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Authors

Lamb, William F
Wiedmann, Thomas
Pongratz, Julia
et al.

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TOPICAL REVIEW

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William F Lamb^{1,2,*}, Thomas Wiedmann³, Julia Pongratz^{4,5}, Robbie Andrew⁶, Monica Crippa⁷, Jos G J Olivier⁸, Dominik Wiedenhofer⁹, Giulio Mattioli^{2,10}, Alaa Al Khourdajie¹¹, Jo House¹², Shonali Pachauri¹³, Maria Figueroa¹⁴, Yamina Saheb¹⁵, Raphael Slade¹¹, Klaus Hubacek¹⁶, Laixiang Sun^{17,18,19}, Suzana Kahn Ribeiro²⁰, Smail Khennas²¹, Stephane de la Rue du Can²², Lazarus Chapungu²³, Steven J Davis²⁴, Igor Bashmakov²⁵, Hancheng Dai²⁶, Shobhakar Dhakal²⁷, Xianchun Tan²⁸, Yong Geng²⁹, Baihe Gu²⁸ and Jan Minx^{1,2}

- ¹ Mercator Research Institute on Global Commons and Climate Change, Torgauer Straße 12–15, 4 EUREF Campus #19, 10829 Berlin, Germany
- ² School of Earth and Environment, University of Leeds, Leeds LS2 9JT, United Kingdom
- ³ Sustainability Assessment Program, School of Civil and Environmental Engineering, UNSW, Sydney, Australia
- ⁴ Max Planck Institute for Meteorology, Bundesstrasse 53, 20146 Hamburg, Germany
- ⁵ Ludwig-Maximilians-Universität Munich, Department of Geography, Luisenstrasse 37, 80333 Munich, Germany
- ⁶ CICERO Center for International Climate Research, Oslo, Norway
- ⁷ European Commission, Joint Research Centre, Ispra, VA, Italy
- ⁸ PBL Netherlands Environmental Assessment Agency, Den Haag, The Netherlands
- ⁹ Institute of Social Ecology, University of Natural Resources and Life Sciences, Schottenfeldgasse 29, 1070 Vienna, Austria
- ¹⁰ Department of Transport Planning, TU Dortmund University, August-Schmidt-Straße 10, 44227 Dortmund, Germany
- ¹¹ Centre for Environmental Policy, Imperial College London, London, United Kingdom
- ¹² School of Geographical Sciences, University of Bristol, University Road, Bristol BS8 1SS, United Kingdom
- ¹³ International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, 2361 Laxenburg, Austria
- ¹⁴ Department of Management Society and Communication, Copenhagen Business School, Copenhagen, Denmark
- ¹⁵ Openexp, 17 Bd Lefebvre, 75015 Paris, France
- ¹⁶ Integrated Research for Energy, Environment and Society, University of Groningen, 9747AG Groningen, The Netherlands
- ¹⁷ Department of Geographical Sciences, University of Maryland, College Park, MD 20742, United States of America
- ¹⁸ School of Finance and Management, SOAS University of London, London WC1H 0XG, United Kingdom
- ¹⁹ Institute of Blue and Green Development, Weihai Institute of Interdisciplinary Research, Shandong University, Weihai 264209, People's Republic of China
- ²⁰ Federal University of Rio de Janeiro (Universidade Federal do Rio de Janeiro—UFRJ), Transport Engineering Programme (Programa de Engenharia de Transportes—PET), COPPE-UFRJ, Rio de Janeiro, Brazil
- ²¹ Energy and Climate Change Consultant, 25 Troubridge Walk, Rugby CV22 7LP, United Kingdom
- ²² Lawrence Berkeley National Laboratory, 1 Cyclotron Rd, Berkeley, CA 94720, United States of America
- ²³ Great Zimbabwe University, School of Natural Sciences, Off Old Great Zimbabwe Road, Box 1235, Masvingo, Zimbabwe
- ²⁴ Department of Earth System Science, University of California, Irvine, United States of America
- ²⁵ Center for Energy Efficiency—XXI, Moscow, Russia
- ²⁶ College of Environmental Sciences and Engineering, Peking University, Beijing, People's Republic of China
- ²⁷ Department of Energy, Environment and Climate Change, School of Environment, Resources and Development, Asian Institute of Technology, Klong Luang, Pathumthani 12120, Thailand
- ²⁸ Institutes of Science and Development, Chinese Academy of Sciences, No.15, Zhongguancun Beiyitiao, Haidian District, Beijing, People's Republic of China
- ²⁹ School of International and Public Affairs, Shanghai Jiao Tong University, No. 1954 Huashan Road, Shanghai, People's Republic of China

* Author to whom any correspondence should be addressed.

E-mail: lamb@mcc-berlin.net

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Supplementary material for this article is available [online](#)

Abstract

Global greenhouse gas (GHG) emissions can be traced to five economic sectors: energy, industry, buildings, transport and AFOLU (agriculture, forestry and other land uses). In this topical review, we synthesise the literature to explain recent trends in global and regional emissions in each of these sectors. To contextualise our review, we present estimates of GHG emissions trends by sector

from 1990 to 2018, describing the major sources of emissions growth, stability and decline across ten global regions. Overall, the literature and data emphasise that progress towards reducing GHG emissions has been limited. The prominent global pattern is a continuation of underlying drivers with few signs of emerging limits to demand, nor of a deep shift towards the delivery of low and zero carbon services across sectors. We observe a moderate decarbonisation of energy systems in Europe and North America, driven by fuel switching and the increasing penetration of renewables. By contrast, in rapidly industrialising regions, fossil-based energy systems have continuously expanded, only very recently slowing down in their growth. Strong demand for materials, floor area, energy services and travel have driven emissions growth in the industry, buildings and transport sectors, particularly in Eastern Asia, Southern Asia and South-East Asia. An expansion of agriculture into carbon-dense tropical forest areas has driven recent increases in AFOLU emissions in Latin America, South-East Asia and Africa. Identifying, understanding, and tackling the most persistent and climate-damaging trends across sectors is a fundamental concern for research and policy as humanity treads deeper into the Anthropocene.

1. Introduction

Greenhouse gas (GHG) emissions from fossil fuels and land use have continuously grown since the 19th century, reaching their highest ever level in 2019. The Paris Agreement in 2015 set out an ambition to limit the global temperature increase to 1.5 °C and 2 °C above pre-industrial levels. Yet, on the basis of current trends in emissions, planned infrastructure, and national policy commitments, the Paris targets are in jeopardy (Höhne *et al* 2020). The time window is narrowing to counter these trends across all sectors and global regions.

Global GHG emissions sources are usually attributed to five broad sectors, characterised by the Intergovernmental Panel on Climate Change (IPCC) Working Group III (WG3) as energy systems, industry, buildings, transport, and AFOLU (agriculture, forestry and other land uses). Together, these sectors cover aspects of energy supply (energy systems), energy demand (industry, buildings and transport), non-energy related process emissions (industry), and land-based emissions and removals (AFOLU).

Each sector encounters its own challenges in terms of climate change mitigation. GHG emissions from energy systems are dominated by coal-powered electricity generation, often from a limited number of highly polluting units that are long-lived and politically challenging to retire (Jakob *et al* 2020). Transport and building emissions are more diffuse and spread across many actors; they are linked to urban form, physical infrastructures and everyday behaviour, thus involving non-trivial technological and social challenges to mitigation (Creutzig *et al* 2015). Industry emissions are associated with the production of metals, chemicals, cement and other basic materials demanded by our economies. Many of these processes are inefficient and offer a large scope for rapid emissions cuts, although some are difficult to fully mitigate (Davis *et al* 2018, Rissman *et al* 2020).

AFOLU emissions and removals are linked to the production of food, feed and timber production—a particularly difficult sector as these are essential services, carried out by millions of actors, on a globally limited area of land with multiple competing demands (IPCC 2019).

There have been few attempts to describe global and regional emissions trends and drivers on a consistent and comprehensive sectoral basis. There is a substantive literature that compiles global emissions inventories for carbon dioxide (CO₂) (Grassi *et al* 2018, Quéré Le *et al* 2018, Friedlingstein *et al* 2019), methane (CH₄) (Kirschke *et al* 2013, Saunio *et al* 2020), and nitrous oxide (N₂O) emissions (Janssens-Maenhout *et al* 2019, Tian *et al* 2020). There are also dedicated IPCC chapters and reports analysing the contributions of each sector, including energy systems (Bruckner *et al* 2014), buildings (Lucon *et al* 2014), transport (Sims *et al* 2014), industry (Fischer *et al* 2014) and AFOLU (Smith *et al* 2014, IPCC 2019). And it is commonplace for national and regional studies to analyse sectoral emissions trends and drivers, such as for China (Guan *et al* 2018), the US (Feng *et al* 2015), or the EU (Spencer *et al* 2017). In this study, we aim to update and synthesise these literatures, comprehensively and consistently covering all sources of GHG emissions, for all world regions and across all sectors, drawing from expertise in each area to explain key trends and drivers. The core research questions of this review are as follows:

- (a) *What are the recent trends in global, regional and sectoral greenhouse gas emissions?*
- (b) *What are the driving factors underlying these trends?*

In addressing these questions, we combine several elements of analysis. First, we draw from a comprehensive GHG emissions dataset to describe recent global and regional trends in sector emissions. This

provides the context for an in-depth review of the main drivers underpinning sector emissions trends. We further support this review with sector specific Kaya decompositions, and other relevant descriptive data. Our aim is to provide a summary of the main trends and challenges, sector by sector, which collectively shape our prospects for a rapid and deep transition to avoid dangerous climate change.

2. Methods and materials

This article is a literature review supported by several elements of empirical analysis. Here we briefly summarise our approach to literature identification, data sources and analysis, with further details provided in the supplementary materials (available online at stacks.iop.org/ERL/16/073005/mmedia).

2.1. Literature search and inclusion

This topical review provides a targeted review of the literature on emission trends and their underlying drivers across different sectors of the economy (energy systems, industry, buildings, transport and AFOLU). Due to the broad scope and a potentially very expansive literature base, we inform and focus our review in each sector with a supplementary data analysis on global and regional emissions trends. This analysis (described in the following section) brings forward the main and fastest growing sources of GHG emissions in each sector, as well as the regional profiles of these emissions. It further identifies on going trends in key driving forces, elaborated in Kaya decompositions.

Based on these analyses, teams of sector experts determined the scope of their review, structured into common components across sectors. These include drivers of global and regional demand, and factors that influence emissions intensity and efficiency. We rely on the deep sectoral knowledge of our sector teams for the identification of the relevant literature. We also conducted targeted keyword searches on the Web of Science and Google Scholar platforms to inform our selection of literature. These include, for example, relevant activity data underlying sector trends (such as trends in ‘building floor space’ per capita, ‘motorisation’, or ‘renewable energy deployment’). This focus on relevant key drivers in our searches ensures tractability given the scope of our review, but we search more exhaustively with a structured keyword query for Kaya literature in particular (the search string is provided in the supplementary materials).

2.2. Global and regional GHG emissions trends

We use the EDGAR v5.0 database to track global, regional and sectoral GHG emissions from 1990 to 2018 (Crippa *et al* 2019). EDGAR includes CO₂ emissions from fossil fuel combustion derived from

International Energy Agency data (IEA 2020c), supplemented with CH₄ and N₂O emissions from savannah burning sourced from the Food and Agricultural Organisation of the United Nations (FAO 2019), and CH₄ and N₂O from forest and peat fires taken from the Global Fire Emissions Database (GFED v4.1s; van der Werf *et al* 2017).

EDGAR does not include land-use change and management CO₂ emissions and removals (hereafter ‘land-use CO₂’ emissions). We therefore source these separately, using the average of three global bookkeeping models (Hansis *et al* 2015, Houghton and Nassikas 2017, Gasser *et al* 2020) in a convention established by the Global Carbon Project (Friedlingstein *et al* 2019). These include CO₂ emissions from peat burning and draining from FAO and GFED.

Land-use CO₂ estimates follow the approach of the global modelling community, which attributes anthropogenic CO₂ fluxes based on underlying drivers, not where they occur (Friedlingstein *et al* 2019). In other words, fluxes caused by direct land-use change and land management processes are accounted for, while fluxes driven by, e.g. indirect anthropogenic effects of changes in environmental conditions on land not subject to modelled management activities, are excluded (Grassi *et al* 2018, Jia *et al* 2019). (Note that the latter would be included in the AFOLU flux under UNFCCC reporting, if they occurred on what countries define as ‘managed land’ for reporting, which is a larger area of forests than considered as subject to management by the models. Thus National Greenhouse gas Inventories sum to larger CO₂ removals (and thus smaller net global CO₂ emissions) than the global models because of the net effects of CO₂-fertilisation, N fertilisation and climate change on the larger areas of ‘managed forests’ (Grassi *et al* 2018)).

We use 100 year global warming potentials as updated for the IPCC 6th Assessment Report (AR6) to facilitate comparability between the different gases in this data set (CO₂, CH₄, N₂O and fluorinated (F-)gases). Emissions are presented as global and regional totals; the latter using a ten region split also developed for IPCC AR6. A list of countries within each region is available in the supplementary materials.

Consistency in the allocation of emissions and energy use to sectors is important for our analysis. We follow the IPCC 5th Assessment Report (AR5) in allocating emissions sources from the EDGAR database exclusively to five overarching sectors: Energy Systems, Industry, Buildings, Transport and AFOLU. Within each sector we construct a second level categorisation (‘sub-sectors’) comprising groups of structurally similar emissions sources. An explanation of these categories and the detailed sector allocation is available as a supplementary data file.

2.3. Direct versus indirect emissions

Our emissions estimates distinguish between two accounting methods: scope 1 or ‘direct’ emissions, comprising the emissions produced by owned or controlled sources; and scope 2, or ‘indirect’ emissions, where the emissions associated with the generation of electricity and heat in the energy systems sector are allocated to sectors where this energy is consumed. A scope 2 reallocation of indirect emissions is particularly consequential for the buildings and industry sectors, where some consumed energy is produced on-site (e.g. in gas boilers), but a large fraction is also sourced upstream from power plants via electricity consumption.

To allocate emissions from the electricity and heat sector to final sectors as indirect emissions, we use estimates provided in the CO₂ emissions dataset of the IEA (2020a). These estimates are based on individual electricity and heat specific emission factors, and assume a fixed efficiency of 90% for heat plants (in order to calculate the share of emissions associated with heat versus electricity in combined heat and power plants). Since the total emissions of the electricity and heat sector in IEA differs to EDGAR, we calculate the proportion of indirect emissions in each final sector in IEA, then multiply these values using the EDGAR electricity and heat total.

We do not consider ‘consumption-based’ emissions, which comprise all embodied emissions associated with the consumption of a product or service. This is relevant for tracking upstream and downstream emissions related to regional and global supply chain networks (Hubacek *et al* 2014, Li *et al* 2020), but is beyond the limits of our work.

2.4. Decomposition of global and sectoral emissions drivers

To support our analysis and review of the main driving forces and regional differences underlying emissions trends, we perform a Kaya decomposition analysis for each sector (Kaya 1990). Kaya analysis is a common method applied across the climate mitigation literature, which expresses emissions (tCO₂) as a function of population (persons), GDP (2010 US\$, PPP) and energy (joules), with the respective terms F, P, G and E:

$$F = P (G/P) (E/G) (F/E)$$

where G/P is GDP per capita, E/G is the energy intensity of GDP and F/E is the carbon intensity of energy. To apply the analysis at a sector level, we use the IEA World Energy Balances (IEA 2020c) to isolate the primary energy supply for the energy systems sector, and total final energy consumption for the industry, transport, and buildings sectors. We then match these sectors with CO₂ emissions (F) sourced from the IEA (2020a). To ensure consistency

in our sector definitions—between the prior emissions trends analysis (which uses EDGAR data) and this Kaya analysis (IEA data)—we rely on a detailed mapping of IEA energy sectors to EDGAR emissions sources, available in the supplementary materials.

The Kaya decomposition for these four sectors is narrower in scope than our overall estimates of GHG emissions, as it focuses only on the CO₂ emissions associated with energy use, i.e. fossil fuel combustion. It does not include GHG emissions from cement, ceramics, landfill, land-use change and agriculture, as these are not directly related to energy use, and thus could not be evaluated in the same decomposition. Nor do we include indirect emissions in the decomposition. Finally, since there is no meaningful way to allocate population and GDP data for sectors, we simply use regional and global totals in every decomposition, using population estimates from the United Nations (UNDESA 2019) and GDP in purchasing-power parity terms from the IEA (2020a), extended with growth rates from the IMF (2020) for the most recent years.

The Kaya decomposition is conceptually straightforward in the case of energy systems, industry, buildings, and transport sectors. However, it is less appropriate for AFOLU, where underlying activities are indirectly driven by energy use and GDP. Instead, area of land under different uses and agricultural output are closer proxy drivers of AFOLU emissions. We therefore substitute the terms for an AFOLU specific decomposition, as established by Hong *et al* (2021), where AFOLU GHG emissions (tCO₂eq) is the function of population (persons), agricultural output (kcal), and agricultural land area (hectares), with the respective symbols H, P, A and L:

$$H = P (A/P) (L/A) (H/L).$$

A/P is agricultural output per capita, L/A is the land required for a unit of agricultural output, and H/L is GHG emissions per unit of land. In this decomposition H is composed of agricultural CH₄ and N₂O emissions from EDGAR supplemented with land-use CO₂ emissions from the bookkeeping models (Hansis *et al* 2015, Houghton and Nassikas 2017, Gasser *et al* 2020). Due to land data constraints, this decomposition misses a single year (1990–2017) relative to other sectors (1990–2018).

2.5. Uncertainties and growth rate calculation

There are different uncertainties associated with historical GHG emissions estimates. These can be traced to uncertainties in (and a lack of) underlying activity and inventory data (particularly in non-OECD countries), the use of average emissions factors across countries and fuel types, different interpretations of oxidation and combustion, and other assumptions (Andrew 2020).

Fossil fuel combustion emissions are generally regarded to have comparatively small uncertainties due to the sophistication and standardisation of historical energy data reporting. By contrast, uncertainties are much higher for AFOLU CO₂ emissions and all other greenhouse gases. Following IPCC AR5 (Blanco *et al* 2014) we assume uncertainties of ±8% for global emissions of CO₂ from fossil fuel combustion, ±20% for CH₄ emissions and F_{gases}, ±50% for AFOLU CO₂ emissions, and ±60% for N₂O emissions.

Two particular subsectors are noteworthy for having both high emissions and high uncertainties: fugitive CH₄ emissions and land-use CO₂ emissions. Regarding the former, recent studies have found substantial discrepancies between nationally reported GHG inventories for oil and gas fugitive emissions versus observational evidence of anthropogenic CH₄ emissions (Alvarez *et al* 2018, Weller *et al* 2020). Notably, Hmiel *et al* (2020) concluded from pre-industrial ice core ¹⁴CH₄ measurements that natural geological sources of methane emissions are a much smaller fraction of total atmospheric methane than previously estimated, with a potential underestimate of global anthropogenic CH₄ emissions of 25%–40%. The likely source is oil and gas infrastructure leaks, which occur across the supply chain, from extraction, processing and up to gas distribution and final use (Christian *et al* 2016, Alvarez *et al* 2018, Weller *et al* 2020).

Uncertainties around AFOLU CO₂ emissions in the latest Global Carbon Budget are around 46% over 2009–2018, based on the mean and one standard deviation of three bookkeeping models (Friedlingstein *et al* 2019). BLUE emission estimates (Hansis *et al* 2015) are globally higher than the Houghton and Nassikas (HN) (2017) model, in part driven by the explicit representation of land-use transitions at the sub-grid scale in BLUE and the preferential allocation of pasture on natural grassland in HN (Hansis *et al* 2015). Further, trends of individual datasets differ over recent years, e.g. with an upward trend in BLUE vs a downward trend in HN since the 2000s for land-use CO₂ emissions. These different trends are at least partly attributable to the underlying land-use forcing (Gasser *et al* 2020). The third model, OSCAR (Gasser *et al* 2020), follows the approximate mean of BLUE and HN.

We derive the growth rates of emissions trends and Kaya factors over periods greater than one year, as follows:

$$r = \left(\frac{E_{FF}(t+n)}{E_{FF}(t)} \right)^{1/n} - 1$$

where E_{FF} is the emissions value or Kaya factor in a given year (t).

