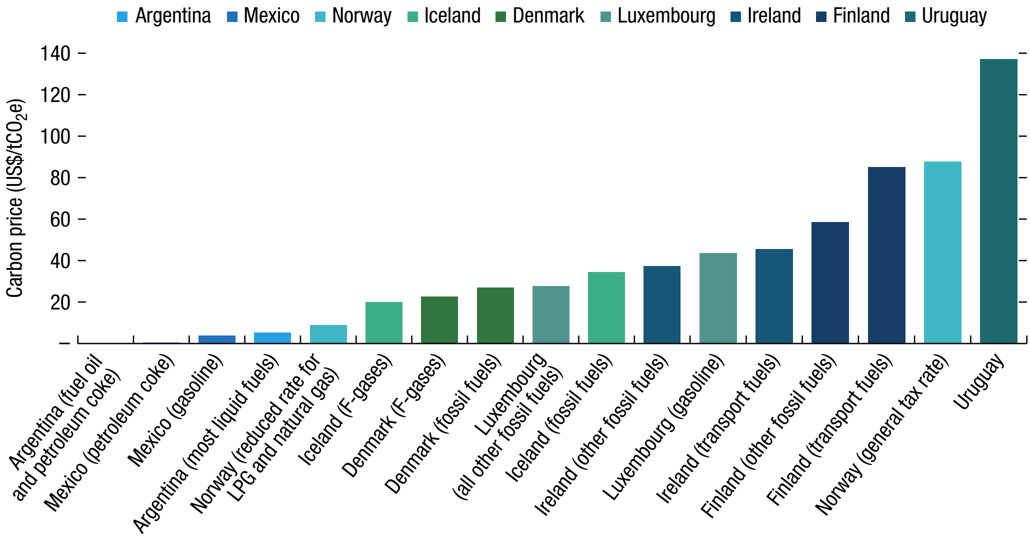
Direct carbon pricing metrics are useful for tracking carbon pricing progress. However, carbon pricing metrics are not well suited for comparing mitigation ambition or effort across jurisdictions (Aldy and Pizer 2016). For example, the level of a carbon price does not account for jurisdiction-specific characteristics, such as access to low-cost abatement options. This means that an identical carbon price applied in different jurisdictions may lead to different impacts on emissions and the economy, depending on local conditions (Productivity Commission 2011). Furthermore, direct carbon pricing metrics do not measure the existence of, or effort applied by, non-price-based policies (which in some jurisdictions represent larger efforts and costs than price-based policies). Accordingly, carbon pricing metrics should be interpreted as what they state: the extent to which the social cost per unit of emissions is internalized in the market prices of the polluting goods.

Another challenge relates to the need to improve the understanding of how carbon prices are applied to embodied emissions, since many direct carbon pricing policies offer free allocation or rebates that can mute the pricing of embodied carbon. The current State & Trends framework focuses on the *marginal* direct carbon price (that is, the legislated carbon tax rate or the emissions trading system permit price paid for allowances). Further data are needed to evaluate the *average* direct carbon price (that is, the price associated with embodied emissions that accounts for free allocation, rebates, and other measures that reduce the average cost burden of carbon pricing). Such data will help determine, for example, the carbon prices paid at the source for a product subject to a carbon border adjustment mechanism, which is designed to adjust for embodied carbon pricing.

Lastly, focusing exclusively on direct carbon pricing provides an incomplete picture of the broader price incentives within an economy. Applying a broader framework to include indirect carbon pricing policies also avoids the potential to arbitrarily include or exclude policies based on definitional nuances or subjective stated policy intents. For example, when Sweden introduced its carbon tax in 1991, it simultaneously reformed and reduced fuel taxes by 50 percent. Similarly, when Uruguay introduced its carbon tax in 2022, it simultaneously reduced its fuel tax on gasoline (Administración Nacional de Combustibles 2021). Uruguay's case stands out, as a carbon tax levied exclusively on gasoline reduces the proportionality of emissions pricing (see Box 5.1), and the motivation for introducing the carbon tax was to (among other things) improve Uruguay's international image and help manage future implications of the EU's Carbon Border Adjustment Mechanism (Government of Uruguay 2020). Figure 5.4 summarizes the carbon prices in carbon taxes that apply multiple rates across fuels, noting that Uruguay applies US$0 to all fuels other than gasoline.

In some cases, omitting indirect carbon prices can mask the true price incentive underpinning carbon-intensive activities. For example, Mexico went from subsidizing carbon emissions (via phasing out consumption subsidies on gasoline and diesel) to the extent of 1.8 percent of GDP in 2008 to positive carbon pricing (via fuel taxes and carbon taxes), generating revenue equivalent to 1.6 percent of GDP in 2018 (Muñoz-Piña, Montes de Oca, and Rivera 2022). These reforms resulted in Mexico achieving its nationally determined contribution for the transportation sector, with around one-third of the emissions reductions delivered by phasing out fossil fuel subsidies (Muñoz-Piña, Montes de Oca, and Rivera 2022). This achievement would not be as transparent if direct and indirect carbon prices were viewed in isolation. Similarly, omitting indirect pricing can also overestimate (or underestimate) the underlying carbon price. For example, Indonesia is planning to introduce a carbon tax on coal-fired power stations in 2022 (World Bank 2022a), yet in May 2022 the parliament approved an increase to energy subsidies by about $23.8 billion, or approximately 2 percent of GDP (Reuters 2022). In such examples, direct carbon pricing metrics would overestimate the extent of the carbon price incentive. The next section presents an approach to provide a more comprehensive view of carbon pricing that includes both direct and indirect carbon prices.

Figure 5.4 Carbon Taxes in Jurisdictions That Apply Multiple Carbon Tax Rates (Rates as of April 1, 2022)



Source: World Bank (2022a).
Note: Carbon price on the *y*-axis is expressed in US$ per metric ton of carbon dioxide equivalent (tCO_2e). LPG = liquid petroleum gas.

TOTAL CARBON PRICING: LOOKING BEYOND DIRECT CARBON PRICING

An integrated view of a jurisdiction's direct and indirect carbon prices presents a more comprehensive picture of progress toward reflecting the social costs of GHG emissions in market prices. It also recognizes the interaction between direct and indirect carbon prices. This is particularly important when positive and negative carbon pricing coexist and affect the mitigation incentive in different directions. Treating direct and indirect carbon pricing policies separately can obfuscate the overall size of price changes.

Measuring Total Carbon Pricing

Agnolucci and others (2022) elaborate the concept of a "total carbon price" that combines direct carbon prices and indirect carbon prices to provide a more comprehensive estimate of the full price signal affecting the combustion of CO_2-emitting fuels. The direct component is a weighted sum of emissions trading system permit (allowance) prices and carbon tax rates, where the weights represent shares of emissions covered by each instrument. The indirect component is the emissions-weighted sum of indirect carbon pricing policies (that is, those that change the marginal carbon price incentive). The TCP is summarized in the following conceptual formula:

Total carbon price = Direct carbon price (emissions trading systems and carbon taxes) + fossil fuel taxation – fossil fuel subsidies – value-added tax deviations

The TCP is a comprehensive metric summarizing the net effect across a combination of pricing measures and can be readily applied to both developed and developing countries. In this way, the TCP is intended to help policymakers, academics, and other stakeholders understand the underpinning price incentives and what is driving progress, as well as to identify whether additional pricing opportunities or internal policy contradictions exist.

TABLE 5.1.

Comparison of TCP and OECD's ECR[1]		
Metric	**OECD's Effective Carbon Rates**	**Total Carbon Price**
Formula	Direct carbon price + fossil fuel taxation	Direct carbon price + fossil fuel taxation – fossil fuel subsidies – value-added tax deviations
Country coverage	44 OECD and G20 countries and an average of those countries	142 countries individually and aggregated[2]
Methodology	Review of statutory tax rates and observed carbon prices	Direct carbon price: Collection of primary data from government sources Indirect carbon price: Price-gap methodology to infer the net taxes or subsidies
Period coverage	Limited to more recent years, including 2012, 2015, and 2018 (for example, the 2021 publication reports the effective carbon rates for 2018).	1990–2021

Source: Authors, based on OECD (2021) and Agnolucci and others (2022).
Note: ECR = effective carbon rates; G20 = Group of Twenty; OECD = Organisation for Economic Co-operation and Development; TCP = total carbon price.

[1] According to the 2021 effective carbon rates (OECD 2021).
[2] Value-added tax deviations accounts for situations where value-added tax rates on fossil fuels are below the standard value-added tax rate applied to other goods in the economy, thereby promoting their use.

The TCP builds on existing efforts to create a comprehensive metric, including Aldy and Pizer (2016), Carhart and others (2022), Dolphin's emissions-weighted carbon price (Dolphin, Pollitt, and Newbery 2020; Dolphin and Xiahou 2022), and the OECD's effective carbon rates (OECD 2021). While it has some important similarities with the OECD's effective carbon rates, the TCP also has an important added value in terms of country, policy, and period coverage (see Table 5.1).

Direct carbon pricing data is taken from State & Trends. Indirect carbon pricing data is more difficult to obtain because it requires information relating to multiple tax arrangements in countries with varying degrees of transparency. For this reason, under the presented TCP estimation, fuel taxes and consumption subsidies are not observed directly, but rather are estimated using the *price-gap methodology*. The current estimation serves as proof of concept of the TCP, however the estimates should be interpreted with care. This approach differs from the OECD's effective carbon rates, which uses statutory-based (and effective) tax rate data. Applying the price-gap methodology allows the TCP to be estimated for all countries, including countries where data on taxes and subsidies are less readily available (especially lower-income countries). The price-gap methodology uses differences between the retail price and supply costs (for each fuel used in a specific sector, country, and year) to infer the existence of a net tax or subsidy (in theory, the retail price of a fuel should equal the supply costs plus all relevant taxes). Supply costs smaller than retail prices reflect the existence of positive net taxes (after subtracting value-added tax payments and upstream carbon prices). Indirect carbon pricing measurements are based on Parry, Black, and Roaf (2021) as recompiled for the Climate Policy Assessment Tool—a joint IMF-World Bank tool (IMF-World Bank 2022).[16] Supply costs higher than retail prices reflect a net energy subsidy. The TCP methodology facilitates estimation of the net tax (or subsidy) for a specific country, sector (within or across countries), and fuel (within or across countries). This allows, for example, the TCP to identify where a specific fuel has a net tax, even where other fuels may have net subsidies.

The TCP metric can be used at different levels: firm, sector, fuel, country, region, and global. Thus, it can help identify pricing opportunities by estimating the pricing gap in specific sectors or fuels. For example, one can compare the TCP on natural gas in the residential (households) and

[16] Further data employed includes consumption data taken from International Energy Agency (IEA) energy balances (IEA 2022), also compiled for IMF-WB (2022), and CO_2 emissions factors obtained from the International Institute for Applied Systems Analysis (IIASA) Greenhouse Gas–Air Pollution Interactions and Synergies (GAINS) model for CPAT (Wagner and others 2020).

industrial sectors. This allows for a comparison of burden sharing of carbon pricing (not mitigation efforts) across different agents in the economy.

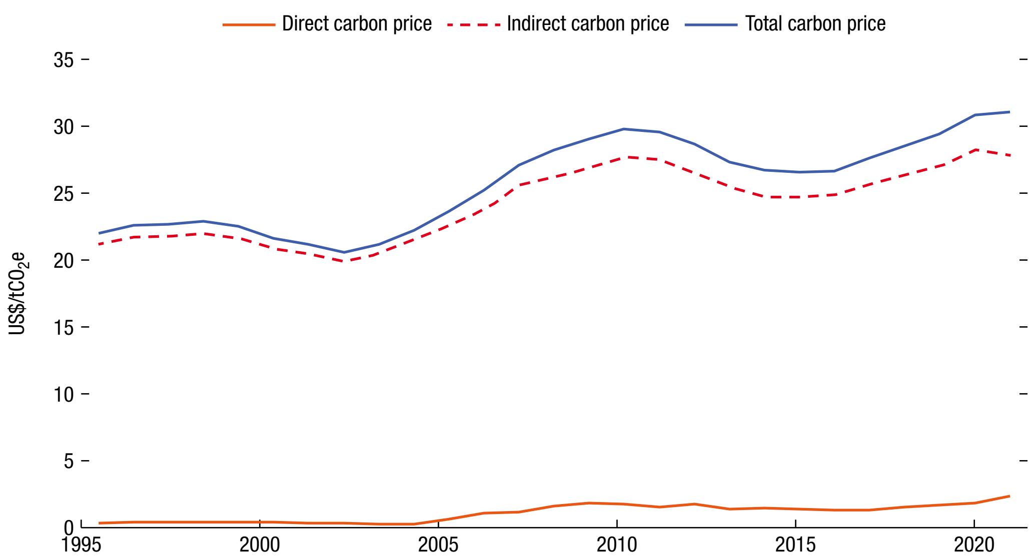
Uses and Global Trends for Total Carbon Prices

Agnolucci and others (2022) estimate the TCP for over 140 countries and a global TCP from 1990 to 2021. This preliminary analysis indicates that the scale of direct carbon pricing instruments is dwarfed by that of indirect measures from energy taxes and subsidies (see Figure 5.5). Consequently, the TCP trend is strongly driven by the evolution of indirect prices, which have increased since the early 2000s. Figure 5.6 highlights that the TCP in the transport sector is significantly higher than that in other sectors. This emphasizes potential opportunities to broaden the application and increase the stringency of carbon pricing instruments to access lower cost abatement in nontransport sectors.

Disaggregating the TCP into its components also provides insights into where opportunities and gaps exist. For example, in 2021, over 80 percent of the global TCP came from indirect price components (primarily fuel taxes). The widespread nature of indirect forms of carbon pricing reveals the potential to leverage them to promote carbon cost alignment and move toward greater proportionality of the existing instruments (see Box 5.1). It also suggests that many countries, including developing countries, already have experience with pricing carbon and have systems in place that can be used to expand carbon pricing. Although preliminary, this analysis suggests similar trends and messages (although different absolute values) to other comparable analyses, including OECD's effective carbon rates.

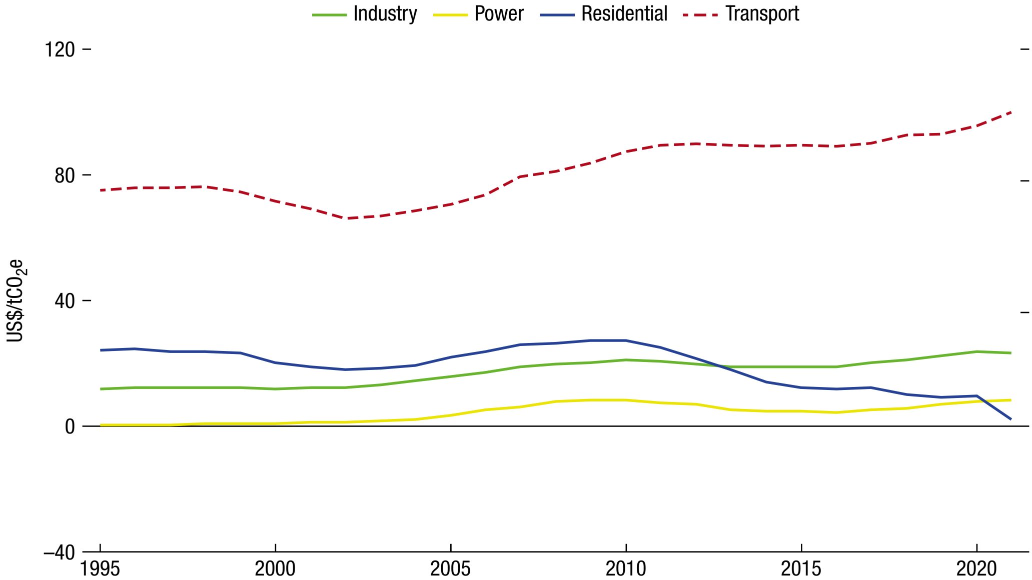
Comprehensive metrics, such as the TCP, have the potential to offer insights that are not visible through a direct carbon pricing lens. Yet, similar to direct metrics, the TCP is also not intended to be a measure of climate mitigation ambition. Further, the higher carbon prices reflected in the TCP (compared to direct carbon pricing metrics) are a function of its broader scope. This broader view

Figure 5.5. Total Carbon Price and Its Components (Globally), Five-Year Moving Average



Source: Agnolucci and others (2022).
Note: Carbon price on the *y*-axis is expressed in US$ per metric ton of carbon dioxide equivalent (tCO_2e). A five-year moving average is used to highlight the trends and remove price volatility caused by the price-gap methodology.

Figure 5.6. Total Carbon Price Across Sectors, Five-Year Moving Average



Source: Agnolucci and others (2022).
Note: Carbon price on the *y*-axis is expressed in US$ per metric ton of carbon dioxide equivalent (tCO_2e). A five-year moving average is used to highlight the trends and remove price volatility caused by the price-gap methodology.

provides additional insights on where gaps and opportunities exist, including identifying priority sectors and fuels for more ambitious carbon pricing.

CONCLUSION

Measuring carbon pricing is necessary to understand the incentives all economic actors face to reduce GHG emissions, particularly from using fossil fuels. Just as the number and global coverage of carbon pricing instruments have increased over the last decade, so has the recognition that a broader set of pricing policies can provide a signal to incentivize emissions reductions. This is reflected by the growing interest and number of contributions in the literature highlighting that carbon pricing is implemented in various forms, directly, such as through emissions trading systems or carbon taxes, and indirectly through other pricing instruments, such as fuel taxes and fossil fuel subsidies.

This chapter provides a framework for measuring carbon pricing, using the metrics and indicators in the World Bank's State & Trends of Carbon Pricing and Carbon Pricing Dashboard as a starting point. While these metrics are important, they are a subset of what is needed for understanding the full incentives influencing consumption and production choices. Accordingly, direct carbon pricing metrics should be complemented with total carbon pricing metrics.

The proposed metrics represent one possible approach to providing an indication of the status and development of carbon pricing incentives and trends. At the same time, these direct, indirect, and total carbon pricing metrics should not be viewed as measures of ambition or mitigation effort across jurisdictions, which would need to include the much larger range of climate policies that are implemented across the world. Rather, these metrics provide useful insights to help us understand the extent to which economies are pricing the social cost of emissions. Ultimately, a combination of metrics, including but going beyond pricing metrics, is needed to understand how countries are responding to the climate mitigation challenge.

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CHAPTER 6

Measuring Fossil Fuel Subsidies—A Global and Country View

Ian Parry, Simon Black, and Nate Vernon

This chapter describes a methodology for measuring fossil fuel subsidies at the global and country level and quantifies the impacts of reform. Subsidies are defined broadly to include undercharging for supply costs (explicit subsidies) plus general consumer taxes and environmental costs (implicit subsidies). The approach involves an extensive compilation of country-level data on sectoral fuel consumption; fuel prices; supply costs; climate, local air pollution, and broader externalities associated with fuel use; and general consumer taxes. A spreadsheet tool for estimating the environmental, fiscal, and economic impacts of fuel-price reform is also briefly discussed.[1]

INTRODUCTION

Getting fossil fuel prices correct is critical for efficiently allocating an economy's scarce resources and investments across sectors and activities. The right price is the socially efficient price that reflects the full societal costs of fuel use. This includes not only the private costs to supply fuels (for example, labor, capital, and raw materials), but also the environmental costs—including global warming—from emissions of carbon dioxide (CO_2), premature deaths from local air pollution, and broader externalities associated with fuel use (for example, road congestion)—and general consumption taxes as applied to other household products. Underpricing of fossil fuels not only undermines domestic and global environmental objectives, but it also has a sizable fiscal cost, while being a highly inefficient way to help low-income households, since most of the benefits accrue to wealthy households (for instance, Coady and others 2015).

The underpricing of fuels as well as their corresponding subsidies are useful metrics for gauging fuel-price reform priorities across fuels, sectors, and countries. Subsidies reflect both the degree of underpricing for a fuel and the consumption to which it applies. For example, subsidy reform may be more of a priority for a fuel with a wide consumption base, even though the degree of underpricing per unit of fuel may be less than that for a fuel with a small base. More targeted instruments can more efficiently address some of the environmental costs. If there are administrative and institutional constraints to implementing targeted instruments however, raising fuel prices provides a "second-best" response and, moreover, may be combined with other measures to better mimic the effects of targeted instruments.[2]

[1] This chapter draws from Parry, Black, and Vernon (2021), an IMF Working Paper that provides detailed estimates for 191 countries (www.imf.org/en/Publications/WP/Issues/2021/09/23/Still-Not-Getting-Energy-Prices-Right-A-Global-and-Country-Update-of-Fossil-Fuel-Subsidies-466004). Country and global estimates are featured in the IMF's *Climate Indicators Dashboard* (https://climatedata.imf.org).

[2] For example, a "first-best" response to reduce local air pollution emissions from coal plants would be to directly tax the emissions, as this would promote the use of end-of-pipe abatement technologies as well as encourage switching from coal to other fuels. Institutional capacity constraints (for example, for monitoring emissions) may, however, limit the viability of emissions fees. Coal taxes by themselves promote only switching to other fuels, but they can be combined with rebates for coal plants with abatement technologies.

Still, reforming energy subsidies can be politically difficult at any time, not least because raising energy prices can make governments unpopular with households and firms. It may be especially challenging while fuel prices are high in the wake of the war in Ukraine. Indeed, governments have been taking measures to prevent the full passthrough of higher international prices into retail prices (Celasun and others 2022). Nonetheless, understanding efficient fuel prices and the extent of energy subsidies remains important for several reasons:

- The price surge, at least in part, is likely to recede as demand and supply adjust over the medium term. As international prices decline, it will provide an opportunity to lock in domestic fuel-price reform without an increase in price levels relative to recent levels.
- Achieving environmental objectives cost-effectively requires a robust price on carbon emissions and other environmental externalities to level the playing field between clean and other investments.
- Country-level experiences with subsidy reform suggest there are strategies for enhancing the acceptability of fuel-price reform, from recycling revenue in ways to promote efficiency and distributional objectives, to providing targeted assistance to vulnerable groups, as well as outreach to stakeholders and the public to garner support.
- Comprehensive policy approaches can involve a mix of fuel-price reform and nonpricing measures, where the latter are less efficient but avoid politically difficult increases in energy prices.[3] Understanding the efficient set of fuel prices provides a benchmark for comparing other approaches and informs policymakers of tradeoffs.

This chapter describes a practical methodology for comparing current fuel prices with their efficient levels and quantifying fuel subsidies, both narrowly and broadly defined to reflect undercharging for supply costs and social costs, respectively. The methodology, which has been developed and refined by International Monetary Fund (IMF) staff over the last decade, applies on a country-by-country basis for 191 countries and for fuels used in the power, industrial, residential, and transport sectors (see Coady and others [2015, 2019]; Parry, Black, and Vernon [2021]). The country-level results are available on the IMF website, while additional data on fuel use and parameters underlying environmental costs are available from the Climate Policy Assessment Tool (CPAT) and other sources described later.[4,5]

The chapter is organized as follows. First, there is a brief conceptual discussion of efficient fuel prices and energy subsidies. Then, there is a discussion of the methodologies and tools used for quantifying efficient prices and subsidies and the impacts of reform. Next, key results are presented at the global and country levels. Finally, there is a conclusion.

Defining Efficient Fuel Prices and Subsidies

Efficient Fuel Prices

The efficient price of a fossil fuel product is given by:

$$\left[\left(unit\ supply\ cost\right)+\left(unit\ environmental\ cost\right)\right]\times \\ \left[1+general\ consumption\ tax\ rate\left(where\ applicable\right)\right]$$

[3] For example, a revenue-neutral feebate that increases the price of emissions-intensive vehicles while lowering the price of relatively clean vehicles can help with decarbonizing transportation without creating a new tax burden on the average household, though (unlike a fuel tax) it does not discourage driving.

[4] See https://www.imf.org/-/media/Files/Topics/Environment/energy-subsidies/fuel-subsidies-template-2022.ashx and also https://climatedata.imf.org/pages/go-indicators#gp3.

[5] CPAT has been developed jointly by IMF and World Bank staff and evolved from an earlier IMF tool used, for example, in IMF (2019a and b). For descriptions of the model and its parameterization, see IMF (2019b), Appendix III, and the Appendix of Black and others (2021).

Supply cost. For a nontradable product (which is largely the case for electricity), the supply cost is the domestic production cost, inclusive of any margins for transportation, processing, and distribution costs. In contrast, for an internationally tradable product (like oil and, increasingly, natural gas), the supply cost is the opportunity cost of consuming the product domestically rather than selling it abroad. This can be measured by the import- or export-parity price (for fuel importing and exporting countries, respectively), with adjustments for domestic margins.

Environmental costs and externalities associated with driving. The environmental costs of coal, natural gas, and liquid fuel combustion include global carbon and local outdoor ("ambient") air pollution. Driving also results in additional external costs, such as congestion.

For all fuels, the *global carbon damage* is the CO_2 emissions factor (in other words, CO_2 emissions per unit of fuel use) times the damage per unit of CO_2 emissions. Expressed per unit of energy, CO_2 emissions factors for a given fuel vary only modestly across countries, though the emissions factor is about 25 percent and 45 percent lower for liquid fuels and natural gas than for coal, respectively (US Energy Information Administration [US EIA] 2021).

The major *local air pollutant from coal* is fine particulate matter ($PM_{2.5}$), that is, particulates with a diameter less than 2.5 micrometers. These are small enough to enter the lungs and bloodstream, increasing the risk of premature mortality from various (for example, heart and lung) diseases. $PM_{2.5}$ is emitted directly from coal combustion and is formed indirectly from chemical reactions in the atmosphere involving sulfur dioxide (SO_2) and nitrogen oxide (NO_x).[6] The local pollution damage per unit of fuel use is the fuel's emissions factor, converted to $PM_{2.5}$ equivalents, times the damage per ton of $PM_{2.5}$ and aggregated over all pollutants. Emissions factors can vary substantially across countries depending on the use of emissions control technologies and fuel quality (for instance, bituminous coal has a higher sulfur content than lignite and anthracite). Burning *natural gas* produces only one substantive local pollutant, NO_x, and even that is in relatively small amounts compared with coal and liquid fuels.

For *road fuels*, CO_2 emissions per liter are about 15 percent higher for diesel than for gasoline, but diesel engines tend to be more fuel efficient. For the same vehicle type, CO_2 emissions per kilometer (km) traveled by diesel vehicles tend to be about 40 percent lower than those for gasoline vehicles. For both fuel types, CO_2 emissions can be moderately reduced by blending them with biofuels. Combusting gasoline and diesel can also produce direct $PM_{2.5}$, SO_2, and NO_x, but emissions rates vary across countries depending on the stringency of (new and used) vehicle emissions rate standards and fuel quality. In general, emissions of these local air pollutants are much higher for diesel than for gasoline.

More broadly, the *use of road fuels in vehicles is associated with other externalities*, most importantly traffic congestion and accidents, and less importantly, wear and tear on the road network. In principle, all three externalities are most efficiently addressed through various distance-based charging systems (for instance, kilometer-based fees that vary with real-time traffic flows on congested roads or with driver/vehicle accident risk). Until such systems are comprehensively implemented, however, which no country has done to date, fuel taxes remain a valid, albeit blunt, second-best instrument (Parry and others 2014). It should also be noted that efficient road fuel taxes depend partly on behavioral responses. To the extent that reductions in fuel use from taxation come from improvements in fleet average fuel economy and shifting to electric vehicles (EVs) rather than from reductions in vehicle kilometers traveled, the efficient road fuel tax will be lower.[7] Externalities for *nonroad uses of petroleum product*s (for example, for home heating, off-road vehicles, or petrochemicals) are limited to CO_2 and local pollution.

[6] Low-lying ozone, formed when heat and sunlight cause chemical reactions between NO_x and volatile organic compounds (VOCs) like benzene, is another local air pollutant, though its mortality impacts are on a smaller scale than those for $PM_{2.5}$.

[7] For example, if a fuel tax induces a shift from internal combustion engine vehicles to EVs, rather than a reduction in use of all vehicles, this will not reduce congestion or accident externalities.

Environmental costs from *electricity consumption* are taken to be zero because global and local pollution are attributed to the fuel inputs. The main unaccounted-for externalities from electricity are the use of EVs and their associated congestion and accident externalities. However, EV use accounts for a very small share of electricity consumption, and hence these externalities are small when expressed relative to total electricity consumption.

General consumption taxes. Standard IMF guidance is to apply the same value-added tax (VAT), or general consumption taxes, to all products consumed by households. The VAT should be applied to the full social cost (supply and environmental cost), as is current practice where VAT is generally applied on top of excise and carbon taxes. Under this approach, revenue is raised from general consumption taxes without distorting relative prices and the choice between different goods (accounting for the full social cost of producing them) (see, for example, Crawford, Keen, and Smith 2010).

Explicit and Implicit Fossil Fuel Subsidies

The explicit subsidy for a fuel in a particular sector is defined by:

$$\left(\left[\textit{unit supply cost}\right]-\left[\textit{price paid by fuel user}\right]\right)\times\left[\textit{fuel consumption}\right]$$

And the total explicit and implicit subsidy combined is defined by:

$$\left(\left[\textit{efficient fuel price}\right]-\left[\textit{price paid by fuel user}\right]\right)\times\left[\textit{fuel consumption}\right]$$

If a price faced by a fuel user exceeds the supply cost, the explicit subsidy is counted as zero, and if it exceeds the efficient price, the implicit and explicit subsidies are both zero. Producer subsidies (for example, favorable tax treatment for fossil fuel extraction) are included in explicit subsidies. Figure 6.1 provides a graphical comparison of subsidies.

Measuring Efficient Fuel Prices and Subsidies: A Step-by-Step Guide

This section discusses the methodology and data needed to assess efficient fuel prices and subsidies. It also presents a tool for measuring the impacts of reform.

Basic Energy Data

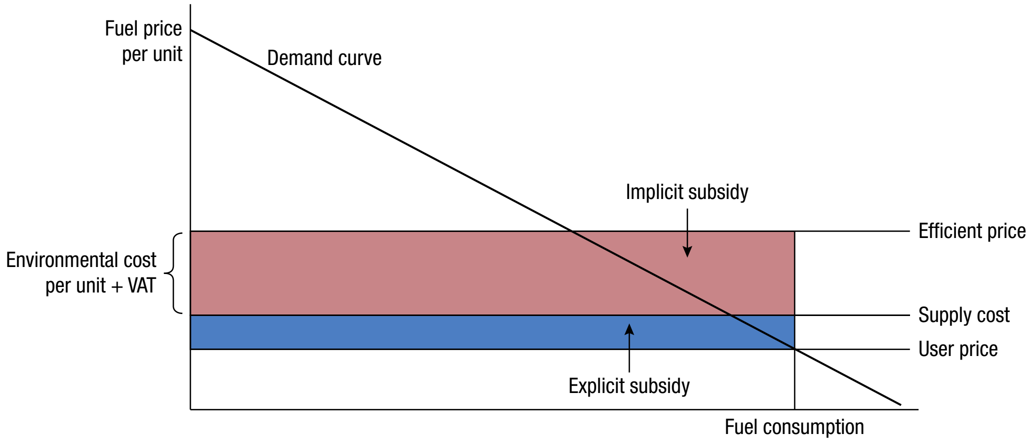
Retail prices. These are the observed prices paid by energy users. For coal, natural gas, and electricity, the subsidy calculation uses prices for each major sector (industrial, residential, and power generation), as prices and subsidies may vary across this dimension. Retail prices are taken from IMF and World Bank country desk data sets as the prioritized sources. For cases where such data are not available, a simple average across various third-party sources is used.[8] Future retail prices are adjusted for changes in international energy prices based on assumptions about pass-through rates.[9]

Supply costs. These are equal to the cost to deliver energy to the end user, assuming no government policies exist to alter or suppress costs or profits for suppliers (for example, loan guarantees and direct financial transfers) outside of standard regulatory measures related to environmental, safety,

[8] These include Enerdata (2022), Eurostat (2022), European Commission (EC) (2022), International Energy Agency (IEA) (2022a), Global Petrol Prices (GPP) (2022), and the UN Economic Commission for Latin America and the Caribbean (CEPAL) (2022). If retail prices are not available, the industrial-sector price for natural gas and coal is assumed to be equal to the power-generation price (if available), and vice versa, with a similar approach taken for residential and industrial electricity prices. For countries with fully missing historical data, retail prices are assumed to be equal to the supply cost plus any known taxes.

[9] Pass-through coefficients are estimated by regressing historical data on retail prices (or supply costs if retail prices are unavailable) for 2010–19 on historical spot prices, with the coefficient constrained to between 0 and 1. For countries with fewer than five observations, the regional average coefficient is used.

Figure 6.1. Graphical Comparison of Explicit and Implicit Fuel Subsidies



Source: IMF staff calculations.
Note: VAT = value-added tax.

competition, and so forth. Moreover, supply costs use an opportunity cost methodology for traded fuels (for instance, petroleum products and natural gas), where the import/export-parity price is assumed, rather than the direct cost to produce the fuel. This is a key assumption for producers as they may have production costs below the international price but could sell the product on international markets and, therefore, the international price represents the opportunity cost (or value) of the commodity.

For *finished petroleum products*, supply costs consist of the hub prices from IEA (2022a), with countries mapped (based on region) to published hub prices for the United States, northwest Europe, or Singapore, plus costs and margins for transportation and distribution (T&D).[10] T&D costs and margins are not observed and are estimated to be $0.15–$0.22 per liter for all countries, with an additional $0.10 per liter for land-locked and small-island developing countries. The T&D values are estimated using data from a sample of countries (British Petroleum [BP] 2021; UN Economic Commission for Latin America and the Caribbean [CEPAL] 2022), including country-specific price buildups (for example, Ghana's National Petroleum Authority [NPA] 2022).

For *natural gas*, supply costs are based on hub, import, or net-back export prices, with upward adjustments for T&D. For large natural-gas-consuming countries (for example, most European and south and east Asian countries), domestic natural gas prices are available through Argus (2022), IEA (2022a), or Enerdata (2022). For liquefied natural gas (LNG) exporters, without a well-functioning domestic natural gas market, country-specific liquefaction and shipping costs (from Steuer 2019) are deducted to net-back prices from delivery abroad. Countries that do not have available domestic prices are mapped to a specific regional hub price (BP 2021, Argus 2022). Markups for within-country T&D are applied, with higher margins for residential users than for industrial power generation (as per EIA 2022a and EC 2018). These markups are $3 per gigajoule (GJ) for power generation and industrial users and $10 per GJ for residential users, with adjustments if country-specific data are available.

For *coal*, the export/import-parity price is inferred using one of five methods, with prioritization given in the following order: supply costs equal to (1) estimated supply costs from IMF country teams, (2) the Organisation for Economic Co-operation and Development (OECD) inventory estimate for per-unit subsidies, (3) the country-specific export or import prices from internal or

[10] While the mapping is not granular, petroleum product prices are internationally traded, with relatively low maritime transportation costs, so broad mapping to regional prices should not substantially impact the accuracy of the supply cost calculation.

third-party sources, (4) the pretax end-user price, or (5) the price at the nearest hub. Again, markups are applied for T&D, with higher markups for residential coal use (markup data come from, for example, the US EIA 2022b). Supply costs for countries with significant domestic production are adjusted downward to reflect the large transportation costs associated with coal.

For *electricity*, supply costs are provided by IMF country teams (in the few cases that they were available) or calculated using a cost-recovery level estimate based on the weighted-average fuel costs and assumptions of T&D that come from IEA (2022b). The calculated supply costs are also available in CPAT.

The constructed supply costs may differ from the actual supply costs, as country-specific conditions vary and coal, natural gas, and electricity do not trade on global markets to the extent that liquid fuels do. This is expected to have minimal impacts on the subsidy estimates where retail price information is not available (about 150 countries for coal and 120 for natural gas), since the supply cost and retail price are assumed to be equal, and generally coal and natural gas are untaxed globally. The remaining channel for which the supply costs matter is through the revenue components of the efficient prices (calculated as the consumption tax rate multiplied by the sum of supply costs and environmental externalities), and this effect tends to be small, especially since coal is not commonly used in the residential sector and the consumption taxes are not paid by firms (in other words, the VAT on firms' inputs is credited and, therefore, not paid).

Fuel and general consumer taxes. Estimates of fuel tax levels and coverage include carbon taxes and emissions trading systems (ETSs), mostly sourced from the World Bank (2022) and country-specific documents. Standard consumption tax rates and rates applicable to specific fuels are generally gathered from third-party sources (PricewaterhouseCoopers [PWC] 2022; International Bureau of Fiscal Documentation [IBFD] 2022).

Fuel consumption. Consumption data is sourced from the IEA (2022c), Enerdata (2022), and EIA (2022c). These are observed values, and no estimation is required.

Environmental Costs

Global warming damages. CO_2 emissions factors per unit of fuel use are publicly available[11] (US EIA 2021; US Environmental Protection Agency [US EPA] 2022). Typical values for coal and natural gas are 0.1 and 0.055 tons of CO_2 per GJ of energy, respectively, and for gasoline and diesel are 0.0027 and 0.0030 tons per liter, respectively.

Damages per ton of CO_2 emissions might be inferred from the carbon prices that are implicit in countries' mitigation pledges, but these prices vary considerably across countries, and at the global level they fall well short of what is needed to get on track with temperature stabilization goals (see IMF 2019a, 2019b; Black and others 2021). Instead, the approach employed here is to use the price of global CO_2 emissions consistent with a least-cost trajectory to meet temperature goals. Based on the literature for aligning emissions with a 2°C target, an illustrative value of $60 per ton of CO_2 for 2020 is used (prices for 1.5°C would be much higher but also would be subject to much higher uncertainties).[12]

Local air pollution. The main component of local air pollution damage assessments is elevated risks of premature mortality for people exposed to $PM_{2.5}$ (see, for example, National Research Council [NRC] 2009).

[11] See www.imf.org/-/media/Files/Topics/Environment/energy-subsidies/gepr-database-2017.ashx.

[12] A review by Stern and Stiglitz (2017) put the value of CO_2 emissions consistent with a 2°C warming target at $40 to $80 per ton in 2020, rising to $50 to $100 per ton by 2030. Updated estimates in Black and others (2021) suggest little change in the needed global prices for 2030.

According to the Global Burden of Disease (GBD), there were 4.5 million premature deaths worldwide caused by exposure to outdoor air pollution in 2019, with 92 percent of those due to $PM_{2.5}$.[13] Two-thirds of deaths were among people aged 65 and over (who are more vulnerable given their higher prevalence of preexisting health conditions). GBD attributes about 60 percent of outdoor air pollution deaths to fossil fuels, but (unlike the approach described here) does not decompose the contributions from individual fuels and sectors.[14] Estimates of air pollution costs by fuel product seen here are compiled from several information sources.[15]

First is the baseline rate of mortality for illnesses whose prevalence is potentially increased by local air pollution exposure, which is publicly available from GBD for 204 countries. Illnesses include ischemic heart disease (accounting for 28 percent of the global outdoor air pollution deaths in 2019), strokes (26 percent), chronic obstructive pulmonary disease (20 percent), lower respiratory infections (11 percent), and trachea/bronchitis/lung cancers (6 percent), with the remainder attributed to other sources. Baseline mortality rates for illnesses vary significantly across countries—they can be relatively high in countries with a higher prevalence of heart and lung disease (for example, from alcohol and cigarette abuse) and lower in countries where people have shorter life expectancies and are more likely to die from other illnesses.

Second are the emissions factors for local air pollutants from use of fossil fuels in different sectors. These are available from the International Institute for Applied Systems Analysis for years 2020 onward.[16] There is extensive cross-country documentation of emissions rates for the power and transport sectors (any data gaps are filled using comparable countries), though this is less true of the industrial and residential sectors (data gaps here are filled using power-sector emissions rates).[17] The emissions rates for power and transport average over newer sources (that may have advanced emissions control technologies) and older sources (that do not). In general, emissions factors tend to decline over time as older capital (subject to less stringent regulation) is replaced.[18]

The third source of information is a measure of population exposure to local pollution. The approach here averages results from two different methodologies: one based on "intake fractions" and the other on local air quality modeling; both approaches have strengths and weaknesses.