3. Results and discussion

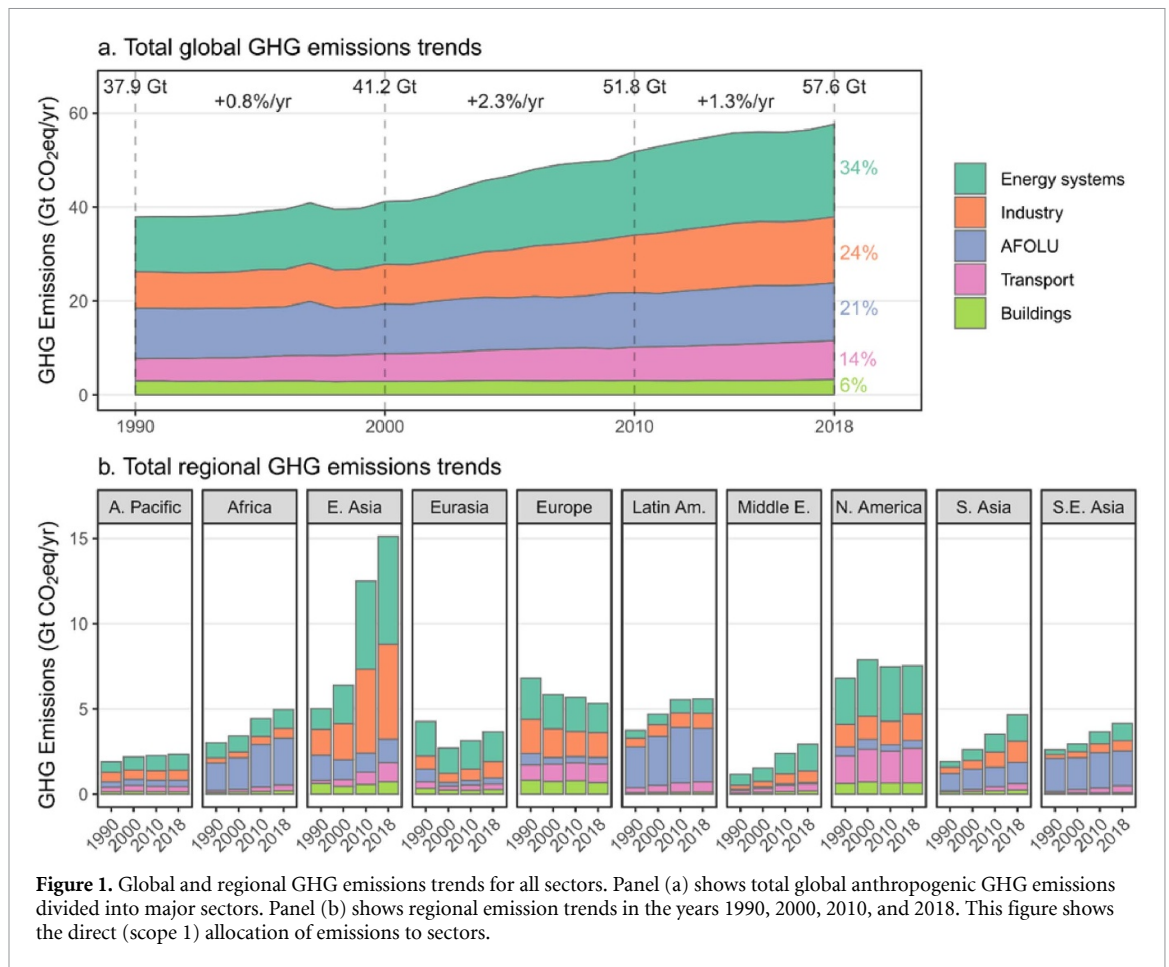
3.1. All sectors

Global GHG emissions continued to rise between 2010 and 2018, although the rate of emissions growth has slowed since 2014 (figure 1). GHG emissions were the highest in human history in 2018, reaching 58 GtCO₂eq. The largest share of emissions in 2018 came from the energy systems sector (34%; 20 GtCO₂eq), followed by industry (24%; 14 GtCO₂eq), AFOLU (21%; 12 GtCO₂eq), transport (14%; 8.3 GtCO₂eq) and the operation of buildings (6%; 3.3 GtCO₂eq). These estimates are based on direct emissions produced in each sector. As we discuss below, the industry and buildings sectors further contributed to emission growth indirectly, by drawing on electricity and heat production in the energy systems sector.

GHG emissions in 2018 were about 11% (5.8 GtCO₂eq) higher than GHG emission levels in 2010 (52 GtCO₂eq). One third of this increase in GHG emissions between 2010 and 2018 was from energy systems (1.9 GtCO₂eq), followed by industry (1.8 GtCO₂eq, 30% of the increase), transport (1.2 GtCO₂eq, 20%), AFOLU (0.72 GtCO₂eq, 12%) and buildings (0.22 GtCO₂eq, 4%).

In terms of regions, East Asia and North America together accounted for 40% of global GHG emissions in 2018, within which emissions are dominated by China and the United States. The highest absolute increase between 2010 and 2018 was in Eastern Asia (2.6 GtCO₂eq), more than double the growth of the next highest region, Southern Asia (1.1 GtCO₂eq). Four regions—the Middle East, Africa, Eurasia and South-East Asia—accounted for the rest of the global emissions increase with approximately 0.5 GtCO₂eq each. The most rapid relative growth in emissions since 2010 occurred in Southern Asia at 3.6% per year, followed by the Middle East (2.6%/yr), Eastern Asia (2.4%/yr) and Eurasia (1.9%/yr). The only region with a decline in emissions since 2010 has been Europe (−0.3 GtCO₂eq, −0.8%/yr). North America, Latin America, and developed countries in the Asia Pacific saw only minimal growth over this period (+0.1%/yr, +0.1%/yr and +0.4%/yr, respectively).

Trends by sector differ widely across regions. Developed countries in Asia Pacific, Europe and North America tend to have higher shares of emissions from energy systems, industry and transport, and lower shares from AFOLU. Overall emissions in these regions are relatively stable, apart from the energy systems sector in Europe and North America, which have seen gradual reductions since 2010 (−1.8%/yr and −1.5%/yr, respectively). This general pattern is reversed in the case of Africa, Latin America and South-East Asia. In these regions AFOLU is the largest emitting sector (specifically: CO₂ emissions from deforestation), yet much of the recent growth comes from the energy systems, industry and



transportation sectors. Similarly, fast growing emissions in Eastern and Southern Asia are mainly associated with the industry, energy systems and transport sectors, some at rates exceeding 4%/yr.

The largest individual sub-sector contributing to global GHG emissions in 2018 was electricity and heat generation at 13.9 GtCO₂eq (24%). This subsector can be reallocated to consuming sectors as indirect (scope 2) emissions, thus highlighting the importance of energy demand as a driver of global climate change (de la Rue du Can *et al* 2015, Creutzig *et al* 2016, 2018). From this perspective, the relative importance of the industry and buildings sectors jump dramatically, from 25% to 35%, and 6% to 17%, respectively (figure 2).

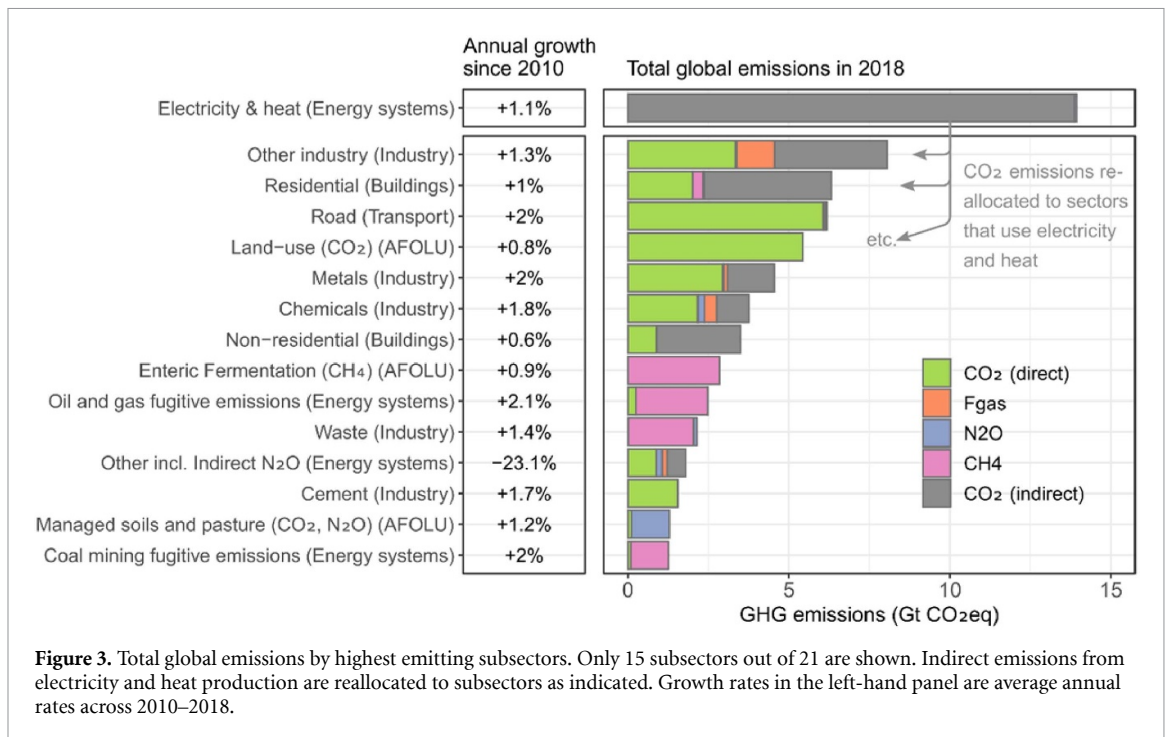
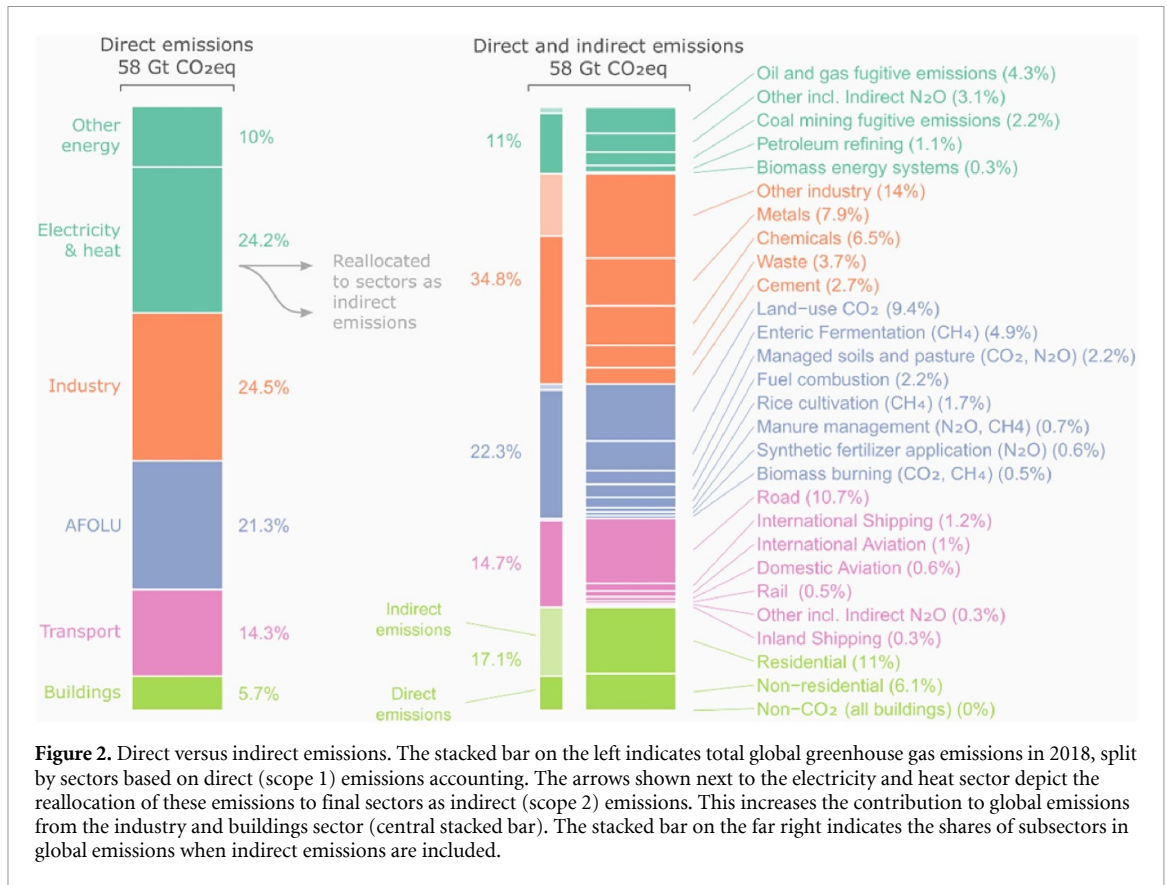
The highest emitting subsectors after electricity and heat are ‘other industry’³⁰, land-use change and management, road transport, residential buildings, metals, chemicals, enteric fermentation (i.e. livestock rearing), non-residential buildings, oil and gas fugitive emissions, and the waste sector. Indirect emissions account for a large proportion of emissions in some of these sectors, particularly the residential and non-residential buildings subsectors (more

than 50% of emissions), and the other industry, metals and chemicals subsectors (more than 20% of emissions). Among the largest sub-sectors, the fastest growing from 2010 to 2018 have been oil and gas fugitive emissions (+2.1%), road transport (+2%), coal mining fugitive emissions (+2%), and metals (+2%) (figure 3). Some of these emissions trends, however, are marked by significant uncertainty (see section 2.5).

Our data runs to 2018 and therefore misses the most recent break in emissions trends resulting from COVID-19 induced lockdowns in 2020. Several studies have observed sharp reductions in global daily emissions over the course of 2020 (Le Quéré *et al* 2020, Lenzen *et al* 2020, Liu *et al* 2020c). The lockdowns impacted emissions in the transport sector most heavily, particularly aviation, followed by electricity and industry emissions (Le Quéré *et al* 2020). Most of these reductions will be temporary, but COVID-19 may shape the driving forces of sectoral emissions in the long run, depending on the nature of stimulus packages and associated investments that are rolled out in the wake of the pandemic (Shan *et al* 2020).

We now turn our attention to the underlying factors of emissions growth. For this purpose, we decomposed the trends of CO₂ emissions from fuel combustion (excluding other GHGs) into several

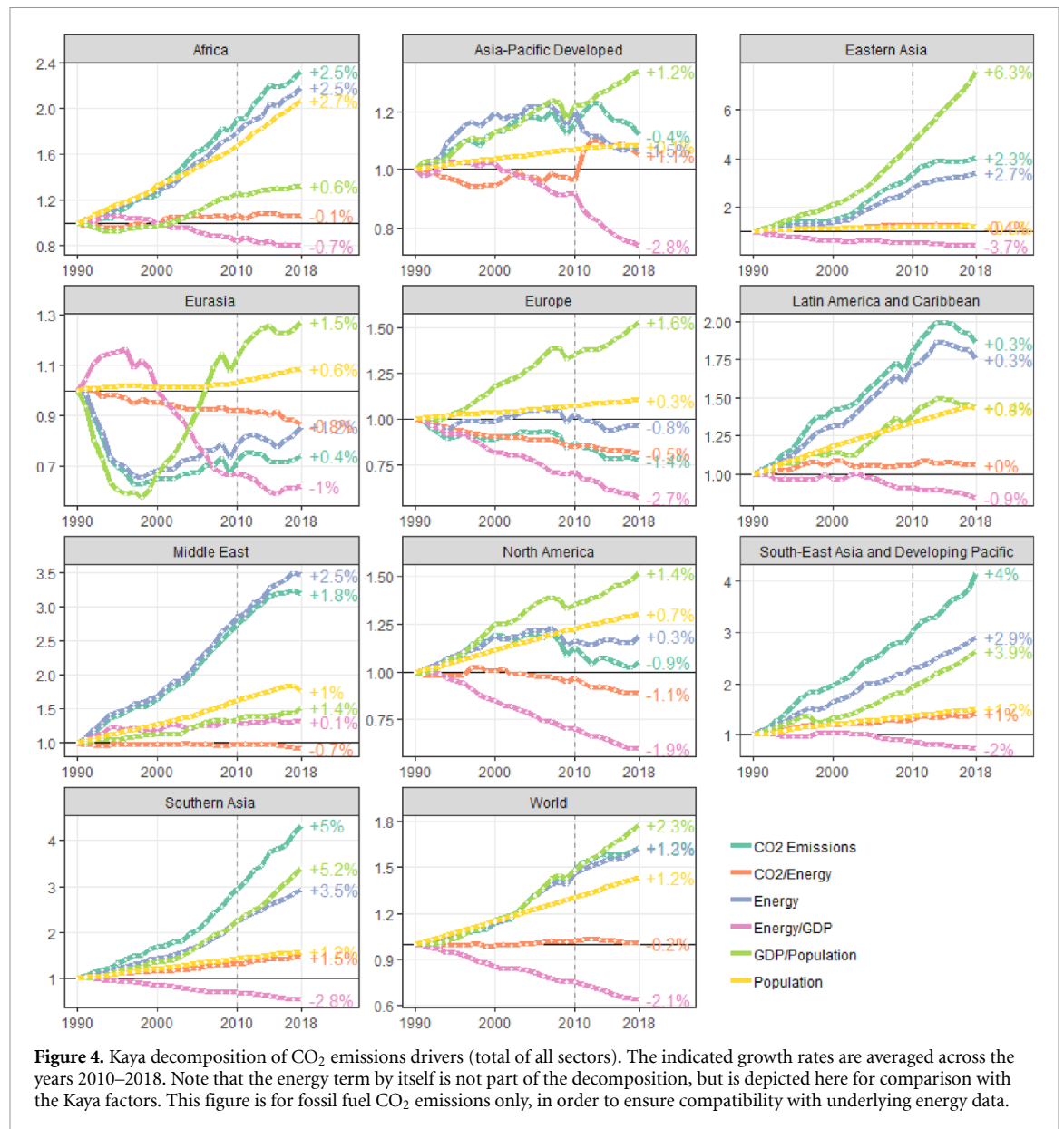
³⁰This broad category includes the paper and pulp sector, food and tobacco processing, industrial sources of fluorinated gases, and other generic industries.



driving factors, starting with an overview of all sectors in figure 4 and then investigating individual sectors in more detail in the following sections.

In general, economic growth (measured as GDP) and its main components, affluence (GDP per capita) and population growth, all remained the strongest drivers of GHG emissions in the last decade, following

the long-term trend (Burke et al 2015, Yao et al 2015, Malik et al 2016, Sanchez and Stern 2016, Stern et al 2017, Chang et al 2019, Dong et al 2019, 2020, Liobikiene and Butkus 2019, Liu et al 2019, Mardani et al 2019, Pan et al 2019, Parker and Bhatti 2020). Globally, affluence remained by far the strongest upward driver, increasing almost in tandem



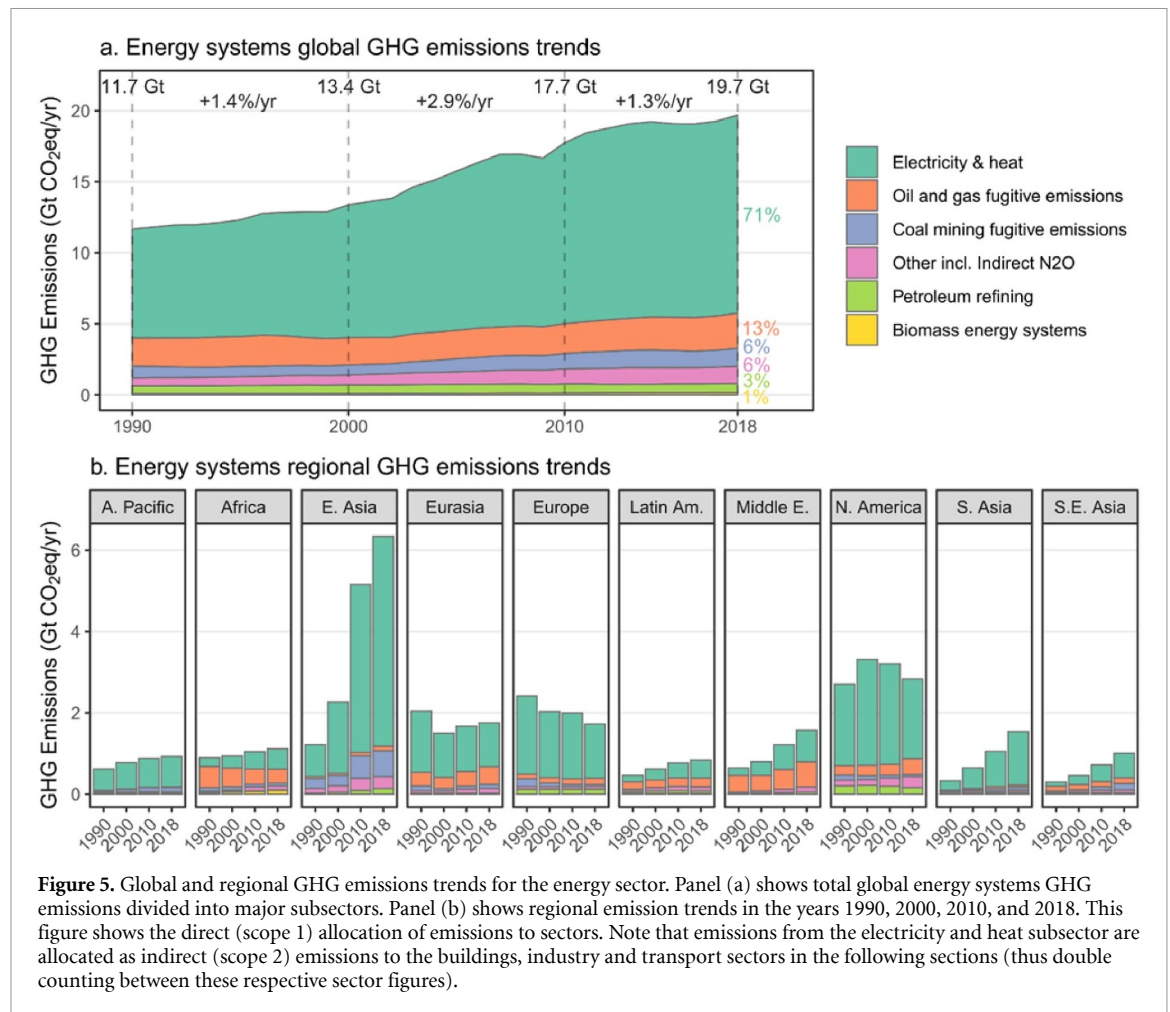
with energy consumption and CO₂ emissions up until 2015, after which some modest relative decoupling occurred (figure 4).

The main counteracting, yet insufficient, factor that led to emissions reductions was decreased energy use per unit of GDP in almost all regions (−2.1% globally). These reductions in energy intensity are a result of technological innovation, regulation, structural change and increased economic efficiency (Yao *et al* 2015, Sanchez and Stern 2016, Chang *et al* 2019, Dong *et al* 2019, Liu *et al* 2019, Marin and Mazzanti 2019, Mohammed *et al* 2019, Stern 2019, Wang *et al* 2019b, Goldemberg 2020). The decades-long trend that efficiency gains were outpaced by an increase in worldwide affluence continued unabated in the last 10 years (Haberl *et al* 2020, Wiedenhofer *et al* 2020, Wiedmann *et al* 2020). Therefore, GHG emissions only show relative, not absolute, decoupling from GDP at the global level (Deutch 2017, Wood *et al* 2018). In addition, the emissions-reducing effects of

energy efficiency improvements are diminished by the energy rebound effect, which has been found in several studies to significantly offset some energy savings (Rausch and Schwerin 2018, Bruns *et al* 2019, Stern 2020).

A significant decarbonisation of the energy system was only noticeable in North America, Europe and Eurasia. Globally, the amount of CO₂ per unit of energy used has remained practically unchanged over the last three decades, as the rapid growth of renewable energy in some regions has been matched by new fossil plants in others (Chang *et al* 2019, Jackson *et al* 2019, Peters *et al* 2020). Population growth has also remained a persistent upward driver in almost all regions (figure 4).

Global economic growth as the main driver of GHG emissions plays out particularly strong in China and India (Liu *et al* 2019, Ortega-Ruiz *et al* 2020, Yang *et al* 2020, Zheng *et al* 2020, Wang *et al* 2020b), although both countries show signs of relative



decoupling because of structural changes (Marin and Mazzanti 2019). A change in China's production structure and consumption patterns (i.e. the type of goods and services consumed) have become the main moderating factors of emissions after 2010, while economic growth, consumption levels and investment remain the dominating factors driving up emissions (Jiborn *et al* 2020, Zheng *et al* 2020). In India low emission efficiency and expansion of production and trade caused the growth of emissions (Wang and Zhou 2020).

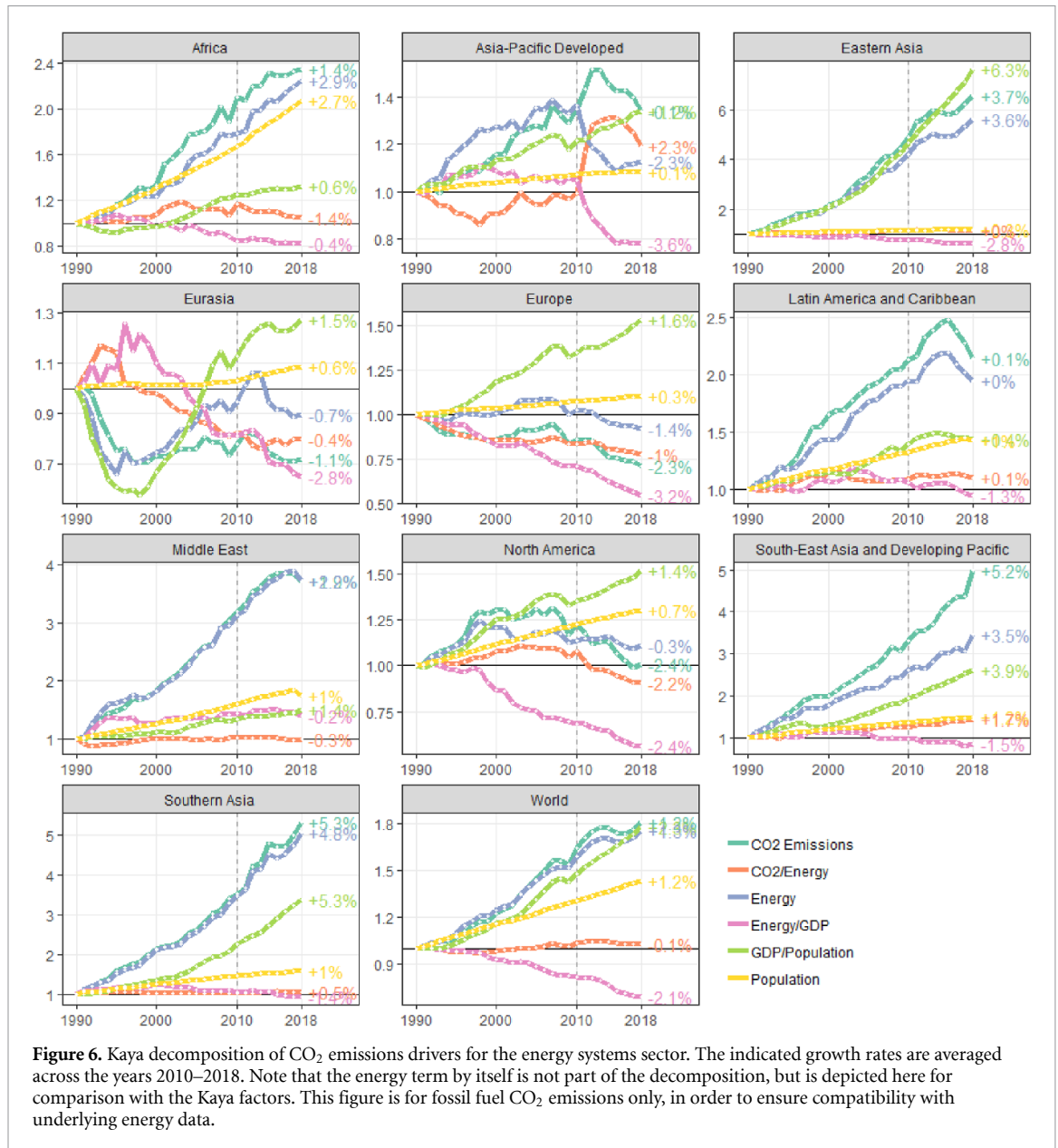
There are pronounced differences both in recent changes in the absolute levels and drivers of GHG emissions when differentiating countries by income levels (Dong *et al* 2019) or by regions (Chang *et al* 2019). In high-income countries, significant improvements in energy intensity led to declining CO₂ emissions between 2010 and 2015, despite increasing income levels and populations (Dong *et al* 2019). In upper middle-income and lower middle-income countries, rising income more than offset any energy structural or intensity gains, leading to increased emissions. And CO₂ emissions increased the most in low-income countries, due to significant increases in carbon intensities, income levels and population (Dong *et al* 2019). Importantly, some of

these trends are partially related to shifts in global supply chains, where some production emissions could also be allocated to final consumers under a so-called consumption-based perspective, mostly in high- and middle-income countries (an issue we do not address in this article) (Peters *et al* 2011).

3.2. Energy systems

Overall, energy systems make up the largest share of the five sectors, with 34% of total global GHG emissions (although electricity and heat emissions can also be reallocated to demand sectors, particularly buildings and industry). GHG emissions in the energy sector grew to 20 GtCO₂eq in 2018, with the strongest growth occurring between 2000 and 2010 (2.9% per year) and slowing down to 1.3% growth per year between 2010 and 2018 (figure 5).

Most energy systems emissions are associated with the power sector, i.e. coal, gas and other plants that produce electricity and heat. These accounted for 71% of the total (14 GtCO₂eq) in 2018. Fugitive emissions from oil and gas production (2.5 GtCO₂eq) and coal mining (1.3 GtCO₂eq) account for the second and third largest contributions. The overall growth of the energy systems sector between 2010 and 2018 (+1.9 GtCO₂eq) can be mainly attributed to

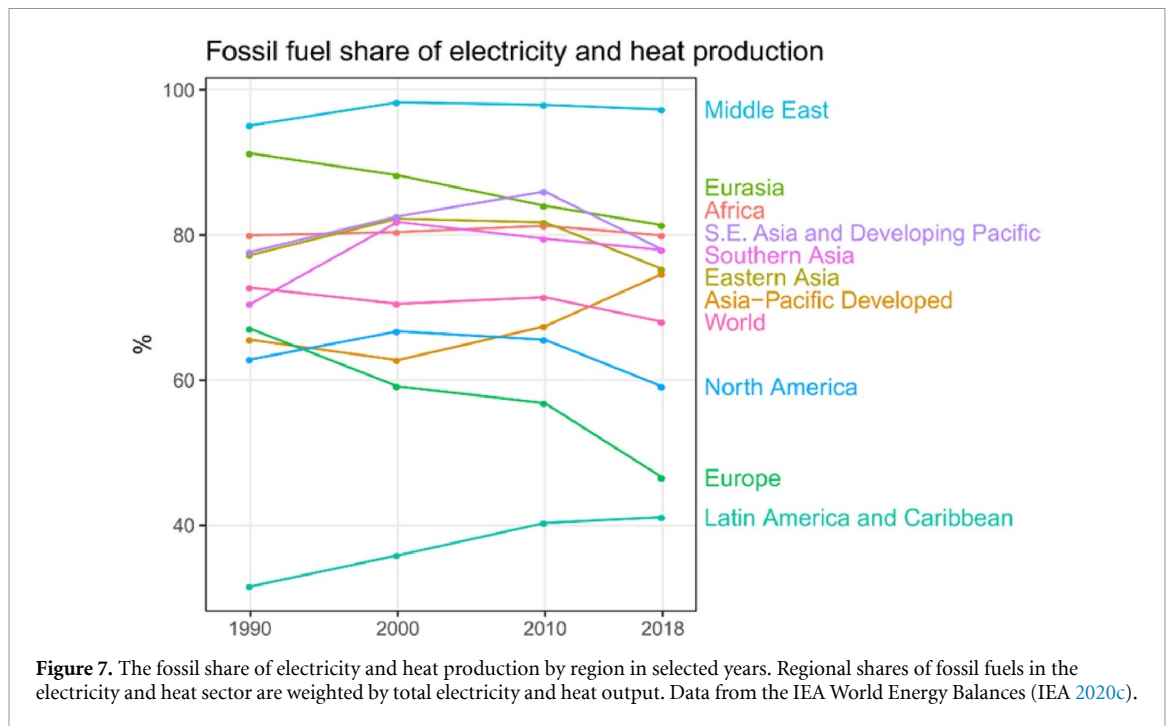


electricity and heat (+1.2 GtCO₂eq, 62% of growth), followed by oil and gas (+0.37 GtCO₂eq, 19% of growth) and coal mining (0.18 GtCO₂eq, 9% of growth) fugitive emissions.

On a regional basis, East Asia stands out as the largest contributor to energy systems emissions in 2018 (6.3 GtCO₂eq) and with the largest absolute growth from 2010 to 2018 (+1.2 GtCO₂eq), averaging 2.6% per year. North America (2.8 GtCO₂eq) is the second highest emitter, followed by Eurasia (1.8 GtCO₂eq) and Europe (1.7 GtCO₂eq). Of these, only Eurasia has grown in emissions (+0.1 GtCO₂eq, 0.6%/yr), while Europe and North America have seen slight declines over the last decade (−1.8%/yr and −1.5%/yr, respectively, leading to −0.27 GtCO₂eq and −0.35 GtCO₂eq reductions). Southern Asia, South-East Asia and the Middle East are not amongst the largest absolute contributors, but they exhibit the largest annual growth rates of 4.9%, 4.3% and

3.3% respectively between 2010 and 2018. Africa, Asia-Pacific Developed and Latin America have seen only modest growth at or below 1% per year. Electricity and heat is currently the dominant source of GHG emissions from energy systems in various regions of the world, representing more than 50% of emissions in most and reaching as high as 80% in Southern Asia and East Asia. However, in some countries and regions fugitive emissions from oil and gas and coal production figure more prominently, such as in the Middle East (39% of energy systems emissions), Africa (31%), Latin America (25%) and Eurasia (24%).

At the global level, growth in CO₂ emissions from energy systems have closely tracked rising GDP per capita (figure 6), affirming the substantial literature describing the mutual relationships between energy, electricity demand, exergy and economic growth (Khanna and Rao 2009, Stern 2011, Haberl



et al 2020, Wiedenhofer *et al* 2020). This relationship has played out strongly in developing regions, particularly in Asia, where a massive scale up of energy supply has accompanied economic growth—with average annual increases of energy demand between 3.5% and 4.8% in the past decade (figure 6). (We cover these drivers of electricity demand in the industry and building sectors). The key downward driver has been declining energy intensities in almost all regions, associated with ongoing improvements in generation and transmission efficiency. Carbon intensities of energy supply have had a neutral effect, remaining globally stable since the 1990s, albeit with regional variations.

On the energy production side, almost all regions have seen steady decreases in energy intensities, at a global average of -2.1% per year since 2010, and at a similar steady pace in most individual regions albeit at varying rates. Technology benchmarking studies show that power generation efficiencies vary widely between (and also within) regions—generally higher in Europe, Japan and the United states, and lower in Russia, China, India and Australia (Maruyama and Eckelman 2009, Oda *et al* 2012). In the case of coal these differences are mainly driven by fuel qualities (e.g. lignite vs black coal) and the level of plant thermal efficiency (subcritical vs supercritical vs combined heat and power plants). Since newly deployed plants have higher efficiencies and older inefficient plants are steadily retired or retrofitted—particularly following concerted policy efforts, as is the case in China—the electricity output for a given quantity of fuel tends to improve over time, hence leading to an aggregate energy intensity improvement (Li *et al* 2020).

Improvements in carbon intensity can be decomposed into two distinct drivers: fossil intensity (the emissions intensity of fossil fuels) and fossil share (the substitution of fossil fuels by renewables) (Peters *et al* 2017). In the United States fossil intensity improvements have had a larger overall effect since 2006, due to a widespread coal to gas switch driven by low gas prices following a shale gas boom, and federal tax credit incentives (Peters *et al* 2017, 2020, Feng 2019, Mohlin *et al* 2019). Nonetheless, the overall share of fossil fuels in electricity production has also recently declined in North America (from 66% in 2010 to 59% in 2018; figure 7), with renewable capacity expanding rapidly in Texas, California and across the Midwest (Mohlin *et al* 2019). Declining fossil intensities associated with a coal to gas switch also drove down emissions in Europe in the early 2000s (Rodrigues *et al* 2020). But since 2007, Europe's carbon intensity improvements have instead been driven the steady expansion of renewables in the share of electricity generation (Peters *et al* 2017, 2020, Le Quéré *et al* 2019, Rodrigues *et al* 2020), with a fossil share decrease of 57% in 2010 to 47% in 2018 (figure 7). Some studies attribute these effects to climate policies, such as the carbon floor price in the UK, the EU emissions trading scheme, and generous renewable energy subsidies across the continent (Dyrstad *et al* 2019, Wang *et al* 2020a). Asia-Pacific Developed stands out in contrast to other developed regions, with a dramatic increase of regional carbon intensity and fossil share since 2010. This was due to the ramp up of coal and gas capacity in Japan following the Fukushima nuclear accident (Kharecha and Sato 2019). Generally, the use of natural gas for electricity production is growing strongly in

most countries and gas has contributed to the largest increase in global fossil CO₂ emissions in recent years (Jackson *et al* 2019, Peters *et al* 2020).

Steady or increasing carbon intensities can be observed in most other regions, indicating further deepening of fossil fuel based energy systems worldwide (figure 6). A major driver of these trends is the global 'renaissance of coal' that started in the 1990s, primarily driven by a huge increase of coal generation capacity in China (Steckel *et al* 2015, Jiang and Guan 2016). The growth of coal emissions slowed after 2010, primarily due to a slowdown of economic growth and fewer coal capacity additions in China, and even declined between 2011 and 2018 (Friedlingstein *et al* 2019, Peters *et al* 2020). Discussions of a global 'peak coal', however, may be premature, as further growth was observed in 2019 (Friedlingstein *et al* 2019, Peters *et al* 2020). In addition, the renaissance has not been limited to China alone, with large ongoing and planned capacity increases in India, Turkey, Indonesia, Vietnam, South Africa and others (UNEP 2017, Edenhofer *et al* 2018, Steckel *et al* 2020).

The declining competitiveness of coal-based generation relative to alternatives, particularly solar PV, as well as its short-term health and environmental impacts, begs the question why many countries have continued to invest in coal capacity (Creutzig *et al* 2017, Lelieveld *et al* 2019, Rauner *et al* 2020). Historically, coal powered generation has been perceived as a relatively low-cost, stable, and technologically accessible option to expand grid electricity and meet growing consumption demands. As private and public utilities have invested in these technologies they locked-in technological pathways and shaped institutional environments (e.g. supportive financial, legal and political structures) that increase the costs of transitioning to alternatives. Recent studies show that incumbent energy utilities have only in rare exceptions transitioned a sizable share of their portfolios towards renewable energy (Alova 2020, Green *et al* 2020). It is rather new actors and interests driving these investments, often against considerable opposition and backlash from interest groups, particularly if implemented policies do succeed in scaling up renewable technologies (Moe 2015, Stokes and Breetz 2018). Fossil-based development pathways may also be chosen to meet the narrow goals of national and international interest groups, such as rent extraction or energy independence, and are shaped by issues such as lobbying, political ideology, and corruption (Dorband *et al* 2020, Jakob *et al* 2020, Lamb and Minx 2020, Roy and Schaffartzik 2021).