The *intake fraction* is the fraction of (direct and indirect) $PM_{2.5}$ emitted from a fuel product that, on average, is inhaled by exposed populations; estimates here use intake fractions calculated in Parry and others (2014).[19] For coal and natural gas plants, these fractions are obtained by mapping geographic data on the location of power plants in different countries to highly granular data on population density at different distances from each plant—up to 2,000 km away—within and across borders, given the long-distance atmospheric transport of emissions released from tall smokestacks. Regression coefficients are then applied indicating how intake fractions at different distances vary with population density. For vehicle and building emissions (where smokestacks are lower to the ground and therefore emissions tend to remain close to ground level), intake fractions are extrapolated nationwide from a database of (ground-level) intake fractions for over 3,000 urban areas.

[13] The Institute for Health Metrics and Evaluation (IHME) (2020) provides detailed country-level mortality data. Eight percent of outdoor air pollution deaths are attributed to ozone. Indoor air pollution caused a further 2.3 million deaths, but the nature of the externality here is less clear as those affected by pollution are also the cause of the pollution.

[14] Other pollution sources include burning crop residue and natural dust. Considerable uncertainties surround local air pollution deaths, however; for example, Vohra and others (2021) estimated global outdoor air pollution deaths from fossil fuels alone at 10 million in 2012—almost four times the GBD's estimate for 2019.

[15] Damage estimates by fuel product and country are available at www.imf.org/-/media/Files/Topics/Environment/energy-subsidies/fuel-subsidies-template-2022.ashx.

[16] Based on the Greenhouse Gas–Air Pollution Interactions and Synergies (GAINS) model (Wagner and others 2020). Emissions factors can be downloaded from https://pure.iiasa.ac.at/id/eprint/17552/1/DOI_dataset.zip.

[17] This likely gives conservative emissions rate estimates as control technologies for the industrial and household sectors are less common than for the power sector.

[18] An exception is diesel vehicles, where emissions rates have been revised upward given recent evidence that vehicles were out of compliance with emissions rate standards.

[19] They can be downloaded at www.imf.org/-/media/Files/Topics/Environment/energy-subsidies/gepr-database-2017.ashx.

Intake fractions tend to be high in densely populated countries and where emissions sources are located inland (for coastally located sources, a large portion of emissions can dissipate across oceans without harming local populations). Fixed coefficients are used to translate intake fractions into increased rates of mortality from pollution-related illness.[20]

The other approach is based on *local air quality modeling*, involving computational estimation of how emissions released from a particular location affect air quality (from $PM_{2.5}$ and ozone) and mortality risk in other regions. The results are based on TM5-FASST, a downscaled "source-receptor" model commonly used and applied at the country level.[21] The air quality modeling approach is more sophisticated than the intake fraction approach in that it accounts for local meteorological and topographical factors influencing ambient pollution concentrations, as well as possible nonlinearities in the relationship between mortality and pollution exposure. However, air quality modeling is potentially less granular for the application of fossil fuel–related sources like power plants, which may imply less precision in measuring population sizes potentially exposed to fossil fuel–related pollution.

The fourth and final source of information comes from attaching a monetary value to health risks, which is contentious but is needed to factor health risks into energy prices. The approach draws on a meta-analysis of several hundred stated preference studies on health risk valuations in different countries (OECD 2012). After updating for inflation and real per capita income growth, this implies a value of around $4.6 million per death avoided for 2020 for the average OECD country. This figure is extrapolated to other countries based on their per capita income relative to the OECD average and an assumed unitary elasticity for the mortality value with respect to per capita income.[22]

Broader externalities for transportation.[23] In measuring the external costs of *road congestion*, it is standard to assume that motorists account for the average costs of travel delays in their driving decisions but not the marginal costs—the latter reflects their impact on adding to congestion, slowing speeds, and adding to delays for other road users. Assessing how much fuel taxation is warranted by congestion requires a nationwide average measure of marginal congestion costs. At present, there is no consistent cross-country database that can be used to measure nationwide marginal congestion costs. The approach therefore relies on rudimentary estimates that were extrapolated from a cross-country, city-level database.[24] Marginal congestion costs are multiplied by kilometer per liter

[20] Again, the data are available at www.imf.org/-/media/Files/Topics/Environment/energy-subsidies/gepr-database-2017.ashx. They incorporate estimates of how mortality rates for different illnesses increase with higher pollution exposure (for example, Burnett and others 2014).

[21] TM5-FASST (the TM5-FAst Scenario Screening Tool; see Van Dingenen and others 2018) is based on a linearized version of TM5, a detailed model of emissions, transport, and atmospheric chemistry leading to pollution formation. The original source-receptor matrices in TM5-FASST are separated into 56 regions, which are downscaled to obtain country-specific matrices and supplemented with local source apportionment studies that estimate the contribution of sources such as fossil fuels to baseline concentrations.

[22] The country-level valuations are available at www.imf.org/-/media/Files/Topics/Environment/energy-subsidies/gepr-database-2017.ashx. The elasticity value is based on Robinson, Hammitt, and O'Keeffe (2019), Tables 3.1 and 3.3, and Viscusi and Masterman (2017). The extrapolations use purchasing power parity income, which takes local price levels into account to more accurately reflect people's willingness to pay for risk reductions from their own income. Mortality valuations may also differ across countries with differences in life expectancy, health, religion, culture, economic and social support, and so on. However, the quantitative implications of these factors are not well understood (Robinson, Hammitt, and O'Keeffe 2019).

[23] Data on transportation externalities, expressed per liter of fuel, are available from https://www.imf.org/-/media/Files/Topics/Environment/energy-subsidies/fuel-subsidies-template-2022.ashx. Where data are unavailable (for example, for many African countries), values are inferred from an average of countries with a similar per capita income level in the region.

[24] Specifically, average travel delays per kilometer across nearly 100 cities were regressed on various transportation indicators. Combining the regression coefficients with nationwide values for the same indicators provided an estimate of nationwide travel delays per kilometer. Average delays were then converted to marginal delays using evidence from urban centers that marginal delays are about four times the average delay. Delays were then monetized based on literature suggesting that people value travel time at about 60 percent of the market wage—country-level wage data is available at www.ilo.org/global/research/global-reports/global-wage-report/lang--en/index.htm. The estimates also make an adjustment for the average occupancy of cars and buses on the road, as that affects how many people are affected by the congestion.

to express them on a per liter basis. In addition, estimates are multiplied by the fraction (assumed to be 0.4) of the fuel demand elasticity that comes from reduced driving (and therefore affects congestion) versus the portion that comes from improved fuel economy/shifting to EVs (that does not affect congestion).[25]

As regards *traffic accidents*, a portion of the costs is commonly viewed as internal to drivers (internalities, such as injury risks to drivers in single-vehicle collisions), while other costs are viewed as external (externalities, such as injury risks to pedestrians, the elevated risks to occupants of other vehicles from multivehicle collisions, or third-party property damage and medical costs). Externalities are measured by apportioning country-level data on traffic fatalities from the International Road Federation (IRF) into external versus internal risks, monetizing them using the preceding approach for mortality valuation, and extrapolating nonfatality accident costs to other countries from several country case studies (Parry and others 2014, ch. 5). For congestion, externalities are expressed as the result per unit of fuel use and by scaling by the kilometer-based fraction of fuel-price elasticities. Coady and others (2019) updated accident externalities with more recent traffic fatality data, and these estimates are used after updating to 2020 for fatality/injury valuations.

Finally, externalities from *wear and tear on the road network* imposed by high-axle-weight vehicles are taken from the update in Coady and others (2019), which is based on highway maintenance expenditures (see IRF [2021] for the latest data) and an assumption that half of these expenditures are attributed to vehicle use as opposed to weather and natural deterioration.

Box 6.1 provides an illustration of how the methodology outlined in the "Basic Energy Data" and "Environmental Costs" sections can be used to calculate efficient fuel prices and subsidies in India.

Box 6.1. Illustrating the Methodology—Diesel and Industrial Natural Gas in India, 2019

This box applies the methodology outlined in the "Basic Energy Data" and "Environmental Costs" sections to diesel and industrial gas use in India in 2019 (the last year for which data for all commodities are available) and then presents the results on efficient prices and subsidies.

Retail prices. Retail prices for diesel and industrial natural gas, $0.96 per liter and $3.76 per gigajoule (GJ) in 2019, are collected from third-party sources (Global Petrol Prices [GPP] and the International Energy Agency [IEA]).

Supply costs. For diesel, the 2019 international crude oil price of $0.40 per liter (IEA 2022a) is adjusted upward by $0.26 per liter to account for processing, marketing, and distribution to reach a supply cost of $0.66 per liter. For natural gas, the average import price for India, $4.78 per GJ in 2019 (Argus 2022), is used, with upward adjustments for marketing and distribution, resulting in a supply cost of $7.78 per GJ.

Consumption. Diesel and industrial natural gas consumption in 2019, 101 billion liters and approximately 0.6 billion GJ, respectively, are observed values published by the IEA but also available at the US Energy Information Administration (EIA 2022c).

Climate change. Carbon dioxide emissions factors for diesel and natural gas are 0.003 tons per liter and 0.055 tons per GJ, respectively (see text). Multiplying them by the illustrative carbon price ($60 per ton) gives global warming damages for diesel and natural gas of $0.16 per liter and $3.31 per GJ, respectively.

Local air pollution. Damages from local air pollution mortality from diesel and industrial natural gas use in India (based on procedures described in the text) are $0.25 per liter and $0.27 per GJ, respectively (they assume a mortality risk valuation of $0.55 million per life).

Broader externalities for transportation. Congestion, accident, and road damage externalities associated with the use of road diesel in India are valued at $0.05, $0.21, and $0.01 per liter, respectively (based on procedures described in the text). The congestion cost figure assumes the value of travel time is $0.69 per hour (based on a market wage of approximately $1.15 per hour).

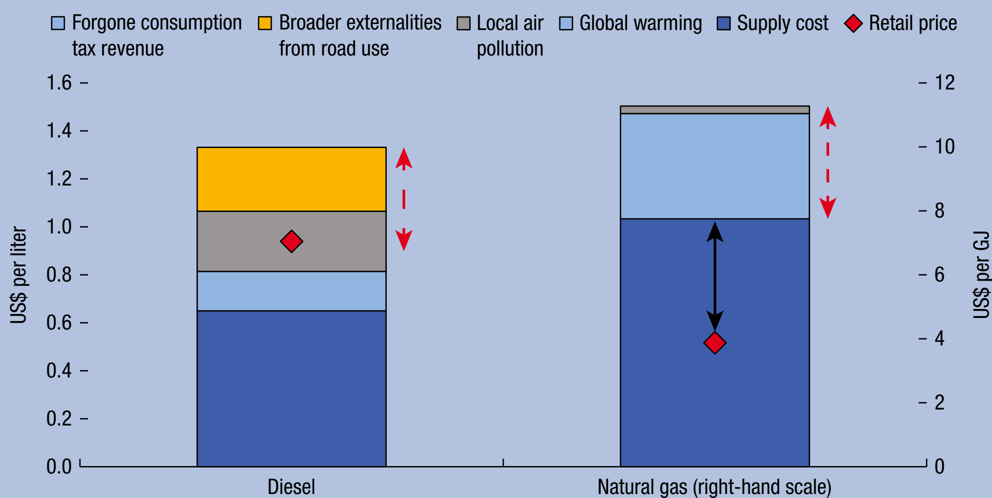
[25] Further adjustments are made to account for the relatively weaker responsiveness of driving on congested roads (which is dominated by commuting) to fuel taxes than driving on free-flowing roads. See Parry and others (2014), ch. 5.

Box 6.1. *(continued)*

Forgone consumption tax revenue. This component is calculated as the excess value-added tax (VAT) revenue from charging a VAT on the efficient price. It is very small for diesel, $0.01 per liter, given that the VAT rate in India was 15 percent in 2019 and only 5 percent of diesel consumption was consumed by households—the component is not applicable for industrial gas as purchasers of industrial gas (in other words, firms) receive a credit for VAT paid on inputs.

Results. In 2019, the industrial natural gas price fell short of the supply cost and efficient price (the sum of supply cost, environmental costs, and forgone consumption tax) by $4.02 and $3.58 per GJ, respectively—see the black and dashed red arrows in the figure. Multiplying by fuel consumption gives explicit and total (explicit plus implicit) subsidies for industrial natural gas use of $2.3 billion and $4.3 billion, respectively. The 2019 diesel price exceeded the supply cost, meaning that there is no explicit subsidy, and falls short of the efficient price by $0.38 per liter. Multiplying by fuel consumption gives total implicit subsidies for diesel of $38.3 billion.[1]

Figure 6.1.1. Diesel and Natural Gas Price Disaggregation, India



Source: Parry, Black, and Vernon (2021).
Note: GJ = gigajoule

[1] The results differ slightly from those in Parry, Black, and Vernon (2021) because they are presented in nominal terms and with some slight simplifying assumptions.

Impacts of Reform

The IMF-WB CPAT model can be used to estimate the environmental, fiscal, and economic welfare impacts of fossil fuel price reform. CPAT, which is a spreadsheet-based model, provides, on a country-by-country basis for 191 countries, projections of fuel use and CO_2 emissions by major energy sector. Projections are based on assumptions about future GDP growth, income elasticities for energy products, annual rates of technological change that improve energy efficiency and the productivity of renewables, and future international energy prices.

The impacts of carbon pricing on fuel use and emissions depend on (1) their proportionate impact on future fuel prices in different sectors, (2) simplified models of generation investment and fuel switching within the power generation sector, and (3) various own-price elasticities for electricity use and fuel use in other sectors. The same basic data on the energy system and environmental costs, as just described, are used to populate the model, while GDP projections are from the latest IMF *World Economic Outlook* forecasts (IMF 2022).[26] Assumptions for fuel-price responsiveness are

[26] International energy prices are projected forward using an average of IEA and IMF projections for coal, oil, and natural gas prices.

chosen to be broadly consistent with empirical evidence and results from other energy models that incorporate considerable detail on existing and emerging energy technologies (fuel-price elasticities are typically between about –0.5 and –0.8).

Key Results

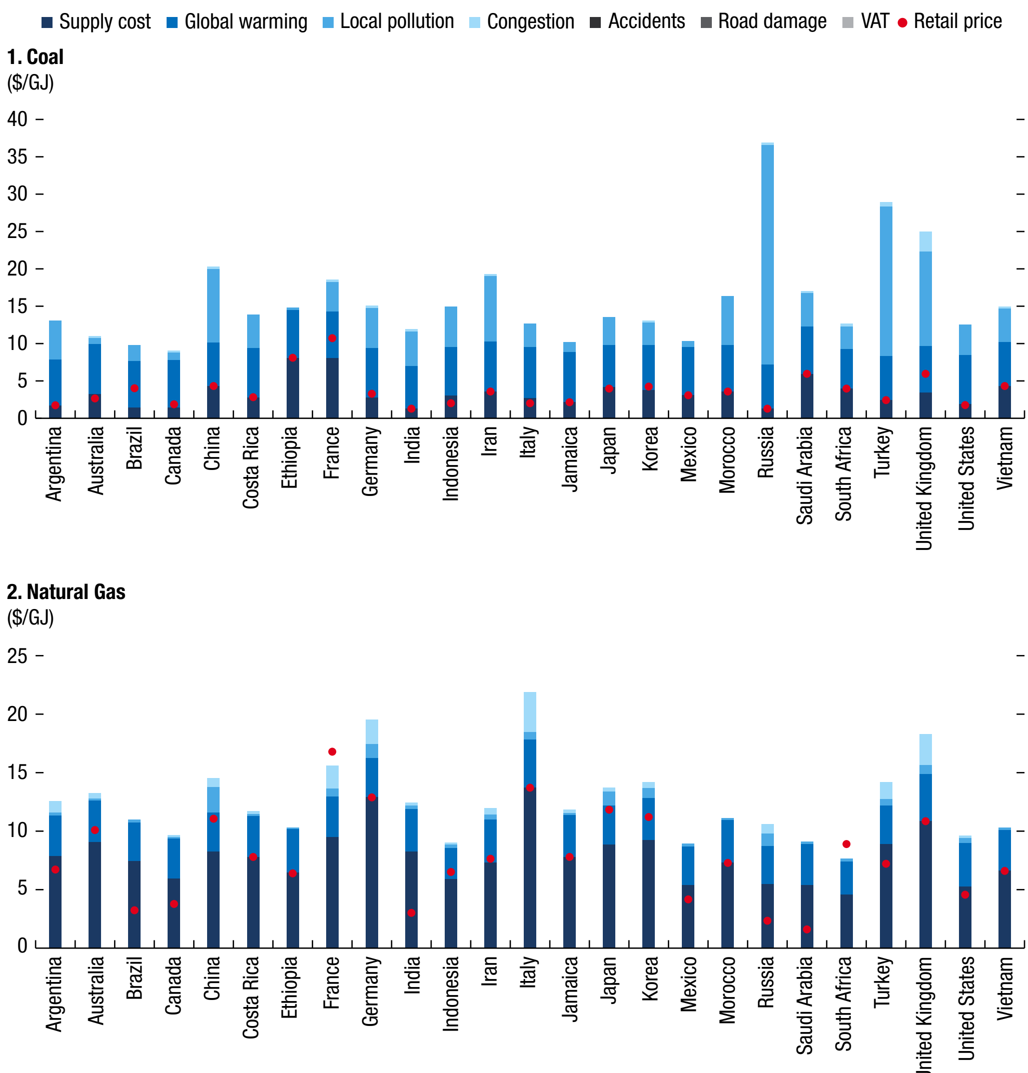
Results are presented next comparing current and efficient fuel prices and the size and breakdown of energy subsidies at the global level and for 25 selected countries, including all G20 countries. Impacts of reform at the global level are also mentioned.

Comparing Current and Efficient Fossil Fuel Prices

Figure 6.2 shows estimates of current and efficient prices in 2020 for coal, natural gas, gasoline, and road diesel, averaged across results for fuel use in different sectors.

For *coal*, supply costs vary substantially from $1.50 to $7 per GJ, though user prices are typically at least as large as supply costs (implying no explicit subsidies). The pricing of environmental costs,

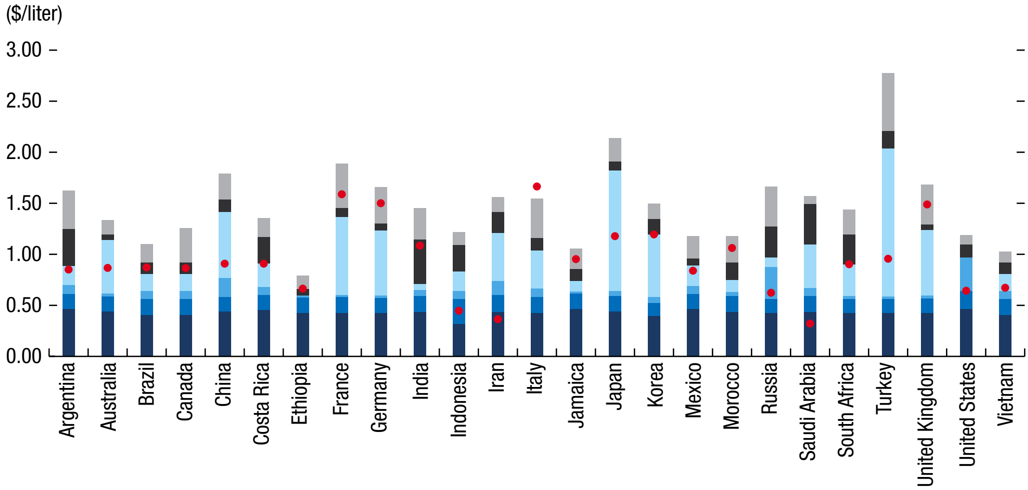
Figure 6.2. Comparing Current and Efficient Fuel Prices, Select Countries



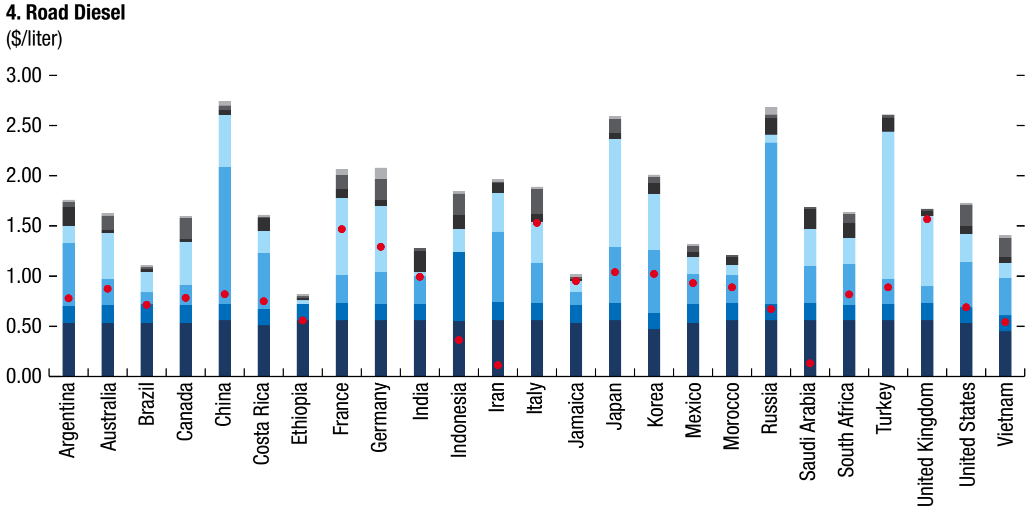
(Continued)

Figure 6.2. *(Continued)*

3. Gasoline



4. Road Diesel



Source: Parry, Black, and Vernon (2021).

Note: Results for coal and natural gas average across uses by power, industry, and households, and for road diesel across light- and heavy-duty vehicles. The chart shows average prices in 2020. GJ = gigajoule; VAT = value-added tax.

however, is generally modest, reflecting limited use of coal excises and carbon pricing. Indeed, global warming damages alone are equivalent to $6.30 per GJ. And local air pollution damages can also be large, but with substantial cross-country variation—more than 50 percent larger than climate costs in some cases (for example, China, Russia) but less than half of climate costs in others (for instance, Australia, Canada, Mexico).

Supply costs for *natural gas* vary from around $5 to $12 per GJ. Prices fall short of supply costs in nine countries (for example, India, Saudi Arabia) and significantly exceed supply costs in seven cases (for instance, Australia, China, South Africa), and in two of those cases prices (moderately) exceed their efficient levels. Global warming damages are around one-third to one-half of supply costs for natural gas, much lower than for coal, reflecting both higher supply costs per GJ for gas and lower emissions rates per GJ. Local air pollution damages from natural gas are generally modest (below $1 per GJ in all but four cases). The VAT component of efficient natural gas prices is also modest when averaged over electricity, industrial, and household uses.

There is little variation in supply costs for *road fuels* across countries, given integrated world markets—supply costs for gasoline and diesel are around $0.50 per liter. Road fuel prices exceed supply costs in all but two countries (Iran, Saudi Arabia) due to excise taxes. Indeed, gasoline prices exceed supply costs by around 50 percent or more in all but five countries and by over 100 percent in 13 countries (for example, many European countries). Most countries impose lower taxes per liter on road diesel than on gasoline.

Global warming damages amount to about one-third of supply costs. *Local air pollution* damages are generally small relative to global warming damages for gasoline but for diesel are typically around one to three times as large as carbon damages. *Congestion and accident externalities* combined are relatively large for gasoline, together warranting charges of around $0.5 to $1.0 per liter. Congestion tends to be the larger externality in densely populated advanced countries (for instance, due to high travel time valuations), and accidents are the larger externality in developing countries (for example, due to high incidences of pedestrian fatalities). For diesel, combined congestion and accident externalities per liter are somewhat smaller as a significant portion of the fuel is used in heavy-duty vehicles, which are driven fewer kilometers on a liter of fuel. The VAT component of the efficient fuel price is significant for gasoline (around $0.2 to $0.4 per liter) but less so for road diesel (where a substantial portion of consumption is an intermediate product).

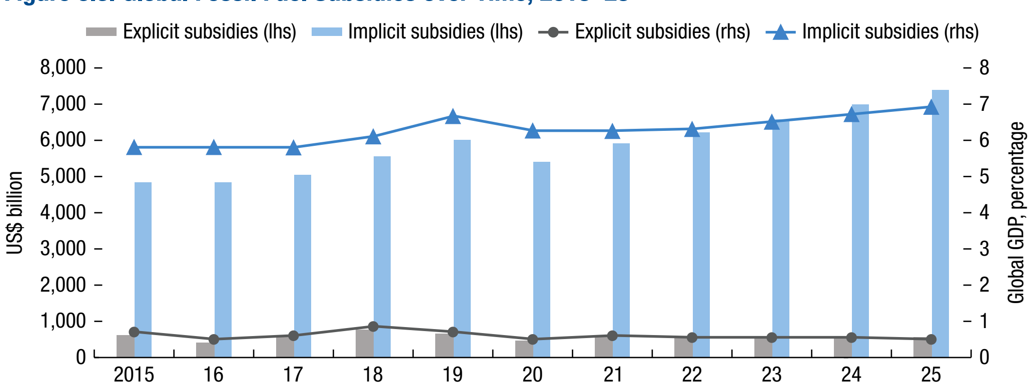
Going forward, global warming damages will rise (given the trajectory of CO_2 prices needed for transitions to net zero emissions). Local air pollution damages will generally decline with declining emissions rates as cleaner capital subject to stricter regulation replaces older capital, though partially offsetting factors include rising urban population densities and rising mortality risk valuations (as per capita income rises). Road fuel taxes will decline in importance and may ultimately be replaced by km-based tax systems, as many countries phase in bans on internal combustion engine vehicles.

The Size of Fossil Fuel Subsidies

The global picture. At the global level (see Figure 6.3), fossil fuel subsidies amounted to $5.9 trillion in 2020, or 6.8 percent of GDP, rising (on current policies) to 7.4 percent of GDP in 2025. Explicit and implicit subsidies accounted for 8 percent and 92 percent of the total, respectively, in 2020.

In absolute terms, (historical and projected) explicit subsidies vary between about $450 billion and $750 billion during the period 2015–25. These subsidies tend to fall when international energy

Figure 6.3. Global Fossil Fuel Subsidies over Time, 2015–25



Source: Parry, Black, and Vernon (2021).
Note: Figures from 2019 and 2021 onwards use projections for fuel use and fuel prices, respectively. lhs = left-hand side; rhs = right-hand side.

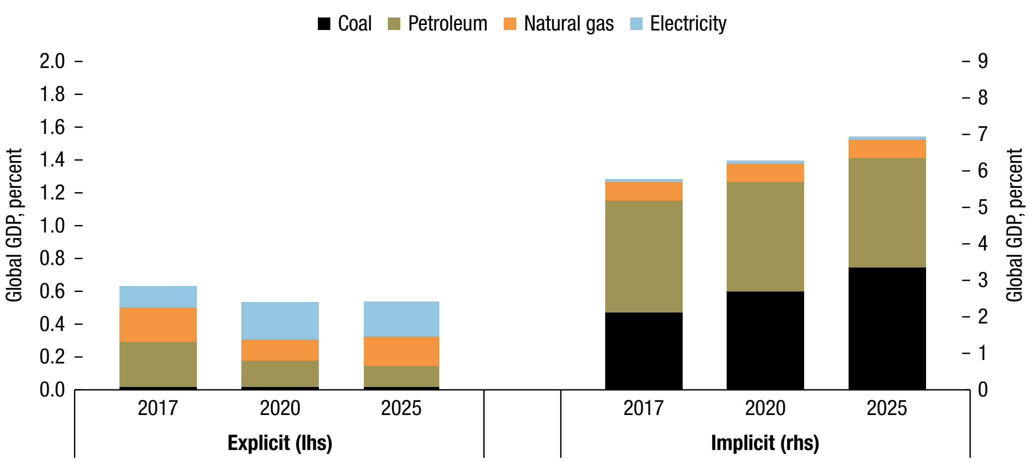
prices decline as this lowers the gap between supply costs and domestic prices in countries with domestic fuel prices below market levels, and vice versa when international prices rise. Implicit subsidies are projected to mildly increase in absolute terms, and as a percentage of global GDP, out to 2025. Although fuel use/GDP and local air emissions rates are generally falling over time, emerging market economies account for a progressively rising share of global fuel consumption, and local environmental costs per unit of fuel used tend to be larger for them. The international energy price surge since mid-2021 will likely have increased explicit subsidies relative to projections in Figure 6.3; implicit subsidies (which depend on environmental factors) are not directly affected but may have fallen indirectly with induced reductions in fuel demand.

Breakdown by fuel product and component. Petroleum, natural gas, and electricity accounted for 28, 27, and 42 percent of the explicit global subsidy in 2020, respectively (Figure 6.4). For petroleum and natural gas, explicit subsidies primarily reflect the setting of domestic prices below international prices in energy-exporting countries, while the subsidy for electricity largely reflects the failure to fully reflect generation costs in domestic tariffs. Globally, only 8 percent of the explicit subsidy in 2020 reflected support for fossil fuel producers (92 percent was consumer-side subsidies).

The breakdown by fuel product is dramatically different for total (explicit plus implicit) subsidies in 2020, however. Here coal accounts for 41 percent of the global total in 2020, reflecting underpricing for carbon and local air pollution damages. Petroleum accounts for 46 percent of the global subsidy, largely reflecting the failure of excises on petroleum products to fully reflect environmental costs and broader externalities. Natural gas (where environmental costs are more moderate) and electricity (where environmental costs are attributed to fuel inputs) account for 9 and 4 percent of the global subsidy, respectively.

Broken down by component (see Parry, Black, and Vernon 2021), undercharging for local air pollution, global warming damages, broader externalities from road use, supply costs, and general consumption taxes accounts for 42, 29, 15, 8, and 6 percent, respectively, of total (explicit and implicit) subsidies in 2020. For coal, local air pollution and global warming account for 58 percent and 40 percent of total subsidies, respectively, while for petroleum, underpricing for local air pollution and broader externalities accounts for 39 percent and 33 percent of the total subsidy, respectively, and global warming a smaller 16 percent. In contrast, for natural gas, global warming is 59 percent of the total subsidy.

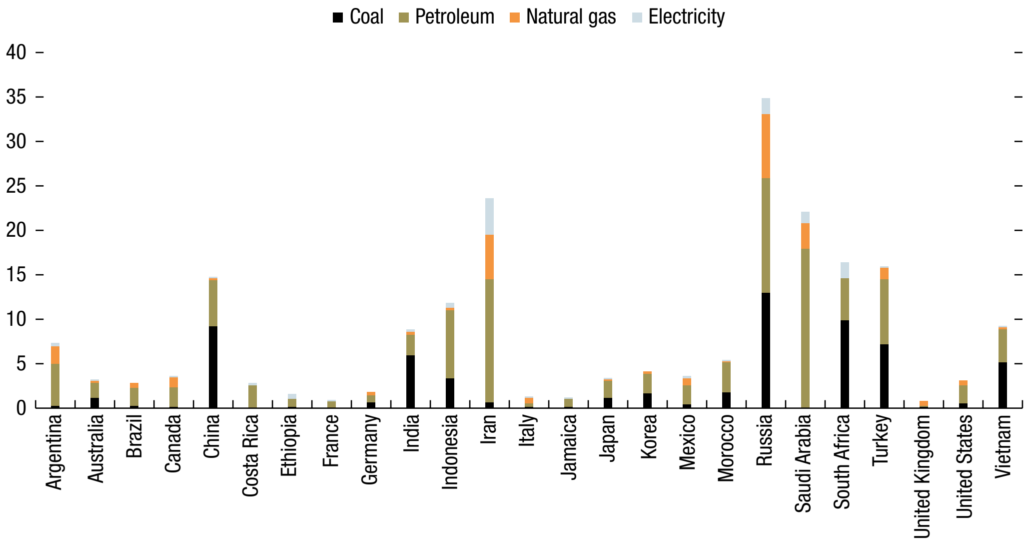
Figure 6.4. Global Fossil Fuel Subsidies by Fuel Product, 2017–25



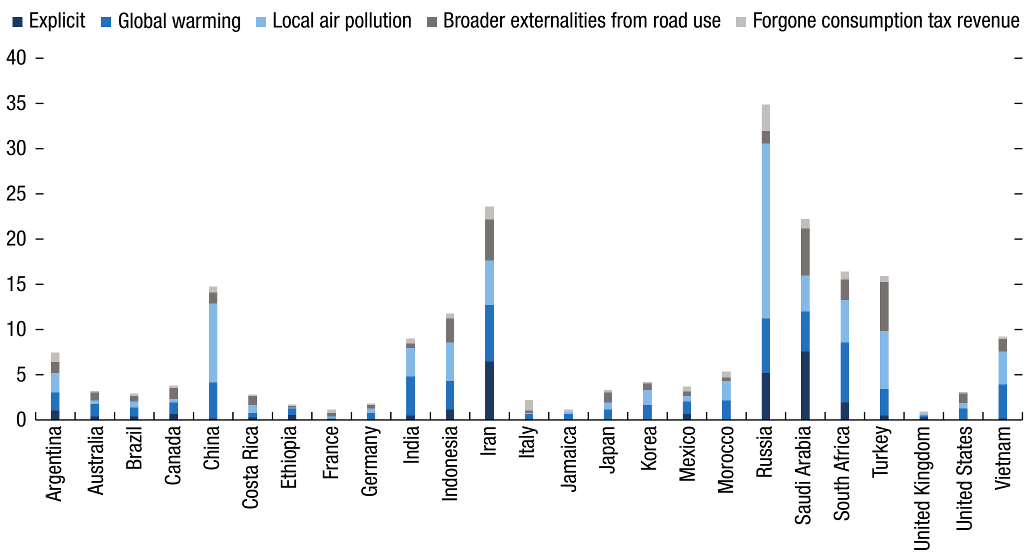
Source: Parry, Black, and Vernon (2021).
Note: lhs = left-hand side; rhs = right-hand side.

Figure 6.5. Fossil Fuel Subsidies at the Country Level
(Percentage of GDP)

1. By Fuel Product



2. By Component



Source: IMF staff calculations, using Parry, Black, and Vernon (2021).

Country-level subsidies. There is substantial variation in total (explicit plus implicit) subsidies, and their breakdown by fuel product and component, across the 25 countries, is shown in Figure 6.5. Total subsidies are less than 2 percent of GDP in six cases, between 2 percent and 5 percent in eight cases, between 5 percent and 10 percent in four cases (Argentina, India, Morocco, Vietnam), and over 10 percent in seven cases (for example, China, Indonesia, Iran, Saudi Arabia, South Africa). The share of petroleum in total subsidies varies from 26 percent (India) to 92 percent (Costa Rica), while that for coal varies from 0 percent (Costa Rica, Saudi Arabia) to 66 percent (India). And the share of local pollution in total subsidies varies from 3 percent (Ethiopia) to 59 percent (China), while the share of explicit subsidies in total subsidies varies from less than 1 percent in five cases to 35 percent (Saudi Arabia).

Impacts of Global Reform

Parry, Black, and Vernon (2021) use CPAT to estimate the environmental, fiscal, and economic welfare impacts from fully eliminating (explicit and implicit) fossil fuel subsidies (in other words, raising the price of all fuel products from current levels to their efficient levels).

At the global level the full fuel-price reform would reduce fossil fuel CO_2 emissions 36 percent below baseline levels in 2025, or 32 percent below 2018 emissions. This reduction is in line with the 25 percent to 50 percent reduction in global emissions needed by 2030 to get on track with containing global warming to the Paris goal of 1.5°C to 2°C. Around 74 percent of the CO_2 reduction comes from reduced use of coal, while 21 percent and 3 percent, respectively, are from reductions in consumption of petroleum and natural gas, which in part reflect the disproportionately large increase in coal prices from fuel-price reform. In contrast, if only explicit subsidies are removed, global CO_2 emissions are reduced by 3 percent below baseline levels in 2025. Full fuel-price reform reduces global air pollution deaths from fossil fuel combustion by 32 percent below baseline levels in 2025, or 0.9 million a year in absolute terms.

Full reform raises additional revenue of $4.2 trillion, or 3.8 percent of global GDP, in 2025 (accounting for revenue losses due to erosion of preexisting fuel tax bases). The revenue generated by the reform in 121 emerging market and developing economies in 2025 would amount to $3 trillion, which is broadly in line with their additional spending needs for Sustainable Development Goals (Gaspar and others 2019). Full fuel-price reform would generate net economic efficiency costs of 1 percent of global GDP. But, with environmental benefits of 3.1 percent of GDP, this leaves a net economic welfare gain of 2.1 percent of GDP.[27]

CONCLUSION

This chapter describes a methodology for estimating efficient fossil fuel prices to reflect supply costs, environmental costs, and general consumer taxes, and the resulting subsidies (both explicit and implicit) implied by charging below efficient fuel prices. The methodology involves extensive data compilation from a diverse range of cross-country databases.

There are significant uncertainties inherent in the estimation of fossil fuel subsidies, most importantly over the measurement of environmental costs. For example, the link between local air emissions and mortality depends on many uncertain factors (for example, dispersion of emissions in the atmosphere, number of people exposed to the pollution, and how exposure affects health risk), and there are differing views on how to value the mortality risks. Policymakers also have varying perspectives on valuing domestic carbon emissions given the global commons nature of the climate change threat. The estimates presented here should thus be viewed as indicative—the implications of alternative views on underlying parameters can be readily inferred from online spreadsheets.

At the global level, fossil fuel subsidies were $5.9 trillion in 2020, or about 6.8 percent of GDP, the vast majority of which were implicit subsidies: undercharging for environmental costs accounts for 86 percent and undercharging of general consumer taxes was 6 percent of the total. Undercharging for supply costs (explicit subsidies) accounted for 8 percent. At the country level, there is substantial variation in the relative and absolute sizes of subsidies across countries, and in the breakdown of subsidies by fuel product and component.

Phasing out explicit subsidies will therefore not be enough: restructuring taxation to reflect full environmental costs, as 193 countries have called for in the Sustainable Development Goals, is

[27] These costs are measured by the value of forgone benefits to fossil fuel consumers less savings in supply costs (or, equivalently, reductions in consumer and producer surplus less government revenue gains). To a large extent, these costs correspond to the annualized costs of using cleaner but more expensive technologies (which are largely passed forward in higher consumer prices).

essential.[28] If the world is to address climate change and other environmental problems effectively and urgently, then getting energy prices right will be a critical first step.

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[28] Per SDG12.c: "Rationalize inefficient fossil-fuel subsidies that encourage wasteful consumption by removing market distortions, in accordance with national circumstances, including by restructuring taxation and phasing out those harmful subsidies, where they exist, to reflect their environmental impacts, taking fully into account the specific needs and conditions of developing countries and minimizing the possible adverse impacts on their development in a manner that protects the poor and the affected communities" (United Nations 2015).

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CHAPTER 7

Carbon Footprint of Bank Loans—A Measure of Transition Risks for the Financial Sector

Mahmut Kutlukaya, Michele Fornino, Kazuko Shirono,[1] Ananthakrishnan Prasad, and Dulani Seneviratne

This chapter presents an experimental indicator—Carbon Footprint of Bank Loans (CFBL)—which is publicly available through the IMF's Climate Change Indicators Dashboard (CID). The indicator aims to quantify the exposure of a country's banking sector to climate transition risks. The CFBL indicator is presented in two versions: (1) intensities-based, including only direct emissions; and (2) multipliers-based, incorporating emissions embodied in inputs from upstream sectors to direct emissions. The CFBL is generally higher in emerging market and developing economies than in advanced economies, has been increasing in emerging market and developing economies and slightly falling in advanced economies, and is significantly higher when indirect emissions are considered. The chapter also discusses how to overcome data limitations related to the CFBL in the context of the broader climate information architecture.