Overall, global energy system emissions growth has slowed in recent years, due to a reduction of fossil capacity additions in China, a structural shift to gas and renewables in the United States (Feng *et al* 2016), and the increasing penetration of renewables in Europe. The worldwide share of fossil fuels shrank

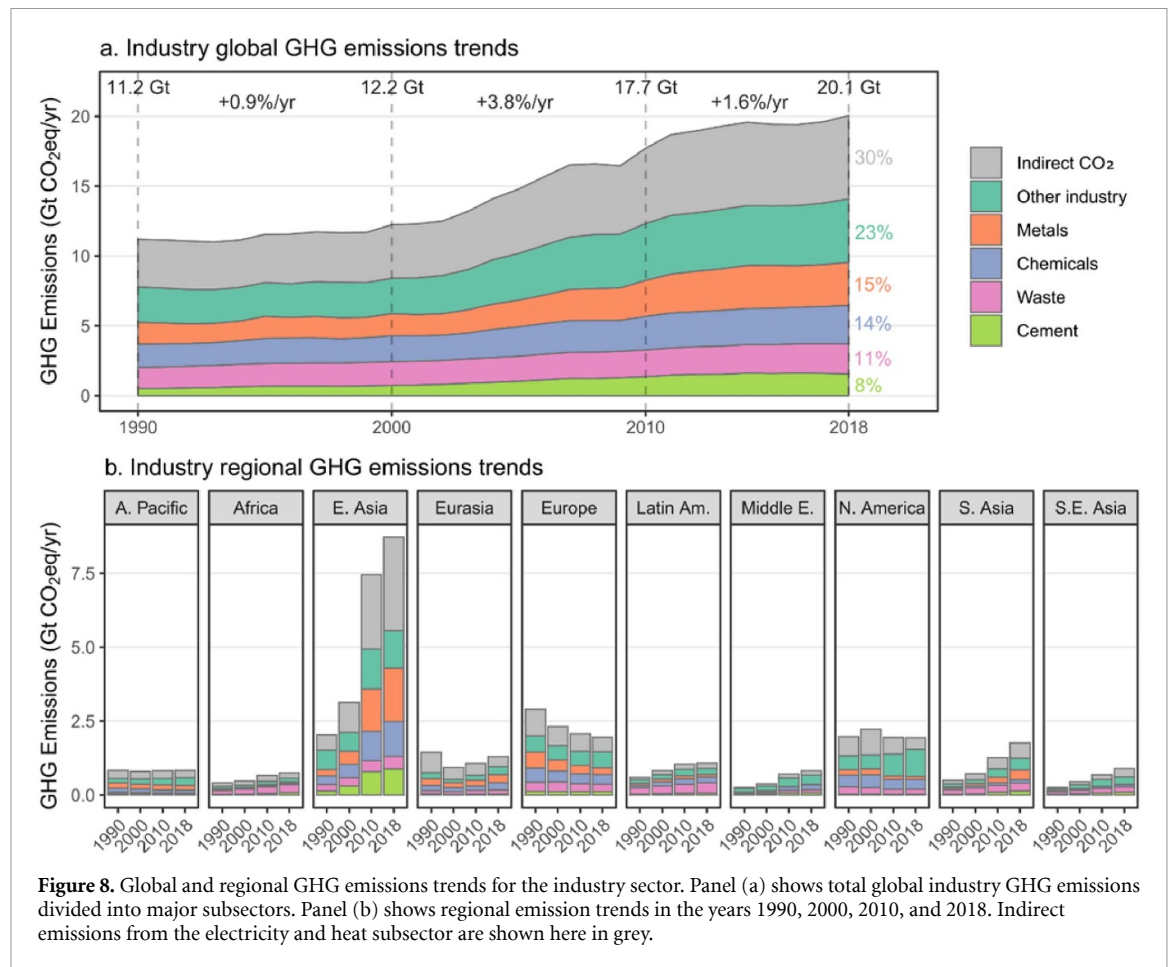
slowly, down from 73% in 1990 to 68% in 2018. Despite this, global oil and gas use is still growing (Jackson *et al* 2019). The switch of coal to gas brings the risk of increased CH₄ emissions from fugitive sources, as well as large cumulative emissions over the lifetime of the new plants that may erase early carbon intensity reductions (Shearer *et al* 2020). The focus of decarbonisation efforts in the energy systems sector needs to be on rapidly shifting to zero-carbon sources and actively phasing out all fossil fuels, rather than relying on the short-lived effects of fuel switching (Jackson *et al* 2019, Peters *et al* 2020).

3.3. Industry

Direct and indirect GHG emissions in the industry sector steadily increased to 20.1 GtCO₂eq in 2018. Based on direct emissions alone, the industry sector is the second largest contributor to total emissions in 2018 (25%), following energy systems. When indirect emissions from electricity and heat production are included, industry becomes the single highest emitting sector (35%). In addition, industry has a steadily increasing share of all direct emissions since 1990 and faces non-trivial technological bottlenecks to mitigation, particularly in steel and cement process emissions, making it a key sector that will shape global mitigation prospects going forward (Davis *et al* 2018, Crippa *et al* 2019, Rissman *et al* 2020).

Apart from indirect emissions from the power sector (5.9 GtCO₂eq, 30% of total), industry emissions in 2018 are largely driven by 'other industry' (4.5 GtCO₂eq, 23% of total). 'Other industry' comprises a multitude of emissions sources associated with the manufacture of pulp and paper, food and tobacco, glass and ceramics, and other generic manufacturing. It also includes the production and use of fluorinated gases for solvents, refrigerants and electrical equipment. Three further subsectors account for basic materials production: metals (3.1 GtCO₂eq, 15% of total), chemicals (2.8 GtCO₂eq, 14% of total) and cement (1.6 GtCO₂eq, 8% of total). Finally, waste (2.1 GtCO₂eq, 11% of total) includes the emissions from incineration and waste disposal on land, as well as industrial, domestic and commercial wastewater processing.

The main period of industry emissions growth occurred between 2000 and 2010, which saw a total increase of 5.5 GtCO₂eq (+3.8%/yr). Growth has subsequently slowed down to 1.6% per year since then, with an approximately proportionate contribution from each subsector. At a regional level, Eastern Asia stands out as the main source of global industry emissions (8.7 GtCO₂eq in 2018, 43% of total), as well as the primary driver of growth since 2010 (+1.3 GtCO₂eq, 2%/yr). At the same time, industry emissions remained high in Europe (2 GtCO₂eq in 2018), but have slowly declined at a rate of -0.7%/yr. North America, Asia-Pacific Developed and Latin America



have had stable industry emissions since 2010 (at 1.9, 0.8 and 1.1 GtCO₂eq each). In all other regions they are growing—most rapidly in Southern Asia (+4.3%/yr to 1.8 GtCO₂eq in 2018), South-East Asia (+3.4%/yr to 0.9 GtCO₂eq) and Eurasia (+2.5%/yr to 1.3 GtCO₂eq).

Regions differ somewhat in their composition of different subsectors, with waste and cement featuring more heavily in developing regions like Africa, Southern Asia and Latin America, while chemicals and other industry play a larger role in Europe and North America. Emissions from metal production take place primarily in East Asia (1.8 GtCO₂eq), followed by Southern Asia (0.33 GtCO₂eq), Eurasia (0.28 GtCO₂eq) and Europe (0.22 GtCO₂eq).

The main global driver of industry emissions has been the massive rise in demand for basic materials, construction minerals and manufactured products. These are in turn driven by rising affluence and consumption, as well as an increase in urban populations and associated infrastructure development (Krausmann *et al* 2017, 2018). Similar to the energy sector, the industry sector generates products that are indirectly used in final sectors—namely the materials that make up the manufactured capital of the physical economy, such as cement, chemicals, steel, aluminium, wood, paper, plastics, lubricants, fertilisers, and so on. These materials are used to build and

maintain stocks of manufactured capital, including buildings, roads, vehicles, electronics, and machinery (also known as ‘material stocks’; Krausmann *et al* 2017). Material stocks, which will remain in use over decadal time periods, reached 928 Gt in 2014, with a growth of 3.9% per year since 2010 and a 26-fold increase since 1900 (Wiedenhofer *et al* 2019). Alone, their production and use accounted for 11 GtCO₂eq of global emissions in 2011, according to Hertwich (2021).

There is strong evidence that the growth of concrete, steel and other construction material use is tightly coupled to economic growth, urbanisation, and associated infrastructure development (Pauliuk *et al* 2013, Cao *et al* 2017, Krausmann *et al* 2017, Plank *et al* 2018, Haberl *et al* 2020). Per-capita stocks of cement and steel show a typical pattern of rapid take-off as countries urbanise and industrialise, before slowing down to low growth at high levels of GDP. Selected wealthy countries even seem to stabilise at high per-capita levels of stocks, although it is unclear if these stabilisations persist and if they result in significant absolute reductions of material use (Liu *et al* 2013, Pauliuk *et al* 2013, Fishman *et al* 2016, Cao *et al* 2017). Hence, in countries that are recently industrialising and urbanising—i.e. Eastern, Southern and South-Eastern Asia—we observe a particularly strong increase of emissions from these

subsectors (figure 8) and a strong overall relationship between GDP growth and industrial CO₂ emissions (figure 9).

Once buildings, roads, ports, vehicles and other physical stocks have been constructed, a continuous throughput of material flows is still required to maintain, renovate, replace and operate them (Wiedenhofer *et al* 2015, Krausmann *et al* 2017). Material consumption in wealthier countries therefore has shown only limited rates of decrease, even though their large existing and only slowly growing stocks open up (as yet unexploited) opportunities for prolonging lifetimes and improving end of life recycling, so as to achieve absolute reductions in extraction activities (Krausmann *et al* 2017, Zink and Geyer 2017). For a given level of economic development, material stock levels and associated material use also varies due a variety of contextual factors, such as differences in prevailing construction methods and building codes (e.g. steel vs timber framing), patterns of urbanisation and infrastructure development (e.g. compact cities vs sprawl), trends in dwelling space and cars per capita, and the overall lifetimes of buildings and infrastructure (Lin *et al* 2016, Hertwich *et al* 2019, Lanau *et al* 2019).

As with the AFOLU sector, industrial emissions are strongly linked to international trade. Materials, especially metals, chemicals, plastics and wood products, are routinely transported between different stages of extraction, refining and production along global supply chains (Schaffartzik *et al* 2016, Plank *et al* 2018). Owing to a series of socio-economic conditions including low priced labour, state-led industrial policy and agglomeration effects, China currently dominates global industrial production, particularly in the manufacture of steel and other basic materials (Reck *et al* 2010, Wang *et al* 2019a). The global shift of energy-intensive industries away from historical centres in the United States and Europe to developing regions explains, to some extent, reductions of industry GHG emissions in the former—even though they continue to consume manufactured products via trade.

On the production side, improvements in the energy efficiency of material extraction, processing and manufacturing have reduced industrial energy use per unit of output (Wang *et al* 2019a; figure 9). These measures, alongside improved material substitution, light-weight designs, extended product and servicing lifetimes, improved service efficiency and increased reuse and recycling could enable substantial emissions reductions in the future (Hertwich *et al* 2019). Switching to lower or zero carbon feedstocks and power further leads to industry sector decarbonisation. Indeed, figure 9 shows that the ratio of industrial energy use to GDP has steadily declined since 2010 in all regions. Absent these improvements in energy intensity, growth of population and GDP per

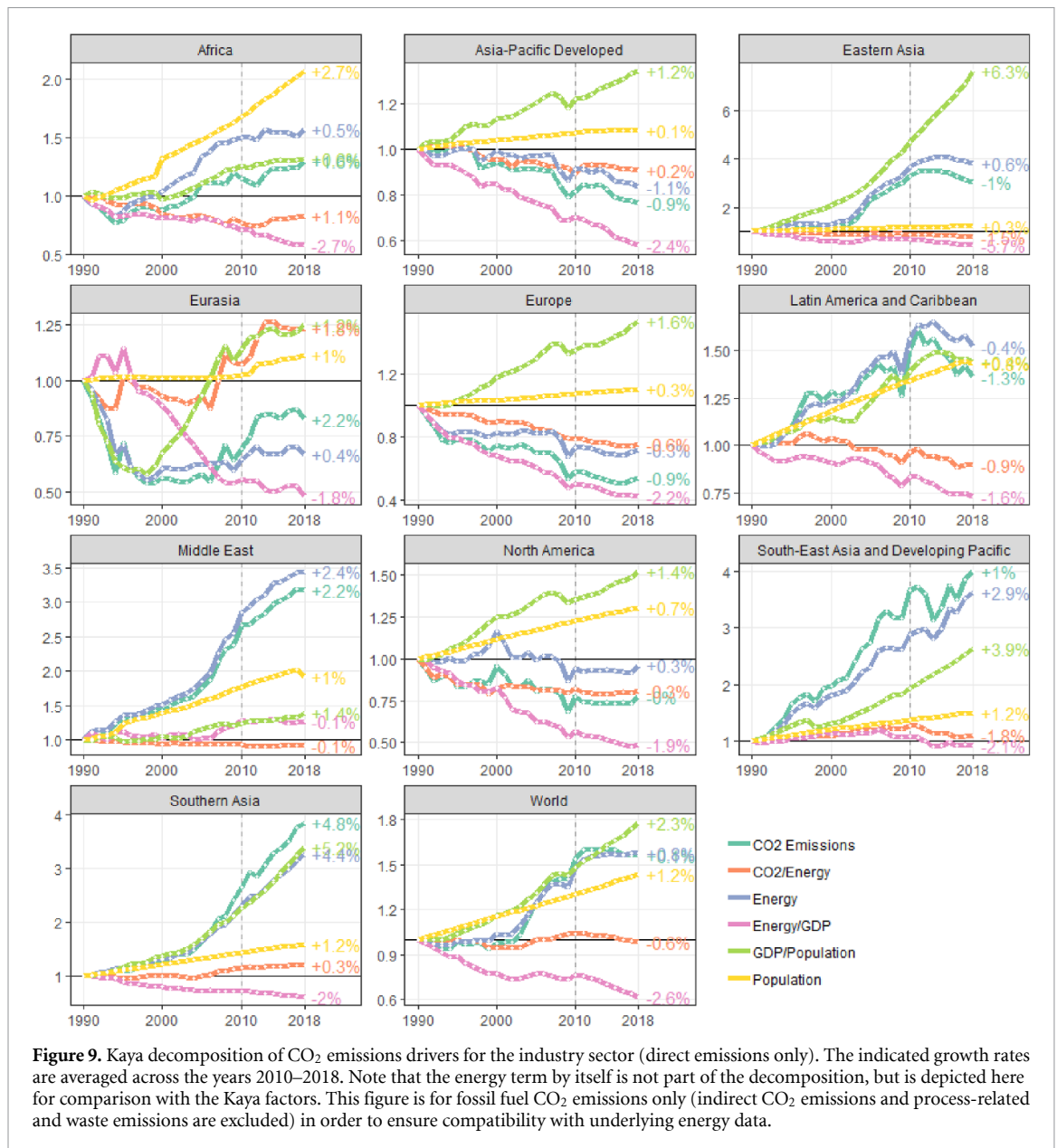
capita would have driven industrial CO₂ emissions to rise by more than 100% by 2017 compared with 1990s, instead of 56%. Nonetheless, many studies point to deep regional differences in efficiency levels and large globally unexploited potentials to improve industrial energy efficiency by adopting best available technologies and practices for metal, cement and chemical production (Gutowski *et al* 2013, Schulze *et al* 2016, Gonzalez Hernandez *et al* 2018, Talaei *et al* 2018). Yet, decarbonising process emissions by technological improvements alone is unlikely to outweigh growing demand, calling for additional demand-side mitigation options to curb emissions from the industry sector (Creutzig *et al* 2016).

Overall, demand for services driven by global affluence and population growth have led to an escalation of material use and associated industry GHG emissions. Recent growth has been driven by emerging economies, but also high-income countries where direct and indirect consumption remains high. The growing complexity of international supply chains makes governance hard and problem-shifting likely. Historically, energy efficiency provided the largest mitigation wedge, but still failed to prevent GHG emissions from increasing. Furthermore, efficiency potentials will decrease in the coming decades as technological options are exhausted. This puts increasing focus on historically weak drivers of decarbonisation, such as demand management in end-use sectors (i.e. more efficient delivery of services), material efficiency (product lightweighting, longer lifetimes, use of secondary materials), fuel switching and electrification, and the decarbonisation of power and feedstocks (IRP 2020).

3.4. Buildings

Global GHG emissions from the buildings sector reached 9.8 GtCO₂eq in 2018, of which 66% (6.5 GtCO₂eq) were upstream emissions from power generation and commercial heat (figure 10). The remaining 34% (3.4 GtCO₂eq) of emissions were directly produced in buildings, for instance by gas and coal boilers, and cooking and lighting devices that burn kerosene, biomass and other fuels. Residential buildings accounted for the majority of this sector's emissions (64%, 6.3 GtCO₂eq, including both direct and indirect emissions), followed by non-residential buildings (35%, 3.5 GtCO₂eq). Some non-CO₂ sources (CH₄ and N₂O) also contribute to building emissions, but these are almost negligible (0.03 GtCO₂eq) compared to other subsectors.

The buildings sector accounts for almost 6% of all direct GHG emissions and 17% when indirect 'scope 2' emissions are included. Yet further emissions components could also be attributed to this sector under alternative accounting schemes, such as consumption-based emissions footprints. Embodied GHG emissions associated with building materials and components, as well as the construction,



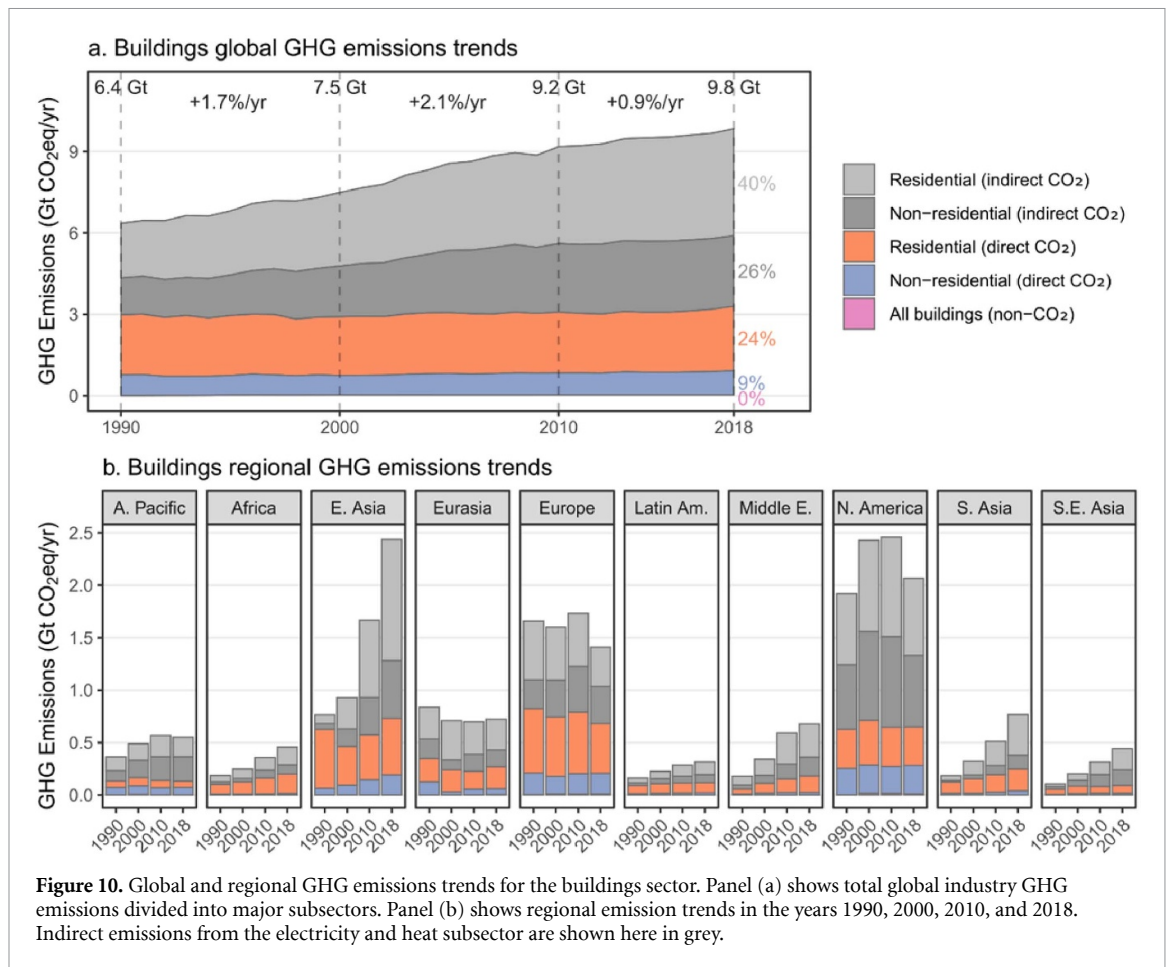
assembly and maintenance of buildings, make up an estimated additional 11% of global energy and process-related CO₂ emissions (Ürge-Vorsatz *et al* 2020). Adding these to the building sector would further increase emissions by approximately 2.21 GtCO₂eq in 2018 (IEA 2020d).

The buildings sector contributed 0.7 GtCO₂eq to global emissions growth between 2010 and 2018, an increase of 0.9% per year, which was relatively lower than prior decades where growth rates averaged between 1.7%/yr and 2.1%/yr (figure 10). A more than proportional amount of growth came from the residential (direct and indirect) subsector (+0.5 GtCO₂eq, 76% of growth), compared to non-residential buildings.

The developed regions of North America, Europe, and Asia-Pacific Developed together accounted for 41% (4 GtCO₂eq) of global building emissions in 2018. In all three regions emissions declined over the

period 2010–2018, at rates of –2.2%/yr, –2.5%/yr and –0.4%/yr, respectively. In the case of North America, almost all of the reduction (99%) was from indirect emissions (i.e. the energy systems sector); while in Europe at least one-third (35%) also came from decarbonisation in direct residential building emissions.

The regions of the global South and Eurasia together accounted for 59% (5.9 GtCO₂eq) of global buildings emissions in 2018. Starting from a much lower base, buildings emissions increased significantly in these regions between 2010 and 2018, at rates of 4.9%/yr in Eastern Asia, 4.8%/yr in Southern Asia, 4.3%/yr South-East Asia, 3.1%/yr in Africa, 1.7%/yr in the Middle East, 1.2%/yr in Latin America and 0.5%/yr in Eurasia. Indirect emissions tended to grow faster than direct emissions, accounting for 80% of growth in Eastern Asia, 75% in Southern Asia and 92% SE Asia. This again underlines the close link



between the buildings sector and energy systems—which over the past decades has tended towards the expansion of fossil-based electricity generation in these regions (section 3.2).

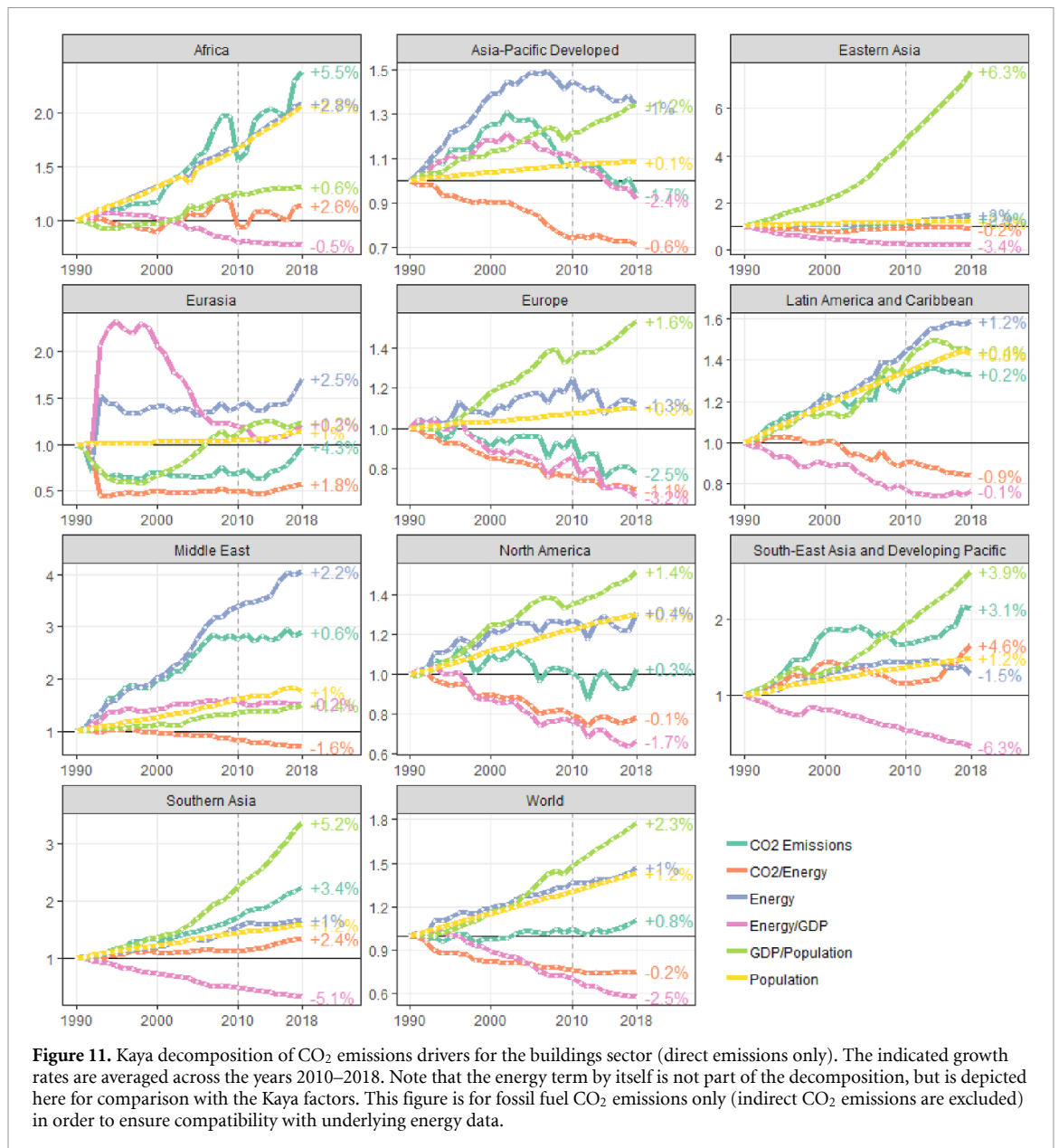
Population and GDP per capita growth are broad drivers of building emissions trends (figure 11), which manifest more specifically in a growing demand for building stock, floor space per capita, and building energy services as countries develop and urbanise (Ürge-Vorsatz *et al* 2015). At the same time, declines in carbon and energy intensities can be observed both globally and regionally over the past decades (figure 11), hinting at the impact of steadily improving efficiencies and shifts in the composition of fuels used in buildings (Ürge-Vorsatz *et al* 2020). Changes in the upstream power sector also figure strongly as drivers of indirect building emissions (but are not included in figure 11).

The global stock of residential and non-residential buildings has been steadily growing over the past decades, driving a huge demand for building energy use and construction materials (Deetman *et al* 2020). Global building stock was estimated at almost 200 billion m² of floor space in 2018, more than double of what it was in 1990 (IEA 2020d). China currently dominates total new additions to building stock, with urban residential buildings almost tripling since 1990 (Huo *et al* 2019, Marinova *et al*

2020, IEA 2020d). The same occurred in Southern Asia, South-East Asia and developing Pacific while it has doubled in the developed world, Eurasia, Latin America and Caribbean as well as Africa and the Middle East (IEA 2020d).

As countries increase in wealth, developers tend to construct larger properties and more floor space is required to service growing demand in the retail, office and hotel sectors (Daioglou *et al* 2012, Deetman *et al* 2020). At the same time, patterns of urbanisation and sprawl further shape the density and overall scale of a country's building stock. In the United States, the stock of floor space in single and multi-family homes has continuously grown over the 21st century, increasing tenfold between 1890 and 2010 (Moura *et al* 2015).

Beyond population and wealth, demographic and social factors drive a cross-national trend of increasing floor space per capita. As populations age and decrease in fertility, and as individuals seek greater privacy and autonomy, households decline in size (Ellsworth-Krebs 2020). At the same time, a lack of 1–2 bed dwellings and the tendency for developers to construct larger family-sized properties may lead to over occupancy (Huebner and Shipworth 2017). Together these factors lead to increased floor space per capita, even as populations stabilise (figure 12). Overall, there remains a stark but converging divide in

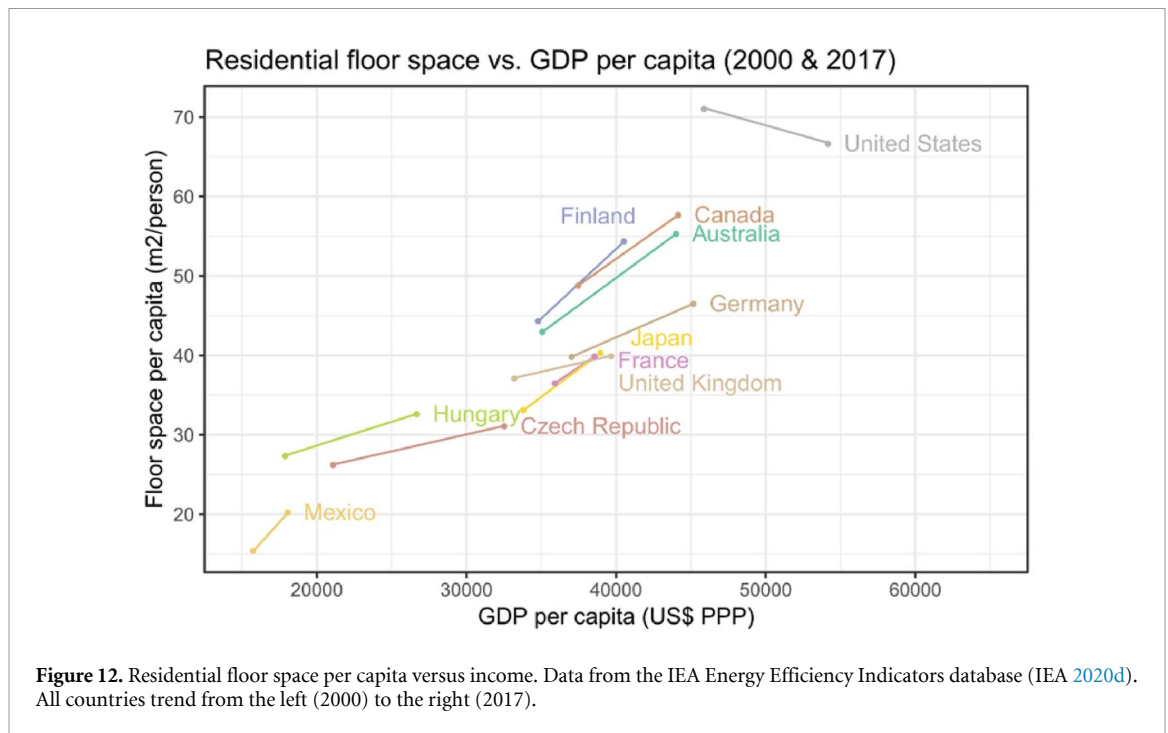


global residential floor space, driven by differences in household and dwelling size—from an upper range of 40–60 m² per person in Western European and North American countries, to approximately 32 m² in China and 20 m² in Mexico (Nie and Kemp 2014; figure 12).

Increasing floor space per capita is a key driver for building sector emissions, because building characteristics such as size and type, rather than occupant behaviour, tend to explain the majority of energy use within dwellings (Guerra Santin *et al* 2009, Huebner and Shipworth 2017). Smaller household sizes result in increased per-capita appliance and equipment ownership (i.e. fewer people share appliances such as fridges and cookers), while larger homes increase the surface area to be illuminated and maintained at comfortable temperatures (Ürge-Vorsatz *et al* 2015).

Energy activity levels further drive regional differences. In Eurasia, Europe and North America, thermal demands for space heating dominate

building energy use, at 66%, 62% and 48% of residential energy demand, respectively (IEA 2020d). In contrast, cooking has a much higher share of building energy use in regions of the Global South, including China (Cao *et al* 2016, Serrano *et al* 2017). And despite temperatures being on average warmer in the Global South, electricity use for cooling is a more prominent factor in the Global North (Waite *et al* 2017). This situation is changing, however, as rapid income growth and demographic changes in the global South enable households to heat and cool their homes (Ürge-Vorsatz *et al* 2015, 2020). Cooling energy demand represented 8% out of total residential energy demand in North America and the Middle East in 2018 (IEA 2020d). It was 3%–4% in Eastern Asia, Latin America and the rest of Asia (growing from less than 1% in 2010) and remained below 1% in Europe, Eurasia and Africa in 2018 (IEA 2020d). Annual variations in temperatures and



extreme weather are also important drivers of overall demand (Idahosa *et al* 2017, Eggimann *et al* 2020).

Energy demand for small and connected devices and appliances is one of the emerging trends in residential buildings. The highest shares of energy demand for small and connected devices were observed in developed Asia-Pacific, with 24% out of total energy demand in residential buildings, followed by 15% in North America, and 13% in Middle East countries (IEA 2020d).

Steady improvements in building energy intensities across regions can be attributed to policies and baseline improvements in building fabrics, appliance efficiencies, and fuel shifts. Many countries have adopted a mix of relevant policies, such as energy labelling, building energy codes and mandatory energy performance requirements (Nie and Kemp 2014, Nejat *et al* 2015). Efforts towards buildings refurbishments and retrofits have also been pursued in several nations, especially for historical buildings in Europe, but evidence suggests that the recent rates of retrofits have not made a significant dent on emissions (Corrado and Ballarini 2016, Kerr and Winskel 2020). Green building retrofit policies in China too have been relatively ineffective to date (Liu *et al* 2020a, 2020b). Still, one major global factor driving down energy intensities has been the global transition from inefficient coal and biomass use in buildings for heating and cooking, towards natural gas and electricity, in part led by concerted policy action in Asian countries (Ürge-Vorsatz *et al* 2015, Kerimray *et al* 2017, Thoday *et al* 2018).

Overall, emissions from the building sector are expected to continue rising, especially in much of the Global South as housing gaps are filled and

demand for floor area increases. As developing countries construct new buildings, there is much potential to reduce and use less carbon-intensive building materials, and to adopt building designs and standards that lower life cycle buildings energy use and allow for passive comfort. A significant shift from the use of solid heating and cooking fuels to gas and electricity in recent years is a trend that will continue and help reduce emissions. However, increasing appliance penetration in regions just gaining access to electricity will increase electricity related emissions from the building sector, unless accompanied by improved standards, labelling, and the decarbonisation of the electricity sector. Within the Global North, significant untapped potential for increasing heating, building fabric and material efficiency exists, as do behavioural shifts towards low-carbon lifestyles.

3.5. Transport

Global transport GHG emissions reached 8.5 GtCO₂eq in 2018 and accounted for 14% of all direct and indirect emissions. Road transport passenger and freight emissions represent by far the largest component and source of this growth (6.1 GtCO₂eq, 73% of total sector emissions), followed by international shipping (0.7 GtCO₂eq, 8%) and international aviation (0.6 GtCO₂eq, 7%). National plus international shipping and aviation emissions together account for 1.8 GtCO₂eq or 21% of the sector total. Emissions from rail, indirect N₂O emissions, and indirect CO₂ emissions from electricity and heat (e.g. from the electrification of rail and bus transport) are relatively small, totalling 0.5 GtCO₂eq or 6% of the current transport total.

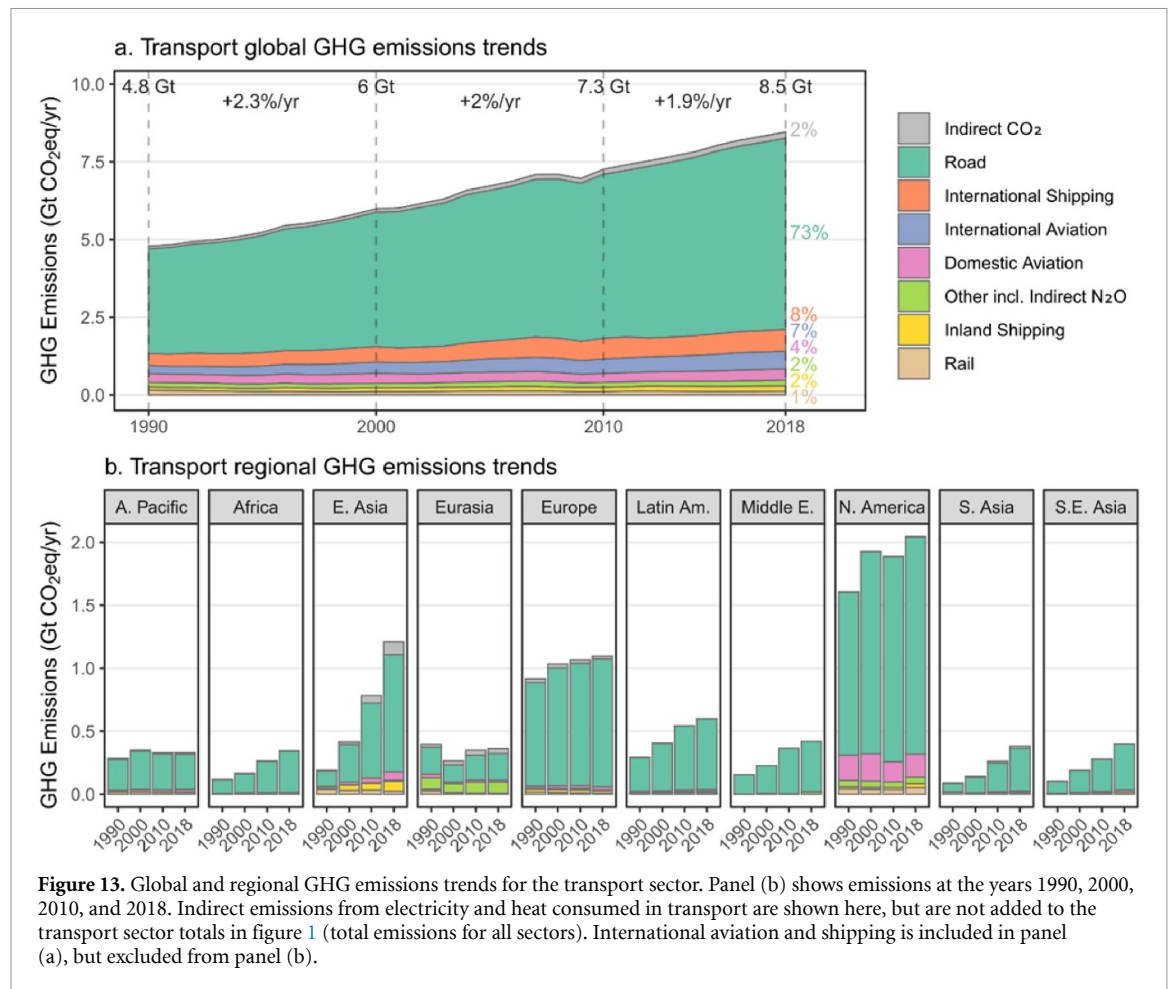


Figure 13. Global and regional GHG emissions trends for the transport sector. Panel (b) shows emissions at the years 1990, 2000, 2010, and 2018. Indirect emissions from electricity and heat consumed in transport are shown here, but are not added to the transport sector totals in figure 1 (total emissions for all sectors). International aviation and shipping is included in panel (a), but excluded from panel (b).