INTRODUCTION

The aim of the 2015 Paris Agreement is to combat climate change by capping the global temperature increase below 2°C compared to preindustrial levels and to accelerate the investment in low-carbon technologies for a sustainable future. Achieving these goals requires reducing greenhouse gas (GHG) emissions substantially over the next few decades, with significant transition risks. The financial system needs to help by channeling financing for the transition to a low-carbon economy and by bolstering climate financing considerably, from an estimated 7 percent of total funding in 2017 to 30 percent in 2030, according to the International Finance Corporation (IFC 2018).[2]

Transition risks are defined as the exposure to losses related to abrupt or unanticipated changes to strategies, policies, investments, and consumer and market preferences as societies pursue lower environmental impacts from productive activities and the consumption of final goods and services (see Vermeulen and others 2018 and references therein). These include, but are not limited to, higher energy costs from carbon taxation or emissions cap schemes, reduction in the market value of emissions-intensive assets (so-called stranded assets), expenses for research and development of green technologies, and regulatory and reporting requirements (Bank for International Settlements 2021a). As such, transition risks vary widely across sectors of the economy. For the financial sector,

[1] This chapter benefited greatly from contributions by Gregory Legoff, Samah Torchani, and Alberto Sanchez, all from the International Monetary Fund.

[2] Climate financing refers to funding areas such as renewables, energy efficiency, green buildings, and climate-smart transportation.

transition risks are a major concern in addition to physical risks, particularly in the medium to long term, as the transition costs could lead to significant losses on financial assets, including loans and securities investments.

Considering the potentially wide-ranging impacts, central banks and international organizations have bolstered their efforts to quantify transition risks in recent years. For instance, the European Central Bank (ECB) has recently introduced a framework to conduct euro-area climate stress tests, with the aim of assessing the resilience of nonfinancial corporations and banks to climate risks in different scenarios under various future climate policies (Dunz and others 2021), while the IMF has incorporated transition risk analysis in the Financial Sector Assessment Program (FSAP). A common characteristic of these efforts is that they mostly focus on those countries and regions that have granular data sets. Climate change, however, is a global phenomenon, and developing comparable cross-country analytical and data frameworks could provide critical insights.

The Carbon Footprint of Bank Loans (CFBL), an indicator made available through the IMF's *Climate Change Indicators Dashboard* (CID), was developed to provide a tool for policymakers to measure the carbon intensity of bank loan portfolios.[3] The CFBL, which is based on aggregated sector-level data, provides a data-lean way to appraise the exposure of the banking system to transition risks for a given country. Less stringent data requirements make it possible to calculate this indicator for a wide range of countries—the CFBL is currently available for 41 countries, including emerging markets and developing economies. The methodology allows for cross-country comparisons, albeit with certain limitations.

A more comprehensive analysis of transition risks would require granular data on bank-level exposures and firm-level emissions. This type of information is needed to assess institutions that are more likely to be affected by climate policies, as well as to identify pockets of risk within the financial sector. In addition, it is essential to develop a forward-looking approach given that transition risks are likely to materialize over time, beyond the horizons over which financial risk management is usually performed. It is thus paramount to improve the climate information architecture to enable the design of effective measures to monitor risks to the financial sector stemming from climate change, including transition risks.[4] Policy-relevant, high-quality, comparable, and consistent data are needed to identify transition risks and to channel funding to those projects that would bring the most benefit to achieve climate goals. Several international initiatives are ongoing to bridge these data gaps (see Box 7.1).[5]

Against this background, this chapter presents a way to track a measure of transition risks for the financial sector—specifically focusing on the CFBL indicator—and ongoing work to fill relevant data gaps. The next section provides an overview of the literature focusing on the quantification of transition risks for financial institutions, which provides the basis for the formulation of the CFBL indicator. The following section discusses methodological aspects of the CFBL indicator. Next is an overview of the CFBL for those countries for which the indicator is compiled. The final section discusses limitations of the indicator and, more broadly, global initiatives to close data gaps to measure transition risks for the financial sector.

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[3] The Bank for International Settlements (BIS) notes that the carbon footprint of banks' assets, measured by combining the lending and investment activities with sectoral- or firm-level data on carbon emissions, is a common indicator used as a proxy for transition risks (BIS 2021b).

[4] An IMF staff climate note (IMF 2021) outlines the three key pillars of a successful climate information architecture: (1) high-quality, reliable, and comparable data; (2) a globally harmonized and consistent set of climate disclosure standards; and (3) globally agreed-upon principles for climate finance taxonomies to align investments with climate goals (see Box 7.5 for further information).

[5] For details, see the recently published G20 Roadmap (G20 2021), the final report of the Committee on Monetary, Financial and Balance of Payments Statistics (CMFB 2021); and reports from the BIS (BIS 2021a, 2021b).

Box 7.1. Climate Finance: Data Gaps and the Climate Change Indicators Dashboard

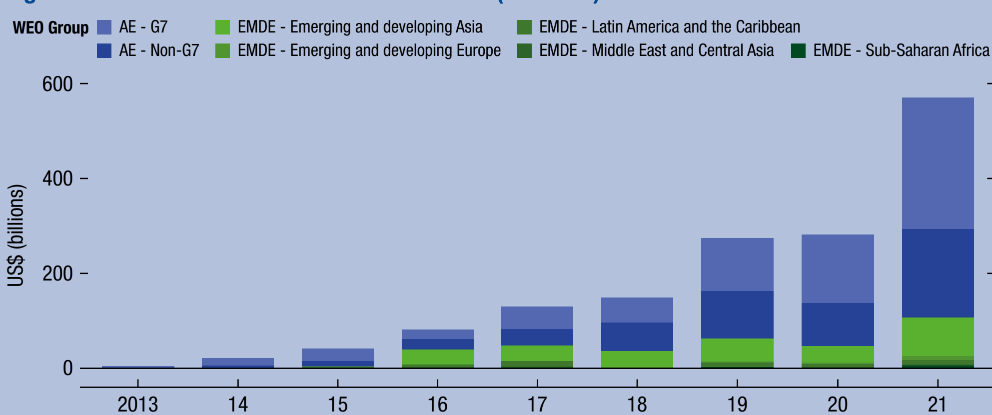
Urgency to tackle climate change requires adequate financing to support a pathway toward low greenhouse gas emissions and climate-resilient development. Prasad and others (2022) note that global investments required to achieve the Paris Agreement's temperature and adaptation goals range between US$3 trillion and $6 trillion per year until 2050, yet only a fraction of these needs have been fulfilled. Multiple challenges, including data-related constraints, hinder attracting and scaling up climate finance.

The October 2022 *Global Financial Stability Report* (IMF 2022b), Chapter 2, highlights four distinct types of instruments and approaches that have emerged due to the innovation in climate finance: (1) structured finance and closed-end fixed-income funds, (2) blended finance for infrastructure and other complex projects, (3) outcome-based sustainable debt instruments, and (4) private finance for public-sector projects. The *Climate Change Indicators Dashboard* (CID) features a Green Bonds indicator, with an aim to cover the identified data gaps on climate finance.

The Green Bonds indicator in the CID covers self-labeled fixed-income instruments where the proceeds are exclusively directed to finance or refinance, in part or in full, new, and/or existing green projects. The indicator is compiled using commercial vendor data based on the Climate Bonds Initiative (CBI) certification. The Green Bonds indicator is available for 76 countries, including advanced economies and emerging market and developing economies, with series going back to 1985. The CID presents the Green Bonds indicator aggregated by year, country, sector, use of proceeds and currency, as well as cumulative issuances. Figure 7.1.1 portrays annual green bond issuances for the period 2013–21. Such issuances have increased significantly in the last decade, reaching around US$600 billion as of end-2021. While advanced economies issue most of the green bonds, issuances by emerging markets and developing economies are also growing. See Green Bond indicators in the CID and accompanying metadata for details.

The new G20 Data Gaps Initiative (new DGI) is expected to tackle climate financing–related data gaps through the development of methodological guidance to produce more comparable indicators on green financing—this will be covered under Recommendation 4 on Green Debt and Equity Securities Financing in the new DGI.

Figure 7.1.1. Global Issuances of Green Bonds (2013–21)



Source: IMF Climate Change Indicators Dashboard.
Note: The chart shows the annual issuances of green bonds over the period 2013–21, broken down by WEO country groups, which are defined in the Statistical Appendix to the April 2022 *World Economic Outlook* (WEO). Overseas territories of IMF member countries and non-IMF members are not included in the WEO groupings and are excluded from these calculations. These include Bermuda (BMU), Cayman Islands (CYM), Guernsey (GGY), Jersey (JEY), Liechtenstein (LIE), and the British Virgin Islands (VGB). AE = advanced economies; EMDE = emerging market and developing economies; G7 = Group of Seven.

LITERATURE REVIEW

The banking sector is crucial for providing funding to the real economy, and bank loans are among the principal tools for this funding across the world. Given the importance of bank loans, the literature on estimating the CFBL is rapidly growing. This section discusses selected studies that provide the methodological basis for the indicator presented in this chapter. The studies are summarized in Table 7.1.

TABLE 7.1.

Approaches to Quantify Carbon Footprint of Financial Institutions in the Surveyed Literature			
Approach	**Description**	**Pros**	**Cons**
IMF CFBL Indicator	Banking sector's carbon intensity weighted by sectoral share of bank loans	• Underlying loans by industry data generally available • Both emissions intensities and multipliers are used	• Focus on broad sectors • Requires nuanced reading if banking sector is financing the transition of brown sectors to greener technologies
Guan and others (2017)	Individual bank's portfolio carbon intensity weighted by shares of loans in all sectors	• Provides bank-level exposure metric	• Focus on broad sectors • Intensive data requirements (individual bank's sectoral exposures)
Boermans and Galema (2019)	Individual pension fund's portfolio carbon intensity weighted by shares of companies in the portfolio	• Provides fund-level exposure metric	• Intensive data requirements (individual funds' sectoral exposures)
Vermeulen and others (2021)	Ratio of average emissions intensity in each global industry to the global average	• Required data generally available • Emissions intensities keep track of embodied emissions (indirect exposures)	• Hard to interpret the indicator as an absolute measure of risk exposure
Faiella and Lavecchia (2020)	Emissions per unit of loans in each sector	• Required data generally available	• Hard to interpret for sectors with low credit balances
Hirvonen, Karhu, and Tolkki (2021)	Banking sector's carbon intensity weighted by individual exposures' bank loans	• Provides granular exposure metrics for financial institutions	• Data requirements are high

Source: IMF staff.
Note: CFBL = Carbon Footprint of Bank Loans.

The framework most relevant for the indicator developed in this chapter is Guan and others (2017), which estimates the carbon intensity of Chinese banks' loan portfolios and explores the associated credit risk. The study develops a Carbon Intensity of Loans (CIL) indicator, defined as carbon emissions per unit of loans. The CIL indicator is computed at the bank level as a weighted average of emissions intensity factors of the sectors to which loans are made, weighted by the share of outstanding loans made to borrowers from that sector. The emissions intensity factors used by this study comprise both direct and indirect emissions, which are obtained by multiplying a vector of sectoral emissions intensity by the Leontief inverse matrix constructed from an input–output (IO) table.[6] This study finds that the share of nonperforming loans is positively correlated with the CIL indicator across the Chinese banking system in the period 2007–14.

Boermans and Galema (2019) follow a similar approach to compute portfolio-level exposure to carbon footprints. Leveraging Dutch pension funds' stock-level data, they explore whether investors are actively decarbonizing their portfolios by reducing their exposure to high-emissions companies. They construct an indicator of carbon footprint as a weighted average of company-level emissions intensity—or carbon inefficiency—defined as total company emissions over sales and weighted with portfolio shares of each company. The study finds that pension funds that measure and report their carbon footprint are more likely to show lower exposure to high-emissions companies.

Vermeulen and others (2021) introduce a stress-testing framework to appraise financial stability risks related to the energy transition. The paper presents a methodology called the Transition Vulnerability Factors (TVF), defined as the ratio of the average emissions intensity in each global industry to the average emissions intensity of the world economy. Emissions intensities are computed using sector-by-country IO data to account for embodied emissions in each sector.[7] TVFs can be

[6] Box 7.2 discusses direct and indirect emissions and emissions scopes in greater detail.

[7] As explained in the next section, embodied emissions include not only the direct emissions that are produced by a sector, but also those that were produced by sectors that produced intermediate inputs.

interpreted as factor loadings in a standard asset pricing model, and their formulation is closely related to the multipliers-based version of the CFBL, which is discussed later.

Faiella and Lavecchia (2020) present an alternative indicator of the carbon footprint of bank loans, using data on Italian banks. They develop an indicator called Loan Carbon Intensity (LCI), defined as GHG emissions (in grams of CO_2 equivalents) per unit of outstanding loans (in euros) made by Italian banks across sectors in the economy.[8] In contrast to the individual bank-level CIL indicator proposed by Guan and others (2017), the LCI is computed at the sectoral level. One drawback of the LCI, however, is that the indicator can show a low carbon intensity of loans for a sector that has high emissions if the loan volume in the denominator of the ratio is also high. To overcome this limitation, the authors propose a methodology to identify carbon-critical sectors as those that show both high emissions and high loan exposure.[9] The study finds that the carbon content of Italian banks' loans has been declining over time, and that sectors responsible for about 50 percent of emissions account for only 10 percent of total loans—suggesting a potential concentration of risks.

There are also growing global efforts to establish standard methodologies to quantify climate-related risks. For example, the Task Force on Climate-Related Financial Disclosures (TCFD) was created to develop consistent climate-related financial risk disclosures for use by companies, banks, and investors to provide information to stakeholders. Similarly, the Partnership for Carbon Accounting Financials (PCAF) is a global partnership of financial institutions that work together to develop and implement a harmonized approach to assess and disclose the GHG emissions associated with their loans and investments.

The 2017 TCFD report presents a set of common carbon footprint and exposure metrics (TCFD 2017). These include the preferred weighted average carbon intensity, which is recommended for asset owners and asset managers to report to their beneficiaries and clients, as well as alternatives that may also be considered for compilation. In general, these indicators have various levels of data requirements and consist of weighted carbon emissions intensities or weighted carbon emissions, where the weights may be either portfolio shares or ratios of investment to market capitalization. Similarly, the Global GHG Accounting and Reporting Standard for the Financial Industry (PCAF 2020) covers in detail the methodological aspects that financial institutions could follow when calculating emissions associated with their loan portfolios. TCFD and PCAF indicators generally take the form of weighted averages of emissions of financed firms, where the weights may take different forms, including the ratio of invested amount to total equity and debt of the financed institution.

Hirvonen, Karhu, and Tolkki (2021) adopt a version of PCAF indicators to quantify the carbon footprint of Finnish banks' loans to nonfinancial corporations.[10] The authors focus on Scope 1 emissions, which they estimate from firm-level Emissions Trading Systems data. Scope 2 emissions (see Box 7.2) of companies in each sector are imputed by considering that sector's share of the sales of the International Standard Industrial Classification of All Economic Activities (ISIC) Division 35 (electricity, gas, steam, and air conditioning supply), evaluated from IO tables,[11] and by further

[8] More specifically, the numerator of the LCI is defined as the total GHG emissions of 63 Nomenclature statistique des activités économiques dans la Communauté européenne (NACE, which is the Statistical Classification of Economic Activities used in the European Community) Rev 2 divisions or sections taken from the National Accounting Matrix, including the Environmental Accounts (NAMEA) data set of Eurostat. The denominator is the total outstanding performing and nonperforming loans made by Italian banks to firms and to households acting as firms.

[9] More specifically, they rank each of the 63 sectors according to total emissions and to total loans (where 1 is the highest and 63 is the lowest) and then take the simple average of these rankings. Carbon-critical sectors are identified as the sectors in the first quintile of this average ranking distribution.

[10] Emissions of nonfinancial corporations are computed from Emissions Trading System's data, corroborated by imputations of emissions for companies that are not covered by the Emissions Trading System. The authors compute financed emissions following the PCAF methodology.

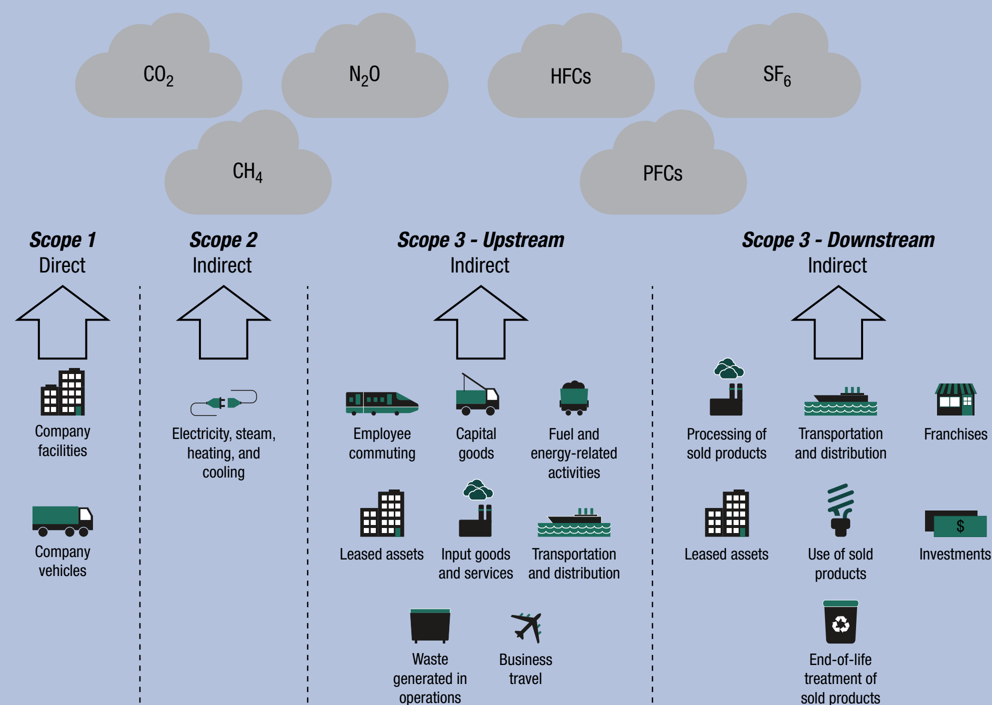
[11] The underlying logic is that the Scope 2 emissions of companies outside of the energy-producing sector consist of the Scope 1 emissions of the energy producers from which that company buys electricity, gas, steam, and air conditioning.

Box 7.2. The Scopes of Greenhouse Gas (GHG) Emissions

A critical step to advance GHG emissions data collection efforts is to define a consistent methodology to identify, quantify, and correctly classify the GHGs that companies are responsible for. The World Business Council for Sustainable Development (WBCSD) and the World Resources Institute (WRI) spearheaded this effort by introducing GHG Protocols—common definitions and minimum reporting standards that all reporting parties should follow when producing and disclosing emissions accounts. These protocols not only define a taxonomy of emissions scopes, but also provide guidance on the estimation of GHG emissions from company activity data when hard physical measurements of released gasses are unavailable (see, for instance, WBCSD and WRI 2004).

According to the WBCSD/WRI taxonomy, disclosed GHG emissions are divided into two types: (1) **direct emissions**, which are generated due to burning of fossil fuels or other chemical processes as a result of activities in company facilities and running of company vehicles (Scope 1); and (2) **indirect emissions**, which are caused by the production of electricity, heat, steam, and cooling used as inputs (Scope 2), or along the value chain (Scope 3). Scope 3 emissions capture the entirety of the eight upstream and seven downstream emissions that arise from a company's activities, including purchasing inputs or selling outputs as well as transportation and waste management (see Figure 7.2.1 for the emissions scopes). The International Sustainability Standards Board (ISSB) proposes that reporting entities disclose their aggregate GHGs for Scopes 1, 2, and 3—expressed in carbon dioxide (CO_2) equivalents (ISSB 2022a, 2022b; see final section of chapter for more details).

Figure 7.2.1. Overview of GHG Protocol Scopes and Emissions across the Value Chain



Source: IMF staff based on GHG Protocol, Corporate Value Chain (Scope 3) Accounting and Reporting Standard.
Note: This infographic shows the Greenhouse Gas (GHG) Protocol emissions scopes and their relationship to company activities. Upstream and downstream refers to the relationship of the emitting entity relative to the reporting firm along the value chain. CO_2 = carbon dioxide; CH_4 = methane; N_2O = nitrous oxide; HFCs = hydrofluorocarbons; PFCs = perfluorocarbons; SF_6 = sulfur hexafluoride.

scaling the company's share of total employment in the sector to which it belongs. In addition, the paper computes the LCI indicator proposed by Faiella and Lavecchia (2020), finding results for the Finnish economy qualitatively similar to those presented for the Italian bank loans—namely, a minority of loans are made to carbon-critical sectors, while most emissions are due to carbon-intensive industries.

While PCAF and TCFD indicators provide useful insights on transition risks to policymakers and financial institutions, data requirements are stringent. These types of indicators invariably rely on firm-level emissions, loans, and balance sheet data that are not publicly available on a global level.[12] While the Carbon Disclosure Project (CDP 2019), as well as private data vendors, have been collecting self-reported emissions data, most companies still neither attempt to measure nor report this information. For this reason, compilation of these indicators may not always be possible. The CFBL, as discussed in detail in the next section, addresses these challenges by providing a data-lean alternative to measure exposure of banks to transition risks.

METHODOLOGY

The CFBL indicator described in this chapter is a country-level indicator constructed as the average of carbon dioxide (CO_2) **emissions factors** from fuels used in each sector, weighted by the **sectoral share of outstanding loans** from deposit takers. Specifically, the CFBL indicator can be expressed as follows:

$$CFBL_{it} = \sum_j \frac{l_{ijt}}{\sum_j l_{ijt}} q_{ijt} = \frac{\sum_j l_{ijt} q_{ijt}}{\sum_j l_{ijt}},$$

where i is the country, j is the industry, t is the calendar year, l_{ijt} denotes total outstanding loans of deposit takers in country i made to firms in industry j at the end of calendar year t, and q_{ijt} represents the emissions factor, expressed in tons of CO_2 per million US dollars of output in sector j in country i during calendar year t.

The indicator leverages two separate sources of data to calculate sectoral shares of outstanding loans and emissions factors. These are depicted conceptually in Figure 7.1 and are determined as follows:

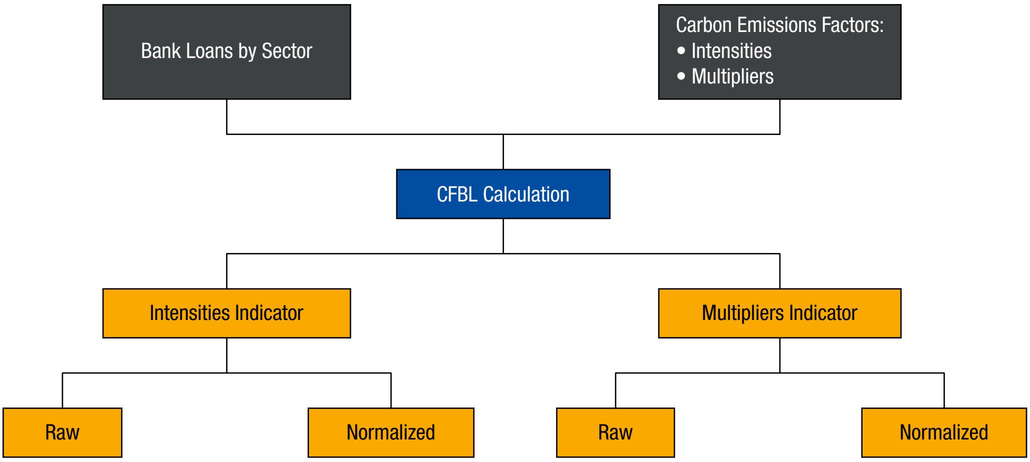
- The values of outstanding loans by sector were obtained from a survey of country authorities conducted by the IMF's Statistics Department in late 2020 (see Annex 7.1 for more details on the survey). Countries provided, on a best-effort basis, annual data on total outstanding domestic loans of deposit takers, broken down by 53 ISIC Rev. 4 sections or divisions.[13] In total, 41 countries reported these data. Countries also submitted metadata that included the unit of account (currency), the scale, and responses to a few questions intended to gather additional information about the adherence to the prescribed ISIC classification standard.[14]

[12] Some of these data, specifically balance sheet data, are available to central banks and bank supervisors.

[13] All ISIC sections were included (letter codes). In addition, sections B—Mining and Quarrying, C—Manufacturing, and J—Information and Communication were further broken down at the level of the constituent divisions (two-digit level). For instance, for B—Mining and Quarrying, these include divisions 05, Mining of coal and lignite, through 09, Mining support service activities.

[14] The focus on ISIC has several objectives. First, this ensures cross-country comparability of the loan data because countries are asked to compile the same data sheet. Second, it ensures that even when the country does not follow the ISIC classification for its internal record keeping, the responsibility for the remapping rests on the authority with the greatest information about the details of the underlying data. Finally, ISIC classification provides a standardized mapping to the OECD Inter-Country Input–Output (ICIO) tables, as the classification adopted in that data set is based on ISIC Rev. 4.

Figure 7.1. Conceptual Depiction of CFBL Calculation



Source: IMF staff.
Note: CFBL = Carbon Footprint of Bank Loans.

- The carbon emissions factors used to compute the CFBL indicator are sourced and adapted from the Economic Activity Indicators of the CID. The carbon emissions factors consist of the following two measures:
  1. **Emissions intensities,** calculated by dividing the CO_2 emissions from fuel consumption in each country and sector by total output from the OECD Inter-Country Input–Output (ICIO) tables expressed in millions of US dollars. CO_2 emissions data is sourced by the OECD from International Energy Agency estimates.
  2. **Emissions multipliers**, calculated by multiplying the Leontief inverse (also known as an output multipliers matrix) from the OECD ICIO tables by the CO_2 emissions intensities described in item 1 above.

The conceptual difference between *emissions intensities* and *emissions multipliers* is that the former quantifies the rate of emissions per million US dollars of economic activity for which a sector is *directly* responsible, while the latter also captures *indirect* emissions (see Box 7.2).

- *Emissions intensities* are akin to Scope 1 emissions, as the OECD ICIO tables rely only on measures of fuels burned.
- *Emissions multipliers* quantify emissions from backward linkages, namely accounting for the interconnection of a particular industry to other industries from which it purchases inputs. Thus, emissions multipliers capture CO_2 emissions from fuel combustion that not only arises from the direct operation of sectoral activities, but is also embodied in the inputs (Scope 2) as well as inputs from all other sectors included in the ICIO tables (upstream Scope 3).

The calculation of the CFBL indicator leverages both emissions intensities and emissions multipliers, yielding two versions of the indicator. In addition, to facilitate easy assessment of the evolution over the years of the carbon content of loans, normalized indicators were constructed for both versions of the CFBL, presented as index numbers set to be 100 in 2015—the year when data are available for all countries. See Annex 7.2 for an example of how to calculate the two versions of the CFBL indicator, including their interpretations. Box 7.3 provides some of the assumptions and limitations of the CFBL indicator that need to be kept in mind when using it to evaluate transition risks for the banking sector.

Box 7.3. Assumptions and Limitations of the CFBL Indicator

This box discusses assumptions and limitations that need to be considered when analyzing the Carbon Footprint of Bank Loans (CFBL) indicator. Many of these limitations are not specific to the CFBL and will affect any attempt at constructing similar macro-level indicators.

First, the emissions intensities and multipliers developed by the Organisation for Economic Co-operation and Development (OECD) consist of carbon dioxide (CO_2) emissions per monetary value of output, rather than per volume of output. These ratios are thus affected by two potentially confounding factors, namely inflation and exchange rate movements. A positive steady-state inflation rate may lead to a trend fall in the CFBL indicator, even if the emissions per unit volume of output were unchanged. This arises because the denominator would get larger over time due to the price effect. Exchange rate movements, on the other hand, may introduce noise and volatility. Future versions of the CFBL indicator could be based on a refined methodology to adjust for these effects.

Second, the emissions considered in the calculation of the CFBL indicator include exclusively CO_2 produced by fuel combustion related to production activities. This excludes emissions of other Kyoto gasses that are released by some production-related processes, such as calcination in the cement industry.[1]

Third, the approach used in the emissions multipliers version of the CFBL indicator, which leverages input–output (IO) tables, requires making certain assumptions. These include the implicit assumption of a fixed structure of production, no relative price movements, and no effect of budget constraints on the final demand. IO tables do not necessarily reflect the exposure to risks that would arise in a situation where the price of carbon, or carbon regulations themselves, were to change. Analyses based on IO multipliers tend to overestimate the impact of a change in the price of carbon emissions on a given sector.

Fourth, the CFBL is constructed using ISIC Rev. 4, a standard sectorization that is not designed to address environmental considerations. For example, Division 35 (electricity, gas, steam, and air conditioning supply) covers a large share of total emissions in every country, but it conflates renewables and fossil fuel technologies. Thus, during the transition to financing of renewable energy, higher investment levels could lead to an increase in the CFBL in the short term. For this reason, the CFBL requires a nuanced interpretation over short time frames. In the long term, it is assumed that transition to green technologies will yield lower carbon intensity and multiplier factors, which will eventually result in the overall reduction of the CFBL figures. Currently, there is no feasible alternative to ISIC that would help overcome the limitations discussed here. In contrast, among the benefits of classifying the data by ISIC is that not only were the loans data integrated with the emissions data, but this was also integrated with other macroeconomic data that would allow the development of additional indicators (for example, by integrating emissions data with employment data, it may be possible to estimate the number of jobs at risk from climate change transition risk).

[1] Cement is produced through crushing and burning limestone along with quartz and slate. When limestone is heated, a chemical process called calcination is initiated, where CO_2 is burned off the limestone. A significant portion of the emissions from the cement industry derive from the calcination process (see, for example, Tomatis and others 2020).

RESULTS

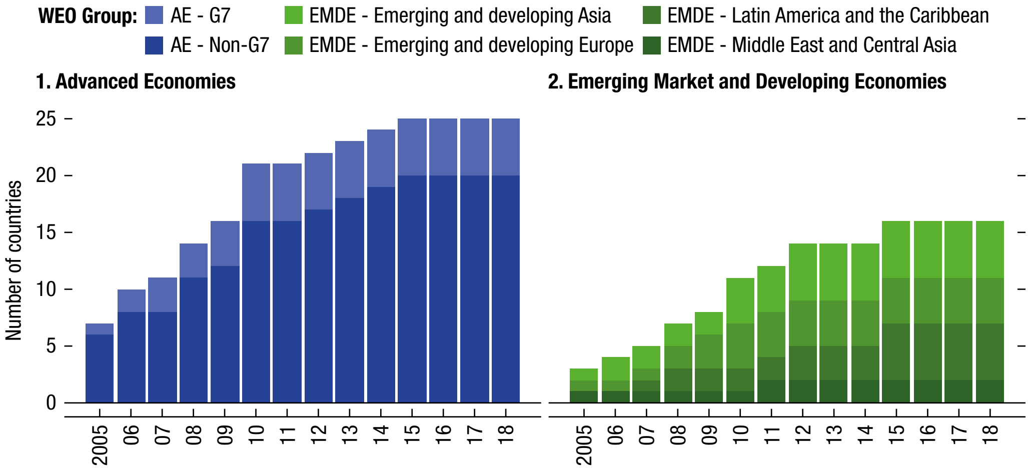
This section presents more detailed information on data coverage, as well as on the level and evolution over time of the carbon footprint indicator measured by the CFBL for 41 countries.[15]

Figure 7.2 shows the number of countries covered over the sample period and the breakdown by IMF WEO group.[16] Out of the 40 advanced economies, the CFBL was calculated for 25 for the period 2015–18. For emerging market and developing economies, the coverage is lower, with 16 countries covered during the same period. The figure shows improved country coverage for more recent years thanks to the greater availability of data for loans by industry.

[15] The historical coverage for the indicator is shorter for some countries in the sample due to lack of loans-by-industry data. Some relatively large emitters such as China, United Kingdom, and United States are not included.

[16] The World Economic Outlook (WEO) criteria are used to assign countries to groupings. At the highest level, a distinction is made between advanced economies and emerging market and developing economies. At a more granular level, the countries are then broken down by regional groups. The definition of the groups can be found in the World Economic Outlook Database April 2022—WEO Groups and Aggregates Information (imf.org).

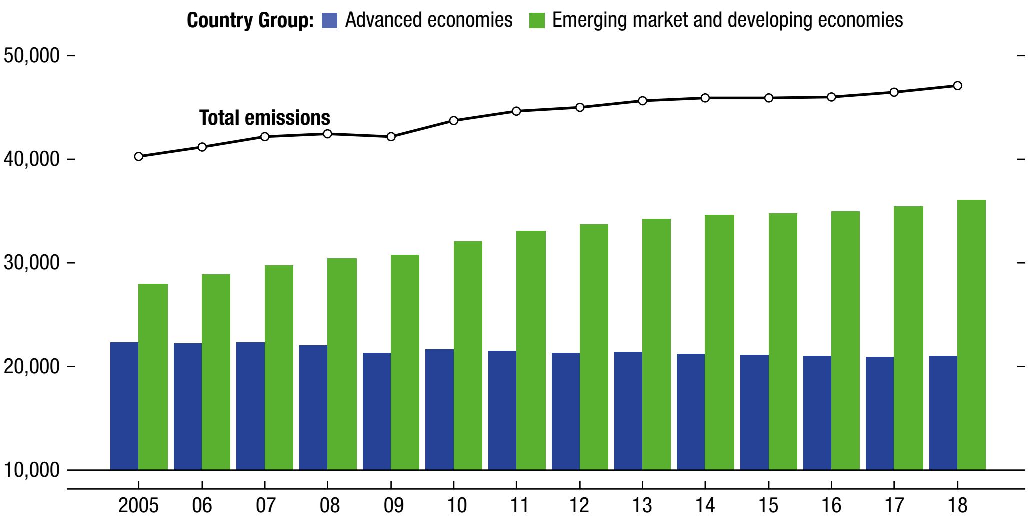
Figure 7.2. Coverage for the CFBL Indicator by Country Group



Source: IMF staff calculations.
Note: Country groups are defined in the Statistical Appendix to the April 2022 *World Economic Outlook* (WEO). AE = advanced economies; CFBL = Carbon Footprint of Bank Loans; EMDE = emerging market and developing economies; G7 = Group of Seven.

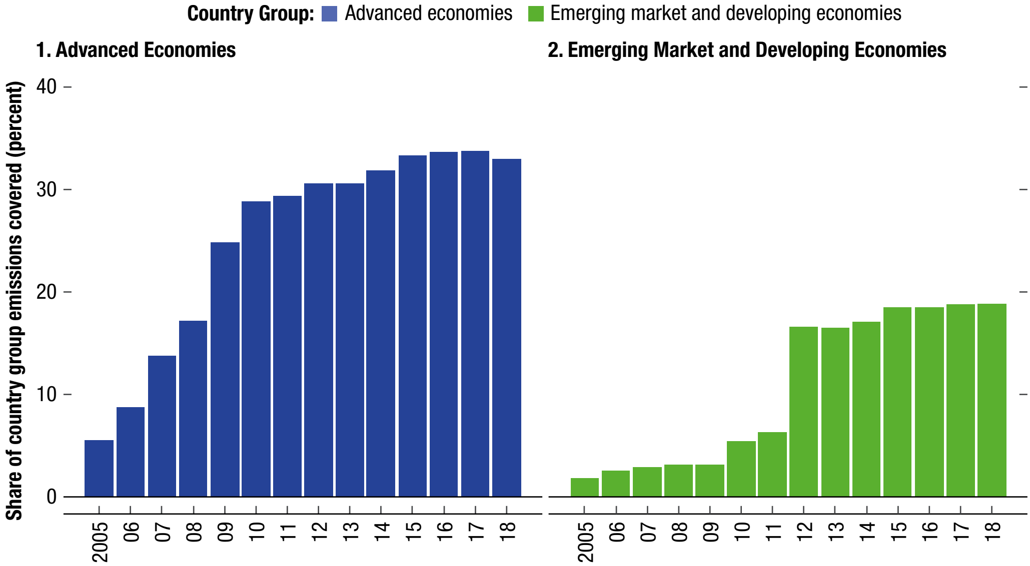
Figure 7.3 shows the total emissions produced globally by all countries, broken down into advanced economies and emerging market and developing economies. It shows a still increasing trend in the emissions for emerging market and developing economies and a decreasing trend in the emissions for advanced economies. As of 2018, the countries represented in this data set account for around 40 percent of total emissions of advanced economies and about 25 percent of total emissions of emerging market and developing economies (Figure 7.4). Emissions coverage for advanced

Figure 7.3. Total Global Emissions by Country Group
(Millions of tons of CO_2e)



Sources: IMF Climate Change Indicators Dashboard; and IMF staff calculations.
Note: Country groups are defined in the Statistical Appendix to the April 2022 *World Economic Outlook* (WEO). Bars represent the total emissions of all countries included in the major WEO groups—advanced economies and emerging market and developing economies—including the ones not covered in the full CFBL sample. The black line represents the total emissions of advanced economies and emerging market and developing economies combined. CFBL = Carbon Footprint of Bank Loans; CO_2e = carbon dioxide equivalent.

Figure 7.4. Coverage of the CFBL Indicator by Country Group



Sources: IMF Climate Change Indicators Dashboard; and IMF staff calculations.
Note: Country groupings are defined in the Statistical Appendix to the April 2022 *World Economic Outlook* (WEO). Bars represent the share of country group emissions coverage by the CFBL. CFBL = Carbon Footprint of Bank Loans.

economies stabilized around 2010, while for emerging market and developing economies it increased substantially when India joined the sample in 2012. To improve the emissions/regional coverage, it will be essential to include some of the large emitters, such as the United States, the Russian Federation, and China, as well as countries in the underrepresented regions, namely Africa, the Middle East and Central Asia, and Latin America.

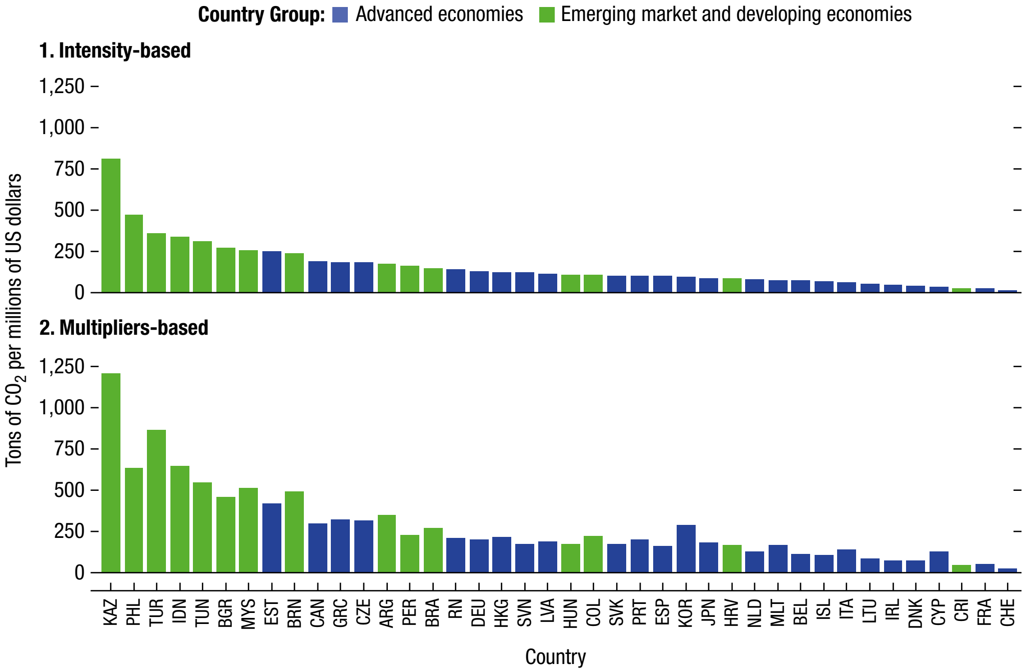
Figure 7.5 shows the CFBL indicator for individual countries in the sample in 2018.[17] The colors of the bars correspond to the breakdown between advanced economies (blue) and emerging market and developing economies (green). Panel 1 presents the intensities-based CFBL, and panel 2 shows the multipliers-based CFBL. The figure suggests that banking systems of emerging market and developing economies tend to have higher carbon footprints, and that the multipliers-based version of the indicator does not drastically change the ordering of countries but leads to significantly higher values of exposures across the board.