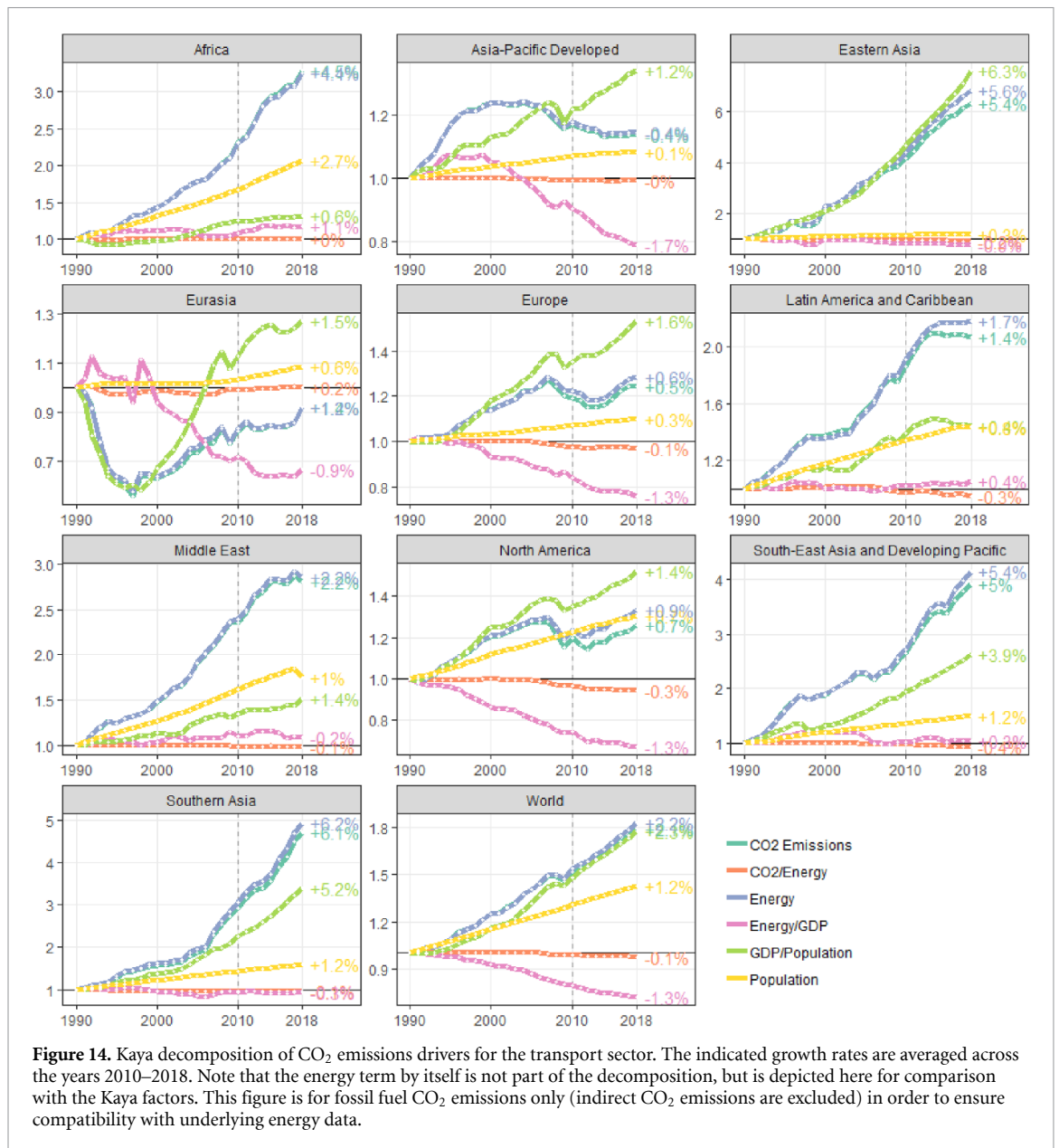
Since 1990, global transport emissions have grown at a constant rate of about 2% per year. The road subsector accounted for most growth since 2010 (+0.9 GtCO₂eq, at 1.9% per year), but inland shipping, domestic aviation and international aviation were the fastest growing subsectors at +3.2%/yr, +2.8%/yr and +2.7%/yr, respectively. North America, Europe and Eastern Asia stand out as the main regional contributors to global transport emissions and together account for 60% of the total. Latin America (in 4th place) is also notable for its high transport emissions, since in all other sectors apart from AFOLU it tends to be one of the lowest regional contributors.

Three regions managed to hold transport emissions relatively stable since 2010—Asia Pacific Developed (+0%/yr), Europe (+0.4%/yr) and Eurasia (+0.4%/yr)—but all others continued to grow. Fastest growth since 2010 occurred in Eastern Asia (+5.6%/yr, +0.4 GtCO₂eq), Southern Asia (+4.9%/yr, +0.1 GtCO₂eq), South-East Asia (+4.5%/yr, +0.1 GtCO₂eq) and Africa (+3.3%/yr, +0.08 GtCO₂eq). The proportion of total final energy used in transport (28%) and its fast expansion over time weighs heavily on climate mitigation efforts as 92% of transport energy comes from oil based-fuels (IEA 2020c). These trends situate transport as one

of the most challenging sectors for climate change mitigation—even wealthier countries have so far been unable to realise significant emissions reductions in the sector.

More so than any other sector, transport energy use has closely tracked GDP per capita growth (figure 14). Transport facilitates the movement of people and goods, enabling access to essential services and social interactions, and driving local and global economies. Developments since 1990 continue a historical trend of increasing travel distances and a shift from low- to high-speed transport modes that goes along with GDP growth (Schäfer *et al* 2009, Gota *et al* 2019). Only modest improvements in energy efficiency have been realised, averaging 1.3% per year globally, while carbon intensities have remained stable (figure 14). Overall, global increases in passenger and freight travel activity levels have out-paced energy efficiency and fuel economy improvements, continuing a long-term trend for the transport sector (Gucwa and Schäfer 2013, Grübler 2015, McKinnon 2016).

While global passenger activity has expanded in all world regions, great disparities exist between low and high income regions, and within countries between urban and rural areas (ITF 2019). These disparities are visible comparing regional levels



of transport emissions (figure 13), and are largely due to differences in modal split and motor vehicle use. Europe and North America underwent a rapid increase in private car use in the 20th century, which has come to dominate most passenger travel activity and emissions, accounting in 2017 for 70.9% of passenger-km by motorised transport in the EU-28, and 81.1% in the US (EC 2019). However, the growth of passenger-km in the OECD has considerably slowed, down to an increase of just 1% between 2000 and 2017 (SLoCaT 2018). It is not clear whether the so-called ‘peak car’ in developed economies is simply the result of economic stagnation and rising fuel prices or whether it reflects deeper lifestyle and demographic change (Goodwin and van Dender 2013, Kuhnimhof *et al* 2013, Bastian *et al* 2016). Meanwhile, emerging countries in the global South are becoming more car dependent, with rapidly growing motorisation and urban sprawl, and

the emergence of local automotive production, while public transport struggles to provide adequate service (Dargay *et al* 2007, Hansen and Nielsen 2017, Pojani and Stead 2017). Between 2000 and 2017 global passenger travel increased in non-OECD countries by 169%, starting from a low baseline (SLoCaT 2018).

Passenger and freight mobility services have seen far reaching advances, aided by information and communication technologies tools that have fostered e-commerce and mobility sharing platforms. The easing of traveling and the lowering of cost conditions attained through use of innovative business models and information technology have contributed as drivers of increasing transport demand and have shaped the way people and goods travel around the globe (Smidfelt Rosqvist and Hiselius 2016). Freight travel activity grew across the globe by 68% in the last two decades driven by global GDP increases, together with the proliferation of online commerce and rapid

(i.e. same-day and next-day) delivery (SLoCaT 2018). Growth has been particularly rapid in heavy-duty road freight transport.

The transport sector global energy intensity dropped by an average of 1.3% per year between 2010 and 2018, primarily driven by wealthier regions, but was relatively level or increasing in all other regions (figure 14). Some countries have mobilised policies to increase vehicle energy efficiency, stimulating technological improvements that steadily reduced the required energy use per passenger-km and per tonne-km of goods delivery for all vehicle applications (light duty, heavy duty and rail) (IEA 2019a). Yet progress in another key policy area, fuel price reform, has been more mixed: fuel taxes increased in 83 countries, but fell in 46 between 2003 and 2015, despite their importance in encouraging the purchase of more efficient vehicles and in limiting travel demand (Bastian *et al* 2016, Ross *et al* 2017).

The energy matrix of the global transport system remains to the present deeply rooted in fossil fuels, with powertrains depending on gasoline and diesel fuels accounting for 92% of final energy use in the light duty vehicle segment (Figueroa *et al* 2014, IEA 2019a). The carbon intensity of the transport sector has remained unchanged between 2010 and 2018 in all world regions (figure 14). In part this is due to the increasing adoption of larger, heavier combustion-based vehicles ('sports utility vehicles' or SUVs), which have tended to far outpace electric and hybrid vehicle sales. Historically this has taken place in the North American car market, but is increasingly the case in Europe and international markets, with 39% of vehicles sold globally in 2018 in the category of SUVs (IEA 2020d). In terms of car size and weight, stringent material efficiency and light-weight design of passenger vehicles alone could cumulatively reduce global GHG emissions until 2060 by 16–39 GtCO₂eq (Pauliuk *et al* 2020). Since 2011, there has also been a steady and increasingly steep decline in the market share of more carbon-efficient diesel vehicles in EU-28 countries; starting in 2017 these developments reversed the previously downward trend of average fuel consumption for newly registered vehicles in Europe (IEA 2020b).

While accounting for a small share of total GHG emissions, national and international aviation and shipping play a fast-growing role, with annual growth rates of +4.2% and 3.1% respectively between 1990 and 2018. Energy efficiency improvements in aviation were considerably larger than in road transport, but were outpaced by even larger increases in activity levels (SLoCaT 2018, Lee *et al* 2021). In 2016, aviation accounted for 31% of tourist arrivals globally (up from 17% in 2005), and for 50% of transport-related CO₂ emissions from tourism (UNWTO 2019). The long term impact of the Covid-19 pandemic is uncertain but it has severely impacted

global passenger aviation in 2020, and to different extent the movement of goods and freight modes (Le Quére *et al* 2020, Newman AO 2020).

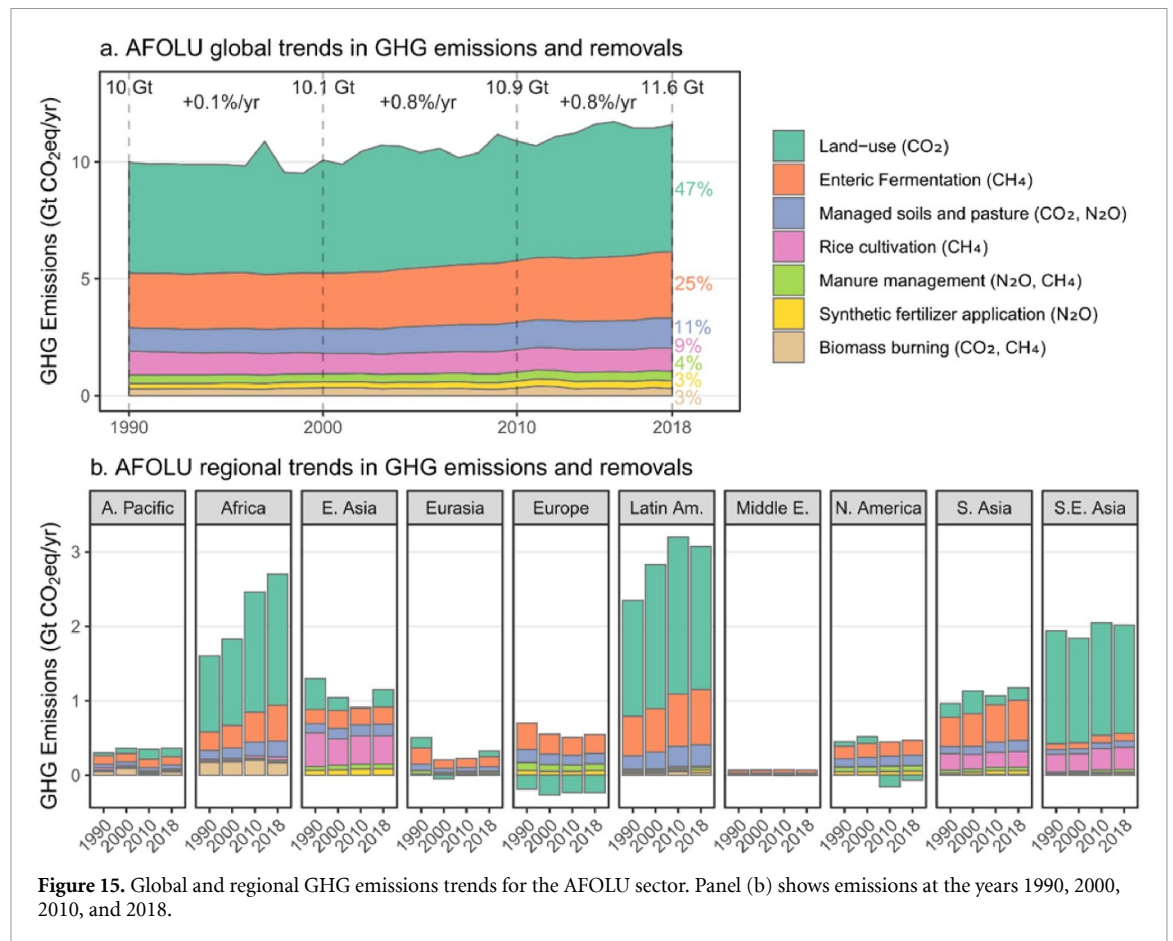
Overall, transport trends reveal a steady increase of emissions, overwhelmingly driven by growing motorisation and road transport activity. This global trend is opposite to what is needed, with a shift from lower to higher-carbon modes only minimally offset by efficiency gains. In recent years, hybrid electric and fully battery electric vehicles however, are becoming increasingly popular (IEA 2019b) and electrification has progressed faster than previously expected just a few years ago, especially in scooters, buses and a variety of micromobility and light urban freight modes such as e-bikes and e-autorickshaws (Taiebat and Xu 2019). Yet while the electrification of road transport holds much promise, its impact has been hardly visible in the period up to 2018, and looking forward it is in danger of being offset by growing levels of travel activity and countervailing trends such as increasing vehicle size and weight. This suggests a key role for more stringent policies and efforts to tackle car dependence, including demand management policies alongside technological innovation (Creutzig *et al* 2018, Mattioli *et al* 2020, Milovanoff *et al* 2020). Demand management is even more crucial for subsectors like aviation where technological options for decarbonisation are currently very limited.

3.6. AFOLU

AFOLU sector emissions and removals reached 11.6 GtCO₂eq globally in 2018, or approximately 21% of global GHG emissions. Reporting in the AFOLU sector is split into two major components: CO₂ emissions and removals from land-use change and management (also known as LULUCF—land use, land use change and forestry); and emissions from agriculture, which are predominantly CH₄ and N₂O.

Land use change and management CO₂ emissions and removals account for 47% of net emissions in the AFOLU sector and are one of the largest global subsectors at 5.4 Gt CO₂eq. A variety of land-based carbon fluxes make up these emissions, including: (a) deforestation (e.g. the clearing of natural vegetation for agricultural purposes); (b) transformations between croplands and pasture; (c) peat drainage and burning; (d) wood harvesting; (e) the regrowth of forest and other natural vegetation after agricultural abandonment and harvest; and (f) soil CO₂ flux due to grassland and cropland management (Hansis *et al* 2015, Houghton and Nassikas 2017, Gasser *et al* 2020).

Emissions from agriculture are mainly comprised of CH₄ emissions from enteric fermentation (e.g. cattle and sheep digestion), at 2.8 GtCO₂eq in 2018, or 25% of the sector total. Smaller emissions components include managed soils and pasture (1.3 GtCO₂eq, 11% of total), rice cultivation (1 GtCO₂eq,



9% of total), and manure management, biomass burning, and synthetic fertiliser application (together 1 GtCO₂eq). These agricultural sources are mainly CH₄ and N₂O emissions. Like land-use and management CO₂ emissions, they are subject to considerable uncertainty (section 2.5).

There has been a gradual upward trend of AFOLU emissions since 2000, at rates of 0.8%/yr. Regionally, this growth has played out via differing patterns of land use and ongoing agricultural transitions. Unlike all other sectors, AFOLU emissions are typically higher in developing compared to developed regions. In Africa, Latin America and South East Asia, CO₂ emissions associated with land-use change and management predominate, dwarfing other AFOLU and non-AFOLU sources, and making AFOLU the single largest sector at more than 50% of emissions in these regions. Land-use and management emissions here is associated with the expansion of agriculture into carbon-dense tropical forest areas, where vast quantities of CO₂ emissions are released due to the removal and burning of biomass, and draining of carbon rich soils (Pearson *et al* 2017, IPCC 2019, Hong *et al* 2021).

By contrast, in Europe and North America, the highest rates of land clearing occurred well before the 20th century, such that legacy land use CO₂ emissions are now negligible (Pongratz and Caldeira 2012). In

Europe, recent forest regrowth and regeneration on abandoned agricultural land has led to an increase of carbon stocks and CO₂ removals since at least 2010 (figure 15). Agricultural N₂O and CH₄ emissions therefore have a substantially larger share of overall AFOLU emissions in these regions compared to tropical countries (Hong *et al* 2021).

Livestock rearing takes place on vast tracts of pasture land worldwide, contributing to large quantities of CH₄ emissions from enteric fermentation in Latin America (0.7 Gt CO₂eq in 2018), Southern Asia (0.5 GtCO₂eq) and Africa (0.5 GtCO₂eq), while also playing a sizable role in the total AFOLU emissions of most other regions. Other emissions components are more specific to regions, such as rice cultivation in East, Southern, and South East Asia; biomass burning in Africa and Asia-Pacific Developed; and manure management in Europe and North America.

Trends in AFOLU emissions from 2010 to 2017 have been driven by increases in population, in particular in Africa, the Middle East, Southern Asia and South East Asia and Developing Pacific, increases in agricultural production per capita in all regions but the Middle East, and increases in emissions per unit of land area. The main downward driver was reductions in the amount of land required per unit of agricultural and forestry production in all regions (−2.7%/yr globally), reflecting agricultural intensification and



technological progress. Notable features since the 1990s are the collapse of the Soviet Union, temporarily increasing land intensity and reducing per-capita production (Schierhorn *et al* 2019), and the increase in the emissions intensity of land use where large areas of pristine rainforest were cleared (in particular Africa, Latin America and Caribbean). Overall, AFOLU emissions are either relatively stable or are increasing steadily across most regions.

Land is the central, limiting resource for the production of food, feed, timber, bioenergy and other biocrops, mediated by growing population numbers, dietary patterns, and production efficiency (Kastner *et al* 2012). Large and on-going land-use and management CO₂ emissions are consistent with a significant global expansion of anthropogenic land-use between 1990 and 2018 (Hurtt *et al* 2020). Humans have expanded cropland areas (+1.38 million km², a 9.1% increase), secondary forests (+5.73 million km², 22.5%), and urban land (+0.24 million km², 64.3%), and have simultaneously shrunk primary forest areas (−7.25 million km², −12.9%) (figure 16). These land-use changes have been led especially by Africa, Latin America, and Southeast Asia (Hurtt *et al* 2020).

The AFOLU sector and its emissions impacts are closely tied to global supply chains. Countries like Brazil and Argentina use about half or more of their cropland for products exported to other countries, mainly the EU and China (Yu *et al* 2013).

Of the soybeans produced in Brazil—the number two country-product combination with respect to GHG emissions in the global AFOLU sector after Indonesian rice (Hong *et al* 2021)—more than half was exported to China in 2017 (zu Ermgassen *et al* 2020). Difficulties in tracking supply chains and limited corporate accountability result in such exports often being associated with illegal deforestation (Vasconcelos *et al* 2020). In South-East Asia, particularly Indonesia, expansions of cropland by 0.18 million km² (28%) was largely driven by international demand for palm oil, rubber, and plantation products (Austin *et al* 2019, Xin *et al* 2021). Here, expansion often occurs on peatlands, leading to high emissions through peat draining (Conchedda and Tubiello 2020) and peat burning (van der Werf *et al* 2017). The strong increases in production per capita and associated GHG emissions seen in Latin America and South-East Asia (figure 17) are thus at least partly attributable to growing exports and not national dietary changes.