Figure 7.6 shows the evolution of the cross-country distribution of the CFBL over time. This information is available for a consistent set of 32 countries for the period 2010–18, of which 21 countries are advanced economies and 11 are emerging market and developing economies. Focusing on advanced economies, the figure reveals that the carbon footprint of loans has been slowly decreasing over time. This is in line with the recent trend that advanced economies have steadily transitioned away from manufacturing and shifted toward services sectors, which tend to have lower carbon emissions. In addition, some advanced economies have implemented policies that explicitly attempt to provide incentives to reduce carbon emissions and incentivize investments in green technologies. These factors all point to reduced exposure of the banking system to high-emitting sectors, as well as a generalized reduction in emissions intensity in advanced economies.[18]

[17] CFBL indicators for India are excluded from this chart, as well as from the CID, as the authorities requested not to disclose the data. These data are used in the charts showing distributions and/or regional groupings only.

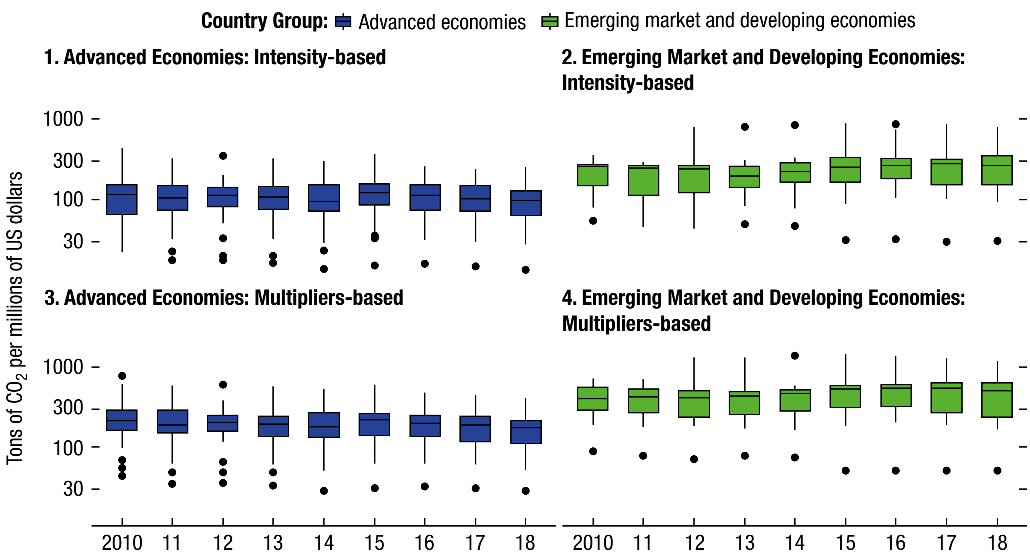
[18] As discussed in Box 7.3, the interpretation of the CFBL must consider the use of nominal values for the measurement of output, which could potentially induce a downward trend in the value of the indicator over time.

Figure 7.5. CFBL Indicator in 2018 for All Countries



Sources: IMF Climate Change Indicators Dashboard; and IMF staff calculations.
Note: Country groupings are defined in the Statistical Appendix to the April 2022 *World Economic Outlook* (WEO). Bars represent the value of the CFBL indicators in 2018. Country ISO3 codes are used on the *x*-axis, and observations are sorted in decreasing order according to the value of the intensities-based version of the CFBL indicator. CFBL = Carbon Footprint of Bank Loans; ISO3 = International Standards Organization three-letter country codes.

Figure 7.6. Carbon Footprint of Bank Loans—Boxplots by Year



Sources: IMF Climate Change Indicators Dashboard; and IMF staff calculations.
Note: Vertical axis is in logarithmic scale. Country groupings are defined in the Statistical Appendix to the April 2022 *World Economic Outlook* (WEO). For each year, the boxplot consists of a lower and an upper hinge, which correspond to the 25th and 75th percentiles; a bar representing the median; lower and upper whiskers, drawn to extend in each direction to 1.5 times the interquartile range. Any values of the CFBL above or below the whiskers are explicitly drawn as outlying points. The sample of countries is kept constant over time, and it consists of 21 advanced economies and 11 emerging market and developing economies. CFBL = Carbon Footprint of Bank Loans.

Turning to emerging market and developing economies (panels 2 and 4 of Figure 7.6), the data show no generalized reduction in the CFBL across the 11 countries included in the sample. The intensity- and multipliers-based versions of the CFBL exhibit broadly the same trend, while the levels of emissions intensity are markedly different, with the multiplier-based CFBL tending to be higher given that it also includes Scope 2 and 3 emissions. In addition, for both advanced economies and emerging market and developing economies, the cross-country dispersion of the multipliers-based version of the CFBL is generally higher, which points to significant cross-country variation in the degree of interdependence of the various sectors of the economies. While it is difficult to generalize these findings given the limited sample size, the CFBL indicators point to the importance of monitoring the trends and developments of transition risks to the financial sector.

The CFBL calculated for all countries in the sample, for the longest available period for each of them, is reported in Annex Figure 7.3.1. Panel 1 groups all advanced economies, while panel 2 groups all emerging market and developing economies. By and large, the CFBL reaches higher levels for emerging market and developing economies than for advanced economies. However, there are some notable cases of advanced economies, such as Estonia and Canada, having relatively high exposures of the financial sector to high-emissions sectors. For some of these countries, the financial sector has more indirect exposure to CO_2 emissions, stemming from the structure of IO linkages.

To compare rates of change across countries, Annex Figure 7.3.2 presents a normalized version of the CFBL indicator over time for each country, with the indicator set to 100 in 2015, the first year when the full sample is available. Most countries, regardless of income group, show a lower value in 2018 than they did in 2015, signaling a general reduction in exposures to high-emitting sectors or general reductions in emissions factors. However, this change is more marked for advanced economies, with some notable exceptions among emerging market and developing economies such as Croatia and Costa Rica.

DATA LIMITATIONS, GLOBAL INITIATIVES, AND THE WAY FORWARD

The IMF produced the CFBL indicator to provide a transparent and readily available tool for policymakers to gauge the carbon content of banks' loans and its evolution over time. Cross-country comparability was a paramount objective in this effort, and it influenced some of the choices made both on data collection and on the underlying compilation methodology of the indicator. There are currently no alternative indicators readily available with comparable cross-country coverage, especially for emerging market and developing economies.

As summarized in Box 7.3, the CFBL indicator has certain limitations. The IMF continues to update and improve the CFBL indicator as part of the wider CID project. Several improvements are under consideration, including a methodological update to reduce the noise induced in emissions intensities data by inflation and exchange rate fluctuations, as well as improvements in the underlying data that may be adjusted to reflect emissions of all Kyoto gasses.

More comprehensive analysis of transition risks would require granular data on domestic and cross-border bank-level exposures and firm-level emissions. In addition, dealing with the nonlinearities associated with climate change necessitates a forward-looking approach to measuring risks. Bridging the existing data gaps is essential in this regard, as is strengthening other aspects of the climate information architecture, including disclosures and taxonomies. Advances in these areas would help improve and develop indicators that better capture financial-sector exposure to transition risks. In light of this consideration, this section provides an overview of the ongoing work related to the climate information architecture and how such an architecture at the global level can help bridge the existing data gaps and enable policymakers and researchers to perform more comprehensive analysis of transition risks, including allowing for further refinement of the CFBL indicator and beyond.

Climate Information Architecture

There are several key considerations for improving the climate information architecture. First, a better understanding is needed of multiple market failures' inhibiting efficient levels of private climate investment, including large environmental externalities, lack of standards, informational costs, and country-specific risks. Second, closing data gaps, standardizing climate-related financial disclosures, and developing principles to align investments to sustainability goals will ensure a higher degree of interoperability and achieve at least a minimum degree of consistency across approaches around the world to help guide market participants and to reduce the risk of fragmentation in capital markets. Finally, a tailored and consistent climate information architecture framework could contribute to many of the objectives that are sought to effectively finance transition policies and manage risks stemming from climate change and other environmental concerns, including the fight against greenwashing practices and the efficient allocation of capital toward transition and low-carbon projects. To support the efforts to strengthen climate information architecture, the IMF published a Staff Climate Note, "Strengthening the Climate Information Architecture," in 2021 (IMF 2021). Box 7.4 summarizes its main takeaways.

There are many global initiatives that are currently under way with the aim of improving the climate information architecture. The success of these initiatives will help overcome limitations associated with climate change indicators, including the CFBL, thus enabling the design of effective measures to monitor risks to the financial sector stemming from climate change.

On data gaps, organizations and forums such as the NGFS, under its Bridging Data Gaps Workstream; the G20 sustainable finance working group, through its roadmap; and the FSB have made significant efforts to overcome data gaps. The NGFS Bridging Data Gaps Workstream has adopted a user-centric approach, informed by interactions with stakeholders from a wide range of geographies and areas of expertise. This approach—based on categorizing use cases, classifying metrics, and linking to data sources—allows for a systematic identification of data gaps and ways to bridge these gaps, including through climate-related disclosures. The TCFD has also published proposals enhancing and amending the TCFD framework, particularly around metrics related to transition risks, such as Scope 3 emissions, risks to value chains, and financed emissions (TCFD 2021). Further improvements and expansions to data, such as improving the availability of more granular information on exposures to high-carbon-emitting industries, availability of CO_2 emissions per volume of output, and availability of emissions of other Kyoto gasses, would benefit the future versions of the CFBL (see Box 7.3 for more details). Closing data gaps worldwide may also help expand the CFBL coverage to include large emitters that are currently excluded from the CFBL as well as countries in underrepresented regions.

Standardizing climate-related financial disclosures is important to support market discipline and to bridge some data gaps, which will ultimately improve the quality of indicators, including the CFBL. In this regard, the International Financial Reporting Standards (IFRS) Foundation is well placed to address the currently fragmented disclosure landscape and develop a global set of sustainability reporting standards. The IFRS Foundation established a new standard-setting board—the International Sustainability Standards Board (ISSB)—to develop baseline global sustainability reporting standards. An advantage of creating a body like the ISSB under the IFRS Foundation is that it establishes correspondence and consistency with the IFRS (accounting standards),[19] set by the International Accounting Standards Board (IASB) under the Foundation. Integrating sustainability reporting with traditional financial reporting will ensure consistency in valuation, measurement, and disclosure of sustainability (including climate)–related issues in corporate financial reporting. The ISSB is adopting a "building blocks" approach by working with standards setters from key jurisdictions to ensure that existing jurisdictional requirements for sustainability disclosures fit into the

[19] Over 160 jurisdictions globally require IFRS (accounting standards) for all or most publicly listed companies at the time the chapter was drafted.

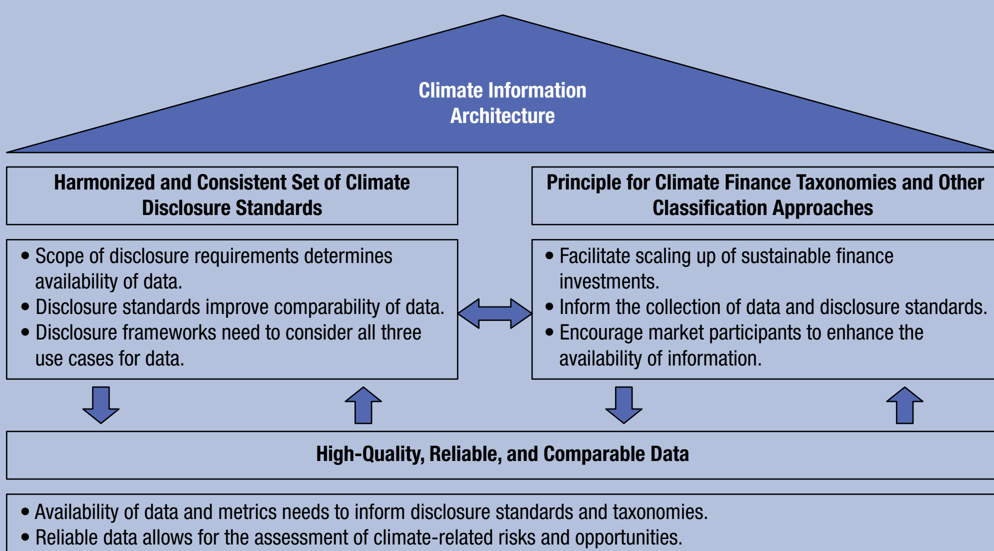
Box 7.4. Strengthening the Climate Information Architecture: Interconnected Pillars

A climate information architecture is a prerequisite to the development of a sustainable financial system. There are three interconnected building blocks that need to be improved to strengthen climate information architecture (see Figure 7.4.1). First, high-quality, reliable, and comparable data to assess risks and foster sustainable finance markets. Second, a harmonized and consistent set of climate disclosure standards. Third, globally agreed-upon principles for sustainable finance classifications, including taxonomies that align investments with climate goals.

There are multiple barriers creating climate-related financial information challenges. Many organizations and forums, including the Network on the Greening of the Financial System (NGFS) and the Financial Stability Board (FSB), have highlighted gaps on climate-related financial information and urge for more forward-looking granular data, as well as better verification and audit mechanisms. Moreover, the need to improve data accessibility remains important. However, there are major impediments, such as the costs of collecting and reporting information and the presence of multiple reporting frameworks. The "sustainability reporting" of climate change risks and opportunities by firms remains underdeveloped. The share of firms that disclose climate change–related metrics in line with the recommendations of the Task Force on Climate-Related Financial Disclosures (TCFD) is low. The multitude of existing frameworks undermines the consistency and comparability of data, increasing the cost and reducing the incentive for firms to disclose. Therefore, a coordinated international effort to develop a global standardized reporting framework is key to providing decision-useful information to investors, policymakers, and other stakeholders.

Sustainable finance classifications, including taxonomies, can help facilitate investments to mitigate climate change by providing investors with easy-to-interpret information, which allows scaling up sustainable finance markets. There are different approaches, such as taxonomies, labels, and other private-sector-led alignment approaches. Currently, regions, countries, and financial market participants sponsor different, separately developed sustainable finance alignment approaches. These classifications have different purposes, do not use consistent definitions, have varying levels of sophistication, and some even differ on their main objectives. This fragmentation of approaches can limit the usefulness of classifications for global investors and warrants an international effort to develop operational guidance to improve the comparability of approaches to align investments to sustainability goals.

Figure 7.4.1. Climate Information Architecture



Source: IMF (2021).

global baseline, while expanding the scope of disclosures. The ISSB has finalized a public consultation in July 2022 on its first two proposed standards (ISSB 2022a, 2022b), setting out general sustainability-related disclosure requirements and climate-related disclosure requirements. As mentioned in Box 7.2, the ISSB has proposed ways to standardize GHG disclosure of the reporting entities; this will improve the quality and comparability of future versions of the CFBL.

In consultation with standard-setters and other international bodies, the FSB published the "Roadmap for Addressing Climate Related Financial Risks" (FSB 2021). The areas of focus include climate-related financial disclosures, data, vulnerabilities analysis, and regulatory and supervisory practices and tools to address climate-related risks to financial stability. The roadmap supports international coordination by promoting relevant initiatives at standard-setting bodies, the NGFS, and other international organizations. By presenting relevant ongoing and planned international work in one place, it helps to identify gaps to be covered by further work, limits overlap, and promotes synergies. It sketches how the FSB can serve as a forum for discussing cross-sectoral and systemic issues and agreeing upon a way forward and provides input into broader international policy considerations by facilitating communication with the G20, G7, and the Conference of the Parties (COP) of the UNFCCC.[20]

Developing principles to align investments to sustainability goals could allow better appraisal of exposures even at the aggregate level. The International Platform for Sustainable Finance (IPSF) announced work toward a "Common Ground Taxonomy," highlighting the commonalities between the existing European and Chinese taxonomies as a first step. However, this is an area that remains less advanced, while global efforts, including those by the IMF, have started to pick up recently. With respect to the CFBL, improved classifications that are aligned to sustainability goals will allow the indicator to better respond to policy needs.

To summarize, efforts are ongoing at multiple international initiatives to address the foundational issues described in the three pillars to the climate information architecture, including disclosure standards and requirements, taxonomies and alignment approaches, and data gaps. These efforts will help strengthen the comprehensiveness of the future versions of the CFBL as well as other transition risks–related financial indicators.

Transition Risks Data for Climate Risk Analysis: The Need for Forward-Looking Analyses

An important aspect of transition risks is the fact that they are likely to materialize over extended time spans, possibly even beyond the horizons over which financial risk management is performed. Therefore, as discussed, the current or past risk exposures, as quantified by the GHG emissions of banks' or financial institutions' counterparties, may not fully reflect the actual risks faced. Hence, in addition to the progress needed in the climate information architecture, there is a need to take a forward-looking approach regarding the quantification of risks arising from the transition to a greener economy.

Recent efforts have been targeted at developing model-based emissions projections, which consider both company-level disclosed emissions and pledges and announced targets, as well as the climate scenarios that are likely to arise in the future. These climate scenarios have notably been adopted by the Intergovernmental Panel on Climate Change (IPCC) in their Representative Concentration Pathways (RCP), which provide projections of future global carbon emissions that are likely to arise as a response to possible policy actions. In turn, these RCP scenarios form the basis of projections by the NGFS, among others, which integrate the physical manifestations of climate change with consistent projections of the future evolution of the global economy in different policy scenarios.

[20] The Conference of the Parties (COP) of the UN Framework Convention on Climate Change (UNFCCC) is the supreme decision-making body of the convention, and it meets every year to discuss key policy issues related to climate change.

Scenario analyses pinpoint the tradeoffs that arise when considering alternative climate policy decisions. In addition to the baseline projection without any policy intervention, five alternate scenarios have been produced by the NGFS to explore different assumptions, such as different temperature targets, policy responses, and/or technology pathways. Orderly transition refers to a situation in which climate policies are introduced early and become gradually more stringent. Disorderly scenarios assume climate policies are not introduced until 2030. Finally, hot house world scenarios assume that only currently implemented policies are preserved. Both the timing and the scope of emissions reduction will be crucial to avert the negative consequences from transition and physical risks. For instance, delayed and disorderly carbon emissions reductions entail the postponement of the necessary policy action to achieve the transition to a low-carbon economy, which may lead to heightened transition risks in the future. Box 7.5 gives more detail on the current IMF approach to assess transition risks in its Financial Sector Assessment Programs (FSAPs), and on how incorporating scenario analyses and improving data availability may improve these risk assessments.

With these projections at hand, the CFBL indicator and other similar metrics could be augmented by a forward-looking component that is crucial to correctly identifying pockets of risk within the financial sector. Specifically, the IMF has recently undertaken efforts in this direction by procuring forward-looking transition risks data from vendors that assemble these projections based on information disclosed by companies both on realized emissions and on pledged emissions reduction targets. The next steps will include leveraging these new data to better gauge the overall risk to the financial sector in a forward-looking manner, including outside of the banking sector.

Box 7.5. IMF Approach to Transition Risks Analysis in Financial Sector Assessment Programs and Data Needs

Countries need effective policies to respond to economic and financial stability threats brought on by climate change and to harness opportunities for growth and job creation offered by the transition to a greener economy.

The IMF's financial sector assessment programs' framework for transition risks focuses on carbon taxes, both domestic and external, as the main source of transition risks.[1] While policies to support the transition to a low-carbon economy can take different forms (for example, subsidies to renewable energy production, caps on fossil-fuel-based power generation), the representation of transition risks as arising from the application of carbon taxes is a convenient, powerful, and relatively tractable assumption that mitigates modeling challenges of decarbonization scenarios. This assumption is also used by central banks and the Network for Greening the Financial System (NGFS) in the design of scenarios where "carbon prices are used as a proxy to represent the level of effort in mitigation policies" (NGFS 2021).

The framework is based on the idea that the introduction of increases in carbon taxation will increase the cost of carbon emissions, which will weigh on the financial performance of carbon-intensive firms, induce relative price shifts that disincentivize the nonrenewables sector, and promote the growth of renewables (especially if the carbon tax proceeds are invested in renewables)—all of which will have an impact on the wider economy and the financial sector. The financial sector will be impacted mostly via an increase in defaults or default rates of carbon-intensive companies, valuation losses on loan collaterals, and market losses on holdings of their bonds or equity shares. Transition risks can also arise from financial institutions' exposure to sovereign counterparts (for example, bonds issued by the governments of fossil fuel–producing countries) or households (for instance, loans to households burdened by the cost of adapting their properties to ambitious efficiency standards).

The approach starts with NGFS scenarios on emissions and temperature. The next step is to derive a carbon price to achieve specified emissions in different scenarios. Assessing the impact of carbon taxes directly on firms' balance sheets is next, which can be supplemented by the macro and sectoral effects of carbon taxes using macro and computable general equilibrium models. Finally, these impacts are translated into financial losses for financial institutions.

As highlighted in the main text, the most relevant data for transition risks analysis are the GHG emissions by country and industry or, ideally, at the firm level. However, current data disclosure is poor, reflecting the

Box 7.5 was prepared by Pierpaolo Grippa (IMF's Monetary and Capital Markets Department).

[1] The focus in this box is exclusively on the IMF framework. The World Bank has also been doing some work on the analysis of transition risks, focusing on the macro impact and collaborating with the IMF on a few occasions.

Box 7.5. (*continued*)

importance of closing the data gaps, of reducing the reliance on nonstandard nomenclatures, and of furthering the work of the NGFS on data and disclosure. Two important characteristics of emissions data are their scope and the time dimension:

1. **Scope.** Greenhouse gas (GHG) emissions are categorized as Scope 1, 2, or 3 (see Box 7.2 for details). While some firms disclose Scopes 1 and 2, currently the availability and quality of Scope 3 emissions disclosures are very limited. This issue is partially mitigated by looking at the economy at large and by using input–output matrices and general equilibrium models, which can leverage the information on Scope 1 emissions by tracking their impact on GHG intensity along the value chains and the shifts in demand and supply schedules triggered by changes in relative prices.
2. **Time dimension.** As explained in the main text, given the likely decades-long time span of the decarbonization process, the path of future (projected) emissions is a crucial piece of information for the analysis. However, only a limited number of firms disclose their emission-reduction plans. Moreover, the horizon of their projections is not necessarily as long as is needed for transition risks analysis, and their reliability is also uncertain (for example, because of the assumptions they use or doubts about the feasibility of their plans). Consequently, future emissions paths need to be estimated under different global or national decarbonization scenarios (as some data vendors do). This, however, introduces another layer of uncertainty to the overall analysis of transition risks.

While GHG emissions are the most important data source, other types of data can be relevant for the estimation of transitions risks (for instance, data on "green" patents, which can provide a sense of how prepared a country, economic sector, or single company can be in finding alternatives to existing GHG-intensive technologies).

CONCLUSION

Strengthening climate information architecture requires globally coordinated efforts from the public sector, private sector, and international organizations to reduce data gaps and strengthen disclosures and classifications.

In this regard, the NGFS Bridging Data Gaps Workstream (co-chaired by the IMF) has pioneered a constructive dialogue on important data issues. A progress report published in May 2021 has underlined persistent climate-related data gaps that hinder the achievement of climate finance objectives and has laid out three building blocks to bridge them under the triptych "disclosures, taxonomies and alignment approaches, metrics." The final report (NGFS 2022) makes actionable recommendations, building on initiatives, regulations, and policies that have emerged under the COP26 umbrella. Furthermore, the report notes that further steps are urgently needed to improve the quality, availability, and comparability of climate-related data through increased reporting requirements, sector-based methodologies, technological innovation, and intensified cooperation among financial regulators, financial institutions, and non-financial-sector stakeholders. All these recommendations are closely linked with the "climate data directory," which will help their successful implementation going forward.[21]

The BIS, IMF, OECD, and World Bank are also collaborating to develop operational guidance on the G20 high-level principles for sustainable finance alignment approaches, including taxonomies to improve the comparability of approaches to align investments with sustainability goals. In the context of the new G20 Data Gaps Initiative (new DGI), the IMF, in close cooperation with the Inter-Agency Group on Economic and Financial Statistics (IAG) and the FSB, has developed a draft workplan consisting of 14 recommendations, 7 of which are on climate change, to cover main

[21] The directory is a practical solution to help bridge data gaps identified by the NGFS' work. It is hoped that the directory will be used by financial-sector stakeholders and the public across all countries. It will be a living catalog of available climate-related data sources for financial-sector stakeholders. The directory is a public good and will need to be periodically updated. Its success lies in its wide use.

statistical and data priorities.[22] The new DGI is expected to make a substantial contribution to the climate change data architecture. Of particular interest for transition risks is Recommendation 5, which will be led by the IMF, with an aim to develop forward-looking physical and transition risks indicators for financial institutions and the wider economy.

Developing a science-based, tailored, and consistent climate information architecture is essential for reducing data gaps and helping to improve the comprehensiveness of future versions of climate indicators, including the CFBL. A strong climate information architecture contributes to many of the objectives that are sought to effectively finance transition policies and manage risks stemming from climate change and other environmental concerns. Lifting data constraints globally—including in emerging economies—is a policy priority in order to effectively develop sustainable finance markets. Indicators such as the CFBL can help guide policymakers in their decisions on climate change in the interim by identifying potential pressure points in banking systems to transition risks at the aggregate level.

[22] In their October 12–13, 2022, meeting, the G20 Finance Ministers and Central Bank Governors (FMCBGs) welcomed the workplan on the new Data Gaps Initiative and asked the International Monetary Fund, the Financial Stability Board, and the Inter-Agency Group on Economic and Financial Statistics to begin work on filling these data gaps.

ANNEX 7.1
BANK LOANS SURVEY DESCRIPTION

In late 2020, the IMF's Statistical Department approached 64 countries for which carbon emissions by industry are available to request deposit takers' domestic-loans-by-industry data for the period 2005–19. The authorities were asked to complete the schedule in Annex Table 7.1.1, which is based on ISIC structure. When the national implementation differed from ISIC classifications, the authorities were requested to submit mapping their data to ISIC classification on a best-effort basis. The authorities were also asked to provide additional metadata covering whether national implementation follows ISIC Rev 4, whether the calendar year is used for reporting, any estimation/approximation used, and the coverage for deposit takers.

ANNEX TABLE 7.1.1

Data Collection Template Used for Bank Loans Survey in 2020

Section / Division	Description	2005	…	2019
A	**Agriculture, forestry, and fishing**			
B	**Mining and quarrying**			
05	Mining of coal and lignite			
06	Extraction of crude petroleum and natural gas			
07	Mining of metal ores			
08	Other mining and quarrying			
09	Mining support service activities			
C	**Manufacturing**			
10	Manufacture of food products			
11	Manufacture of beverages			
12	Manufacture of tobacco products			
13	Manufacture of textiles			
14	Manufacture of wearing apparel			
15	Manufacture of leather and related products			
16	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials			
17	Manufacture of paper and paper products			
18	Printing and reproduction of recorded media			
19	Manufacture of coke and refined petroleum products			
20	Manufacture of chemicals and chemical products			
21	Manufacture of basic pharmaceutical products and pharmaceutical preparations			
22	Manufacture of rubber and plastics products			
23	Manufacture of other nonmetallic mineral products			
24	Manufacture of basic metals			
25	Manufacture of fabricated metal products, except machinery and equipment			
26	Manufacture of computer, electronic, and optical products			
27	Manufacture of electrical equipment			
28	Manufacture of machinery and equipment not elsewhere classified			
29	Manufacture of motor vehicles, trailers, and semitrailers			
30	Manufacture of other transport equipment			
31	Manufacture of furniture			
32	Other manufacturing			
33	Repair and installation of machinery and equipment			
D	**Electricity, gas, steam, and air conditioning supply**			
E	**Water supply; sewerage, waste management, and remediation activities**			

(*continued*)

ANNEX TABLE 7.1.1 *(continued)*

Data Collection Template Used for Bank Loans Survey in 2020

Section / Division	Description	2005	...	2019
F	**Construction**			
G	**Wholesale and retail trade; repair of motor vehicles and motorcycles**			
H	**Transportation and storage**			
I	**Accommodation and food service activities**			
J	**Information and communication**			
58	Publishing activities			
59	Motion picture, video, and television program production, sound recording, and music publishing activities			
60	Programming and broadcasting activities			
61	Telecommunications			
62	Computer programming, consultancy, and related activities			
63	Information service activities			
K	**Financial and insurance activities**			
L	**Real estate activities**			
M	**Professional, scientific, and technical activities**			
N	**Administrative and support service activities**			
O	**Public administration and defense; compulsory social security**			
P	**Education**			
Q	**Human health and social work activities**			
R	**Arts, entertainment, and recreation**			
S	**Other service activities**			
T	**Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use**			
U	**Activities of extraterritorial organizations and bodies**			
Unallocated				
Total				

Source: IMF staff based on United Nations Statistics Division.

ANNEX 7.2
A STYLIZED EXAMPLE OF CFBL CALCULATION

This annex provides a stylized example of how to calculate the CFBL indicator, with the aim to showcase the interpretation of the intensities- and multipliers-based versions for an extreme case that, while possibly not realistic, clearly highlights the rationale for introducing the two versions.

Suppose a closed economy consists of three sectors, S (services), E (energy), and M (manufacturing), as described in Annex Table 7.2.1. These sectors are interrelated in the sense that some of the output of one sector is used by others, as shown in the IO table below. It is also assumed that direct emissions intensities are given by $\boldsymbol{q}'^{direct} = (q_S, q_E, q_M)' = (50,500,300)'$, so that sector E has the highest emissions per unit of output, followed by sectors M and S. Assume that the banking sector provides loans exclusively to firms in sector S, so that loan concentration is 1 for S and 0 for both E and M. Suppose the E and M sectors rely only on internal financing (equity or retained earnings).

ANNEX TABLE 7.2.1

Input-Output Matrix for the Example Economy

		Intermediates			Final Demand	Production
		S	E	M		
Sectors	S	15	5	10	40	70
	E	2	0	6	2	10
	M	5	2	3	10	20

Source: IMF staff calculations.

The two versions of the CFBL indicator can be helpful to quantify the exposure of the banking sector to climate-related transition risks for this economy. When measured using the intensities-based CFBL indicator, the exposure of the banking sector through loans is 50 tons (t) of carbon dioxide equivalent (CO_2e)/million US$, equivalent to the direct emissions by Sector S, as it is the only sector directly financed by banks.

However, the presence of IO linkages may significantly alter this risk assessment. If regulations were imposed to significantly curtail or tax emissions in the M and E sectors, this could still lead to losses in S, insofar as services are used as an input in the production of M and E. In this case, the multipliers-based version of the CFBL would lead to a higher value for the emissions content of the loans of the banking sector. To see this, one can compute the Leontief inverse matrix, associated with Annex Table 7.2.1, and denoted by $\boldsymbol{L}$, obtaining

$$\boldsymbol{L} = \left(I - \underbrace{Z\hat{x}^{-1}}_{A}\right)^{-1} = \left(\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} - \begin{pmatrix} 15 & 5 & 10 \\ 2 & 0 & 6 \\ 5 & 2 & 3 \end{pmatrix}\begin{pmatrix} 1/70 & 0 & 0 \\ 0 & 1/10 & 0 \\ 0 & 0 & 1/20 \end{pmatrix}\right)^{-1} \approx \begin{pmatrix} 1.41 & 0.94 & 1.16 \\ 0.08 & 1.13 & 0.45 \\ 0.14 & 0.34 & 1.38 \end{pmatrix},$$

where Z represents the matrix of IO linkages, $\hat{x}^{-1}$ is the diagonal matrix constructed from the inverses of final production in each sector, and A is the so-called technical coefficients matrix obtained from multiplying Z and $\hat{x}^{-1}$. With this matrix at hand, it is straightforward to compute the multipliers-based version of the CFBL indicator by first computing the multipliers-based emissions intensities,

$$\boldsymbol{q}'^{total} = \boldsymbol{q}'^{indirect} + \boldsymbol{q}'^{direct} = \boldsymbol{q}'^{direct}\boldsymbol{L} = (50,500,300)\begin{pmatrix} 1.41 & 0.13 & 0.33 \\ 0.57 & 1.13 & 0.89 \\ 0.48 & 0.17 & 1.38 \end{pmatrix} \approx (152.9,715.5,695.4),$$

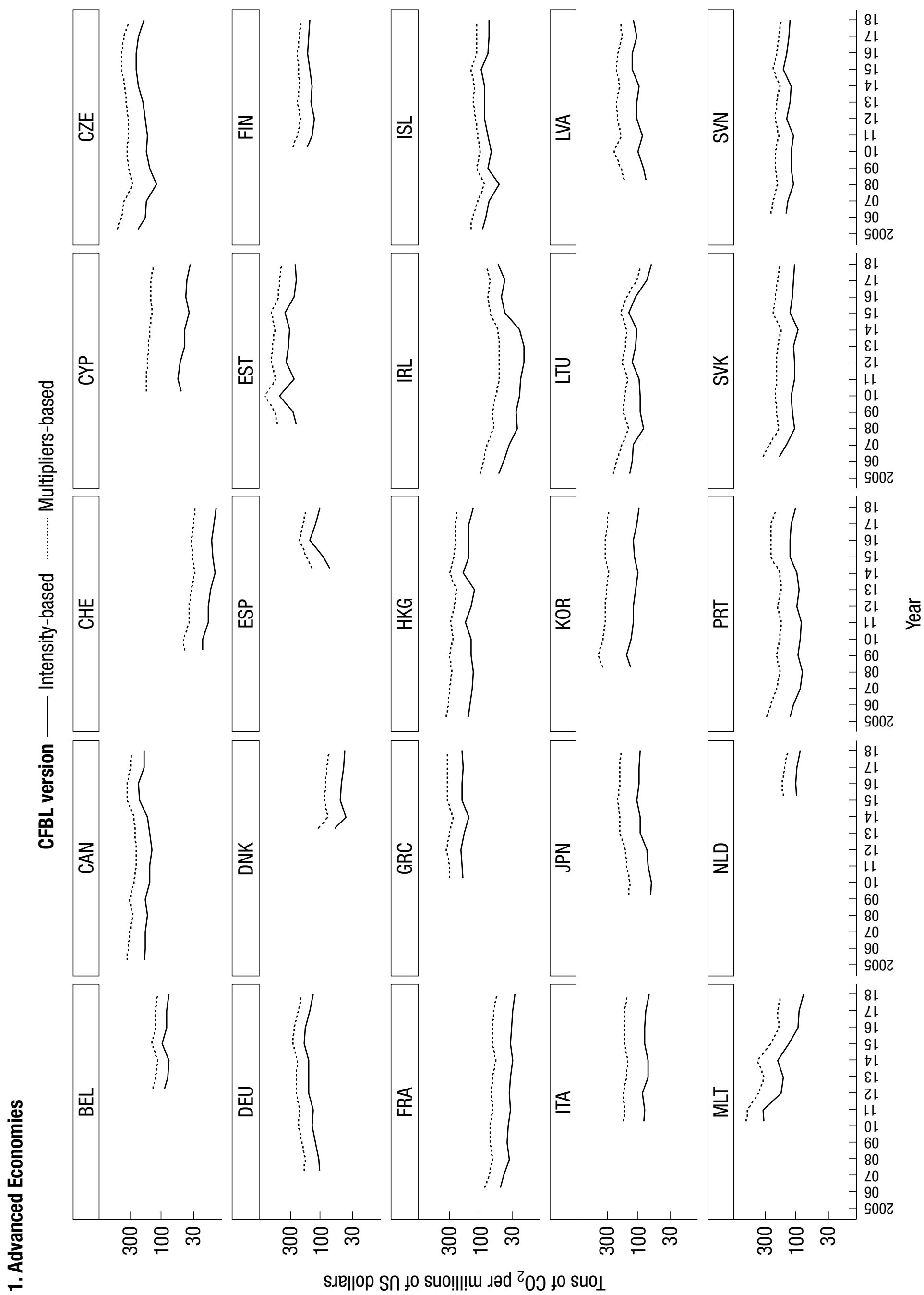
and then applying the formula in the main text to obtain a value of CFBL of ≈152.9 tCO_2e/$m for sector S, which is significantly higher than the CFBL figure based only on direct emissions (50 tCO_2e/$m).

ANNEX 7.3

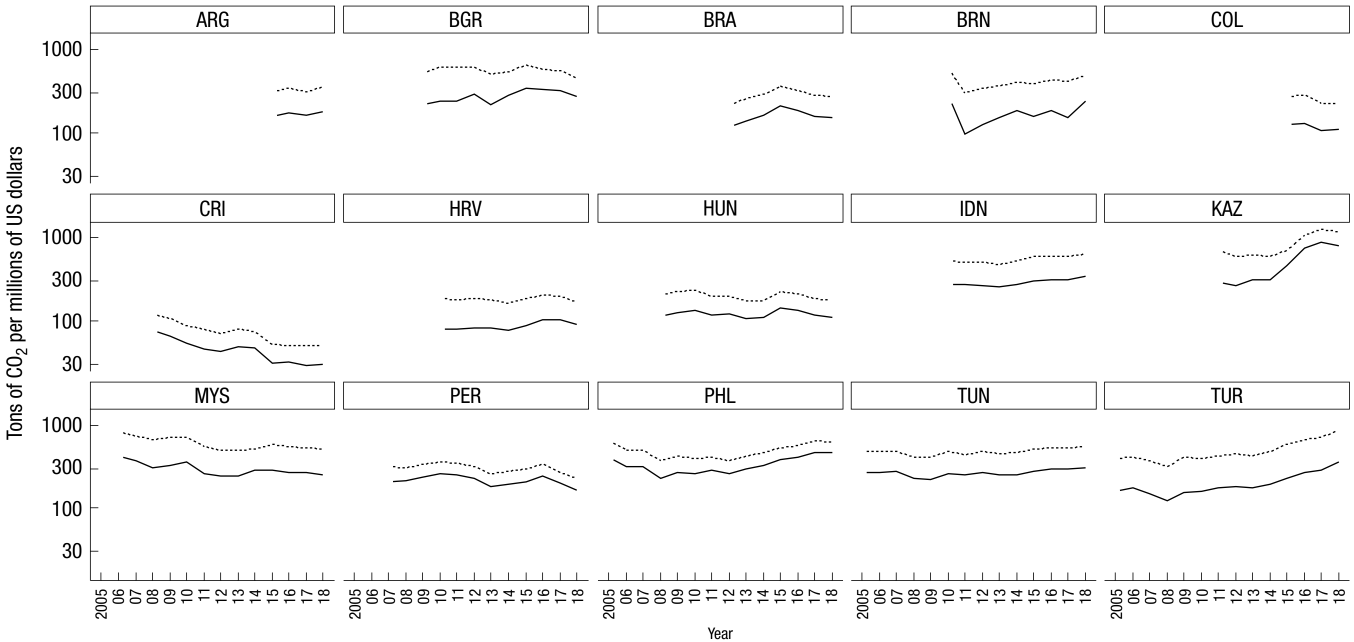
CFBL ADDITIONAL FIGURES

This annex shows the complete time series of the CFBL indicators for all countries for which these could be calculated and that agreed to publishing. ISO3 country codes from April 2022 WEO are used (IMF 2022a).

Annex Figure 7.3.1. Carbon Footprint of Bank Loans—Raw Indicator



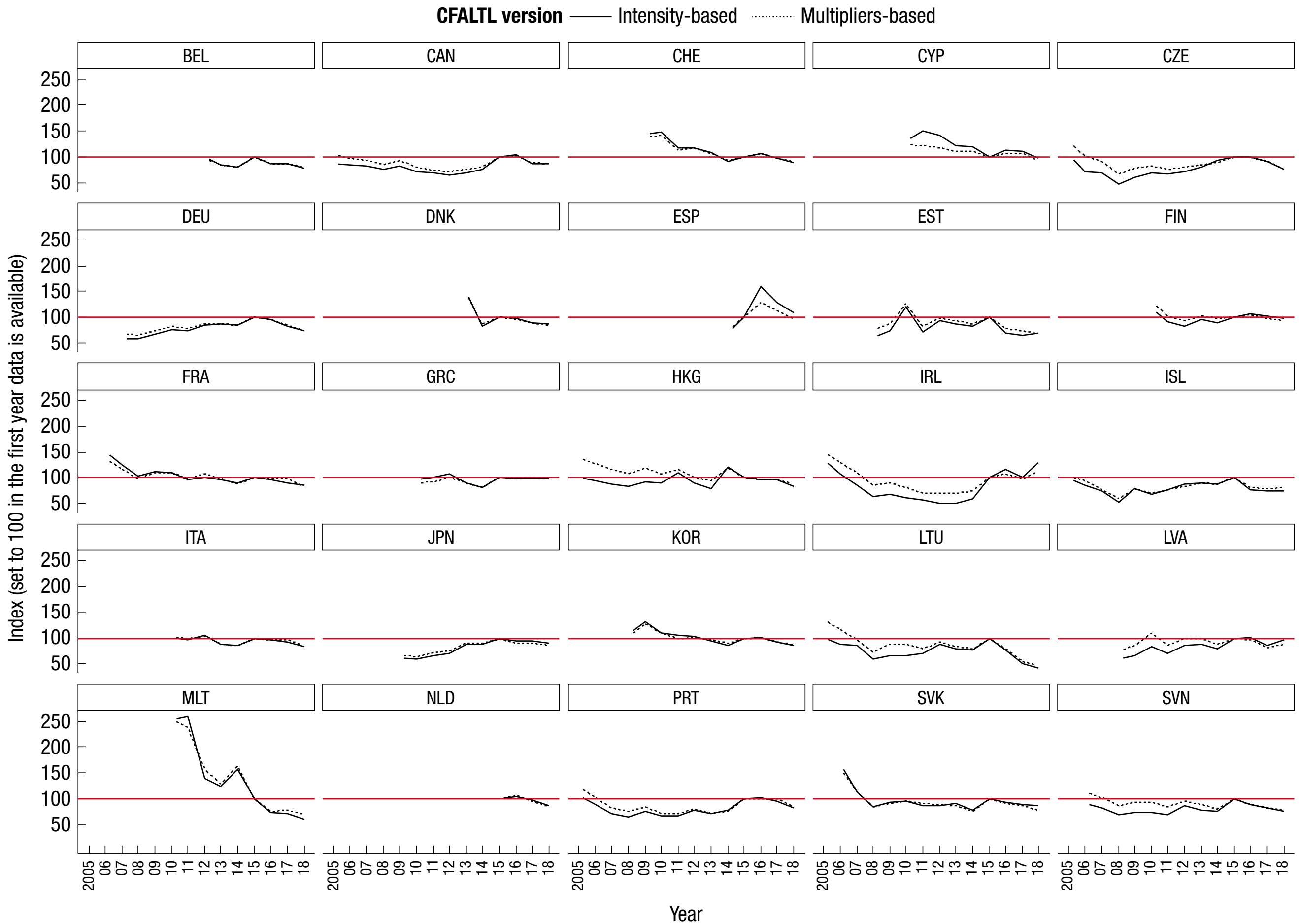
2. Emerging Markets and Developing Economies



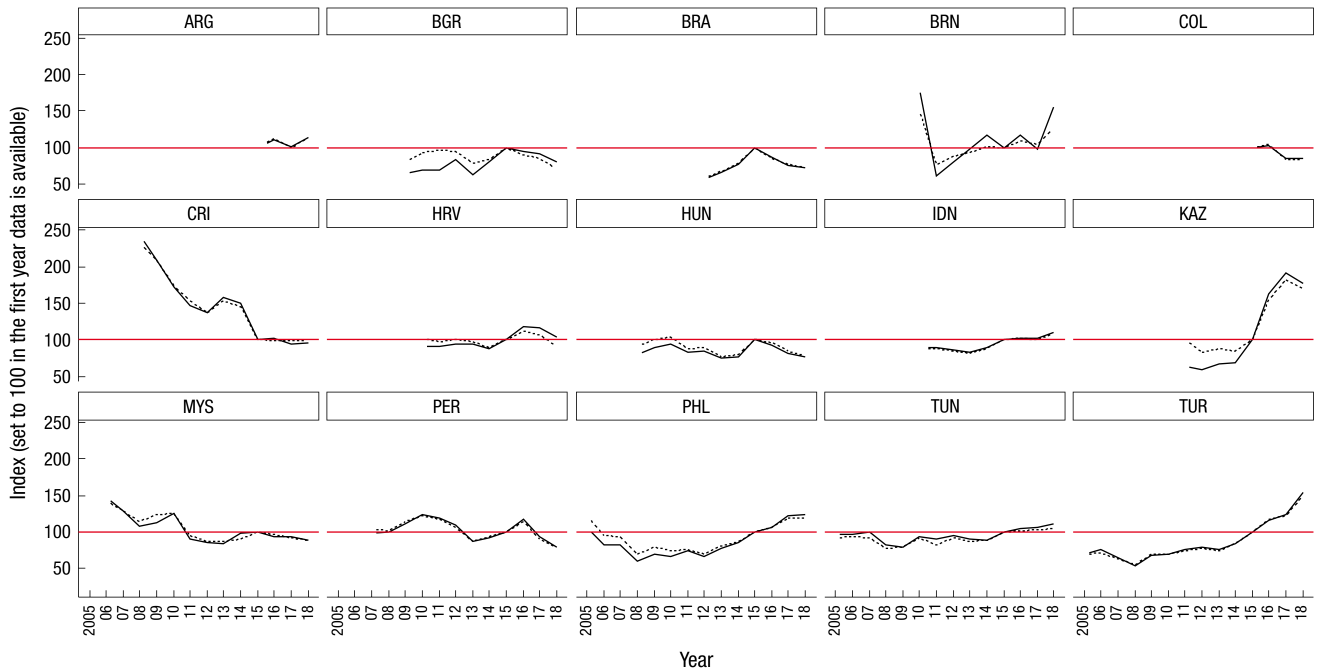
Source: IMF staff calculations.
Note: Vertical axis is in logarithmic scale. Country groupings are defined in the Statistical Appendix to the April 2022 *World Economic Outlook* (WEO). Data labels in the figure use International Organization for Standardization (ISO) country codes. CFBL = Carbon Footprint of Bank Loans.

Annex Figure 7.3.2. Carbon Footprint of Bank Loans—Normalized

1. Advanced Economies



2. Emerging Markets and Developing Economies



Source: IMF staff calculations.
Note: Index set to 100 in 2015 for all countries. Country groupings are defined in the Statistical Appendix to the April 2022 *World Economic Outlook* (WEO). Data labels in the figure use International Organization for Standardization (ISO) country codes. CFALTL = carbon footprint-adjusted loans to total loans.

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CHAPTER 8

Measuring CO_2 Emissions of Foreign Direct Investment

Maria Borga, Kenneth Egesa, Dmitrii Entaltsev, Gregory Legoff, Achille Pegoue, and Alberto Sanchez Rodelgo

Is foreign direct investment (FDI) helping to address climate change, or is it a way to circumvent tighter emissions standards? This chapter presents a statistical framework for estimating the carbon emissions associated with FDI in host economies. There are two sets of estimates available at the International Monetary Fund's Climate Change Indicators Dashboard. The first measures carbon emissions from the capital formation financed by FDI—from, for example, constructing new plants and equipment. The second measures direct and indirect carbon emissions from the production of foreign-owned firms. We find that the carbon intensity of capital formation financed by FDI has decreased and is smaller than the carbon emissions from the ongoing operations of multinational enterprises (MNEs). High emissions intensities by MNEs are accompanied by high export intensities in mining, transport and storage, and manufacturing industries. The quality of the estimates could be improved, including by developing statistics to identify carbon emissions by MNEs.

INTRODUCTION

The impact of foreign direct investment (FDI) on host economies, particularly on their carbon emissions, is complex.[1] FDI can affect carbon emissions by (1) increasing the scale of economic activity, (2) contributing to demand for addressing climate change, and (3) diffusing low-carbon knowledge and technology across borders.

One potential benefit of FDI for the host economy is expanded productive capacity and greater production that would generally emit greenhouse gases (GHGs), even if the foreign investor used lower-carbon technologies; the impact on global emissions would depend on whether the increased production was in addition to or replaced production elsewhere. If demand for environmental quality increases as incomes rise (the environmental Kuznets curve argument[2]), then, as FDI increases incomes, it will increase environmental demand in host economies. Another view is that FDI is usually associated with higher carbon emissions, especially in low-income economies because such economies tend to set lower pollution standards to attract resource-seeking FDI ("pollution havens").[3] Yet another view is that FDI is cleaner than domestic investment because it deploys new technologies that are cleaner than domestic producers, thus supporting improvements in the

[1] FDI is a form of cross-border investment in which an investor resident in one economy establishes a lasting interest in and a significant degree of influence over an enterprise resident in another economy. Ownership of 10 percent or more of the voting power is evidence of an FDI relationship, as defined in the IMF's *Balance of Payments and International Investment Position,* 6th edition, paragraphs 6.8 and 6.12, and the OECD's *Benchmark Definition of Foreign Direct Investment,* 4th edition, paragraph 11.

[2] See Kuznets 1955; Grossman and Krueger 1991; Cole, Raynor, and Bates 1997; and Dinda 2004.

[3] See Zhu, Duan, Guo, and Yu 2016; Lee 2013; Shahbaz, Balsalobre-Lorente, and Sinha 2019; Mabey and McNally 1999; Seker, Ertugrul, and Cetin 2015; and Shao 2018.

environment of the host economy.[4] Such "pollution halos" would reduce carbon emissions through better management, adherence to higher standards, and use of better technology; in short, FDI is an important channel for the transfer of low-carbon technology across borders.[5]

This chapter contributes to this debate by developing a statistical framework to estimate the contributions of FDI to carbon emissions in host economies.[6] The framework relies on industry-level information on production, trade, investment, and carbon emissions, and distinguishes between multinational enterprises (MNEs) and domestically owned enterprises. Estimates of carbon emissions are derived directly from the investment and production activities of MNEs, as well as from their indirect emissions (for example, their use of electricity generated within the host economy). Avenues are also provided for future work to address data limitations.

The estimates can help to answer the following questions:

1. What is the effect on carbon emissions of FDI that finances investments in new productive capacity, such as new plants and equipment?

   A first set of indicators, namely *carbon emissions embodied in gross fixed capital formation*[7] *funded by FDI* in the host economy, examines the financing role of FDI. FDI flows are often used for new investments (greenfield investments) and/or for extensions of capacity of existing enterprises. Each of these investment activities results in gross fixed capital formation in the host economy, which is associated with carbon emissions in the industries that supply the products that go into such capital formation.

2. What is the contribution to emissions from the operations (that is, economic activity) of foreign-owned enterprises (hereafter MNEs) in host economies?

   The second set of indicators, namely *carbon emissions in MNE output*, provides estimates of emissions from the ongoing operations of MNEs in the host economy. We also develop comparable estimates of carbon emissions from operations of domestically owned enterprises.[8]

3. Does the production of MNEs, as well as the emissions embodied in that production, meet domestic demand, or is it exported to meet foreign demand?

   The third set of indicators, namely *carbon emissions embodied in gross exports of MNEs*, assesses the effect of MNEs on emissions in the host economies by offshoring production of goods that ultimately end up being sold to third economies through exports. For example, some of the emissions generated by a relatively poor economy whose emissions embodied in their production are higher than the emissions embodied in their consumption may result from the activities of MNEs. This could be especially true if these MNEs have located carbon-intensive stages of productions in host economies and then export the final production to relatively rich economies.

The indicators derived from the framework indicate that the expansion of productive capacity resulting from FDI (for example, gross fixed capital formation financed by FDI) contributes to carbon emissions in the host economy, but they may have actually fallen relative to FDI flows. Still, carbon emissions from the ongoing operations of MNEs are larger than those associated with their capital formation. At the industry level, manufacturing; transport and storage; and electricity, gas, and water had the highest overall emissions and emissions intensities among MNEs. A comparison between

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[4] See Blackman and Wu 1999; and Zarsky 1999.

[5] See Pigato and others 2020.

[6] The framework is described in Borga, Pegoue, Legoff, Sanchez Rodelgo, Entaltsev, and Egesa 2022.

[7] Gross fixed capital formation is the acquisition of assets that are intended to be used in the production of goods and services for a period of more than one year less the disposal of such assets. It is limited to produced assets (that is, assets that result from a production process) and thus excludes nonproduced assets, such as land and natural resources. It includes purchases of secondhand assets as well as production of such assets by producers for their own use.

[8] In the data source used in the estimates presented later in this chapter, domestically owned enterprises include both the parent companies of domestic-owned MNEs (that is, MNEs headquartered in the economy with affiliates in other economies) as well as enterprises that only operate domestically. Data do not allow one to distinguish between these two concepts.

MNEs and domestically owned enterprises shows that the latter generally had higher carbon intensities, but there were a few cases in low-carbon-intensive economies where MNEs had higher carbon intensities.[9] MNEs also tend to have higher export intensities than those of domestically owned enterprises; high emissions intensities of MNEs are accompanied by high export intensities in mining, transport and storage, and manufacturing industries.

The chapter is organized as follows. The first section presents the methodology and data used for developing the indicators. The subsequent section discusses data limitations and efforts to address them. The next section presents key results, and the final section concludes with policy implications and potential areas of further research.

METHODOLOGY AND DATA USED

Estimating Carbon Emissions Embodied in Gross Fixed Capital Formation

Foreign direct investment (FDI) expands production capacity in the host economy through greenfield investments as well as new investments in existing operations. These include new buildings, infrastructure, machinery, and equipment, which are measured in gross fixed capital formation. Carbon emissions are generated by the production units involved in the creation of gross fixed capital formation.

The first set of indicators aims to estimate the total amount of carbon emissions that result from the creation of the fixed assets that go into gross fixed capital formation by the respective production units located in the host economy. We refer to this set of indicators as carbon emissions embodied in gross fixed capital formation funded by FDI.

The methodology for estimating these indicators involves, first, determining the carbon emissions embodied in the production of industries that is used in capital formation by using input–output tables combined with emissions data and then apportioning the emissions between those funded by FDI and those funded from other sources. Direct emissions are based on International Energy Agency (IEA) estimates of carbon emissions from fuel combustion during production, using IEA energy data and the default methods and emissions factors from the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories (IEA 2020).[10]

To determine the carbon emissions embodied in supplies to gross fixed capital formation, CO_2 emissions multipliers are used that include both direct emissions from fuel combustion as well as indirect emissions embodied in inputs (for example, emissions generated to produce cement used as an input for the construction of buildings). CO_2 emissions multipliers are measured as CO_2 emissions per unit of output. The output of each industry supplied for final use in gross fixed capital formation is multiplied by the CO_2 emissions multipliers to estimate total emissions (both direct and indirect) from capital formation. These estimates are then multiplied by the estimated amount of capital formation financed by FDI to derive the estimates of carbon emissions embodied in gross fixed capital formation funded by FDI. Specifically, this process involves the following:

Step 1—Obtain information on the total emissions emitted during production for each industry for each economy.

[9] Due to data limitations, it is assumed that all firms in the same industry have the same carbon intensities; therefore, the differences in carbon intensity between MNEs and domestically owned enterprises are the result of differences in industry distributions and sourcing behavior.

[10] The IEA uses the simplest (Tier 1) methodology to estimate carbon dioxide (CO_2) emissions from fuel combustion based on the 2006 guidelines (https://www.ipcc.ch/site/assets/uploads/2019/05/01_2019rf_OverviewChapter.pdf). The computation follows the concept of conservation of carbon from the fuel combusted into CO_2. Generally, the Tier 1 estimation of CO_2 emissions from fuel combustion for a given fuel can be summarized as the product of fuel consumed and an emissions factor. Emissions are then summed across all fuels consumed for each industry.

Step 2—Calculate the direct emissions intensity (C^{direct}) during production for each industry by dividing total emissions for each industry by its output.

Step 3—Estimate the total carbon emissions coefficients for the direct and indirect emissions from various industries by using estimates of direct carbon emissions coefficients and respective domestic input coefficients obtained from input–output tables:

$$C^{total} = C^{direct}(I - A)^{-1} \tag{8.1}$$

where C^{total} denotes a $(1 \times n)$ vector of total emissions coefficients of direct and indirect emissions; C^{direct} is a $(1 \times n)$ vector of direct emissions coefficients; A is the $(n \times n)$ input coefficient matrix of the input–output table; I is the $(n \times n)$ identity matrix, and n is the number of industries. Thus, $(I - A)^{-1}$ is the $(n \times n)$ Leontief inverse matrix.[11]

Step 4—Estimate total carbon emissions associated with gross fixed capital formation by adapting the central equation system of input–output analysis through multiplying the total carbon emissions coefficients derived for each industry by their respective supply for final use in gross fixed capital formation (GFCF):

$$Carbon\ emissions\ of\ GFCF = C^{total} \times final\ use\ in\ GFCF \tag{8.2}$$

Step 5—Apportion the total emissions associated with gross fixed capital formation of FDI by multiplying the share of FDI in capital formation by the total emissions derived by equation 8.2.

$$Carbon\ emissions\ of\ GFCF\ of\ FDI = C^{total} \times final\ use\ in\ GFCF \times {}^{FDI}\!/_{GFCF} \tag{8.3}$$

To enable meaningful comparability between industries and across economies, industry-level estimates of carbon emissions embodied in the production of industries that is used in gross fixed capital formation funded by FDI are divided by the respective industry-level final demand[12] for domestic products, which are derived from the input–output tables.

Estimating Carbon Emissions in MNE Output

FDI can increase the scale of economic activity in the host economy, increase export diversification, and lead to structural changes in the economy by introducing new industries. These production activities generate carbon emissions in the host economy. Data on the activities of MNEs make it possible to establish the operations of a subset of FDI enterprises where direct investors have control.[13] The OECD Analytical Activities of Multinational Enterprises (AMNE) database (see the section "Use of the Intercountry Input-Output Tables") is used to track the production activity of these MNEs and domestically owned enterprises over time for individual industries in each economy in the sample to derive respective estimates of emissions associated with their production activity.

First, the total carbon emissions coefficient of direct and indirect emissions is estimated using the Leontief inverse matrix of the intercountry input–output (ICIO) requirement matrix, as shown in equation (8.4). This matrix produces direct and indirect output multipliers of economies' MNEs and domestically owned enterprises (DOEs) by industry, under the assumption that a single matrix merging them reflects the relationships within and between MNEs and domestically owned enterprises:

$$C^{total}_{MNEs\ \&\ DOEs} = C^{direct}_{MNEs\ \&\ DOEs}\left(I - A_{MNEs\ \&\ DOEs}\right)^{-1} \tag{8.4}$$

[11] For a description of the methodology used to derive the CO_2 emissions intensities and CO_2 emissions multipliers, see "Note on CO_2 Emissions, Intensities, and Multipliers" (June 2022).

[12] Final domestic demand consists of final consumption (for example, by households, nonprofit institutions, and government), gross fixed capital formation, changes in inventories, and direct purchases abroad by residents.

[13] That is, the data on MNEs cover only control relationships defined as owning over 50 percent of the voting power in the enterprise, while FDI covers both control and influence relationships defined as owning 10–50 percent of the voting power.

where $C^{total}_{MNEs\ \&\ DOEs}$ denotes a $(1 \times n)$ vector of total (direct and indirect) emissions coefficients, A is the $(n \times n)$ requirement matrix estimated from the ICIO, I is the $(n \times n)$ identity matrix, $(I - A_{MNEs\ \&\ DOEs})^{-1}$ is the $(n \times n)$ Leontief inverse matrix for MNEs and domestically owned enterprises, n is the product of the number of economies and the combined number of industries for MNEs and domestically owned enterprises, and C^{direct} is calculated as above.

C^{total}*MNEs & DOEs* is further split into C^{total}*MNEs* and C^{total}*DOEs* for each economy and industry. This breakdown allows the estimation of carbon emissions in the output of MNEs and domestically owned enterprises for final demand (FD) of economies' industries:

$$Carbon\ emissions\ in\ MNEs\ Output\ for\ FD = C^{total}_{MNEs} \times MNEs\ Output\ for\ FD \quad (8.5)$$

$$Carbon\ emissions\ in\ DOEs\ Output\ for\ FD = C^{total}_{DOEs} \times DOEs\ Output\ for\ FD \quad (8.6)$$

Estimating Carbon Emissions Embodied in Gross Exports of MNEs and of Domestic Firms Embodied in Exports

MNEs tend to have higher export intensities than domestically owned enterprises,[14] including from their role in the creation and management of global value chains and their propensity to be more productive and innovative. The production of exports contributes to carbon emissions in the host economy, although such emissions are embodied in products that satisfy foreign rather than domestic demand. We estimate the emissions associated with MNE exports using data on reported exports from host economies by industry. We also estimate emissions associated with exports of domestically owned enterprises for comparison purposes:

$$Carbon\ emissions\ of\ Exports\ of\ MNEs = C^{total}_{MNEs} \times Exports\ of\ MNEs \quad (8.7)$$

$$Carbon\ emissions\ of\ Exports\ of\ DOEs = C^{total}_{DOEs} \times Exports\ of\ DOEs \quad (8.8)$$

Use of the Inter-Country Input–Output Tables

The AMNE database provides a matrix of the transactions of domestically owned and multinational enterprises in 59 economies plus the rest of the world in the host economy.[15] The matrix covers 34 industrial sectors over the period 2005–2016. There are four main elements in the AMNE database: the intermediate consumption matrix, the final demand matrix, the value-added vector, and the gross output vector. Figure 8.1 provides a compressed extract that shows the intermediate consumption matrix in the shaded parts for illustrative purposes. Cells in columns correspond to an economy's/sector's inputs by ownership; cells in rows correspond to the output of an economy/sector by ownership. Gross output of each economy is equal to the sum of rows and final demand, or the sum of columns and value added. The shaded part shows how each cell of the intermediate consumption matrix for each sector is divided into four cells corresponding to the inputs used by domestically owned firms from domestic and foreign-owned firms and inputs used by foreign-owned firms from domestic and foreign-owned firms. The final demand matrix is split across rows to reflect the demand of products from domestically owned and foreign-owned firms. The value-added and gross output vectors are split across columns to indicate the value added and gross output of domestically owned and foreign-owned firms in each economy and sector.

Table 8.1 summarizes the data used in producing the estimates. The data support estimates of the first indicator from 2005 to 2018 and for the second and third indicators from 2005 to 2015.

[14] Domestically owned enterprises also include the parent companies of domestically owned MNEs. These companies would be more similar to foreign-owned MNEs than to enterprises that operate only domestically.

[15] See https://www.oecd.org/sti/ind/analytical-AMNE-database.htm#database and Cadestin and others 2018.

Figure 8.1. Structure of the Analytical AMNE Tables for Each Year for a Single Economy

			Country 1				Country 2				Country 1	Country 2
			Sector 1		Sector 2		Sector 1		Sector 2		Final Demand	Final Demand
			Dom	For	Dom	For	Dom	For	Dom	For		
Country 1	Sector 1	Dom										
		For										
	Sector 2	Dom										
		For										
Country 2	Sector 1	Dom										
		For										
	Sector 2	Dom										
		For										
Value-added												
Gross output												

Source: Organisation for Economic Co-operation and Development Analytical AMNE database.
Note: AMNE = Activities of Multinational Enterprises.

TABLE 8.1

Data Sources

Data	Source	Period Used in the Analysis
Carbon emissions	IEA production-based emissions	2005–18
Output	OECD National Accounts database	2005–18
Input coefficients	OECD Input–Output database	2005–18
Gross fixed capital formation	OECD National Accounts database	2005–18
Inward FDI of non-SPEs	OECD FDI financial flows database	2005–18
Final demand	OECD Input–Output database	2005–18
MNE and DOE final demand	OECD Analytical AMNE database	2005–15
MNE and DOE exports	OECD Analytical AMNE database	2005–15
MNE and DOE input coefficients	OECD Intercountry Input–Output Tables from the Analytical AMNE database	2005–15

Source: Authors' compilation.
Note: Annual data on carbon emissions are generally available about nine months after the reference year; annual data on output and gross fixed capital formation are available generally about three months after the reference year; the OECD FDI financal flows database by industry is generally available nine months after the reference year; the OECD Input–Output database and Intercountry Input–Output database released in November 2021 have data through 2018; and the OECD Analytical AMNE database released in June 2017 has data through 2015. AMNE = Activities of Multinational Enterprises; DOE = domestically owned enterprise; FDI = foreign direct investment; IEA = International Energy Agency; MNE = multinational enterprise; OECD = Organisation for Economic Co-operation and Development; SPE = special-purpose entities.

Data and Methodological Limitations and Ways to Improve them

Estimating the three indicators reveals several data limitations. While some of these were overcome by making assumptions, addressing them would improve the analytical value of these estimates.

Carbon Emissions Embodied in Gross Fixed Capital Formation Funded by FDI

The main limitation is that the total FDI flows not only finance gross fixed capital formation, but also include funding that could be used for other expenditures besides capital formation. For instance, FDI could be used to finance changes in ownership of existing capital, such as with mergers and acquisitions, or could be used as transit capital through special-purpose entities (SPEs).[16] FDI could also be used to acquire financial assets.

To address this, estimates are excluded for economies with large, well-known, offshore financial centers (Ireland, Luxemburg, and the Netherlands). Also used are data on inward FDI flows to operating entities—that is, that excluded flows to SPEs; excluding these flows provides better estimates of FDI with a real impact on the host economy.

Looking forward, scope exists for updates to the international statistical standards, and it is recommended that economies compile statistics on greenfield investments and extensions of capacity from FDI. This could be done, for example, by decomposing FDI flows by use, such as for mergers and acquisitions, for greenfield investments and extensions of capacity, and for financial restructuring in the host economy.[17] Such guidance would make statistics on FDI for greenfield investment and extensions of capacity more widely available.

Carbon Emissions Embodied In MNE Output and in the Gross Exports of MNEs

The main limitation is the absence of separate direct carbon emissions data for MNEs and domestically owned enterprises. This means that the assumption needs to be made that the direct emissions intensities of MNEs are the same as those of domestically owned enterprises in the same industry in that economy.[18] Another limitation is the geographical coverage, especially for the carbon emissions embodied in gross fixed capital formation funded by FDI that is limited to OECD economies.

Methodological limitations include the fact that the central equation system of input–output analysis fails to reflect dynamic interaction between the respective variables. For instance, the timing of the deployment of FDI funds for gross fixed capital formation could occur with lags, but in the estimation, it is assumed that there are no lags. Other related caveats of input–output analysis pertain to a lack of constraints on the factors of production and on the supply side, a fixed input structure and fixed ratios for production for each industry, lack of budget constraints that might prevent households or producers from purchasing all additional output, and the assumption that households consume goods and services in proportion to their initial budget shares.[19]

Finally, the direct carbon emissions used in the estimation are based on IEA estimates of carbon emissions from fuel combustion during production derived using the Tier 1 method. We use the IEA estimates because they are available with wider geographic coverage and throughout the period of study. However, some economies may have estimates of carbon emissions based on the more sophisticated Tier 2 or Tier 3 methods, with economy-specific information (for example, on different technologies or processes).

Looking forward, estimates could be improved by having more information on the direct emissions of MNEs. Such information would, for example, reflect differences in the respective production functions and technologies of MNEs and domestically owned enterprises. For the estimates here, the variation in the emissions for both MNEs and domestically owned enterprises is mainly due to differences in their industry distribution and sourcing patterns. This is especially the case between domestic and imported inputs, as reflected by the differences in the respective input coefficients. Better data on the emissions of MNEs, especially by geographic location, and of domestically owned enterprises would result in better estimates of the carbon emissions embodied in MNEs and in their gross exports,

[16] SPEs are entities that have little or no employment or physical presence in the host economy but that provide services to the MNE, such as raising capital or holding assets and liabilities. The IMF began a data collection of SPEs in 2021 and released its first SPE database in March 2022, covering cross-border flows and positions of SPEs.

[17] Such a recommendation is under consideration, see guidance note D.1: Direct Investment Task Team (DITT) (imf.org).

[18] Alternatively, data identifying the home economy of the MNEs would enable the assumption that the MNEs have the same carbon intensity as domestically owned enterprises in the same industry as in the home economy. This would assume that the foreign operations of MNEs are more similar in carbon intensity to firms in their home economy than to firms in their host economy. Assuming that the technology is the same as in the home economy would assume away the possibility that the parent company used more carbon-intensive technology in host economies with less stringent emissions standards.

[19] For a description of the methodological limitations and guidance on the use of input–output analysis to support policymaking, see Note on CO_2 Emissions, Intensities, and Multipliers—June 2022 | Climate Change Indicators Dashboard (imf.org).

likely showing larger differences between MNEs and domestically owned enterprises. There are several initiatives under way to develop standards for such reporting, including through the Financial Stability Board's Task Force on Climate-related Financial Disclosures; the International Financial Reporting Standards Foundation's International Sustainability Standards Board; and the work of the Sustainability Accounting Standards Board on environmental, social, and governance metrics.

Further, international organizations with greater geographical membership could start collecting FDI flows by industry. Greater availability of FDI data by industry would enable geographic expansion to more developing economies where FDI is more likely to lead to greenfield investment, as opposed to OECD economies. While the carbon emissions embodied in MNE output and gross exports are available for more economies, they exclude many smaller developing economies where FDI could play an important role in their economies and in their integration in global value chains. This could be addressed by expanding the economy coverage of the ICIO tables as well as increasing the number of economies for which statistics on the production activity of foreign-owned firms are available.

RESULTS

This section will examine what the two sets of indicators—the carbon emissions embodied in gross fixed capital formation financed by FDI, and carbon emissions in MNE output—tell us about trends in carbon emissions related to FDI and the industries that are the largest sources of emissions related to FDI. It will also compare the indicators across economies to shed light on how the carbon emissions related to FDI vary across host economies.

Carbon Emissions Embodied in Gross Fixed Capital Formation

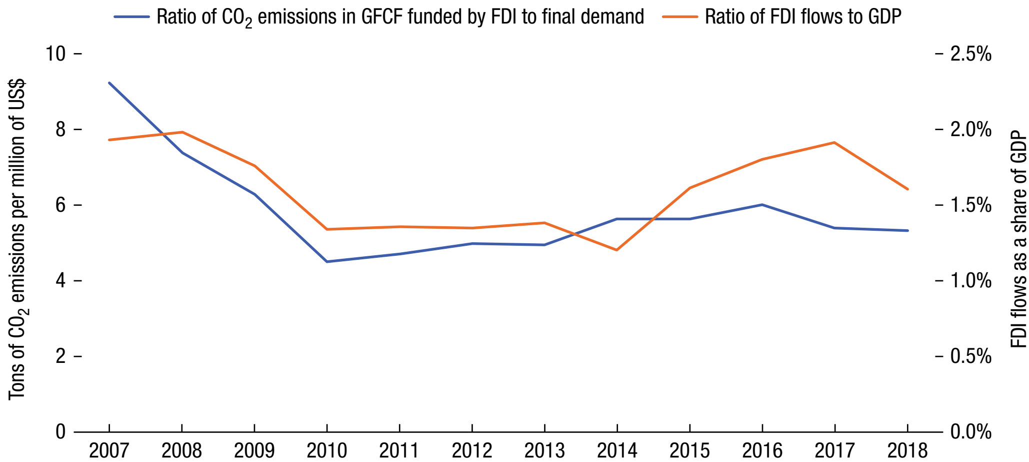
Our indicators provide insights into the main sources of emissions in host economies resulting from the investment impact of FDI. They also allow us to compare emissions by industry in an economy and across economies. The estimates are in metric tons of emissions and metric tons of emissions per US$1 million of output generated to meet final demand. We cover 20 economies[20] during the period from 2005 to 2018 and 36 industries based on the International Standard Industrial Classification (ISIC) Revision 4 classification. We also present results by industry across all economies that have more complete annual and industry estimates.

Figure 8.2 compares trends in total carbon emissions of gross fixed capital formation funded by FDI per US$1 million of final demand and the total of inward FDI flows for the economies covered; the FDI flows are shown relative to the size of the economies as measured by GDP. The figure shows a three-year moving average from 2007 to 2018 so that the trends are easier to discern, and shows that the CO_2 emissions embodied in gross fixed capital formation funded by FDI declined along with FDI flows during the beginning of the period. When FDI flows began to increase in 2015, the CO_2 emissions embodied in capital formation funded by FDI did not increase as much, implying that CO_2 emissions embodied in gross fixed capital formation funded by FDI have fallen slightly relative to FDI inflows.

Figure 8.3 shows carbon emissions embodied in the production of industries that is used in gross fixed capital formation funded by FDI by industry. The data are summed across all economies in the data set. They show that the industry with the greatest contribution to CO_2 emissions from FDI-financed capital formation was construction, with emissions several times larger than in machinery and equipment manufacturing and wholesale and retail trade, which are ranked second and third, respectively. The emissions from construction are larger than those for any other industry in each year and reflect not only the fact that construction is a carbon-intensive industry but also that much of its output is for capital formation. Gross fixed capital formation in motor vehicle manufacturing;

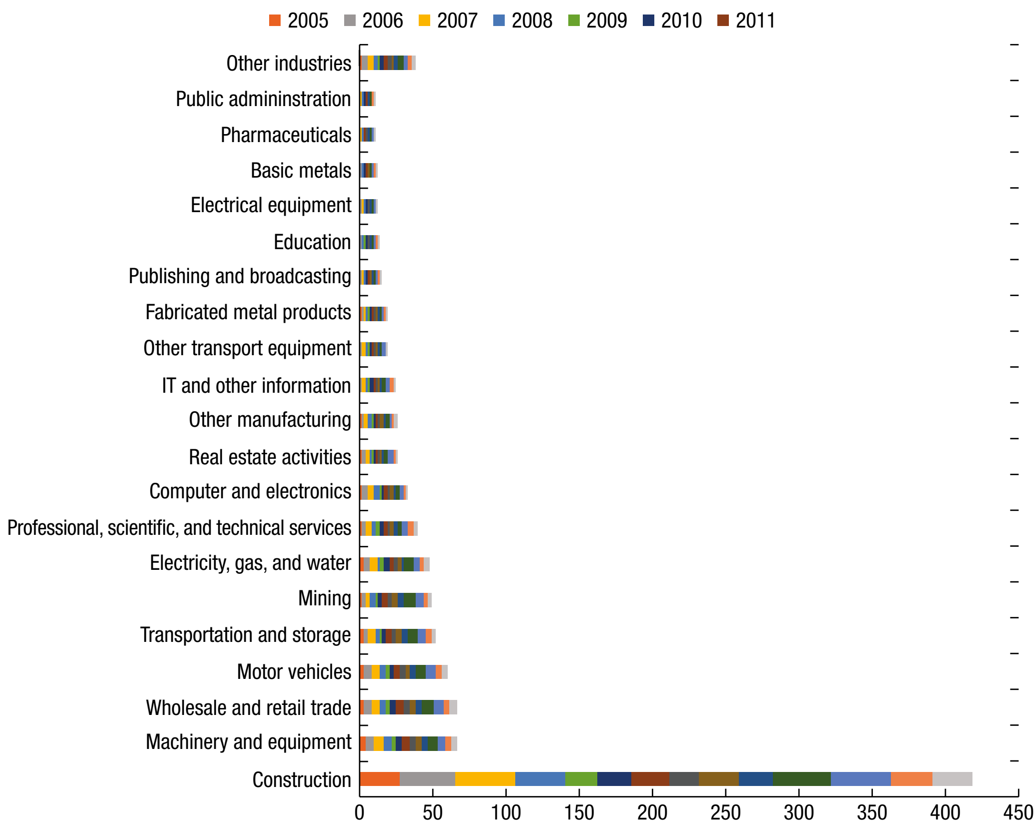
[20] Austria, Chile, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Italy, Mexico, the Netherlands, New Zealand, Norway, Poland, Slovak Republic, Republic of Slovenia, Sweden, and the United States.

Figure 8.2. Carbon Emissions Embodied in GFCF Funded by FDI and FDI Flows, 2007–18



Source: Author's calculations from OECD data.
Note: Three-year moving average. CO_2 = carbon dioxide; FDI = foreign direct investment; GFCF = gross fixed capital formation; OECD = Organisation for Economic Co-operation and Development.

Figure 8.3. Cumulative Carbon Emissions by Industry, 2005–18
(Millions of metric tons of CO_2)



Source: Authors' calculations from Organisation for Economic Co-operation and Development data.
Note: For Austria, Chile, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Italy, Mexico, the Netherlands, New Zealand, Norway, Poland, Slovak Republic, Republic of Slovenia, Sweden, and the United States. CO_2 = carbon dioxide; IT = information technology.

transportation and storage; mining; and electricity, gas, and water supply industries also made significant contributions to CO_2 emissions.

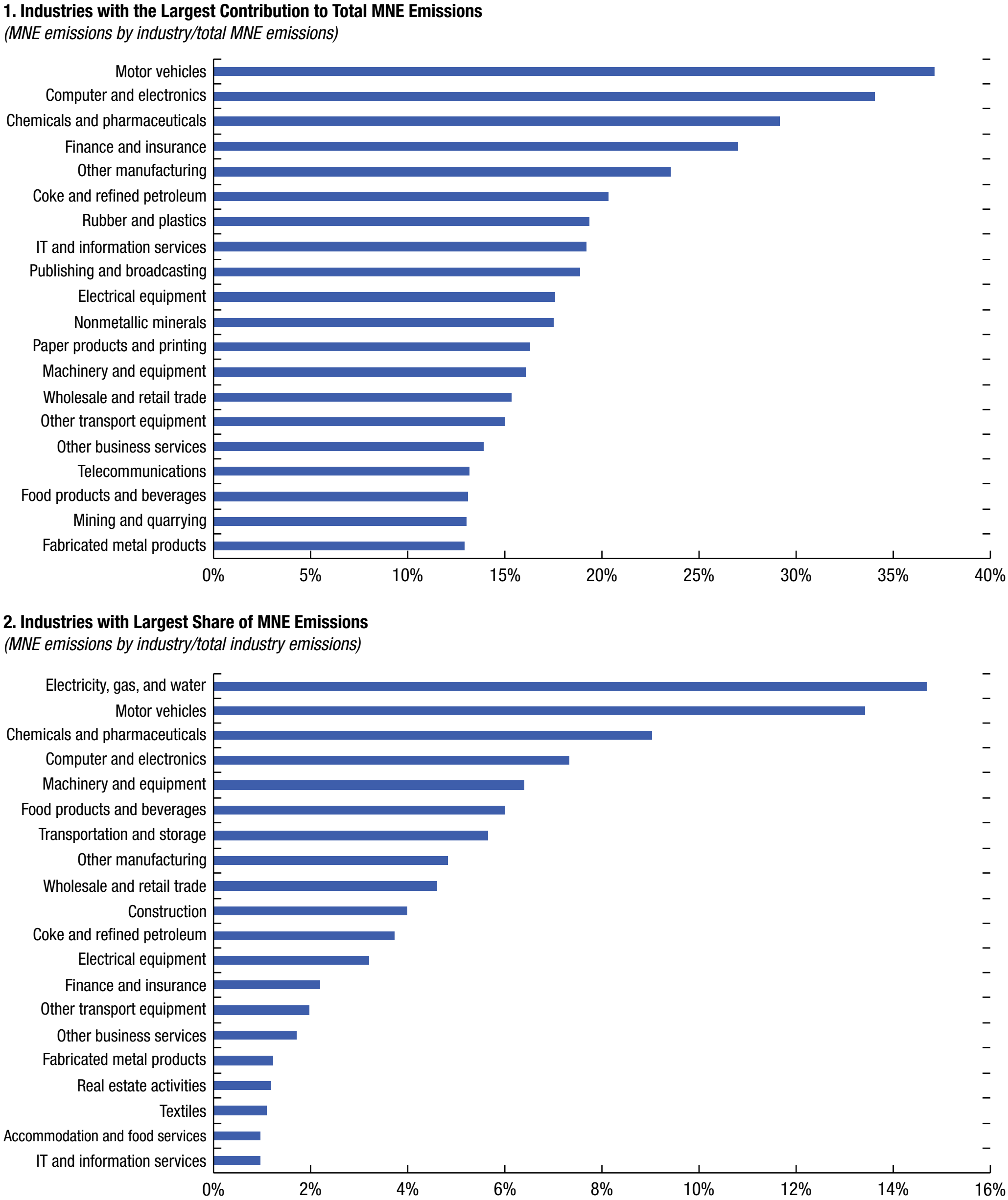
Carbon Emissions in MNE Output

Estimates of carbon emissions from the ongoing operations of MNEs are based on activities of MNEs operating in 59 economies[21] from 2005 to 2015 in 34 industries based on ISIC Revision 4 (Figure 8.4).