At the same time, efforts to promote environmental sustainability in regions like the EU and the US (but also fast-growing emerging economies such as China) can take place at the cost of increasing land displacement elsewhere to meet their own demand (Meyfroidt *et al* 2010, Yu *et al* 2013). Creutzig *et al* (2019) emphasise these global connections via different country ‘archetypes’ that explain co-occurring land use changes: ‘Consumers’ such as

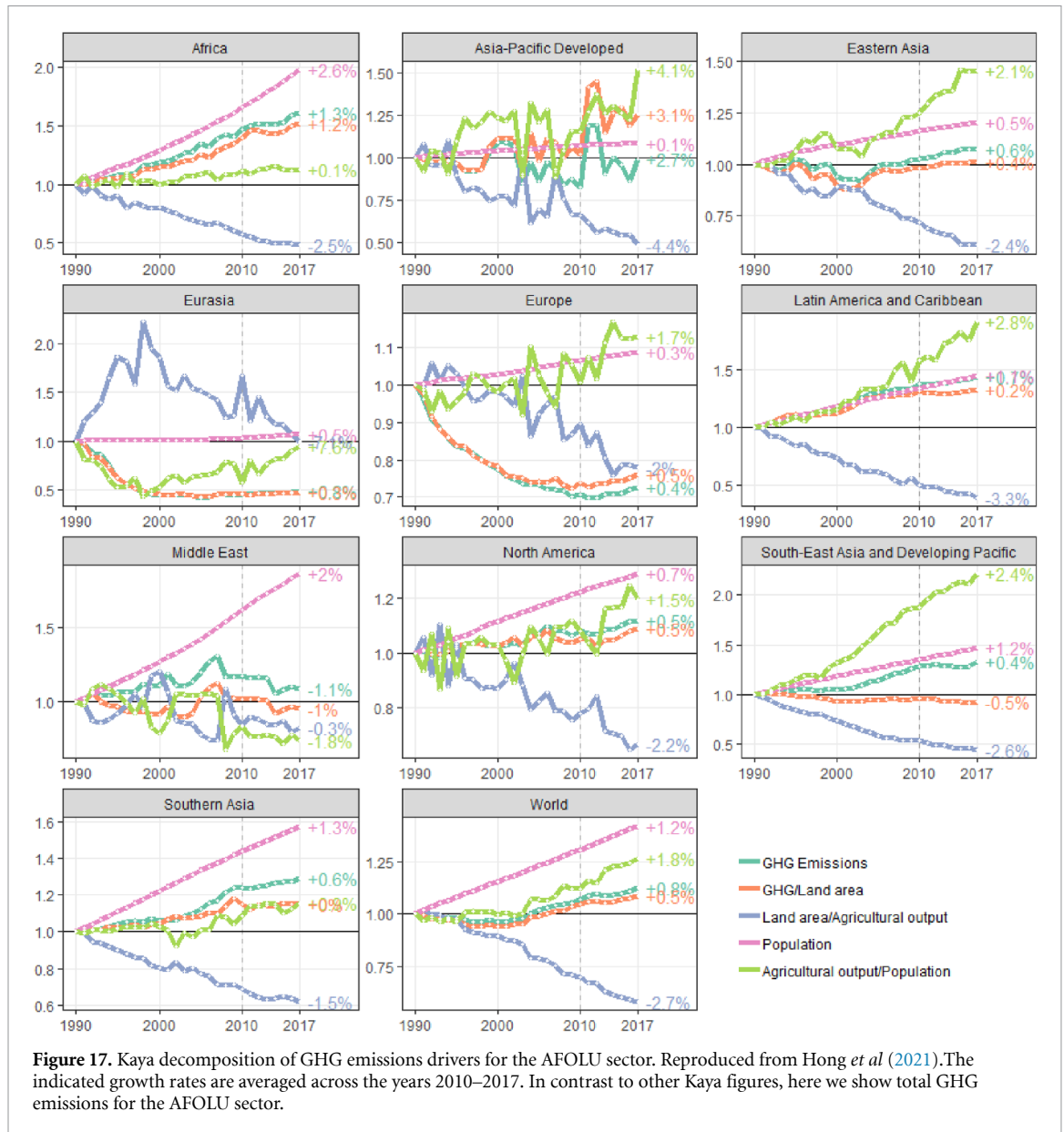


Figure 17. Kaya decomposition of GHG emissions drivers for the AFOLU sector. Reproduced from Hong *et al* (2021). The indicated growth rates are averaged across the years 2010–2017. In contrast to other Kaya figures, here we show total GHG emissions for the AFOLU sector.

Europe feature stagnating population, agricultural intensification, and a high reliance on imports. ‘Producers’ are regions with high biocapacity and low institutional capacity such as South America, Russia, Indonesia. In these countries, exports play a large role for land-use trends. Other regions of Asia and Africa belong to the ‘movers’, where high population growth is rather the main driver.

GHG emissions per unit of land also increased recently in tropical regions, as a portion of deforestation activities moved into carbon-dense rainforests. In Latin America, land-use and management CO₂ emissions grew from 1990 to 2010 (figure 15) due to high continuous Amazon deforestation rates until the mid-2000s alongside accumulating legacy emissions (INPE 2020). However, deforestation rates subsequently decreased until 2018 following government initiatives and international moratoria (Nepstad *et al* 2014). This trend in emissions is likely

to reverse past our time period of analysis, as the 2019 and 2020 seasons saw the highest Amazon deforestation rates since 2008 (Silva Junior *et al* 2021). In other regions, emission intensity increases are often due to an overall increase in agricultural intensification, such as fertiliser application. The higher emission intensity for both land use CO₂ and agricultural emissions is the cost for requiring less land per unit of production, which becomes evident in almost all regions.

Global diets are a key driver of production per capita, and thus land pressure and AFOLU emissions. As per capita incomes rise and populations urbanise, traditional diets that emphasise starchy foods, legumes and vegetables transition towards energy-intensive products such as refined sugars and fats, oils and meat (Tilman and Clark 2014). At a certain point in national development, diets thus override population growth as the main driver of

AFOLU emissions (Kastner *et al* 2012). Over the last few decades, low- and middle-income countries such as India, Brazil, Egypt, Mexico and South Africa have experienced such a rapid dietary ‘westernisation’ (Pathak *et al* 2010, Vermeulen *et al* 2012, De Carvalho *et al* 2013, Popkin 2015). Another driver of higher food requirements per capita is food waste, the amounts of which increased more or less continuously since the 1960s in all regions but Europe (Porter and Reay 2016). Globally, 25%–30% of food produced is lost, in particular at the consumer stage in developed countries, and in the production, harvesting and distribution stages in less developed countries (Porter and Reay 2016, IPCC 2019). In other words, a significant fraction of the world’s agricultural area is used annually to produce food that is wasted.

Overall, the AFOLU sector contributes to one quarter of global GHG emissions and the Paris Agreement must include mitigation efforts from this sector. AFOLU emissions were rather constant between 1990 and the early 2000s, despite continuous population growth and higher agricultural production per capita in most regions. The key counteracting process was less land required per unit of agricultural production due to agricultural intensification. Starting in 2001, however, AFOLU emissions increased again due to the clearing of pristine, carbon-dense forests. Tropical regions across all continents cause the majority of AFOLU emissions, with increasing emissions in Latin America and Southeast Asia clearly linked to global supply chains. These trends do not appear to be stabilising, underlining the urgency of interventions at all scales. Per capita emissions have also not fallen below 0.5 tCO₂eq in any region (Hong *et al* 2021), suggesting a current frontier of mitigation efforts. If there is a residual of AFOLU emissions that cannot be eliminated, carbon dioxide removal methods such as re/afforestation and biomass plantations with carbon capture and storage would be required to meet stringent climate targets, further putting pressure on global land resources (Allen *et al* 2018).

4. Conclusions

Global GHG emissions have continued their steady rise, following over a century and a half of growth. Emissions have risen across sectors and subsectors, in electricity production, from industrial sources, land-use and management, and transport, through to comparatively small sources such as fugitive emissions, waste burning and aviation. Among the major emitting regions, recent trends show a picture of stable emissions in North America and modest declines in Europe, as fuel switching from coal to gas and the ramp up of renewables start to take hold. The huge emissions growth in Eastern Asia (China) is now also slowing due to fewer coal power additions in recent years. Together these trends led to a dampening of growth in 2010–2018, compared to previous decades.

As emerging regions—Africa, Southern Asia, and South East Asia—are now poised to accelerate economic growth and establish high emitting infrastructures, it remains unclear whether a global peak in greenhouse gases will be reached soon. Regardless, recent growth has locked in a large body of infrastructure that will continue driving emissions into the future, in the absence of stringent climate policy or early retirement.

Across sectors, there is a growing demand for the products and services that underpin global emissions. In part this is due to the physical expansion of economies worldwide, with more infrastructures, vehicles, buildings, supply chains and other material stocks being put into place that demand energy for their production and use. Unfortunately, prevailing consumption patterns have also tended to aggravate energy use and emissions, with the long-term trend led by developed regions. Residential buildings have grown larger, have fewer inhabitants, and are heated and cooled to higher comfort standards. Motor vehicles, too, have grown in size and are driven over greater distances. Diets rich in meat and refined products, internationally sourced, are globalising and replacing traditional and seasonal produce. Regional and local contexts account for much variation, and there remains a chasm between the consumption levels of the global North and the South, the poor and the rich (Hubacek *et al* 2017, Oswald *et al* 2020, Wiedmann *et al* 2020). Nonetheless, the overall trend tracks towards westernised and highly unsustainable norms and patterns of consumption, for a small but growing global population.

Decarbonisation gains from improvements in energy efficiency and switching towards lower-carbon services across different sectors have been largely wiped out by increases in demand (or in some cases a trend towards higher carbon intensities). One exception is energy systems emissions in Europe, where a combination of stable demand, energy efficiency improvements, fuel switching and a scale up of renewables has led to an absolute decline in emissions. Other regions and sectors have deepened their reliance on inefficient, carbon-intensive infrastructures and production patterns. The continued failure to decarbonise transport, and the recent expansion of anthropogenic land-use into tropical rainforests, are two notable examples. There are huge unexploited mitigation potentials to be gained from avoiding these and other highly carbon-intensive activities, including by adopting the best available technologies and practices across sectors.

The energy systems, industry, buildings, transport and AFOLU sectors are deeply interconnected. Important linkages are electrification and heating, which ties emissions in the building and industry sectors upstream to energy systems, and material use, which ties embodied emissions in buildings to the industry sector. Following the

general trend of electrification, which has yet to occur at scale in the transport sector, energy system decarbonisation will further increase in importance. Yet if the industry sector lags behind in electrification and the decarbonisation of process emissions (Davis *et al* 2018), it may become the primary source of indirect emissions embodied in the capital stocks of other sectors. Indeed, GHG emissions embodied in buildings and infrastructure, machinery and transport equipment already exceed 50% of their present carbon footprint (Chen *et al* 2018). Multi-sector and integrated policies are therefore crucial for meeting the mitigation challenge.

Overall, sectoral trends reveal limited progress towards decarbonisation. The prominent global pattern is a continuation of underlying drivers with few signs of emerging limits to demand, nor of a deep shift towards the delivery of low and zero carbon services across sectors. The main gap in knowledge is how rapid technological transitions, demand management and alternative economic models could be implemented to mitigate these persistent and powerful upward drivers. Linked to this is the question of how the physical material throughput of economies can be reduced without jeopardising economic and social well-being. Above all, there is a neglect of research on transitions towards even more unsustainable technologies and practices (Antal *et al* 2020). Climate mitigation cannot be achieved if status-quo trends continue, nor if low-carbon technologies and practices are left to gradually phase-in on an uneven playing field. Meeting the Paris Agreement goals of 1.5 °C and 2 °C requires policies that ensure sustainable land-use practices, limit excessive demand, and actively phase out fossil fuels.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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ORCID iDs

William F Lamb  <https://orcid.org/0000-0003-3273-7878>

Thomas Wiedmann  <https://orcid.org/0000-0002-6395-8887>

Dominik Wiedenhofer  <https://orcid.org/0000-0001-7418-3477>

Shonali Pachauri  <https://orcid.org/0000-0001-8138-3178>

Raphael Slade  <https://orcid.org/0000-0002-5297-4224>

Laixiang Sun  <https://orcid.org/0000-0002-7784-7942>

Hancheng Dai  <https://orcid.org/0000-0003-4251-4707>

Jan Minx  <https://orcid.org/0000-0002-2862-0178>

References

- Allen M *et al* 2018 Summary for policymakers *Global Warming of 1.5°C: An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-industrial Levels and Related Global Greenhouse Gas Emissions Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change* (Cambridge: Cambridge University Press)
- Alova G 2020 A global analysis of the progress and failure of electric utilities to adapt their portfolios of power-generation assets to the energy transition *Nat. Energy* **5** 920–27
- Alvarez R A *et al* 2018 Assessment of methane emissions from the U.S. oil and gas supply chain *Science* **361** 186–8
- Andrew R M 2020 A comparison of estimates of global carbon dioxide emissions from fossil carbon sources *Earth Syst. Sci. Data* **12** 1437–65
- Antal M, Mattioli G and Rattle I 2020 Let's focus more on negative trends: a comment on the transitions research agenda *Environ. Innovation Societal Transitions* **34** 359–62
- Austin K G, Schwantes A, Gu Y and Kasibhatla P S 2019 What causes deforestation in Indonesia? *Environ. Res. Lett.* **14** 24007
- Bastian A, Börjesson M and Eliasson J 2016 Explaining 'peak car' with economic variables: a comment *Transp. Res. A* **88** 236–50
- Blanco G, Gerlagh R, Suh S and Barrett J 2014 Drivers, trends and mitigation *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed O Edenhofer *et al* (Cambridge: Cambridge University Press) pp 351–412
- Bruckner T, Bashmakov I A, Mulugetta Y and Chum H 2014 Energy systems *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed O Edenhofer *et al* (Cambridge: Cambridge University Press) pp 527–32
- Bruns S B, Moneta A and Stern D I 2019 Estimating the economy-identified structural vector autoregressions

- Burke P J, Shahiduzzaman M and Stern D I 2015 Carbon dioxide emissions in the short run: the rate and sources of economic growth matter *Glob. Environ. Change* **33** 109–21
- Cao X, Dai X and Liu J 2016 Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade *Energy Build.* **128** 198–213
- Cao Z, Shen L, Løvik A N, Müller D B and Liu G 2017 Elaborating the history of our cementing societies: an in-use stock perspective *Environ. Sci. Technol.* **51** 11468–75
- Chang C-P, Dong M, Sui B and Chu Y 2019 Driving forces of global carbon emissions: from time- and spatial-dynamic perspectives *Econ. Model* **77** 70–80
- Chen Z M et al 2018 Consumption-based greenhouse gas emissions accounting with capital stock change highlights dynamics of fast-developing countries *Nat. Commun.* **9** 3581
- Chini L et al 2021 Land-use harmonization datasets for annual global carbon budgets *Earth Syst. Sci. Data* (<https://doi.org/10.5194/essd-2020-388>) under review
- Christian S, Celia M A, Mauzerall D L, Bill M, Miller A R, Chen Y, Conrad M E, Darrah T H and Jackson R B 2016 Identification and characterization of high methane-emitting abandoned oil and gas well *Proc. Natl Acad. Sci. USA* **113** 13636–41
- Conchedda G and Tubiello F N 2020 Drainage of organic soils and GHG emissions: validation with country data *Earth Syst. Sci. Data* **12** 3113–37
- Corrado V and Ballarini I 2016 Refurbishment trends of the residential building stock: analysis of a regional pilot case in Italy *Energy Build.* **132** 91–106
- Creutzig F et al 2018 Towards demand-side solutions for mitigating climate change *Nat. Clim. Change* **8** 260–71
- Creutzig F, Agoston P, Goldschmidt J C, Luderer G, Nemet G and Pietzcker R C 2017 The underestimated potential of solar energy to mitigate climate change *Nat. Energy* **2** 17140
- Creutzig F, Bren d'Amour C, Weddige U, Fuss S, Beringer T, Gläser A, Kalkuhl M, Steckel J C, Radebach A and Edenhofer O 2019 Assessing human and environmental pressures of global land-use change 2000–2010 *Glob. Sustain.* **2** 1–17
- Creutzig F, Fernandez B, Haberl H, Khosla R, Mulugetta Y and Seto K C 2016 Beyond technology: demand-side solutions for climate change mitigation *Annu. Rev. Environ. Resour.* **41** 173–98
- Creutzig F, Jochem P, Edelenbosch O Y, Mattauca L, van Vuuren D P, McCollum D and Minx J 2015 Transport: a roadblock to climate change mitigation? *Science* **350** 911–2
- Crippa M, Oreggioni G, Guizzardi D, Muntean M, Schaaf E, Lo Vullo E, Solazzo E, Monforti-Ferrario F, Olivier J G J and Vignati E 2019 *Fossil CO₂ and GHG Emissions of All World Countries—2019 Report* (Luxembourg)
- Daiooglou V, van Ruijven B J and van Vuuren D P 2012 Model projections for household energy use in developing countries *Energy* **37** 601–15
- Dargay J, Gately D and Sommer M 2007 Vehicle ownership and income growth, worldwide: 1960–2030 *Energy J.* **28** 143–70
- Davis S J et al 2018 Net-zero emissions energy systems *Science* **360** eaas9793
- De Carvalho A M, César C L G, Fisberg R M and Marchioni D M L 2013 Excessive meat consumption in Brazil: diet quality and environmental impacts *Public Health Nutr.* **16** 1893–9
- de la Rue du Can S, Price L and Zwickel T 2015 Understanding the full climate change impact of energy consumption and mitigation at the end-use level: a proposed methodology for allocating indirect carbon dioxide emissions *Appl. Energy* **159** 548–59
- Deetman S, Marinova S, van der Voet E, van Vuuren D P, Edelenbosch O and Heijungs R 2020 Modelling global material stocks and flows for residential and service sector buildings towards 2050 *J. Cleaner Prod.* **245** 118658
- Deutch J 2017 Decoupling economic growth and carbon emissions *Joule* **1** 3–5
- Dong K, Hochman G and Timilsina G R 2020 Do drivers of CO₂ emission growth alter overtime and by the stage of economic development? *Energy Policy* **140** 111420
- Dong K, Jiang H, Sun R and Dong X 2019 Driving forces and mitigation potential of global CO₂ emissions from 1980 through 2030: evidence from countries with different income levels *Sci. Total Environ.* **649** 335–43
- Dorband I I, Jakob M and Steckel J C 2020 Unraveling the political economy of coal: insights from Vietnam *Energy Policy* **147** 111860
- Dyrstad J M, Skonhøft A, Christensen M Q and Ødegaard E T 2019 Does economic growth eat up environmental improvements? Electricity production and fossil fuel emission in OECD countries 1980–2014 *Energy Policy* **125** 103–9
- EC 2019 *EU Transport in figures 2019* (European Commission) (available at: <https://op.europa.eu/en/publication-detail/-/publication/f0f3e1b7-ee2b-11e9-a32c-01aa75ed71a1>)
- Edenhofer O, Steckel J C, Jakob M and Bertram C 2018 Reports of coal's terminal decline may be exaggerated *Environ. Res. Lett.* **13** 1–9
- Eggimann S, Usher W, Eyre N and Hall J W 2020 How weather affects energy demand variability in the transition towards sustainable heating *Energy* **195** 116947
- Ellsworth-Krebs K 2020 Implications of declining household sizes and expectations of home comfort for domestic energy demand *Nat. Energy* **5** 20–25
- FAO 2019 Food and agriculture organisation of the United Nations: FAOSTAT database (available at: <http://faostat.fao.org/>)
- Feng K 2019 Drivers of peak and decline *Nat. Clim. Change* **9** 188–9
- Feng K, Davis S J, Sun L and Hubacek K 2015 Drivers of the US CO₂ emissions 1997–2013 *Nat. Commun.* **6** 7714
- Feng K, Davis S J, Sun L and Hubacek K 2016 Correspondence: reply to 'Reassessing the contribution of natural gas to US CO₂ emission reductions since 2007' *Nat. Commun.* **7** 10693
- Figuerola M, Lah O, Fulton L M, McKinnon A and Tiwari G 2014 Energy for transport *Annu. Rev. Environ. Resour.* **39** 295–325
- Fischedick M et al 2014 *Industry Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed O Edenhofer et al (Cambridge: Cambridge University Press) pp 739–810
- Fishman T, Schandl H and Tanikawa H 2016 Stochastic analysis and forecasts of the patterns of speed, acceleration, and levels of material stock accumulation in society *Environ. Sci. Technol.* **50** 3729–37
- Friedlingstein P et al 2019 Global carbon budget 2019 *Earth Syst. Sci. Data* **11** 1783–838
- Gasser T, Crepin L, Quilcaill Y, Houghton R A, Ciaia P and Obersteiner M 2020 Historical CO₂ emissions from land use and land cover change and their uncertainty *Biogeosciences* **17** 4075–101
- Goldemberg J 2020 The evolution of the energy and carbon intensities of developing countries *Energy Policy* **137** 111060
- Gonzalez Hernandez A, Paoli L and Cullen J M 2018 How resource-efficient is the global steel industry? *Resour. Conserv. Recycl.* **133** 132–45
- Goodwin P and van Dender K 2013 'Peak car'—themes and issues *Transp. Rev.* **33** 243–54
- Gota S, Huizenga C, Peet K, Medimorec N and Bakker S 2019 Decarbonising transport to achieve Paris Agreement targets *Energy Effic.* **12** 363–86
- Grassi G et al 2018 Reconciling global-model estimates and country reporting of anthropogenic forest CO₂ sinks *Nat. Clim. Change* **8** 914–20
- Green J F, Hadden J, Hale T and Mahdavi P 2020 *Transition, Hedge, or Resist? Understanding Political and Economic Behavior toward Decarbonization in the Oil and Gas Industry* vol 2507 (available at: <https://ssrn.com/abstract=3694447>)
- Grübler A 2015 *Technology and Global Change* (Cambridge: Cambridge University Press)