- Figure 8.4, panel 1 shows estimates of direct and indirect carbon emissions (hereafter carbon emissions) by industry embodied in the output of MNEs used for final demand, measured as a share of total MNE emissions. This chart identifies the industries that made the largest contributions to the carbon emissions embodied in MNE output across all host economies. Manufacturing made the largest contribution to MNE emissions when all subsectors are combined. When disaggregated, gas and water supply; manufacturing of motor vehicles, trailers, and semitrailers; and manufacturing of chemicals and pharmaceuticals accounted for the largest shares.
- Figure 8.4, panel 2 shows the estimates of the share of direct carbon emissions of MNEs in each industry averaged across host economies. This identifies the industries in which MNEs play the most significant role in carbon emissions across all host economies. The share of MNE emissions was highest in the manufacturing of motor vehicles, trailers, and semitrailers; computer electronics and optical products; and chemicals and pharmaceuticals, indicating the very important role that MNEs play in these industries worldwide. The shares of MNE emissions in construction and agriculture were low despite the two sectors' having fairly high carbon intensities, indicating a limited role of MNEs.
- Figure 8.5 shows estimates of the direct and indirect carbon intensity (hereafter carbon intensity) of final demand for products produced by MNEs compared to domestically owned enterprises. Carbon intensity is measured in metric tons of emissions per 1 million US dollars of output.
- Figure 8.5, panel 1 presents the industry distribution and shows that electricity, manufacturing of nonmetallic mineral products, manufacturing of basic metals, and transportation and storage had the highest carbon intensities. Carbon intensities of MNEs were lower than those of domestically owned enterprises in almost all industries with the exception of transport and storage, construction, and some manufacturing subsectors, including wood and wood products, machinery and equipment, motor vehicles, and textiles.
- Figure 8.5, panel 2 shows estimates of the carbon intensity of multinational enterprises and domestically owned enterprises by economy. South Africa had MNEs with the highest carbon intensity, followed by China, Saudi Arabia, India, and Vietnam. MNEs in Switzerland, Norway, Sweden, Luxemburg, and France had the lowest average intensities. Domestically owned enterprises had higher carbon intensities than MNEs in the dozen economies with the highest carbon intensities except in Indonesia. In contrast, MNEs in low-carbon-intensity economies had higher carbon intensities than domestically owned enterprises, except in Cyprus. The largest differences between carbon intensities of MNEs and domestically owned enterprises were in Cyprus and Malta (where those of domestically owned enterprises exceeded

[21] Argentina, Australia, Austria, Belgium, Brazil, Bulgaria, Canada, Chile, China, Colombia, Costa Rica, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hong Kong SAR, Hungary, Iceland, India, Indonesia, Ireland, Israel, Italy, Japan, Korea, Latvia, Lithuania, Luxembourg, Malaysia, Malta, Mexico, Morocco, the Netherlands, New Zealand, Norway, Philippines, Poland, Portugal, Romania, the Russian Federation, Saudi Arabia, Singapore, Slovak Republic, Republic of Slovenia, South Africa, Spain, Sweden, Switzerland, Taiwan Province of China, Thailand, Türkiye, the United Kingdom, the United States, and Vietnam.

Figure 8.4. Carbon Emissions in MNEs Output, 2005–15 Average



Source: Authors' calculations from Organisation for Economic Co-operation and Development data.
Note: IT = information technology; MNE = multinational enterprise.

those of MNEs) and in Hong Kong SAR, Switzerland, and Iceland (where those of MNEs exceeded those of domestically owned enterprises).

- Figure 8.6 compares the industry-level carbon intensities of MNEs and domestically owned enterprises between selected economies with overall high carbon intensities (China and South Africa) and overall low carbon intensities (Norway and Switzerland). The difference between the carbon intensity of MNEs and domestically owned enterprises in highly carbon-intensive economies was quite small except for the electricity, gas, and water industry. For the low-carbon-intensity economies, differences in the carbon intensity of MNEs compared to domestically owned enterprises were much larger.

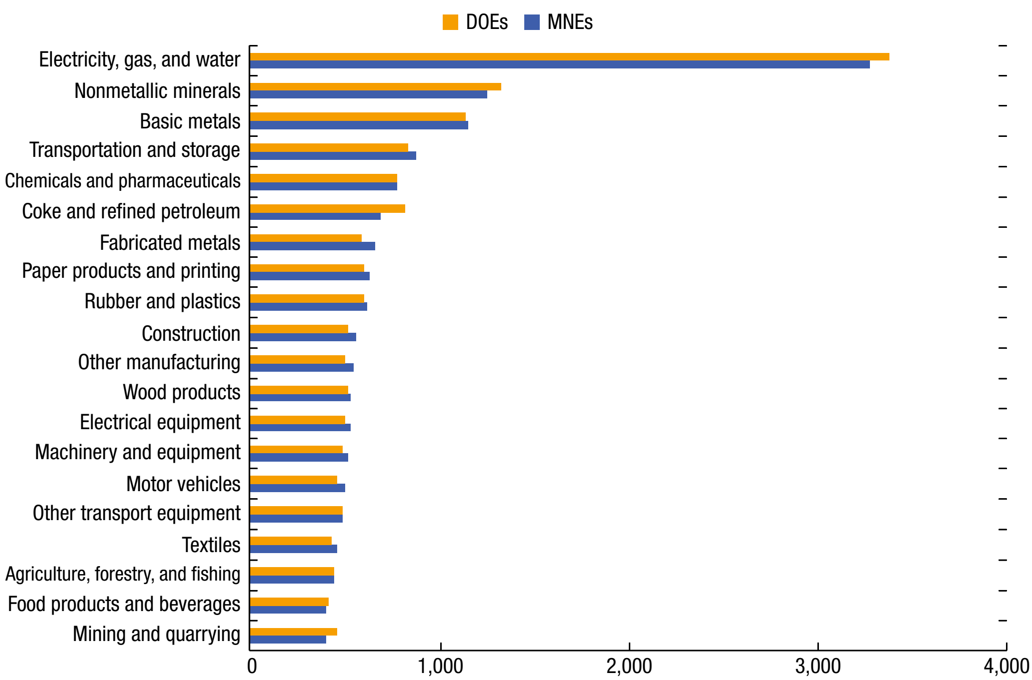
Carbon Emissions Embodied in Gross Exports of Multinational Enterprises and Domestically Owned Enterprises

Figure 8.7 examines the exporting behavior of MNEs and domestically owned enterprises to determine the amount of emissions embodied in their production that meet external demand and how many meet domestic demand.

- In Figure 8.7, panel 1, industry carbon intensities of MNEs are plotted against the corresponding shares of emissions in exports out of total emissions of MNEs. Except for electricity, industries with high carbon intensities (transport; manufacture of basic metals, chemicals, and pharmaceutical products; and nonmetallic mineral products) have export intensities between 30 percent and 60 percent, suggesting that a significant share of the emissions in high-carbon-intensity industries is driven by foreign demand. Several low-carbon-intensity industries (accommodation, manufacture of textiles, electrical equipment, machinery, and computers and electronic products) also have most of their output exported, and their combined effect on domestic emissions to meet foreign demand is significant.
- In panel 2 of Figure 8.7, carbon intensities of MNEs by economy are plotted against the corresponding shares of emissions in exports out of total emissions of MNEs.[22] Similar to panel 1, economies with fairly low carbon intensities have large shares of their output exported. The implication is that a sizeable share of the emissions in the low-carbon-intensity economies is driven by foreign demand. For instance, the chart shows that although MNEs in economies

Figure 8.5. Carbon Intensities of Output (Tons per US$1 Million), 2005–15 Average

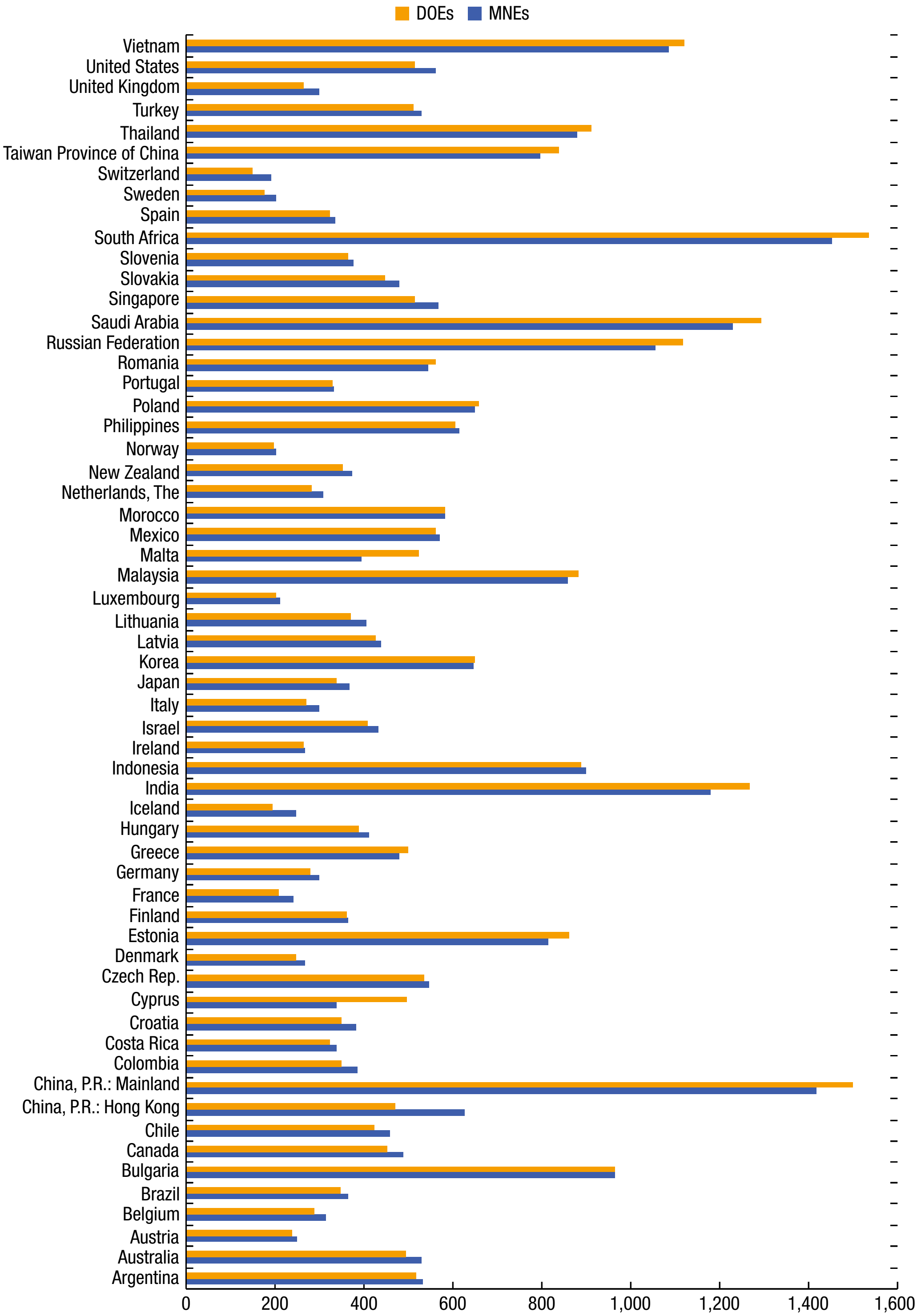
1. By Industry (Top 20 Industries)



[22] Sectors with export shares of less than 30 percent are not shown in panel 1, and countries with export shares of less than 45 percent are not shown in panel 2.

Figure 8.5. *(Continued)*

2. By Economy



Source: Authors' calculations from Organisation for Economic Co-operation and Development data.
Note: DOEs = domestically owned enterprises; MNEs = multinational enterprises.

like Costa Rica, Cyprus, Hungary, Iceland, Ireland, Luxemburg, Republic of Slovenia, and Switzerland have relatively low emissions intensities, more than half of their output is exported. Notable exceptions include China, Thailand, and Vietnam, which have both high carbon intensity and large export shares.

Figure 8.8 compares the share of MNE emissions in exports out of respective emissions in their output against corresponding estimates for domestically owned enterprises by economy and superimposes a bar chart for the economy's carbon intensity. As one moves to the right in the chart, the share of exported CO_2 emissions in MNE output increases. Export-related emissions shares are higher for MNEs compared to domestically owned enterprises in all economies, indicating that more of their output, and the CO_2 emissions embodied in it, meets foreign demand than for domestically owned enterprises. In economies with lower carbon intensities, the gap between the export shares of emissions of MNEs and domestically owned enterprises tends to be higher. The reverse is also true as economies with higher carbon intensities tend to have smaller gaps between the export shares of

Figure 8.6. Carbon Intensities of Output (Tons per US$1 Million), 2005–15 Average

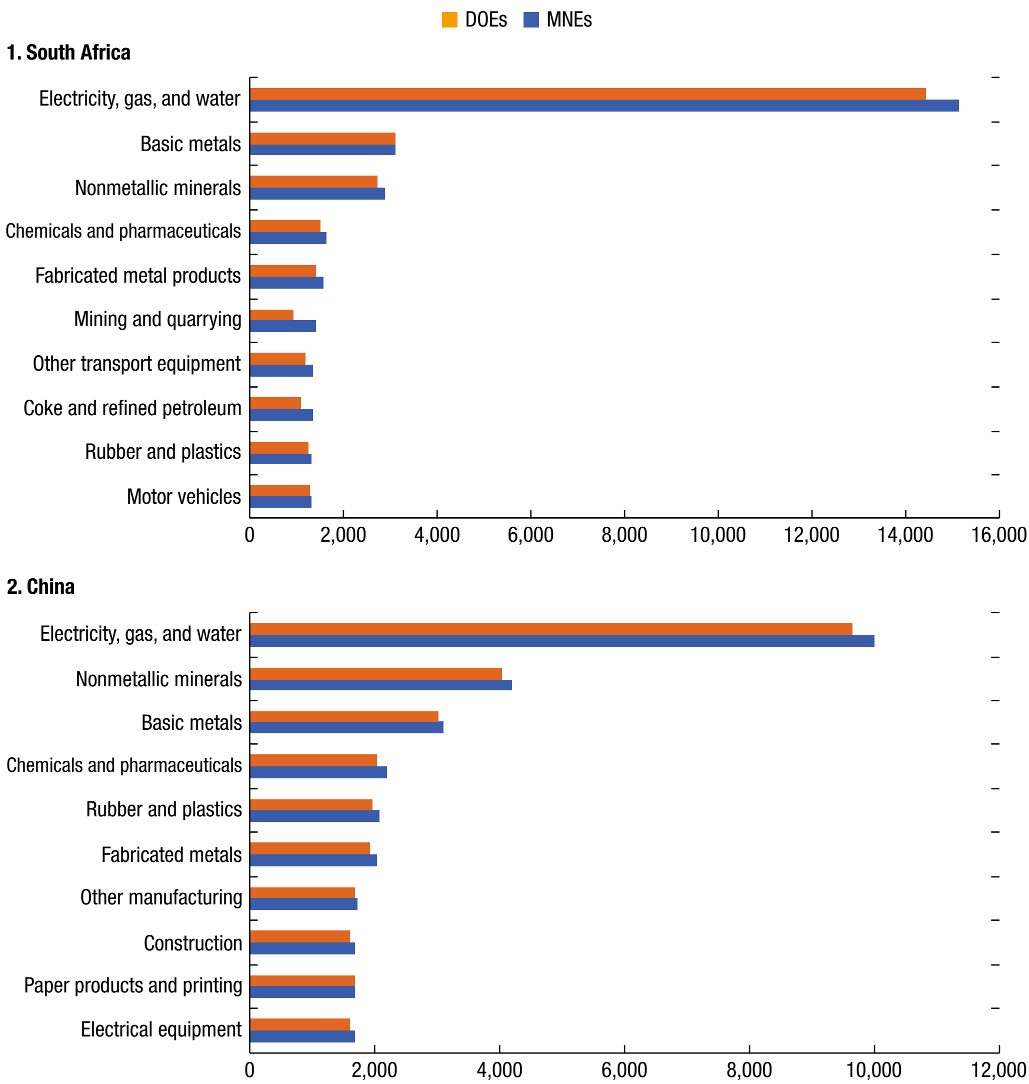
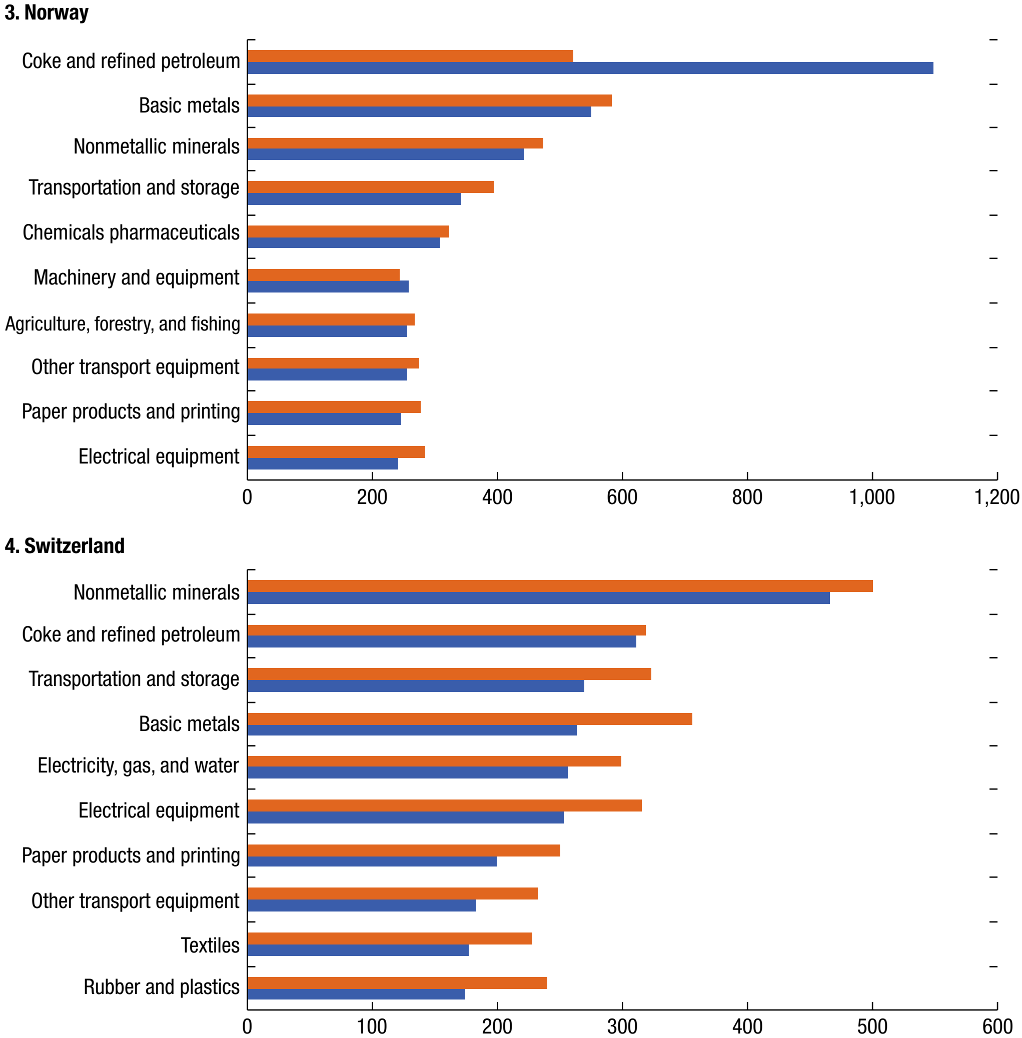


Figure 8.6. *(Continued)*



Source: Authors' calculations form Organisation for Economic Co-operation and Development data.
Note: DOEs = domestically owned enterprises; MNEs = multinational enterprises.

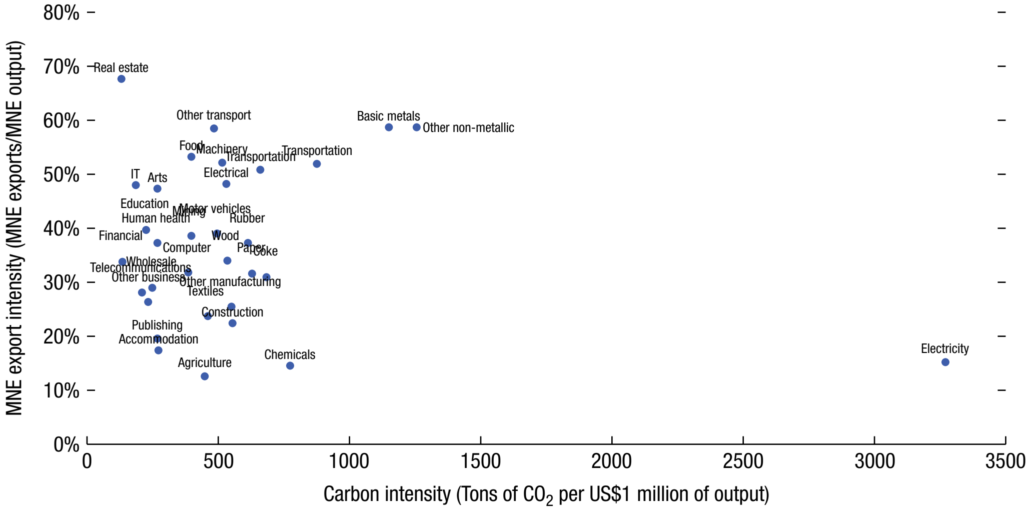
emissions of MNEs and domestically owned enterprises, with some notable exceptions, such as China, India, South Africa, Thailand, and Vietnam.

CONCLUSION AND POLICY IMPLICATIONS

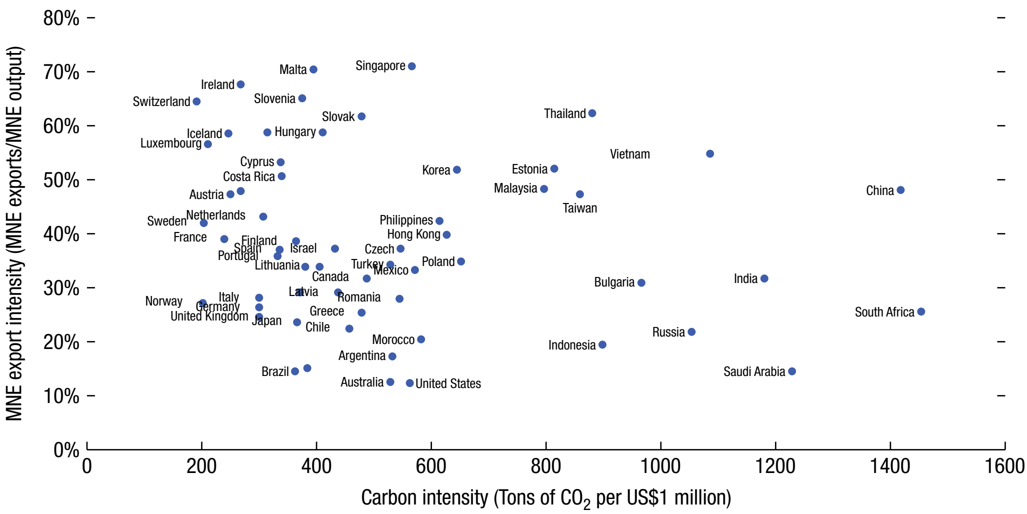
This chapter presents an experimental framework for estimating the effect of foreign direct investment (FDI) on carbon emissions in host economies through investment, production, and export-related activities. The purpose of the chapter is twofold. First, it makes use of already available data, and second, it is intuitive and thus easy to follow and replicate for many economies, especially as data sources become more widely available. The estimates are comparable within and across economies and industries.

Figure 8.7. MNE Carbon and Export Intensities, 2005–15 Average

1. Export Intensity versus Carbon Intensity by Industry



2. Export Intensity versus Carbon Intensity by Economy

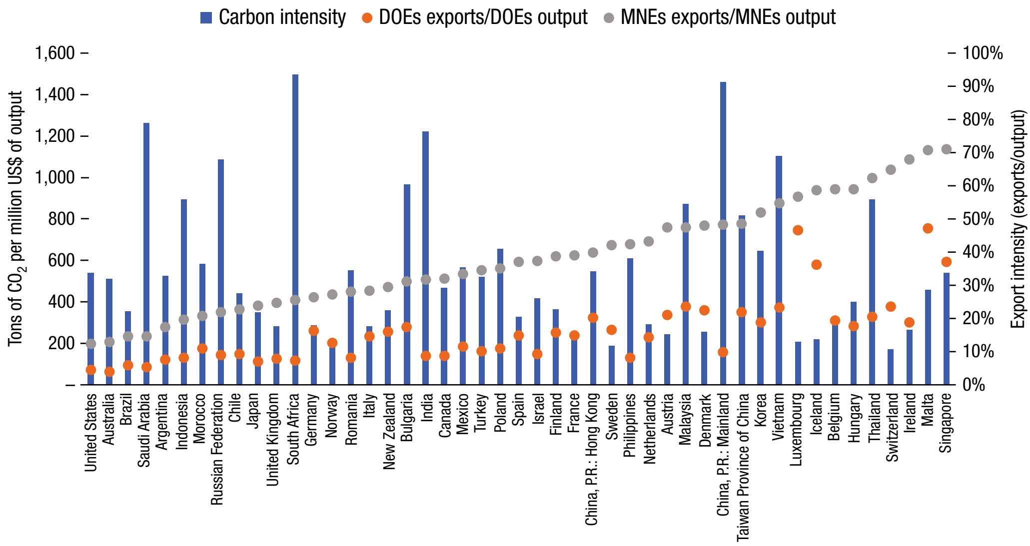


Source: Authors' calculations from Organisation for Economic Co-operation and Development data.
Note: For Argentina, Australia, Austria, Belgium, Brazil, Bulgaria, Canada, Chile, China, Colombia, Costa Rica, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hong Kong SAR, Hungary, Iceland, India, Indonesia, Ireland, Israel, Italy, Japan, Korea, Latvia, Lithuania, Luxembourg, Malaysia, Malta, Mexico, Morocco, the Netherlands, New Zealand, Norway, Philippines, Poland, Portugal, Romania, the Russian Federation, Saudi Arabia, Singapore, Slovak Republic, Republic of Slovenia, South Africa, Spain, Sweden, Switzerland, Taiwan Province of China, Thailand, Türkiye, the United Kingdom, the United States, and Vietnam. IT = information technology; MNEs = multinational enterprises.

The framework can be used to generate relevant indicators for policy questions on the role of FDI in CO_2 emissions of the host economy. Estimates show that MNEs can have an important impact on global and host economy carbon emissions. They suggest that policies by home and host economies could help in reducing global carbon emissions.

For home economies, policies that incentivize their domestic direct investors to meet high environmental and emissions standards not only in their operations in the home economy but also in their foreign operations could contribute to reducing emissions globally ("good stewardship").

Figure 8.8. Carbon Intensities and Shares of Export Emissions to Output Emissions for Selected Economies, 2005–15 Average



Source: Authors' calculations from Organisation for Economic Co-operation and Development data.
Note: DOEs = domestically owned enterprises; MNEs = multinational enterprises.

Policies could also induce MNEs to demand lower-carbon infrastructure and transportation in the host economies. And if firms were encouraged to reduce emissions along their supply chains, it could lead them to demand that their suppliers reduce their carbon emissions as well. For host economies, it is important to remove barriers to investment in environmental goods and services industries as well as in low-carbon technologies to promote positive spillovers, including knowledge and technology transfer. In addition, host economies should analyze the impact of new foreign direct investment on carbon emissions as part of their FDI attraction strategies. Finally, developing a standard for companies to disclose their carbon emissions will provide valuable information that can help us better understand the role of all enterprises in carbon emissions.

Future work could address methodological and data limitations of the framework. Possible areas include FDI estimates that distinguish between the use of FDI resources for acquisition of assets versus greenfield investment and capacity extension; expanded information on the role of MNEs in carbon emissions, such as actual estimates of their direct carbon emissions by activity/sector; and the use of models to capture dynamic interactions, including as factor substitutions that are not possible with the fixed input structure of input output analysis. While easing the assumption that MNEs and domestically owned enterprises in the same economy and industry have the same carbon intensity is a priority for improving the estimates, sensitivity analysis on the differences in direct emissions between MNEs and domestically owned enterprises could provide useful information into how sensitive the indicators are to this assumption and yield insights on how to structure climate-related incentive schemes.

Once the estimates have been improved, future analysis could also explore whether there are spillovers in the form of reduced carbon intensity at domestically owned enterprises from the operations of MNEs in the host economy. And it would be interesting to better understand the relationship between the role of FDI in production and export diversification and the host economy's carbon emissions.

Box 8.1 provides an illustration of how the indicators can shed light on how much an economy's production, consumption, and investment activities can contribute to carbon emissions for China and the United States.

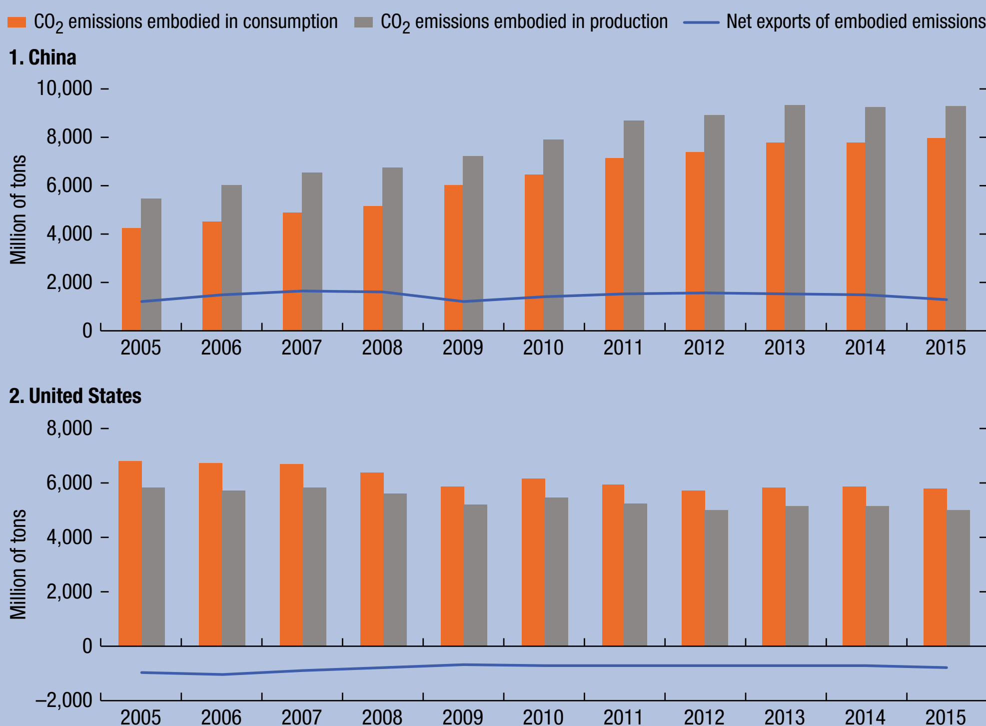
Box 8.1. Carbon Emissions in Trade and Investment in China and the United States

This box illustrates how the methodology of the chapter can enrich the analysis of carbon emissions by adding an investment or ownership perspective to the production and consumption views of carbon emissions.

Production and consumption. The production perspective on carbon emissions looks at the emissions associated with the production of units that are resident in the economic territory of a given jurisdiction; the consumption perspective looks at the carbon emissions associated with the products that are finally used in an economy. These perspectives can show if a country is reducing its domestic production of carbon emissions by offshoring emissions to other economies, highlighting that changes in both production and consumption activity are necessary to reduce carbon emissions.

Figure 8.1.1 shows the estimates for China and the United States from 2005 to 2015. In an economy with export-oriented carbon-intensive industries like China, the production-related carbon emissions were higher than the consumption-related emissions. Conversely, in a comparably service-dominated economy like the United States, the emissions embodied in consumption were higher than the production-related emissions.

Figure 8.1.1. Carbon Emissions Embodied in the Production and Consumption of China and the United States, 2005 to 2015

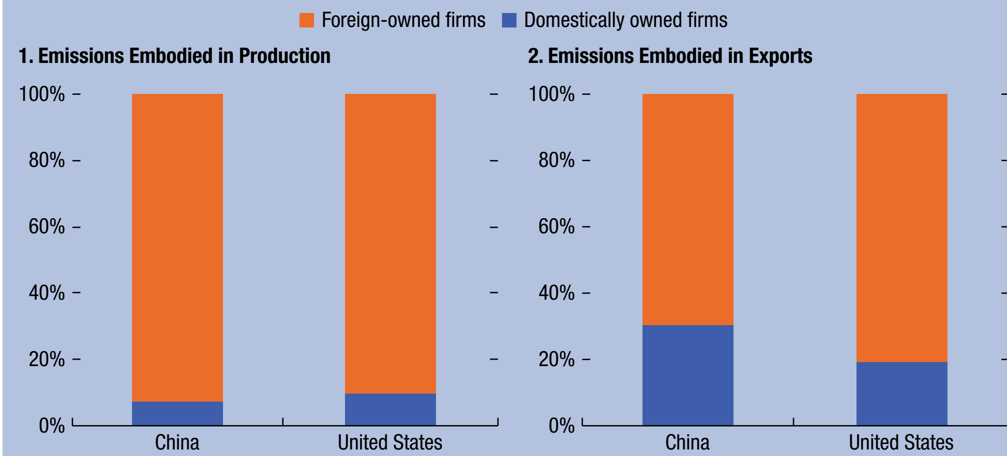


Sources: IMF Direction of Trade Statistics (DOTS); OECD Carbon Emissions Embodied in Trade; and IMF staff calculations.

Investment perspective. Foreign direct investment may be a way to circumvent tighter emissions standards by locating more carbon-intensive stages of production in economies with less stringent standards (for example, carbon leakage) and then exporting the final production to other economies. For example, a portion of emissions generated by carbon-intensive export-oriented economies may result from the activities of foreign-owned firms.

This ownership dimension can be added to the production and consumption perspectives shown in the figure by breaking down the carbon emissions resulting from production by industry between domestically owned and foreign-owned firms based on their share of production in that industry and their sourcing behavior. Panel 1 of Figure 8.1.2 shows the results for 2015 for China and the United States. Not surprisingly, domestically owned firms account for the largest share of carbon emissions from production in both countries.

Figure 8.1.2. Share of Carbon Emissions Embodied in Production and Exports by Foreign-Owned and Domestically Owned Firms in China and the United States, 2015



Sources: IMF Direction of Trade Statistics (DOTS); OECD Carbon Emissions Embodied in Trade; IMF staff calculations.

The carbon emissions embodied in exports can also be broken down between foreign-owned firms and domestically owned firms based on the share of their production that they export. Panel 2 of Figure 8.1.2 shows that domestically owned firms account for the largest share of carbon emissions embodied in exports in both countries. But foreign-owned firms account for a higher share of carbon emissions embodied in exports than in production, reflecting the higher export intensity of foreign-owned firms.

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CHAPTER 9

Trade in Low-Carbon Technology Products

Kristy Howell, Simon Black, Rainer Lanz, Marc Bacchetta, and Enxhi Tresa[1]

What are low-carbon technologies (LCTs), and how can we leverage trade to rapidly diffuse them to help achieve global climate change mitigation? Better data would inform international negotiations on trade policy and climate finance while supporting domestic policy reforms. This chapter discusses how to estimate trade in LCT products, providing a new set of indicators that is available on the IMF's Climate Change Indicators Dashboard (CID). It also discusses recent trends in LCT trade, provides an overview of barriers to trade in LCTs, and discusses policy uses and applications of the experimental indicators estimated.

INTRODUCTION

Rapid diffusion of LCTs globally is critical for accelerating climate change mitigation. For instance, shifting electricity generation toward renewables while electrifying end uses of energy implies mass adoption of LCTs—which are defined as technologies that emit fewer greenhouse gases, such as carbon dioxide (CO_2), through the entirety of their lifecycle than other technologies and include technologies such as wind energy, solar energy, and carbon capture. These existing, commercially proven technologies account for about two-thirds of what is needed to achieve net zero, with the remainder requiring innovations in LCTs (IEA 2020).

International trade will play a central role in diffusing LCTs across economies. Trade in LCT products can support countries' efforts to meet their emissions targets, defined in nationally determined contributions under the Paris Agreement. For policymakers, data on trade in LCT products can be useful for (1) promoting trade in these products, (2) informing the international climate negotiations and monitoring progress, (3) designing and implementing domestic mitigation policies, (4) identifying key supply-chain dependencies for these products, and (5) fostering domestic production and export of LCT products through technology and green policies.

This chapter is organized as follows: the first section starts with a review of the literature on LCTs and on how trade affects greenhouse gas (GHG) emissions. The second section discusses a statistical methodology for compiling an indicator on trade in LCT products, and the next section presents recent trends based on this indicator. The following section provides an overview of tariff and nontariff barriers to trade in LCT products. The final section concludes with a discussion on the policy uses of the data.

BACKGROUND AND LITERATURE REVIEW

Mitigating climate change requires large changes to all economic systems, especially in the generation, distribution, and consumption of energy. A central challenge is shifting power systems away from the combustion of fossil fuels toward renewables. Also, end uses of energy—such as gasoline

[1] The authors would like to thank Marisol Dar Ali Rothschuh (WTO) for statistical assistance and Dmitrii Entaltsev and Alessandra Sozzi (IMF) for assistance with data and graphics.

and diesel consumption in vehicles or trains—require electrification or, where electrification is not possible, substitution with "green fuels" (for example, ammonia in ships, green hydrogen in heavy industry like steel, carbon capture in cement, and synthetic carbon capture–based fuels in aviation).[2] And, to achieve the more ambitious Paris goal of limiting global warming to 1.5°C, "negative emissions technologies" like direct air capture are likely to be needed.[3]

Generally, LCTs are less carbon intensive in their use, although not always in their production.[4] LCTs also tend to be more complex in their production than other technologies. This in turn may require higher human and state capabilities to absorb, but also may confer higher learning-by-doing spillovers and hence better economic growth benefits for countries that innovate and produce them (Mealy and Teytelboym 2020). Lastly, LCTs can entail higher up-front capital costs but tend to have lower variable costs. For example, geothermal power plants have large up-front costs but low running costs compared with coal or gas plants (though new solar and wind technologies are becoming rapidly cheaper than both new and existing coal and gas power[5]).[6]

As with all new technologies, a key transmission channel in the development, production, and adoption of low-carbon technologies is trade (Cirera and Maloney 2017). Other transmission channels include foreign direct investment (see Pigato and others 2020), but this chapter focuses on the trade transmission channel. This includes trade in not only physical goods, such as raw materials, intermediate parts, and final products, but also the patents and other knowledge that allow for international adoption and production of new technologies. National capabilities, notably an educated workforce and physical infrastructure, are critical to allow for absorption of LCTs through such channels,[7] and so is the broader policy environment. This includes the stringency of environmental policies (such as carbon prices) in the importing country, as well as the level of tariff and nontariff barriers (see Table 3.5 in Pigato and others 2020). As a result, trade liberalization could help countries accelerate the adoption of LCTs and achieve their emissions targets (see Box 9.1).

Most analytical work has focused on the broader concept of "environmental goods," which includes products related to environmental protection and resource management. More recent work has focused on LCTs or "mitigation technologies," which include only those products that reduce emissions of GHGs. Yet there is no internationally agreed-upon list for environmental goods or LCTs, though several lists have been developed for varying reasons (see Box 9.2). The use of different lists of environmental goods and of LCT products complicates the interpretation of analytical

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[2] For a discussion on decarbonizing power generation and consumption, see Bogdanov and others (2021); for the maritime sector, see Englert and Losos (2021); for steel, see Nimubona and Benchekroun (2021); for cement, see Habert and others (2020); for carbon capture–based aviation fuels, see Friedmann and others (2020).

[3] Three of the four 1.5°C-aligned scenarios of the Intergovernmental Panel on Climate Change (IPCC) require large-scale negative emissions in the second half of this century; see IPCC (2018). For a discussion of negative emissions technologies, see the National Academies of Sciences, Engineering, and Medicine (2019).

[4] For example, an electric vehicle (EV) may require as much or more energy to produce—and hence emit the same or more carbon dioxide—as an internal combustion engine vehicle. However, over the EV's lifetime—assuming it is powered by renewable electricity—it can be expected to emit far fewer emissions than an internal combustion engine vehicle. Under this definition, the lifecycle emissions of a product (its production and use) determine whether a product is "low carbon." Additionally, widespread adoption of EVs is necessary to achieve global climate mitigation goals. Hence, EVs can also be regarded as a "mitigation technology," which is synonymous with "low-carbon technology" in this chapter.

[5] Solar and wind power plants are already cheaper than new coal and gas plants in most countries of the world. As costs continue to decline, new solar is becoming cheaper even than existing coal and gas generation. For estimates of levelized costs of electricity (which is a measure of the average net present value of generation for electricity sources, including up-front and variable costs) see https://www.lazard.com/perspective/levelized-cost-of-energy-levelized-cost-of-storage-and-levelized-cost-of-hydrogen/.

[6] See Way and others (2021). For other characteristics of LCTs, see Table 1.1 in Pigato and others (2020).

[7] For example, Pigato and others (2020) find that human and physical capital deepening (through higher educational achievement or larger gross fixed capital formation per capita) is associated with more rapid imports and exports of LCT, while financial and firm-level capital deepening has statistically significant but much weaker effects. See Table 5.5 in Pigato and others (2020).

Box 9.1. Effects of Trade Liberalization in LCT Products on Emissions and Related Channels

Trade liberalization in low-carbon technologies (LCTs) facilitates their use in both production and consumption, which in turn induces three effects on emissions through composition, scale, and technique.

First, holding the scale of the economy and emissions intensities constant, the lowering of tariffs and nontariff measures on imports of LCT products will lead to changes in countries' allocations of resources toward activities with either higher or lower emissions intensities depending on a country's comparative advantage (**composition effect**). The composition effect can thus either contribute to an increase or a reduction in emissions. If a country's comparative advantage is based on less stringent environmental regulations, LCT trade liberalization may reinforce the so-called pollution haven effect (Copeland and Taylor 2004), implying that trade increases emissions.[1] Similarly, when firms slice up production along value chains, the carbon-intense parts of production might be shifted from countries with stringent to those with weaker regulation (Cherniwchan 2017; Cole, Elliott, and Zhang 2017).

Second, increased trade in LCT products, holding constant the mix of goods produced and production techniques, means more economic activity and more transportation, and this increases emissions (**scale effect**) (Copeland and Taylor 2004). Indeed, liberalization of trade in LCT products lowers their domestic price, raises real income, and raises demand for all products, trade, and economic activity. The increase in economic activity due to trade liberalization leads also to more emissions from transportation, that is, an additional scale effect.

Third, holding scale and composition constant, improved access to LCTs encourages a switch to low-carbon production techniques, and this reduces emissions (**technique effect**). In fact, trade accelerates the cross-country diffusion of environmental technologies that make local production processes more energy efficient and environmentally sound (Garsous and Worack 2021). For instance, for developing countries trade provides an opportunity to switch to environmental technologies without having to go through the technological learning curve that caused so much environmental damage in developed countries (European Commission 2012). Trade liberalization in LCTs can also stimulate innovation spillovers through the diffusion of knowledge embodied in intermediate environmental goods and services. It has been shown that reducing trade barriers is associated with a boost in environmental innovation globally (Dechezleprêtre and Glachant 2014),[2] allowing a switch to cleaner technologies.

Considering these three effects, several studies have looked at the impact of trade liberalization in LCT products on emissions. Using a simulation exercise, Hu and others (2020) found that lowering the cost of clean environmental inputs relative to that of conventional technology inputs induces a transition from nonrenewable to renewable energy production and thus a reduction of emissions. However, such a reduction in production costs also generates an increase in economic activity, leading to more emissions. Several empirical studies have focused on the effect of trade in environmental goods on different outcome variables, showing that the effect on emissions is sometimes ambiguous due to opposite effects on different types of emissions and the dual use of LCTs (that is, that some LCTs do not only have an environmental purpose, but might also be used in conventional sectors that pollute more) (Zugravu 2018, 2019). Other studies compared the impact of opening trade in environmental goods and in nonenvironmental goods on environmental quality measured by different types of emissions and found that opening trade in environmental goods improves environmental quality significantly more than opening trade in nonenvironmental goods (Alwis 2015). Tamini and Sorgho (2017), using a gravity approach, estimated a modest positive effect of trade liberalization of environmental goods on emissions, pointing out the importance of addressing nontariff barriers.

[1] The pollution haven effect can be conceptualized as follows: Consider a framework with two countries that differ in environmental regulations, and two sectors that require different emissions intensities. Under free trade, the country with laxer environmental standards gains a comparative advantage in the high-emissions-intensity sector, which then expands. Accordingly, trade increases emissions.

[2] For the general issue of technology transfer, Gorodnichenko, Svejnar, and Terrell (2010) find that foreign competition, horizontal and vertical relationships with foreign firms, and international trade improve domestic firms' efficiency and innovation in 27 emerging market economies.

results and points to the need for further analysis of the classification of LCT products as well as for delving deeper into the different avenues through which trade in LCTs can contribute to reducing emissions.

Box 9.2. Identifying Trade in Environmental Goods and Low-Carbon Technologies

A challenge of measuring trade in low-carbon technology (LCT) products (or the broader concept of environmental goods) is that no single list of products exists. Historically, there have been many attempts to develop lists of LCT products or environmental goods. For example, some have been developed to help understand the scope of the environmental industry, while others were intended to support trade liberalization of environmental products. Such lists include the following:

- The Organisation for Economic Co-operation and Development (OECD)/Eurostat list, published in 1999 (OECD and Eurostat 1999), was intended "primarily for analytical purposes" but has since been used to inform World Trade Organization negotiations (Steenblik 2005, p. 3).
- The World Bank list, from a 2007 report (World Bank 2007), includes 43 traded climate-friendly and clean-energy technologies. The report highlights the need to liberalize trade in these technologies.
- The Asia-Pacific Economic Cooperation (APEC) List of Environmental Goods consists of 54 commodities endorsed in 2012 by APEC members who pledged "to reduce applied tariff rates on these products to 5 percent or less by the end of 2015" (Pigato and others 2020, p. 31). According to Steenblik (2005), the roots of the APEC list can be traced to 1995 when "APEC leaders agreed to identify industries in which the progressive reduction of tariffs could have a positive impact on trade and economic growth" (p. 6). Although no consensus was reached, the APEC list has been used in subsequent negotiations at the WTO (Steenblik 2005).
- A list from Glachant and others (2013) identified 30 LCTs in their research on the international diffusion of LCTs.

The scope and coverage of these lists reflects, in part, their varied purposes. Regardless of the scope of the concept to be covered, there is a recognition that any list of identified products will need to be adapted over time as the science around climate change evolves. A recent APEC report acknowledged that "the addition of new products to the APEC List of Environmental Goods is worth exploring since technology is moving fast" (Kuriyama 2021, p. 1).

It should also be noted that the "climate-friendly" status of some products may change over time. Catalytic converters for automobile exhaust, for example, are included on many lists of environmental goods (and in the list of LCT products used in this chapter) because of their role in reducing air pollution. However, research has shown that by increasing the need for energy slightly and possibly increasing nitrous oxides, catalytic converters may increase greenhouse gas emissions (Pearce 1998). Other products that have been included in lists of LCT products reflect transitional energy solutions—such as natural gas and nuclear energy—which may be necessary in the transition to a low-carbon economy, but do not represent the ideal low-carbon solution. The European Commission recently reached political agreement on the Second Delegated Act of the EU Taxonomy Regulation that sets out conditions under which nuclear and gas activities can be included as transitional activities.[1]

Therefore, rather than static, any list of LCT products or environmental goods should be considered a living list that can be modified as technologies continue to emerge and the sector continues to evolve.

[1] See https://ec.europa.eu/commission/presscorner/detail/en/ip_22_711.

MEASURING TRADE IN LCT PRODUCTS

There are two broad approaches to estimating trade in a certain class of goods, such as LCT products: a top-down approach or a bottom-up approach. The International Monetary Fund (IMF) approach is a top-down approach, applying a consistent methodology and definition to data available for a wide range of economies.[8] A bottom-up approach by national statistical compilers could

[8] The methodology described in this chapter was developed for the IMF's CID; see https://climatedata.imf.org/.

produce more detailed results from granular, economy-level information, but this would reduce the comparability of the statistics across economies.[9]

To measure trade in LCT products, the first step is to determine a list of commodities to be included. This chapter establishes a definition of what an LCT product is and presents a list based on that definition, which can be used to track trends over time.

LCT products are defined as products that produce less pollution—especially of CO_2 and other GHGs—over their lifetime than their traditional counterparts and will play a vital role in the transition to a low-carbon economy. The LCT product designation used in the CID methodology builds on Pigato and others (2020) and includes products like wind turbines, solar panels, and hybrid and electric vehicles. Pigato and others (2020) drew from three well-established lists[10] to provide "a representative and manageable sample of traded climate change mitigation technology products . . . backed by a degree of consensus on their environmental friendliness" (pp. 30–31); the resulting list included 107 products. The IMF expanded and updated this list in 2021 to 124 products.[11]

In a second step, the list can be applied to detailed (commodity-level) trade data. In this chapter, the data used for the estimation of trade in LCT products are from UN Comtrade,[12] a database of monthly trade flows by commodity and by partner economy reported by approximately 178 economies according to Harmonized Commodity Description and Coding System (HS) codes (see Annex 9.1 for other sources of commodity-level trade data). The HS is "an international nomenclature for the classification of products" introduced in 1988 and used to classify goods for customs purposes. It comprises approximately 5,300 article/product descriptions. At the international level, it is a six-digit code system. The latest data are based on HS 2017.

The third step extracts values (in US$) for six-digit commodity categories that meet the definition of LCT products and sums them to estimate "LCT products" aggregates.[13]

And the last step is to derive indicators as follows:

- **Exports of LCT products**, which comprise all LCT products leaving the national territory. They can be estimated by economy, with all economies summed to get a "world" total. Exports of LCT products can also be expressed as a share of total exports (all commodities) by taking an economy's LCT exports divided by its total goods exports (aggregated from the same source data). A relatively high share indicates that an economy produces and sells a significant share of LCT products to other economies. Likewise, the share of LCT trade in the "world" total can

[9] For example, Vossenaar (2014) uses additional detail available in the national data for the United States to develop more accurate estimates of trade in a subset of LCTs—those related to wind energy. The European Statistical Office (Eurostat) employs a bottom-up approach in publishing statistics on the environmental goods sector for the European economies, which includes statistics on exports. The Eurostat data set is also based on a list of products—in this case the list of products covers the broader scope of environmental goods—but is compiled by EU Member States using more granular information available at the economy level. The environmental goods sector data are compiled according to the concepts and definitions of the System of Environmental-Economic Accounting 2012—Central Framework (SEEA-CF) and are available at https://ec.europa.eu/eurostat/databrowser/view/ENV_AC_EGSS2/default/table?lang=en&category=env.env_egs.

[10] Specifically, the World Bank Group Climate-Friendly and Clean-Energy Technologies List (43 commodities), the APEC List of Environmental Goods (54 commodities), and the Glachant, Dussaux, and Dechezleprêtre List of Climate Change–Related Technologies (30 commodities).

[11] Because these three lists were based on 2007 Harmonized Commodity Description and Coding Systems (HS) codes, the Pigato list did not include LCT products that were not separately identified under HS 2007. The IMF updated this list by mapping it to the HS 2017 and including LCT products that were separately identified in the HS beginning with the 2012 and 2017 updates, such as hybrid and electric vehicles and rechargeable batteries.

[12] United Nations International Trade Statistics Database, Department of Economic and Social Affairs/Statistics Division.

[13] For the CID, global trade aggregates from the IMF's Direction of Trade Statistics (DOTS) database are also used to calculate some of the LCT product indicators. In the DOTS data set, reported data are supplemented by estimates whenever such data are not available or current. Therefore, the global aggregates from DOTS provide a better denominator to use in calculating shares of total trade than the global aggregates one would get from summing the country-reported data from UN Comtrade.

be calculated. Exports of LCT products can also be expressed as a percentage of the GDP.[14] A relatively high percentage indicates that an economy produces and sells a significant share of LCT products to other economies.

- **Imports of LCT products**, which comprise all LCT products entering the national territory. The series is the aggregation of all imports reported by each economy that meet the definition of "LCT products." It can be estimated by economy, and then all economies can be summed to get a "world" total. As with exports, imports of LCT products can also be expressed as a share of total imports and as a percentage of an economy's GDP. A relatively high import share indicates that an economy is consuming or investing in LCT products by importing from other economies.
- **Trade balance in LCT products**, which is calculated as exports of LCT products *minus* imports of LCT products. A positive trade balance means an economy has a surplus in LCT products (exports are greater than imports), while a negative trade balance means an economy has a deficit in LCT products (imports are greater than exports). This series can be used to identify which economies are net exporters and which are net importers of LCT products. The trade balance in LCT products can also be expressed as a percentage of GDP.
- **Total trade in LCT products**, which is the sum of exports and imports of LCT products. This measure provides an indication of an economy's involvement in (openness to) trade in LCT products, which is important for understanding how these technologies can be transferred between economies. It can also be expressed as a percentage of GDP.
- **Comparative advantage in LCT products,** which is a measure of the relative advantage or disadvantage a particular economy has in a certain class of goods (in this case, LCT products), and can be used to evaluate export potential in that class of goods. Comparative advantage is calculated as the ratio between the proportion of an economy's exports that are LCT products and the proportion of global exports that are LCT products. A value greater than one indicates a relative advantage in LCT products, while a value of less than one indicates a relative disadvantage. The formula is as follows:

$$\frac{\frac{LCTX_c}{TGX_c}}{\frac{LCTX}{TGX}}$$

where:
$LCTX_c$ = *LCT products exports of economy c, derived from UN Comtrade*
$LCTX$ = *LCT products exports of all economies (world total), derived from UN Comtrade*
TGX_c = *total goods exports of economy c, derived from UN Comtrade*
TGX = *total exports of all economies (world total), from DOTS*

- **Partner economy indicators.** Using the partner economy data from the trade data set, LCT indicators can be derived for each economy vis-à-vis the rest of the world as well as vis-à-vis each partner economy. Bilateral trade flows can provide interesting insights into the destination of an economy's LCT exports or the origin of an economy's LCT imports.

Limitations

There are some limitations to the estimates of LCT products. They are mostly related to the ability to define LCT products and measure them using trade data. The commodity codes used to report trade flows were developed for customs purposes, to impose duties, and not for statistical purposes, such as for

[14] For the CID, an economy's national-accounts-basis GDP at current prices from the World Economic Outlook is used as the denominator for "percentage of GDP" calculations.

measuring trade in LCT products. For example, some LCT products have no equivalent HS code (or "subheading"). In other cases, LCT goods are classified under HS codes that include unrelated products, meaning that the indicators may capture trade in commodities that are not LCT products.[15,16]

Improvements have been made to the HS nomenclature in recent years to try to better identify goods related to environmental protection.[17] For example, separate subheadings were introduced in HS 2012 for rechargeable batteries, and in HS 2017 for hybrid vehicles and EVs and certain LED lighting. These improvements have enabled better analysis of trade in these products. In the latest amendments to the HS (HS 2022) additional improvements were adopted, including separate identification of lighting-related products using LEDs, additional types of EVs, and solar technologies such as solar water heaters, photovoltaic generators, and photovoltaic cells. These improvements will be incorporated into the estimates of LCT products when data based on the 2022 update of the HS become available.[18]

TRADE IN LCT PRODUCTS—RECENT TRENDS

The indicators derived above can provide valuable insights into which economies are exporting and importing LCT products, whether LCT products are becoming more important in merchandise trade over time, and which economies have a comparative advantage in these goods.

Trends[19]

In 2021, the top five exporters of LCT products were China, Germany, the United States, Japan, and Korea, which together accounted for 55 percent of world LCT exports (Figure 9.1, panel 1). The top five importers of LCT products were the United States, China, Germany, the United Kingdom, and France, with a share of 41 percent of world imports (Figure 9.1, panel 2).

However, looking at the top five in terms of the share of LCT products to total goods shows a very different picture. Here, the top five exporters were North Macedonia, Slovak Republic, Japan, Hungary, and Germany, while the top five importers were Norway, Kazakhstan, Kuwait, Iceland, and Sweden. These economies all had LCT export and import shares that exceeded the global share, which was 5.2 percent for exports and 4.9 percent for imports.

Economies with the highest share of LCT products in total merchandise exports have often specialized in certain technologies. For example, North Macedonia exports emissions control catalysts that are used to filter diesel vehicle exhaust. These systems are mostly exported to other European countries to meet the Euro IV Heavy Duty Diesel Emissions Standards. Japan stands out as well due to its production of electric vehicles and other machinery used in low-carbon alternatives. Economies with high shares of imports of LCT products are consuming and investing in LCTs. For example,

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15 UNCTAD (2014) explains that "this systematic feature of tariff classification tends to inflate the size of environmental goods trade" (p. 5).

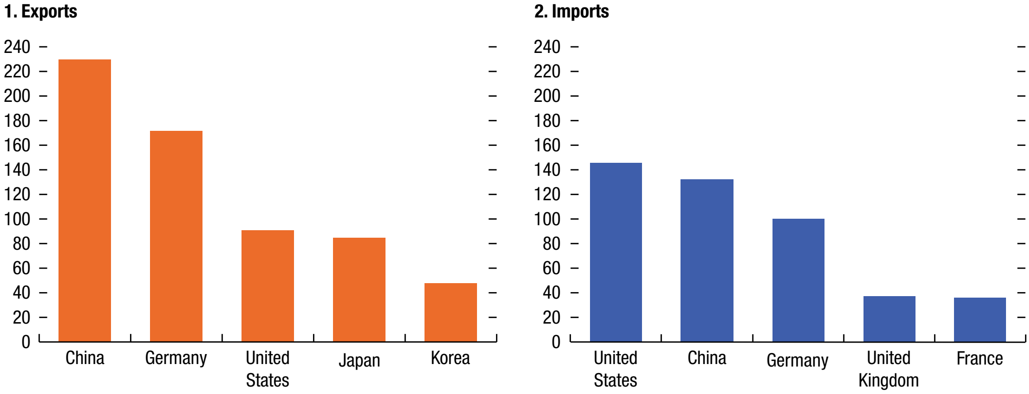
16 At the individual economy or regional level, the commodity codes are more granular—with eight- or ten-digit codes, which allow for the identification of more detailed products within a six-digit category. Since these more detailed codes are not harmonized across all economies, they cannot be used to estimate LCT products for a broad set of economies.

17 In addition, new subheadings have been added to better identify environmentally damaging, or hazardous, goods, such as goods containing chlorofluorocarbons and hydrofluorocarbons.

18 Although these amendments to the HS nomenclature can facilitate the analysis of trade in these products, the changes do introduce breaks in the statistical series. The introduction of new codes for EVs in HS 2017, in particular, introduced a break in the LCT statistics between 2016 and 2017.

19 The results are similar to those presented in Pigato and others (2020), which, as described earlier, used a list of 107 commodities based on an earlier version of the HS. For 2016 (the most recent period reported in Pigato and others 2020), Pigato estimates US$699 billion in LCT exports and US$685 billion in LCT imports, compared to US$696 billion and US$695 billion, respectively, estimated here. In both sets of results, the top five exporters and importers are the same.

Figure 9.1. Largest Exporters and Importers of LCT Products, 2021
(Billions of US dollars)

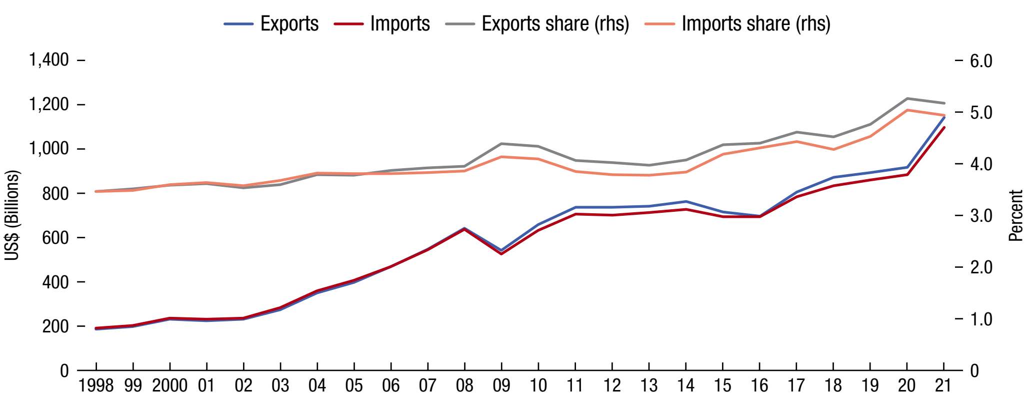


Sources: Department of Economic and Social Affairs/United Nations Statistics Division, United Nations Comtrade database; and IMF staff calculations.
Note: LCT = low-carbon technologies.

Kuwait imports parts for gas turbines and other equipment related to the use of natural gas in electrical power generation.[20]

Trade in LCT products has been growing (Figure 9.2, left axis), including as a share of total goods trade (Figure 9.2, right axis). Some of this growth, however, is due to structural breaks in the series when new HS codes are introduced. For example, there is a break in the series between 2016 and

Figure 9.2. Growth in Low-Carbon Technology Trade

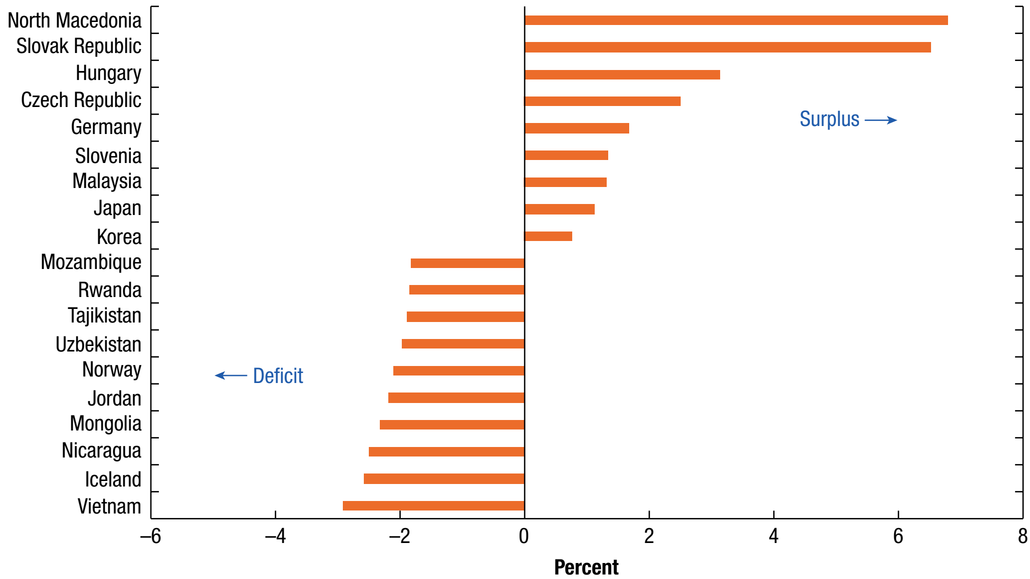


Sources: Department of Economic and Social Affairs/United Nations Statistics Division, United Nations Comtrade database; and IMF staff calculations.
Note: rhs = right-hand side.

[20] These products are considered LCT products because electrical power generation using natural gas produces lower emissions compared with traditional fire power generation methods. The classification of gas and nuclear activities as "sustainable" or "green" goods has been a source of debate internationally (see Box 9.2).

Figure 9.3. Net Exporters and Importers
(Percent of nominal GDP)

Trade Balance in Low-Carbon Technology Products, 2021



Sources: Department of Economic and Social Affairs/United Nations Statistics Division, United Nations Comtrade database; World Economic Outlook database; and IMF staff calculations.

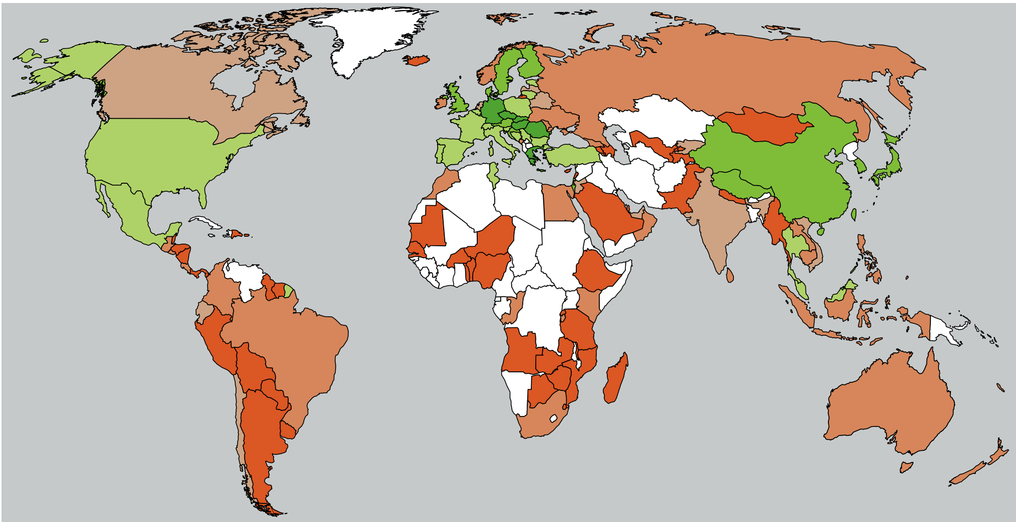
2017 due to a large number of new HS codes being introduced with the 2017 update of the HS nomenclature.

LCT production remains concentrated in high-income economies. Together, high-income economies accounted for 70 percent of LCT exports in 2021, down from 92 percent in 1998. The decline in the high-income share is offset by an increase in the upper-middle-income share, which is attributable to China.

Figure 9.3 shows the economies with the largest LCT product trade surpluses and deficits (as a percentage of nominal GDP). The LCT trade balance may be an important indicator for understanding how the transition to a low-carbon economy may impact an economy's trade balance and thus its balance of payments. For example, several economies that generally run deficits in total goods trade have trade surpluses in LCT products, such as North Macedonia and Romania. This generally reflects their comparative advantage in LCT products.

The map in Figure 9.4 shows which economies have a relative advantage in LCT products (index greater than one, shown in green) and which economies have a relative disadvantage in LCT products (index less than or equal to one, shown in red). North Macedonia has the highest comparative advantage because of a few specialized products that account for a significant share of its exports, as mentioned earlier. In total, 22 economies have a relative advantage in LCT products—most prominently Slovak Republic, Japan, Hungary, Germany, Romania, Czech Republic, and Denmark—while the remaining 115 countries have a relative disadvantage. Given the expectation that global decarbonization will substantially increase global LCT trade, this highlights the potential for climate mitigation to support development if developing countries are able to improve their comparative advantage toward this segment of world trade.

Figure 9.4. Comparative Advantage in LCT Products, 2021



Sources: Environmental Systems Research Institute; Food and Agriculture Organization; IMF Climate Change Indicators Dashboard 2022; National Oceanic and Atmospheric Administration; and United States Geological Survey.
Note: Economies shown in white are ones for which data are not available for 2021. LCT = low-carbon technology.

TRADE POLICY RELATING TO LCT PRODUCTS

Trade policy has an important role in promoting trade in LCT products. This section provides an overview of tariffs and nontariff measures that apply to LCT products, as well as of climate-related objectives of measures relating to LCTs.

Tariffs on LCT Products

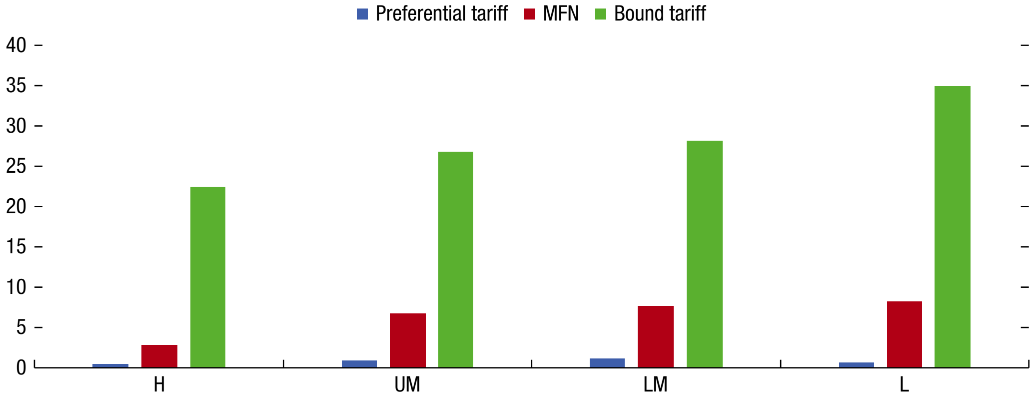
Tariffs raise the price of and thereby tend to reduce the demand for imported products. In the World Trade Organization (WTO) context, bound tariff levels indicate the maximum level of duty that WTO members have committed to apply on goods imported from other members, as indicated in their schedules of concessions. Most-favored nation (MFN) applied tariffs correspond to the tariffs that WTO members commit to accord to imports from all other WTO members with which they have not signed a preferential agreement. Where the bound tariff exceeds the applied tariff, governments have the flexibility to raise the applied level up to the bound level without breaching their commitments. Data on tariffs come from the WTO Integrated Database and the UN Comtrade database for 2019.[21] All product codes are converted into the HS 2017 nomenclature using concordance tables. The database includes 108 importing countries (with the European Union counted as one) and 215 exporting countries.

For the whole sample, the simple average bound tariff is 28 percent, whereas the simple average MFN applied tariff is 6.3 percent and the simple average preferential tariff is 0.8 percent.[22] Figure 9.5 shows that, for all income groups, there is an important gap between bound and MFN tariffs and between the MFN and the preferential tariffs. While the bilateral preferential tariffs for the list of

[21] See https://stats.wto.org/.

[22] The simple average preferential tariff is computed among all trade partners that apply a preferential tariff.

Figure 9.5. Bound, Most Favored Nation, and Preferential Tariffs on LCT Products
(Percent)



Source: Tariffs data is from the WTO Integrated Database (IDB) and Department of Economic and Social Affairs/United Nations Statistics Division, United Nations Comtrade database.
Note: Income groups follow the classification of the World Bank into high income (H), upper-middle income (UM), lower-middle income (LM), and low income (L). LCT = low-carbon technology; MFN = most favored nation.

LCT products are relatively low, MFN applied tariffs on LCT products exceed 5 percent on average for all income groups, apart from high-income countries, where it is lower.[23]

Nontariff Measures on LCT Products

Inventory data on nontariff measures (NTMs) are obtained from the United Nations Conference on Trade and Development (UNCTAD) Trade Analysis Information System (TRAINS) database. Each nontariff measure is identified by an identifier code and belongs to a Multi-Agency Support Team (MAST) category. Technical Barriers to Trade (TBTs) are among the most common NTMs and are also better documented in terms of data coverage. The extensive margin of TBTs, which reflects the range of traded LCT products affected by at least one TBT, can be identified through the frequency index, which is defined as the share of traded LCT product HS6 lines affected by at least one TBT in the total number of traded LCT product HS6 lines, a ratio that is averaged across all countries within an income group. On average, 55 percent of LCT product lines are affected by at least one TBT. Eighty-one percent of traded LCT product lines are affected by at least one TBT in high-income countries, 51 percent in upper-middle-income countries, and around 45 percent in lower-middle- and low-income countries.[24]

The intensity of TBTs is computed as the average number of TBTs targeting an LCT product imposed by countries belonging to an income group. The total number of TBTs is counted, per product, and then the average is computed for LCT products and other goods for 2019. Figure 9.6 shows that the average number of TBTs is lower for LCT products compared to other goods, except for upper-middle-income countries.

Not all NTMs are trade restrictive. For example, regulatory measures based on international standards or subsidies might promote trade. Even so, and notwithstanding the fact that NTMs are not necessarily more prevalent for LCT products than for non-LCT products (see WTO 2022b),

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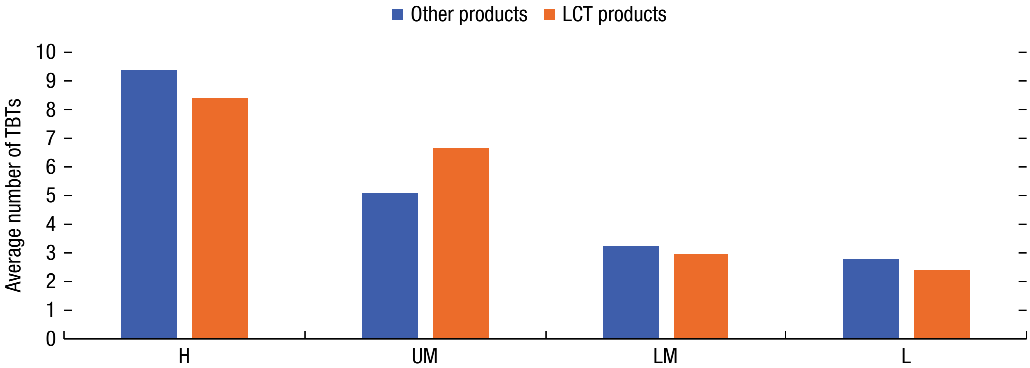
[23] Note that the average bound tariff on LCT products for high-income economies considered as developed economies in the WTO context is 5.3 percent.

[24] The TRAINS database covers 57 countries, of which 11 are high-income countries (with EU included as a country group), 36 are middle-income countries, and 10 are low-income countries.

Figure 9.6. Average Number of TBTs for LCT Products and Other Products



Source: Authors' computations based on UNCTAD TRAINS database.
Note: Based on Multi-Agency Support Team (MAST) chapters of nontariff measures information on Technical Barriers to Trade. Income groups follow the classification of the World Bank into high income (H), upper-middle income (UM), lower-middle income (LM), and low income (L). LCT = low-carbon technology; TBTs = technical barriers to trade

harmonizing or promoting mutual recognition and equivalence of NTMs can facilitate trade in LCT products and thereby generate environmental benefits.

Also, it is worthwhile recalling that governments often put NTMs in place to pursue public policy objectives. For instance, addressing climate change is a main objective of technical regulations and subsidies for clean energy installations or EVs, which can also have trade-promoting effects for the targeted products. Governments' use of trade-related policies to promote environmental objectives is illustrated by the WTO Environmental Database, which contains WTO members' notifications of environment-related trade measures (see Box 9.3).[25]

Specific Trade Concerns

Specific trade concerns are concerns raised by WTO members in certain WTO committees about measures put in place by other countries and generally deemed to restrict trade (WTO 2012). Discussions on specific trade concerns can help ease trade tensions by providing further information and helping with the identification of mutually satisfactory solutions. The WTO Trade Concerns Database allows users to search for trade concerns raised in the Committee on Market Access, Sanitary and Phytosanitary Committee, and Technical Barriers to Trade Committee, and provides members' profiles regarding their participation in specific trade concerns.

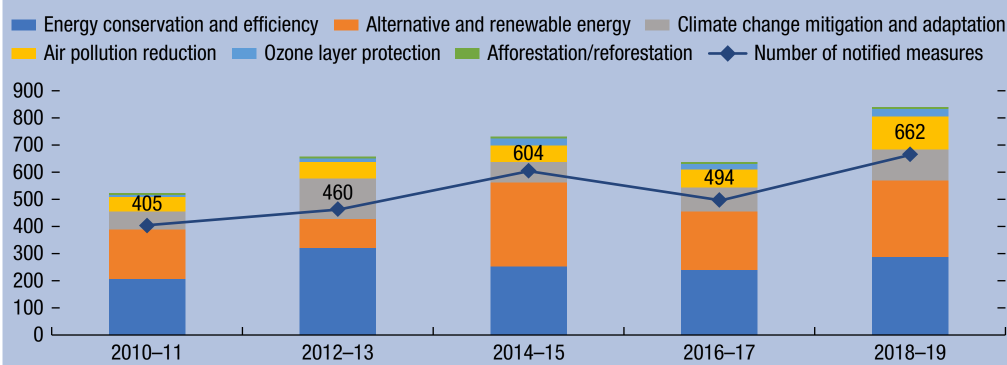
Specific trade concerns raised in the Technical Barriers to Trade Committee relate to technical regulations and conformity assessment procedures that potentially impede trade. Between 2010 and 2020, some 85 specific trade concerns were raised in that committee relating to LCT products (Figure 9.7). This corresponds to close to a quarter of all specific trade concerns related to technical barriers to trade raised during that period. Specific trade concerns on LCT products are concentrated in HS chapters 85 and 84, which each account for around one-third of the 85 LCT-related specific trade concerns. The highest number of new specific trade concerns relating to LCT products were raised in 2010 and 2020 with 14 each, while in 2019 only two such specific trade concerns were raised. Figure 9.7 furthermore reveals that measures underlying specific trade concerns related to TBTs on LCT products potentially affect a large value of trade. For example, such concerns covered LCT product imports of US$215 billion in 2014, US$160 billion in 2018, and US$154 billion in 2011.

[25] An overview of measures included in the WTO Environmental Database (EDB) is contained in WTO (2022). In addition to notifications, the EDB also includes information on policies mentioned in WTO members' Trade Policy Reviews.

Box 9.3. WTO Environmental Database: Climate-Related Trade Measures

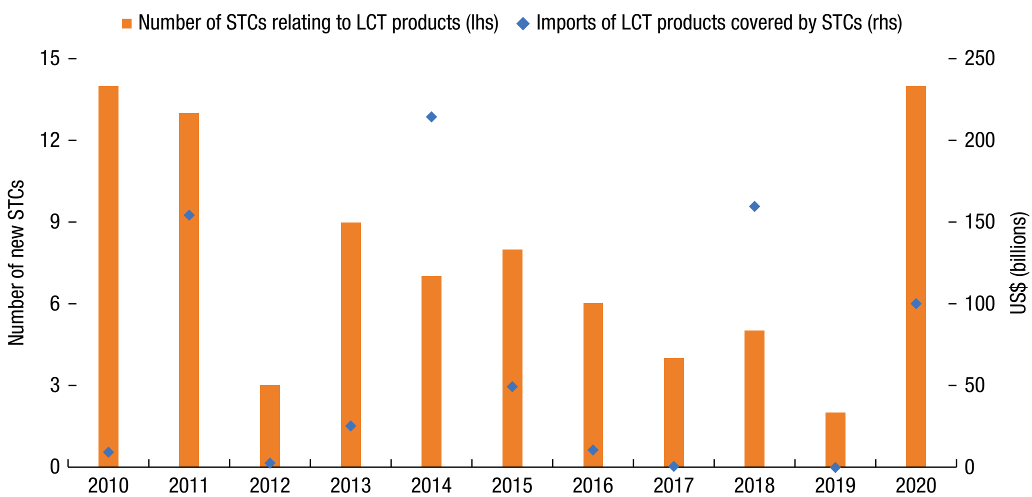
The World Trade Organization (WTO) Environmental Database (EDB) assigns trade policy measures to 25 harmonized environmental objectives, including six climate-related objectives (WTO 2022a). Between 2010 and 2019, the WTO was notified of 4,355 climate-related measures (WTO 2021), including 2,625 measures covering Harmonized System chapters 84 (nuclear reactors, boilers, and machinery), 85 (electrical machinery and equipment), and 90 (optical, photographic, measuring, and precision instruments), where three-quarters of the 124 low-carbon technology (LCT) products are classified (see Figure 9.3.1). Energy conservation and efficiency as well as alternative and renewable energy were the objectives of more than 40 percent of such measures relating to LCT products during 2018–19, while air pollution reduction as well as climate change mitigation and adaptation were the objectives of close to 20 percent of these measures. The most common types of measures used by WTO members to promote climate-related objectives were technical regulations (39 percent) and conformity assessment procedures (17 percent) under the Agreement on Technical Barriers to Trade, as well as financial support—grants and direct payments (27 percent) and tax concessions (16 percent)—under the Agreement on Subsidies and Countervailing Measures.

Figure 9.3.1. Climate-related Measures Relating to LCT Products in HS Chapters 84, 85, and 90, by Objective



Source: WTO Secretariat based on the WTO's Environmental Database (EDB).
Note: The sum of measures by objective is larger than the number of notified measures as a notified measure can be assigned to multiple objectives. As information on Harmonized System (HS) codes are not available for all types of measures in the EDB, this figure relies on the HS allocation to EDB measures by Bellelli and Xu (2022) and present statistics for HS chapters 84, 85, and 90 to broadly capture measures relating to LCT products with climate-related objectives. LCT = low-carbon technology; WTO = World Trade Organization.

Figure 9.7. Number of New Specific Trade Concerns Relating to LCT Products and Imports Covered, 2010–20



Source: WTO Secretariat based on WTO Trade Concerns Database.
Note: LCT = low-carbon technology; lhs = left-hand side; rhs = right-hand side; STCs = specific trade concerns; WTO = World Trade Organization.

THE ROLE OF MINERALS AND METALS IN LCT PRODUCTS

Because metals are critical inputs into LCT products (see Box 9.4), it is useful to understand the impact of metal prices on LCT products. This allows the private sector to better adjust consumption and investment, preventing supply and demand mismatches and mitigating price fluctuations.

Against this background, the IMF introduced an Energy Transition Metals Price Index in its Primary Commodity Price System. The system is a go-to source for publicly available monthly commodity price data. It includes 68 commodity price series covering energy, agriculture, fertilizers, and metals, as well as several aggregated commodity price indices.[26]

Box 9.4. Metals for Low-Carbon Technologies

Metals are critical inputs into low-carbon technology (LCT) products, such as solar cells and batteries (see Table 9.4.1). For example, a typical EV battery pack requires around 8 kilograms of lithium, 35 kilograms of nickel, and 14 kilograms of cobalt, while charging stations use substantial amounts of copper. As a result, an accelerated decarbonization of the economy will likely cause upward pressure on prices for these critical minerals, potentially making the decarbonization more expensive and delaying it (Boer, Pescatori, and Stuermer 2021).

TABLE 9.4.1

Metals for Low-Carbon Technology Products

Metal	Exchange Traded	Energy Transition Usage				Production
		Renewable	Network	Battery	Hydrogen	(2020, US$ billion)
Copper	✓	✓	✓	✓		123.0
Aluminum	✓	✓	✓	✓	✓	107.0
Nickel	✓	✓		✓	✓	28.0
Zinc	✓	✓				28.0
Lead	✓	✓		✓	✓	26.0
Silver	✓	✓				13.0
Manganese	No	✓		✓	✓	25.0
Chromium	Recent	✓				19.0
Silicon	No	✓				14.0
Molybdenum	Recent	✓			✓	5.0
Cobalt	Recent			✓		4.1
Lithium	Recent			✓		1.8
Vanadium	No			✓		1.3
Graphite	No			✓		1.3

Sources: International Energy Agency (2021a); World Bank (2020); and IMF staff calculations.
Note: The column "Production" is the value of refined and unrefined mining production.

Many markets for critical metals are not transparent, and prices are not readily available to the public. This is particularly true for minor but "rising" metals, such as lithium, cobalt, and vanadium, which have not been in wide use before. In contrast, some metals critical for the energy transition, such as copper and aluminum, have been major metals for a long time, reflected in the fact that they have a long history of being traded on public exchanges.

For the new Energy Transition Metals Price Index, the subindices and their weights differ along the following two dimensions:

1. The first dimension is the set of metals included in each subindex—all relevant metals are included in Subindex 1 versus only "rising" metals (that is, only non-exchange-traded metals) being included in Subindices 2 and 3.
2. The second dimension is related to the relative importance of each metal in the energy transition. The relative importance of each metal is measured by computing the value of consumption for each metal used in clean energy technologies relative to all the other metals in the set. The estimation is based on the 2020 consumption data from IEA (2021b) and actual prices in Subindices 1 and 2. Subindex 3 focuses on the future importance of the rising metals by weighting them based on their projected demand for clean energy technologies in 2040, under the IEA (2021b) Net-Zero Emissions Scenario, multiplied by their respective prices under the same scenario derived in Boer, Pescatori, and Stuermer (2021).

Rachel Brasier, Andrea Pescatori, and Martin Stuermer contributed to this box.

[26] The data are publicly available at https://www.imf.org/en/Research/commodity-prices.

The new Energy Transition Metals Price Index and its subindices provide a tool for evaluating movements in prices based on each metal's relative importance for LCT products. Using the index, governments and international organizations can get better insights into the input cost pressures for LCT products. Figure 9.8 shows that Subindex 2, capturing demand for the "rising" metals that are expected to be most important for the energy transition, reflects a strong increase in demand at the turn of 2021. The increase is even steeper if the index uses weights based on expected 2040 trade values rather than current values (Subindex 3). Subindex 1, including all relevant metals based on weights of current value of consumption shows the least steep increases.

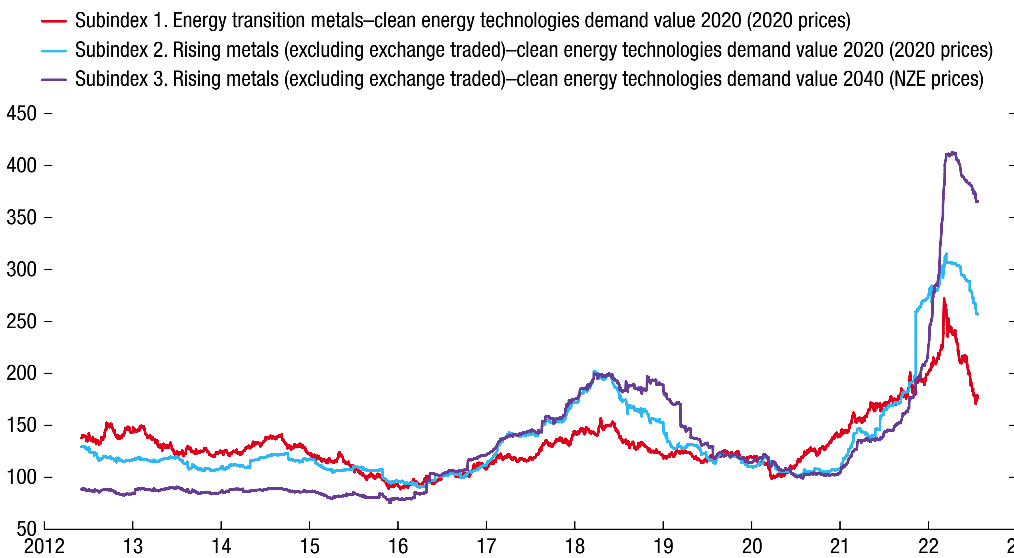
CONCLUSION AND POLICY IMPLICATIONS

The indicators derived in this chapter have multiple policy uses.

Trade policy. First, facilitating trade flows in LCTs requires good data (Hoekman, Maskus, and Saggi 2004). Several attempts have been made to develop internationally agreed-upon lists of environmental goods to be included in a possible environmental goods trade agreement (including negotiations within the WTO in 2016[27]). Information on trade in LCTs—a narrower range of goods specifically needed for global decarbonization—could aid in the future development of multilateral or bilateral agreements. Data on LCT trade as well as policy measures can be used by policymakers to promote trade in LCT products/environmental goods through various trade policies (including tariffs and nontariff measures).

Figure 9.8. Index for Metals Critical to LCT Products

(Index, 2016 = 100)



Sources: International Energy Agency; Refinitiv Datastream; and IMF staff calculations.

Note: NZE refers to the IEA Net-Zero Energy scenario. Energy transition metals includes aluminum, chromium, cobalt, copper, lead, lithium, manganese, molybdenum, nickel, palladium, platinum, rare earth elements, silicon, silver, vanadium, and zinc. Rising metals includes only non-exchange-traded energy transition metals (chromium, cobalt, lithium, manganese, molybdenum, palladium, rare earth elements, silicon, and vanadium). LCT = low-carbon technology; NZE = net-zero energy.

[27] See https://www.wto.org/english/tratop_e/envir_e/ega_e.htm.

International climate negotiations and monitoring of progress on decarbonization. LCTs play a prominent role in the international negotiations on climate change. Accelerating the development and transfer of LCTs, including toward developing countries, has been at the core of international climate change negotiations since the 1992 UN Framework Convention on Climate Change (UNFCCC). The 2015 Paris Agreement further established a technology framework, under Article 10, to accelerate transfer of LCTs to developing countries, including through trade. Indeed, at COP26, 45 countries agreed to accelerate the adoption of LCTs globally in four key sectors (power, road transport, steel, and hydrogen). These sectors are already trade-intensive sectors, and accelerated adoption will require further ramping up of trade in them.[28] The data set here can assist countries in their negotiations on climate change and monitoring of flows of LCTs and assessing whether those flows are aligned with global temperature targets.

International funding for low-carbon innovations. There are a few international instruments for accelerating innovation and production in LCTs, such as the UNFCCC's Technology Mechanism (which supports accelerated technology transfer to developing countries). Future international instruments could include those that pool funds for investing into low-carbon innovations, for example, for purchasing and open-sourcing patents in LCTs or for providing advance market commitments (to purchase new LCTs).

Domestic climate policy. In addition to tariff reductions, governments could use information on LCTs to inform domestic climate policies. It is widely acknowledged that carbon pricing—carbon taxes and emissions trading systems (ETSs)—is the most efficient tool for achieving emissions cuts, and hence for accelerating the adoption of LCTs.[29] Data on trade flows of these products can help inform the design of carbon pricing, including their complementarities or inconsistencies with trade policies. In addition, subsidies and tax incentives could be informed by flows of LCTs. For example, tax relief has been an effective tool for reducing the costs of solar (Gerarden 2017) and wind (Kirchherr and Urban 2018). Subsidies for currently expensive but necessary technologies like direct air capture may also be needed. All can be informed through better modeling of trade impacts, for example, through integration of material and financial flows into multiregion input–output analyses to examine the output, employment, and trade ramifications of accelerating LCT adoption.

Technology and green industrial policies. Green industrial policy programs are gaining in popularity globally given their potential for both accelerating decarbonization and providing jobs (Fischer 2016). Under such programs governments may support domestic research and development in or adoption of LCTs subject to relevant WTO disciplines (Pigato and others 2020; IMF and others 2022). Information on LCT trade could be used to inform the design of green industrial policies subject to their starting conditions, such as human and state capabilities, comparative advantages, and the similarity between the skills and networks in existing production chains and those required for LCTs (Mazzucato 2016).

Metals. Considering the link between metals and LCTs, it would be useful to develop better insights into input cost pressures for LCT products. The IMF plans to release more data on metals, such as graphite, when trading data becomes more standardized and widely available. The underlying demand scenarios and derived price scenarios can also be updated frequently. This will contribute to making these critical metals markets more transparent, as the world economy becomes more metals intense.

[28] See https://ukcop26.org/cop26-world-leaders-summit-statement-on-the-breakthrough-agenda/.

[29] There are a variety of considerations when choosing between carbon taxes and emissions trading schemes as the key mitigation instrument; see Parry and others (2022).

ANNEX 9.1

DATA SOURCES FOR MEASURING TRADE IN LCT PRODUCTS

There are several data sources for commodity- or product-level trade information. The low-carbon technology (LCT) indicators in the IMF's *Climate Change Indicators Dashboard* (CID) are derived from the UN Comtrade data set.

National data sources. Analysts interested in measuring trade in LCT products for an individual economy can use the trade statistics produced by the country's national statistical office. These statistics often provide additional granularity because many economies have commodity classifications at the national level that expand on the six-digit-level detail of the Harmonized System (HS) nomenclature.

International data sources. Besides national sources, there are several international trade databases at the product level, including UN Comtrade, the Centre d'Etudes Prospective et d'Informations Internationales (CEPII) Base pour l'Analyse du Commerce International (BACI) database, and the OECD Balanced International Merchandise Trade Statistics (BIMTS).

UN Comtrade database. The UN collects and disseminates monthly trade data by product and by partner economy from over 170 economies. Because UN Comtrade presents the official trade statistics as reported by each economy, it includes two different figures for each bilateral trade flow (for example, partner economy A's reported exports to partner economy B, and partner economy B's reported imports from partner economy A) and these amounts rarely match. The primary reasons for trade asymmetries are (1) the application of different criteria of partner economy attribution in import and export statistics, (2) the use of different valuation bases for import and export statistics, and (3) the application of different trade systems in data compilation.[30] The guidelines for international merchandise trade statistics recommend that imports are recorded by "country of origin," while exports are recorded by "country of export" or "country of last known destination." This inevitably means that import data will not mirror export data (see Markhonko 2014). Other sources of trade asymmetries include differences in classification and time of recording.

CEPII and OECD databases. To address trade asymmetries such as in the UN database, some organizations have produced balanced trade data sets, which reconcile the asymmetric flows through statistical methods to have a single consistent figure for each bilateral flow. Using "mirror" data reported by partner economies, they are also able to improve geographic coverage. Annex Table 9.1.1 compares UN Comtrade with two of the most used balanced trade data sets, BACI and BIMTS.

ANNEX TABLE 9.1.1

Data Sources for International Trade at the Product Level

Source	Time Coverage (annual data)	Geographical Coverage	Product Detail[1]	Adjusted?
UN Comtrade	1988–2021[2]	Over 170 countries/ areas	HS0–HS5, as reported, 6-digit	No
CEPII BACI	1995–2021	Over 200 countries/ areas	HS0–HS5, 6-digit	Imports converted to free-on-board valuation; asymmetries reconciled through statistical methods; missing countries/areas estimated using mirror flows
OECD Balanced International Merchandise Trade Data Set	2007–2018	Over 160 countries/ areas	HS5, 6-digit	Imports converted to free-on-board valuation; asymmetries reconciled through statistical methods and using special adjustments for unallocated and confidential trade, re-exports (for selected jurisdictions), and product misclassifications; missing countries/areas estimated using mirror flows

Note: CEPII = Centre d'Études Prospectives et d'Informations Internationales; OECD = Organisation for Economic Co-operation and Development; UN = United Nations.

[1] Revisions to the Harmonized System (HS) are made about every five years. The vintages are notated as H0 (1988), H1 (1996), H2 (2002), H3 (2007), H4 (2012), and H5 (2017).

[2] Trade data are available in UN Comtrade from 1962, but HS-level detail is available only from 1988.

[30] Further information available at https://unstats.un.org/wiki/display/comtrade/Bilateral+asymmetries.

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APPENDIX A

Data Sources in this Book

This appendix provides a collective list of data sources mentioned in this book, with hyperlinks for ease of access. The links are subject to change.

Institution	Data Source	Hyperlink
Argus Direct Media	Argus Oil and Fuel Prices	https://direct.argusmedia.com
British Petroleum	Statistical Review of World Energy	https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html
Bureau van Dijk	Orbis	https://www.bvdinfo.com/en-gb/our-products/data/international/orbis
Centre d'Études Prospective et d'Informations Internationales (CEPII)	Base pour l'Analyse du Commerce International (BACI)	https://www.cepii.fr/CEPII/en/bdd_modele/bdd_modele_item.asp?id=37
Centre for Research on the Epidemiology of Disasters (CRED)	Emergency Events Database (EM-DAT)	https://www.emdat.be
Enerdata	Global Energy and CO_2 data	https://www.enerdata.net/services.html
European Central Bank (ECB)	Analytical Credit Dataset (AnaCredit)	https://www.ecb.europa.eu/stats/money_credit_banking/anacredit/html/index.en.html
European Central Bank (ECB)	Securities Holdings Statistics (SHS)	https://www.ecb.europa.eu/stats/financial_markets_and_interest_rates/securities/html/index.en.html#holdings
European Commission	Disaster Risk Management Knowledge Centre (DRMKC)	https://drmkc.jrc.ec.europa.eu/partnership/Scientific-Partnerships/Risk-Data-Hub
European Commission	Emergency Management Service (EMSR)	https://emergency.copernicus.eu/mapping/#zoom=2&lat=17.44093&lon=29.71939&layers=0BT00
European Commission	Emissions Database for Global Atmospheric Research (EDGAR)	https://edgar.jrc.ec.europa.eu/
European Commission	Energy Statistics—Prices of Natural Gas and Electricity	https://ec.europa.eu/eurostat/web/energy/data/database
European Commission	European Forest Fire Information System (EFFIS)	https://effis.jrc.ec.europa.eu
European Commission	European Pollutant Release and Transfer Register (E-PRTR)	https://ec.europa.eu/environment/industry/stationary/e-prtr/legislation.htm
European Commission	Global Human Settlement Layer (GHSL) database	https://ghsl.jrc.ec.europa.eu/
European Commission	River Flood Hazard Maps at European and Global Scale	https://data.jrc.ec.europa.eu/collection/id-0054
European Drought Center	European Drought Impact Report Inventory (EDII)	https://www.geo.uio.no/edc/droughtdb/index.php
European Drought Center	European Drought Reference (EDR) database	https://www.geo.uio.no/edc/droughtdb/index.php
European Insurance and Occupational Pensions Authority (EIOPA)	Insurance Protection Gap Dashboard	https://www.eiopa.europa.eu/document-library/feedback-request/pilot-dashboard-insurance-protection-gap-natural-catastrophes_en
European Union (EU)	Copernicus—Earth observation programme	https://www.copernicus.eu
European Union (EU)	Corine Land Cover database	https://land.copernicus.eu/pan-european/corine-land-cover
European Union (EU)	European Settlement Map (ESM)	https://land.copernicus.eu/pan-european/GHSL/european-settlement-map/esm-2015-release-2019
Eurostat	Geographic Information System of the Commission (GISCO)	https://ec.europa.eu/eurostat/web/gisco
Eurostat	GEOSTAT	https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/population-distribution-demography/geostat#geostat11

Institution	Data Source	Hyperlink
Eurostat	Nomenclature of Territorial Units for Statistics (NUTS)	https://ec.europa.eu/eurostat/web/nuts/background
Eurostat	Quarterly GHG emissions in the EU	https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Quarterly_greenhouse_gas_emissions_in_the_EU&oldid=565161
Eurostat	Regional statistics by NUTS classification	https://ec.europa.eu/eurostat/web/regions/data/database
Food and Agriculture Organization (FAO)	The Global ADMinistrative Areas (GADM)	https://data.apps.fao.org/map/catalog/srv/eng/catalog.search#/metadata/5e20fcf5-e376-4798-94a8-13ce49481cb2
Global Petrol Prices (GBP)	Retail Energy Prices	https://www.globalpetrolprices.com/data_download.php
IMF	Climate Change Indicators Dashboard	https://climatedata.imf.org
IMF	Energy Subsidy Template	https://www.imf.org/-/media/Files/Topics/Environment/energy-subsidies/fuel-subsidies-template-2021-updated-131021.ashx
IMF	Government Finance Statistics	https://data.imf.org/gfs
IMF	Direction of Trade Statistics (DOTS)	https://data.imf.org/dot
IMF	Primary Commodity Prices	https://www.imf.org/en/Research/commodity-prices
IMF	Special Purpose Entities (SPE) database	https://data.imf.org/bop
IMF	World Economic Outlook (WEO) database	https://www.imf.org/external/datamapper/datasets/WEO
Intergovernmental Panel on Climate Change (IPCC)	Global climate data and projections	https://interactive-atlas.ipcc.ch
International Energy Agency (IEA)	Energy Prices and Taxes Statistics	https://www.oecd-ilibrary.org/energy/data/iea-energy-prices-and-taxes-statistics_eneprice-data-en
International Energy Agency (IEA)	GHG Emissions from Energy database	https://www.iea.org/data-and-statistics/data-tools/greenhouse-gas-emissions-from-energy-data-explorer
International Energy Agency (IEA)	World Energy Balances	https://www.iea.org/data-and-statistics/data-product/world-energy-balances-highlights
International Science Council	Sendai Hazard Definitions and Classification Review	https://council.science/sendai-hazard-review
Moody's ESG Solutions	Four Twenty Seven	https://esg.moodys.io/
National Aeronautics and Space Administration (NASA)	Global climate data and projections	https://data.nasa.gov
National Aeronautics and Space Administration (NASA)	Global Landslide Catalog (GLC)	https://data.nasa.gov
National Aeronautics and Space Administration (NASA)	Landslide Reporter Catalog (LRC)	https://gpm.nasa.gov/landslides/index.html
National Aeronautics and Space Administration (NASA)	NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP)	https://www.nccs.nasa.gov/services/data-collections/land-based-products/nex-gddp
National Oceanic and Atmospheric Administration (NOAA)	National Centers for Environmental Information	https://www.ncei.noaa.gov/maps/hazards
Network for Greening the Financial System (NGFS)	Physical and transition risk scenarios	https://www.ngfs.net/ngfs-scenarios-portal/data-resources
OECD	Air Emissions Accounts	https://stats.oecd.org/Index.aspx?DataSetCode=OECD-AEA
OECD	Air Transport CO_2 emissions database	https://stats.oecd.org/Index.aspx?DataSetCode=AIRTRANS_CO2
OECD	Analytical Activities of Multinational Enterprises (AMNE)	https://www.oecd.org/sti/ind/analytical-AMNE-database.htm#database

Institution	Data Source	Hyperlink
OECD	Balanced International Merchandise Trade Statistics (BIMTS)	https://stats.oecd.org/Index.aspx?DataSetCode=BIMTS_HS2017
OECD	Climate Dashboard	https://www.oecd.org/climate-action/ipac/dashboard
OECD	Environmentally Related Tax Revenue	https://stats.oecd.org/Index.aspx?DataSetCode=ERTR
OECD	Global Revenue Statistics	https://stats.oecd.org/Index.aspx?DataSetCode=RS_GBL
OECD	Green Growth Indicators	https://www.oecd.org/greengrowth/green-growth-indicators
OECD	Input–Output Tables (IOTs)	https://www.oecd.org/sti/ind/input-outputtables.htm
OECD	Intercountry Input–Output (ICIO) tables	https://www.oecd.org/sti/ind/inter-country-input-output-tables.htm
OECD	Policy Instruments for the Environment (PINE) database	https://www.oecd.org/environment/indicators-modelling-outlooks/policy-instrument-database
OECD	Trade in Embodied CO_2 (TECO2) database	https://www.oecd.org/sti/ind/carbondioxideemissionsembodied-ininternationaltrade.htm
OpenStreetMap	Open Street Map (OSM)	https://www.openstreetmap.org
United Nations	Comtrade	https://comtrade.un.org
United Nations Conference on Trade and Development (UNCTAD)	Trade Analysis Information System (TRAINS) database	https://unctad.org/topic/trade-analysis/data-statistics-and-trends
United Nations Framework Convention on Climate Change (UNFCCC)	National Inventory Submissions	https://di.unfccc.int/time_series
United States Department of Agriculture (USDA)	Keetch-Byram Drought Index (KBDI) for Forest Fire	https://www.srs.fs.usda.gov/pubs/viewpub.php?index=40
United States Energy Information Administration (US EIA)	Energy Consumption by Country	https://www.eia.gov/international/data/world
United States Environmental Protection Agency (US EPA)	Greenhouse Gas Equivalencies Calculator	https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator
University of Colorado	Dartmouth Flood Observatory (DFO)	https://floodobservatory.colorado.edu
VITO	Global Land Cover database	https://lcviewer.vito.be/2018
World Bank	Carbon Pricing Dashboard	https://carbonpricingdashboard.worldbank.org/
World Bank	Official Boundaries	https://datacatalog.worldbank.org/search/dataset/0038272
World Bank	State and Trends of Carbon Pricing	https://openknowledge.worldbank.org/handle/10986/13334
World Resources Institute (WRI)	Global climate data and projections	https://datasets.wri.org
WTO	Environmental Database (EDB)	https://edb.wto.org
WTO	Integrated Database	https://stats.wto.org
WTO	Trade Concerns Database	https://tradeconcerns.wto.org

Phrases and Associated Hyperlinks in this Book

This appendix provides a collective list of the phrases that appear throughout the book and the hyperlinks with which they are associated. Links are subject to change.

Phrase	Chapter	Data Source	Hyperlink
A Drought Index for Forest Fire Control	4	Keetch, Byram (1968)	https://www.srs.fs.usda.gov/pubs/viewpub.php?index=40
A Structural Decomposition Analysis of Pollution in the Netherlands	1	Economic Systems Research	https://www.tandfonline.com/doi/abs/10.1080/09537320120052452
Analytical Credit dataset (AnaCredit)	4	ECB	https://www.ecb.europa.eu/stats/money_credit_banking/anacredit/html/index.en.html
Carbon Footprint of Bank Loans (CFBL)	7	IMF	https://climatedata.imf.org/pages/fi-indicators
Carbon Pricing Dashboard	5	World Bank	https://carbonpricingdashboard.worldbank.org/
CEPII BACI	9	CEPII	http://www.cepii.fr/CEPII/en/bdd_modele/bdd_modele_item.asp?id=37
Climate Change Indicators Dashboard	4	IMF Climate Change Indicators Dashboard	https://climatedata.imf.org
climatedata.imf.org	3	IMF Climate Change Indicators Dashboard	https://climatedata.imf.org
CO_2 Emissions from Air Transport: A Near-Real-Time Global Database for Policy Analysis	1	OECD	https://doi.org/10.1787/ecc9f16b-en
Copernicus	4	Copernicus (European Union's Earth Observation Programme)	https://cds.climate.copernicus.eu/cdsapp#!/home
Corine Land Cover	4	European Union (EU)	https://land.copernicus.eu/pan-european/corine-land-cover
Corine Land Cover nomenclature	4	European Union (EU)	https://land.copernicus.eu/user-corner/technical-library/corine-land-cover-nomenclature-guidelines/html
dashboard	4	European Insurance and Occupational Pensions Authority (EIOPA)	https://www.eiopa.europa.eu/document-library/feedback-request/pilot-dashboard-insurance-protection-gap-natural-catastrophes_en
DFO	4	Dartmouth Flood Observatory (DFO)	https://floodobservatory.colorado.edu/
Direct Investment Task Team (DITT) (imf.org)	8	IMF	https://www.imf.org/en/Data/Statistics/BPM/DITT
EDII/EDR	4	European Drought Reference (EDR)/ European Drought Impact Report Inventory (EDII)	https://www.geo.uio.no/edc/droughtdb/index.php
EFFIS	4	European Forest Fire Information System (EFFIS)	https://effis.jrc.ec.europa.eu/
EM-DAT	4	EM-DAT (Emergency Events Database)	https://www.emdat.be/

Phrase	Chapter	Data Source	Hyperlink
EMSR	4	Copernicus (European Union's Earth Observation Programme)	https://emergency.copernicus.eu/mapping/
European Commission Disaster Risk Management Knowledge Centre (DRMKC)	4	DRMKC	https://drmkc.jrc.ec.europa.eu/partnership/Scientific-Partnerships/Risk-Data-Hub
European Pollutant Release and Transfer Register (E-PRTR)	4	European Commission	https://ec.europa.eu/environment/industry/stationary/e-prtr/legislation.htm
European Settlement Map (ESM)	4	European Union (EU)	https://land.copernicus.eu/pan-european/GHSL/european-settlement-map/esm-2015-release-2019
European Statistical System (ESS) Guidelines on Temporal Disaggregation, Benchmarking, and Reconciliation—2018 edition	1	Eurostat	https://ec.europa.eu/eurostat/web/products-manuals-and-guidelines/-/ks-06-18-355
Eurostat (2022)	1	Eurostat's Estimates of Quarterly Greenhouse Gas Emissions Accounts	https://ec.europa.eu/eurostat/documents/1798247/6191529/Methodological-note-on-quarterly-GHG-estimates.pdf/6bd54bde-4dd7-ebac-6326-f08c73e-b9187?t=1644394935594
Eurostat Estimates of Quarterly Greenhouse Gas Emissions Accounts	1	Eurostat	https://ec.europa.eu/eurostat/documents/1798247/6191529/Methodological-note-on-quarterly-GHG-estimates.pdf/6bd54bde-4dd7-ebac-6326-f08c73e-b9187?t=1644394935594
Eurostat GEOSTAT project	4	Eurostat	https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/population-distribution-demography/geostat#geostat11
Eurostat GISCO website	4	Eurostat	https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/administrative-units-statistical-units
Eurostat regional data sets	4	Eurostat	https://ec.europa.eu/eurostat/web/regions/data/database
Four Twenty Seven / Moody's	4	Moody's ESG Solutions	https://esg.moodys.io/climate-solutions
Geoasset database	4	Spatial Finance Initiative	https://www.cgfi.ac.uk/spatial-finance-initiative/geoasset-project/geoasset-databases/
GHG emissions of all world countries - 2021 Report	1	European Union	https://edgar.jrc.ec.europa.eu/report_2021
GHG Protocols	7	Greenhouse Gas Protocol	https://ghgprotocol.org/
GLC	4	Global Landslide Catalog (GLC)	https://data.nasa.gov/Earth-Science/Global-Landslide-Catalog/
Global ADMinistrative Areas (GADM)	4	Food and Agriculture Organization (FAO)	https://data.apps.fao.org/map/catalog/srv/eng/catalog.search#/metadata/5e20fcf5-e376-4798-94a8-13ce49481cb2
Green Bond indicators in the CID and accompanying metadata	7	IMF	https://climatedata.imf.org/pages/fi-indicators
Handbook on Quarterly National Accounts—2013 edition	1	Eurostat	https://ec.europa.eu/eurostat/web/products-manuals-and-guidelines/-/ks-gq-13-004
HANZE	4	Historical Analysis of Natural Hazards in Europe (HANZE)	https://essd.copernicus.org/articles/10/565/2018/
HARCI	4	HARmonized grids of Critical Infrastructures in EUrope (HARCI-EU)	https://www.nature.com/articles/s41597-019-0135-1
HARmonized grids of Critical Infrastructures in EUrope (HARCI-EU)	4	European Commission	https://doi.org/10.6084/m9.figshare.7777301.v5

Phrase	Chapter	Data Source	Hyperlink
IBGE	4	Spatial data on roads for Brazil	https://www.ibge.gov.br/geociencias/organizacao-do-territorio/redes-e-fluxos-geograficos/15793-logistica-dos-transportes.html?=&t=acesso-ao-produto
IMF Climate Change Indicators Dashboard	1	IMF Climate Change Indicators Dashboard	https://climatedata.imf.org
IMF Climate Change Indicators Dashboard	4	IMF Climate Change Indicators Dashboard	https://climatedata.imf.org
IMF Government Finance Statistics Database	3	IMF	https://data.imf.org/gfs
Intergovernmental Panel on Climate Change (IPCC)	4	IPCC	https://interactive-atlas.ipcc.ch/regional-information#eyJ0eXBlIjoiQVRMQVMiLCJjb21tb25zIjp7ImxhdCI6OTc3MiwibG5nIjo0MDA2OTIsInpvb20iOjQsInByb2oiOiJFUFNHOjU0MDMwIiwibW9kZSI6ImNvbXBsZXRlX2F0bGFzIn0sInByaW1hcnkiOnsic2NlbmFyaW8iOiJzc3A1ODUiLCJwZXJpb2QiOiIyIiwic2Vhc29uIjoieWVhciIsImRhdGFzZXQiOiJDTUlQNiIsInZhcmlhYmxlIjoidGFzIiwidmFsdWVUeXBlIjoiQU5PTUFMWSIsImhhdGNoaW5nIjoiU0lNUExFIiwicmVnaW9uU2V0IjoiYXI2IiwiYmFzZWxpbmUiOiJwcmVJbmR1c3RyaWFsIiwicmVnaW9uc1NlbGVjdGVkIjpbXX0sInBsb3QiOnsiYWN0aXZlVGFiIjoicGx1bWUiLCJtYXNrIjoibm9uZSIsInNjYXR0ZXJZTWFnIjpudWxsLCJzY2F0dGVyWVZhciI6bnVsbCwic2hvd2luZyI6ZmFsc2V9fQ==
International Standard Industrial Classification of All Economic Activities, Rev. 4	1	United Nations	https://unstats.un.org/unsd/publication/seriesm/seriesm_4rev4e.pdf
IPCC	4	Intergovernmental Panel on Climate Change (IPCC)	https://interactive-atlas.ipcc.ch/
ISIC	1	International Standard Industrial Classification of All Economic Activities (ISIC)	https://unstats.un.org/unsd/publication/seriesm/seriesm_4rev4e.pdf
JRC RDH	4	The Risk Data Hub (RDH) platform of the Disaster Risk Management Knowledge Centre (DRMKC) of the Joint Research Centre (JRC)	https://drmkc.jrc.ec.europa.eu/risk-data-hub#/
LRC	4	Landslide Reporter Catalog (LRC)	https://gpm.nasa.gov/landslides/index.html
Manual for Air Emissions Accounts	1	Eurostat	https://ec.europa.eu/eurostat/web/products-manuals-and-guidelines/-/ks-gq-15-009
Monthly Energy Statistics	1	IEA	https://iea.blob.core.windows.net/assets/18d269a6-777a-4368-b073-c407a2b8e44c/Monthlyelectricitystatistics_Documentation.pdf
Monthly Oil Statistics	1	IEA	https://www.iea.org/data-and-statistics/data-product/monthly-oil-statistics
Moody's ESG Solutions	4	Moody's	https://esg.moodys.io/climate-solutions
NASA/NCCS	4	NASA Center for Climate Services (NCCS)	https://effis.jrc.ec.europa.eu/
National Aeronautics and Space Administration (NASA)	4	NASA	https://data.nasa.gov/
NEX-GDDP	4	NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP)	https://www.nccs.nasa.gov/services/data-collections/land-based-products/nex-gddp

Phrase	Chapter	Data Source	Hyperlink
NOAA	4	National Oceanic and Atmospheric Administration (NOAA)	https://www.ncei.noaa.gov/maps/hazards/
NUTS	4	Eurostat	https://ec.europa.eu/eurostat/web/nuts/background
Note on CO_2 Emissions, Intensities, and Multipliers (June 2022)	8	IMF	https://climatedata.imf.org/documents/dde2fa06078943a8a0c098fb7cc70e10/explore
OECD (2020)	3	OECD	https://doi.org/10.1787/52465399-en
OECD (2022c)	3	OECD	https://stats.oecd.org/Index.aspx?DataSetCode=ERTR
OECD (2022d)	3	OECD	https://doi.org/10.1787/2302f188-en
OECD (2022e)	3	OECD	https://doi.org/10.1787/data-00735-en
OECD Analytical Activities of Multinational Enterprises (AMNE) Database	8	OECD	https://www.oecd.org/sti/ind/analytical-amne-database.htm#:~:text=The%20Analytical%20AMNE%20database%20includes%20a%20full%20matrix,period%202005-2016.%2034%20unique%20industrial%20sectors%20are%20covered
OECD Balanced International Merchandise Trade data set	9	OECD	https://www.oecd.org/sdd/its/balanced-trade-statistics.htm
OECD database	1	OECD Air Emissions Accounts	https://stats.oecd.org/Index.aspx?DataSetCode=OECD-AEA
oil statistics	1	IEA Oil Statistics	https://www.iea.org/data-and-statistics/data-product/monthly-oil-statistics
Open Street Map (OSM)	4	OpenStreetMap	https://www.openstreetmap.org
ORBIS	4	Bureau van Dijk	https://orbis.bvdinfo.com/version-202283/Orbis/Companies/Login?returnUrl=%2Fversion-202283%2FOrbis%2FCompanies
Quarterly National Accounts Manual 2017	1	IMF	https://www.imf.org/external/pubs/ft/qna/pdf/2017/QNAManual2017.pdf
Quarterly Update of Australia's National Greenhouse Gas Inventory	1	Australian Department of Climate Change and Energy Efficiency	https://www.industry.gov.au/sites/default/files/2020-07/nggi-quarterly-2011-dec.pdf
Resource Watch	4	Resource Watch	https://resourcewatch.org/data/explore
Securities Holdings Statistics (SHS)	4	ECB	https://www.ecb.europa.eu/stats/financial_markets_and_interest_rates/securities/html/index.en.html#holdings
SEEA	1	System of Environmental-Economic Accounting (SEEA)	https://seea.un.org/sites/seea.un.org/files/seea_cf_final_en.pdf
Sendai Framework for Disaster Risk Reduction	4	International Science Council	https://council.science/sendai-hazard-review/
SPE database	8	IMF	https://data.imf.org/?sk=7A51304B-6426-40C0-83DD-CA-473CA1FD52
Stanford University	4	Spatial data on roads for Mexico and South Africa	https://earthworks.stanford.edu/?_=1462045970854&f%5Bdc_format_s%5D%5B%5D=Shapefile&f%5Bdct_spatial_sm%5D%5B%5D=South+Africa&f%5Blayer_geom_type_s%5D%5B%5D=Line&per_page=100&sort=dc_title_sort+asc
State & Trends of Carbon Pricing 2022	5	World Bank	https://openknowledge.worldbank.org/handle/10986/37455
Statistical Forum	4	IMF 9th Statistical Forum	https://www.imf.org/en/News/Seminars/Conferences/2021/11/17/9th-statistical-forum-measuring-climate-change
statistics	1	IEA Electricity Statistics	https://www.iea.org/data-and-statistics/data-product/monthly-electricity-statistics
stats.oecd.org	3	OECD	https://stats.oecd.org
System of Environmental-Economic Accounting 2012 Central Framework	1	United Nations	https://seea.un.org/content/seea-central-framework

Phrase	Chapter	Data Source	Hyperlink
System of National Accounts (SNA) 2008	1	United Nations	https://unstats.un.org/unsd/nationalaccount/sna2008.asp
The European Statistical Office (Eurostat)	4	Eurostat	https://ec.europa.eu/eurostat
Towards Global SEEA Air Emissions Accounts: Description and Evaluation of the OECD Methodology to Estimate SEEA Air Emissions Accounts for CO_2, CH_4, and N_2O in Annex-I countries to the UNFCCC	1	OECD	https://doi.org/10.1787/7d88dfdd-en
UN Comtrade	9	United Nations	https://comtrade.un.org/data/
weather for energy tracker	1	IEA Weather for Energy Tracker	https://www.iea.org/articles/weather-for-energy-tracker
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World Bank provides specifications for administrative boundaries	4	World Bank	https://datacatalog.worldbank.org/search/dataset/0038272
World Economic Outlook Database April 2022 -— WEO Groups and Aggregates Information (imf.org).	7	IMF	https://www.imf.org/external/pubs/ft/weo/2022/01/weodata/groups.htm
World Energy Balances Highlights 2021	1	IEA World Energy Balances	https://www.iea.org/data-and-statistics/data-product/world-energy-balances-highlights
World Resources Institute (WRI)	4	WRI	https://datasets.wri.org/
WRI	4	World Resources Institute (WRI)	https://www.wri.org/data
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"This book presents a much-needed coordinated discussion to step up efforts to ultimately provide a common framework for measuring the economic and financial dimensions of climate change. While the general topic is well known, there are still some critical and rather urgent agreements to reach, such as those involving economic and financial classifications and taxonomies. From a central banker perspective, I hope the book will facilitate international policy cooperation on the implications of climate change for financial stability, supervision, and, more generally, economic policy."

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