- Guan D, Meng J, Reiner D M, Zhang N, Shan Y, Mi Z, Shao S, Liu Z, Zhang Q and Davis S J 2018 Structural decline in China's CO₂ emissions through transitions in industry and energy systems *Nat. Geosci.* **11** 551–5
- Gucwa M and Schäfer A 2013 The impact of scale on energy intensity in freight transportation *Transp. Res. D* **23** 41–49
- Guerra Santin O, Itard L and Visscher H 2009 The effect of occupancy and building characteristics on energy use for space and water heating in Dutch residential stock *Energy Build.* **41** 1223–32
- Gutowski T G, Sahni S, Allwood J M, Ashby M F and Worrell E 2013 The energy required to produce materials: constraints on energy-intensity improvements, parameters of demand *Phil. Trans. R. Soc. A* **371** 20120003
- Haberl H et al 2020 A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part II: synthesizing the insights *Environ. Res. Lett.* **15** 065003
- Hansen A and Nielsen K B 2017 *Cars, Automobility and Development in Asia: Wheels of Change* ed A Hansen and K B Nielsen (London: Taylor and Francis)
- Hansis E, Davis S J and Pongratz J 2015 Relevance of methodological choices for accounting of land use change carbon fluxes *Glob. Biogeochem. Cycles* **29** 1230–46
- Hertwich E G et al 2019 Material efficiency strategies to reducing greenhouse gas emissions associated with buildings, vehicles, and electronics—a review *Environ. Res. Lett.* **14** 43004
- Hertwich E G 2021 Increased carbon footprint of materials production driven by rise in investments *Nat. Geosci.* **14** 151–5
- Hmiel B et al 2020 Preindustrial 14CH₄ indicates greater anthropogenic fossil CH₄ emissions *Nature* **578** 409–12
- Höhne N et al 2020 Emissions: world has four times the work or one-third of the time *Nature* **579** 25–28
- Hong C, Burney J A, Pongratz J, Nabel J E M S, Mueller N D, Jackson R B and Davis S J 2021 Global and regional drivers of land-use emissions 1961–2017 *Nature* **589** 554–61
- Houghton R A and Nassikas A A 2017 Global and regional fluxes of carbon from land use and land cover change 1850–2015 *Glob. Biogeochem. Cycles* **31** 456–72
- Hubacek K, Baiocchi G, Feng K, Sun L and Xue J 2017 Global carbon inequality *Energy Ecol. Environ.* **2** 361–9
- Hubacek K, Feng K, Minx J C, Pfister S and Zhou N 2014 Teleconnecting Consumption to Environmental Impacts at Multiple Spatial Scales *J. Ind. Ecol.* **18** 7–9
- Huebner G M and Shipworth D 2017 All about size? The potential of downsizing in reducing energy demand *Appl. Energy* **186** 226–33
- Huo T, Cai W, Ren H, Feng W, Zhu M, Lang N and Gao J 2019 China's building stock estimation and energy intensity analysis *J. Cleaner Prod.* **207** 801–13
- Hurttt G C et al 2020 *Harmonization of Global Land Use Change and Management for the Period 850–2100 (LUH2) for CMIP6* vol 13
- Idahosa L O, Marwa N N and Akotey J O 2017 Energy (electricity) consumption in South African hotels: a panel data analysis *Energy Build.* **156** 207–17
- IEA 2019a *Fuel Economy in Major Car Markets: Technology and Policy Drivers 2005–2017* (available at: www.iea.org/reports/fuel-economy-in-major-car-markets)
- IEA 2019b *Global EV Outlook 2019* (Paris: International Energy Agency) (available at: www.iea.org/reports/global-ev-outlook-2019)
- IEA 2020a *CO₂ Emissions from Fossil Fuel Combustion* (Paris) (available at: <https://webstore.iea.org/co2-emissions-from-fuel-combustion-2019-highlights>)
- IEA 2020b *Energy efficiency indicators* (Paris: International Energy Agency) (available at: www.iea.org/reports/energy-efficiency-indicators)
- IEA 2020c *World Energy Balances* (Paris: International Energy Agency) (<https://doi.org/10.5257/iea/web/2013>)
- IEA 2020d *World Energy Outlook* (Paris) (available at: www.iea.org/topics/world-energy-outlook)
- IMF 2020 *World Economic Outlook, October 2020: A Long and Difficult Ascent* (available at: www.imf.org)
- INPE 2020 *Terrabrasilis* (available at: <http://terrabrasilis.dpi.inpe.br>)
- IPCC 2019 Summary for Policymakers *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems* ed P R Shukla et al accepted
- IRP 2020 *Resource Efficiency and Climate Change: Material Efficiency Strategies for a Low-Carbon Future* ed E Hertwich, R Lifset, S Pauliuk and N Heeren (Nairobi: A report of the International Resource Panel. United Nations Environment Program)
- ITF 2019 *ITF Transport Outlook 2019* (Organisation for Economic Cooperation and Development (OECD), International Transport Forum (ITF)) (available at: www.oecd-ilibrary.org/transport/itf-transport-outlook-2019_transport-outlook-en-2019-en)
- Jackson R B, Friedlingstein P, Andrew R M, Canadell J G, Le Quéré C and Peters G P 2019 Persistent fossil fuel growth threatens the Paris Agreement and planetary health *Environ. Res. Lett.* **14** 121001
- Jakob M, Flachsland C, Christoph J and Urpelainen J 2020 Energy research & social science actors, objectives, context : a framework of the political economy of energy and climate policy applied to India, Indonesia, and Vietnam *Energy Res. Soc. Sci.* **70** 101775
- Janssens-Maenhout G et al 2019 EDGAR v4.3.2 global atlas of the three major greenhouse gas emissions for the period 1970–2012 *Earth Syst. Sci. Data* **11** 959–1002
- Jia G et al 2019 Land–climate interactions *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems* ed P R Shukla et al pp 131–248 accepted
- Jiang X and Guan D 2016 Determinants of global CO₂ emissions growth *Appl. Energy* **184** 1132–41
- Jiborn M, Kulionis V and Kander A 2020 Consumption versus technology: drivers of global carbon emissions 2000–2014 *Energies* **13** 339
- Kastner T, Rivas M J I, Koch W and Nonhebel S 2012 Global changes in diets and the consequences for land requirements for food *Proc. Natl Acad. Sci. USA* **109** 6868–72
- Kaya Y 1990 *Impact of Carbon Dioxide Emission Control on GNP Growth: Interpretation of Proposed Scenarios* (Paris: IPCC Energy and Industry Subgroup, Response Strategies Working Group)
- Kerimray A et al 2017 Coal use for residential heating: patterns, health implications and lessons learned *Energy Sustain. Dev.* **40** 19–30
- Kerr N and Winkler M 2020 Household investment in home energy retrofit: a review of the evidence on effective public policy design for privately owned homes *Renew. Sustain. Energy Rev.* **123** 109778
- Khanna M and Rao N D 2009 Supply and demand of electricity in the developing world *Annu. Rev. Resour. Econ.* **1** 567–96
- Kharecha P A and Sato M 2019 Implications of energy and CO₂ emission changes in Japan and Germany after the Fukushima accident *Energy Policy* **132** 647–53
- Kirschke S et al 2013 Three decades of global methane sources and sinks *Nat. Geosci.* **6** 813–23
- Krausmann F, Lauk C, Haas W and Wiedenhofer D 2018 From resource extraction to outflows of wastes and emissions: the socioeconomic metabolism of the global economy, 1900–2015 *Glob. Environ. Change* **52** 131–40
- Krausmann F, Wiedenhofer D, Lauk C, Haas W, Tanikawa H, Fishman T, Miatto A, Schandl H and Haberl H 2017 Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use *Proc. Natl Acad. Sci.* **114** 1880–5

- Kuhnimhof T, Zumkeller D and Chlond B 2013 Who made peak car, and how? A breakdown of trends over four decades in four countries *Transp. Rev.* **33** 325–42
- Lamb W F and Minx J C 2020 The political economy of national climate policy: architectures of constraint and a typology of countries *Energy Res. Soc. Sci.* **64** 101429
- Lanau M, Liu G, Kral U, Wiedenhofer D, Keijzer E, Yu C and Ehler C 2019 Taking stock of built environment stock studies: progress and prospects *Environ. Sci. Technol.* **53** 8499–515
- Le Quéré C et al 2020 Temporary reduction in daily global CO₂ emissions during the COVID-19 forced confinement *Nat. Clim. Change* **10** 647–54
- Le Quéré C, Korsbakken J I, Wilson C, Tosun J, Andrew R, Andres R J, Canadell J G, Jordan A, Peters G P and van Vuuren D P 2019 Drivers of declining CO₂ emissions in 18 developed economies *Nat. Clim. Change* **9** 213–7
- Lee D S et al 2021 The contribution of global aviation to anthropogenic climate forcing for 2000–2018 *Atmos. Environ.* **244** 117834
- Lelieveld J, Klingmüller K, Pozzer A, Burnett R T, Haines A and Ramanathan V 2019 Effects of fossil fuel and total anthropogenic emission removal on public health and climate *Proc. Natl Acad. Sci. USA* **116** 7192–7
- Lenzen M, Li M, Id A M, Pomponi F, Sun Y, Wiedmann T, Faturay F, Fry J, Id B G and Geschke A 2020 Global socio-economic losses and environmental gains from the coronavirus pandemic *PLoS One* **15** e0235654
- Li J, Zhang Y, Tian Y, Cheng W, Yang J, Xu D, Wang Y, Xie K and Ku A Y 2020 Reduction of carbon emissions from China's coal-fired power industry: insights from the province-level data *J. Cleaner Prod.* **242** 118518
- Lin C, Liu G and Müller D B 2016 Characterizing the role of built environment stocks in human development and emission growth *Resour. Conserv. Recycl.* **123** 67–72
- Liobikiene G and Butkus M 2019 Scale, composition, and technique effects through which the economic growth, foreign direct investment, urbanization, and trade affect greenhouse gas emissions *Renew. Energy* **132** 1310–22
- Liu D, Guo X and Xiao B 2019 What causes growth of global greenhouse gas emissions? Evidence from 40 countries *Sci. Total Environ.* **661** 750–66
- Liu G, Bangs C E and Müller D B 2013 Stock dynamics and emission pathways of the global aluminium cycle *Nat. Clim. Change* **3** 338–42
- Liu G, Li X, Tan Y and Zhang G 2020a Building green retrofit in China: policies, barriers and recommendations *Energy Policy* **139** 117834
- Liu G, Tan Y and Li X 2020b China's policies of building green retrofit: a state-of-the-art overview *Build. Environ.* **169** 106554
- Liu Z et al 2020c Near-real-time monitoring of global CO₂ emissions reveals the effects of the COVID-19 pandemic *Nat. Commun.* **11** 5172
- Lucon O et al 2014 Buildings *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* vol 33 ed O Edenhofer et al (Cambridge: Cambridge University Press) pp 1–66
- Malik A, Lan J and Lenzen M 2016 Trends in global greenhouse gas emissions from 1990 to 2010 *Environ. Sci. Technol.* **50** 4722–30
- Mardani A, Streimikiene D, Cavallaro F, Loganathan N and Khoshnoudi M 2019 Carbon dioxide (CO₂) emissions and economic growth: a systematic review of two decades of research from 1995 to 2017 *Sci. Total Environ.* **649** 31–49
- Marin G and Mazzanti M 2019 Structural change and the environment
- Marinova S, Deetman S, van der Voet E and Daioglou V 2020 Global construction materials database and stock analysis of residential buildings between 1970–2050 *J. Cleaner Prod.* **247** 119146
- Maruyama N and Eckelman M J 2009 Long-term trends of electric efficiencies in electricity generation in developing countries *Energy Policy* **37** 1678–86
- Mattioli G, Roberts C, Steinberger J and Brown A 2020 The political economy of car dependence: a systems of provision approach *Energy Res. Soc. Sci.* **66** 101846
- McKinnon A C 2016 Freight transport deceleration: its possible contribution to the decarbonisation of logistics *Transp. Rev.* **36** 418–36
- Meyfroidt P, Rudel T K and Lambin E F 2010 Forest transitions, trade, and the global displacement of land use *Proc. Natl Acad. Sci. USA* **107** 20917–22
- Milovanoff A, Posen I D and MacLean H L 2020 Electrification of light-duty vehicle fleet alone will not meet mitigation targets *Nat. Clim. Change* **10** 1102–7
- Moe E 2015 *Renewable Energy Transformation or Fossil Fuel Backlash—Vested Interests in the Political Economy* (London: Palgrave Macmillan)
- Mohlin K, Bi A, Brooks S, Camuzeaux J and Stoerk T 2019 Turning the corner on US power sector CO₂ emissions—a 1990–2015 state level analysis *Environ. Res. Lett.* **14** 084049
- Mohammed A, Li Z, Olushola Arowolo A, Su H, Deng X, Najmuddin O and Zhang Y 2019 Driving factors of CO₂ emissions and nexus with economic growth, development and human health in the top ten emitting countries *Resour. Conserv. Recycl.* **148** 157–69
- Moura M C P, Smith S J and Belzer D B 2015 120 years of U.S. residential housing stock and floor space *PLoS One* **10** 1–18
- Nejat P, Jomehzadeh F, Taheri M M, Gohari M and Muhd M Z 2015 A global review of energy consumption, CO₂ emissions and policy in the residential sector (with an overview of the top ten CO₂ emitting countries) *Renew. Sustain. Energy Rev.* **43** 843–62
- Nepstad D et al 2014 Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains *Science* **344** 1118–23
- Newman AO P 2020 COVID, CITIES and CLIMATE: historical precedents and potential transitions for the new economy *Urban Sci.* **4** 32
- Nie H and Kemp R 2014 Index decomposition analysis of residential energy consumption in China: 2002–2010 *Appl. Energy* **121** 10–9
- Oda J, Akimoto K, Tomoda T, Nagashima M, Wada K and Sano F 2012 International comparisons of energy efficiency in power, steel, and cement industries *Energy Policy* **44** 118–29
- Ortega-Ruiz G, Mena-Nieto A and García-Ramos J E 2020 Is India on the right pathway to reduce CO₂ emissions? Decomposing an enlarged Kaya identity using the LMDI method for the period 1990–2016 *Sci. Total Environ.* **737** 139638
- Oswald Y, Owen A and Steinberger J K 2020 Large inequality in international and intranational energy footprints between income groups and across consumption categories *Nat. Energy* **5** 231–9
- Pan X, Uddin M K, Ai B, Pan X and Saima U 2019 Influential factors of carbon emissions intensity in OECD countries: evidence from symbolic regression *J. Cleaner Prod.* **220** 1194–201
- Parker S and Bhatti M I 2020 Dynamics and drivers of per capita CO₂ emissions in Asia *Energy Econ.* **89** 104798
- Pathak H, Jain N, Bhatia A, Patel J and Aggarwal P K 2010 Carbon footprints of Indian food items *Agric. Ecosyst. Environ.* **139** 66–73
- Pauliuk S, Heeren N, Berrill P, Fishman T, Nistad A, Tu Q, Wolfram P and Hertwich E 2020 Global scenarios of resource and emissions savings from systemic material efficiency in buildings and cars *Nat. Res. preprint* (<https://doi.org/10.21203/rs.3.rs-93217/v1>)
- Pauliuk S, Wang T and Müller D B 2013 Steel all over the world: estimating in-use stocks of iron for 200 countries *Resour. Conserv. Recycl.* **71** 22–30

- Pearson T R H, Brown S, Murray L and Sidman G 2017 Greenhouse gas emissions from tropical forest degradation: an underestimated source *Carbon Balance Manage.* **12** 3
- Peters G P, Andrew R M, Canadell J G, Friedlingstein P, Jackson R B, Korsbakken J I, Le Quéré C and Pregon A 2020 Carbon dioxide emissions continue to grow amidst slowly emerging climate policies *Nat. Clim. Change* **10** 2–10
- Peters G P, Andrew R M, Canadell J G, Fuss S, Jackson R B, Korsbakken J I, Le Quéré C and Nakicenovic N 2017 Key indicators to track current progress and future ambition of the Paris Agreement *Nat. Clim. Change* **7** 118–22
- Peters G P, Minx J C, Weber C L and Edenhofer O 2011 Growth in emission transfers via international trade from 1990 to 2008 *Proc. Natl Acad. Sci. USA* **108** 8903–8
- Plank B, Eisenmenger N, Schaffartzik A and Wiedenhofer D 2018 International trade drives global resource use: a structural decomposition analysis of raw material consumption from 1990–2010 *Environ. Sci. Technol.* **52** 4190–8
- Pojani D and Stead D 2017 *The Urban Transport Crisis in Emerging Economies* (Cham: Springer)
- Pongratz J and Caldeira K 2012 Attribution of atmospheric CO₂ and temperature increases to regions: importance of preindustrial land use change *Environ. Res. Lett.* **7** 034001
- Popkin B M 2015 Nutrition transition and the global diabetes epidemic *Curr. Diabetes Rep.* **15** 1–8
- Porter S D and Reay D S 2016 Addressing food supply chain and consumption inefficiencies: potential for climate change mitigation *Reg. Environ. Change* **16** 2279–90
- Quéré L C et al 2018 Global carbon budget 2018 *Earth Syst. Sci. Data* **10** 2141–94
- Rauner S, Bauer N, Dirnaichner A, Dingenen Van R, Mutel C and Luderer G 2020 Coal-exit health and environmental damage reductions outweigh economic impacts *Nat. Clim. Change* **10** 308–12
- Rausch S and Schwerin H 2018 *Does Higher Energy Efficiency Lower Economy-Wide Energy Use?* (CER-ETH—Center of Economic Research at ETH Zurich)
- Reck B K, Chambon M, Hashimoto S and Graedel T E 2010 Global stainless steel cycle exemplifies China's rise to metal dominance *Environ. Sci. Technol.* **44** 3940–6
- Rissman J et al 2020 Technologies and policies to decarbonize global industry: review and assessment of mitigation drivers through 2070 *Appl. Energy* **266** 114848
- Rodrigues J F D, Wang J, Behrens P and De Boer P 2020 Drivers of CO₂ emissions from electricity generation in the European Union 2000–2015 *Renew. Sustain. Energy Rev.* **133** 110104
- Ross M L, Hazlett C and Mahdavi P 2017 Global progress and backsliding on gasoline taxes and subsidies *Nat. Energy* **2** 16201
- Roy B and Schaffartzik A 2021 Talk renewables, walk coal: the paradox of India's energy transition *Ecol. Econ.* **180** 106871
- Sanchez L F and Stern D I 2016 Drivers of industrial and non-industrial greenhouse gas emissions *Ecol. Econ.* **124** 17–24
- Saunio M et al 2020 The global methane budget 2000–2017 *Earth Syst. Sci. Data* **12** 1561–623
- Schäfer A, Heywood J B, Jacoby H D and Waitz I A 2009 *Transportation in a Climate-Constrained World* (Cambridge, MA: MIT Press)
- Schaffartzik A, Mayer A, Eisenmenger N and Krausmann F 2016 Global patterns of metal extractivism, 1950–2010: providing the bones for the industrial society's skeleton *Ecol. Econ.* **122** 101–10
- Schierhorn F, Kastner T, Kuemmerle T, Meyfroidt P, Kurganova I, Prishchepov A V, Erb K-H, Houghton R A and Müller D 2019 Large greenhouse gas savings due to changes in the post-Soviet food systems *Environ. Res. Lett.* **14** 65009
- Schulze M, Nehler H, Ottosson M and Thollander P 2016 Energy management in industry—a systematic review of previous findings and an integrative conceptual framework *J. Cleaner Prod.* **112** 3692–708
- Serrano S, Ürge-Vorsatz D, Barreneche C, Palacios A and Cabeza L F 2017 Heating and cooling energy trends and drivers in Europe *Energy* **119** 425–34
- Shan Y, Ou J, Wang D, Zeng Z, Zhang S, Guan D and Hubacek K 2020 Impacts of COVID-19 and fiscal stimuli on global emissions and the Paris Agreement *Nat. Clim. Change* **11** 200–6
- Shearer C, Tong D, Fofrich R and Davis S J 2020 Committed emissions of the U.S. power sector, 2000–2018 *AGU Adv.* **1** e2020AV000162
- Silva Junior C H L et al 2021 The Amazon's deforestation rate in 2020 is projected to be the greatest of the decade *Nat. Sustain.* **5** 144–5
- Sims R et al 2014 *Transport Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed O Edenhofer et al (Cambridge: Cambridge University Press) pp 599–670
- SLoCaT 2018 *Transport and Climate Change Global Status Report 2018*
- Smidfelt Rosqvist L and Hiselius L W 2016 Online shopping habits and the potential for reductions in carbon dioxide emissions from passenger transport *J. Cleaner Prod.* **131** 163–9
- Smith P et al 2014 Agriculture, forestry and other land use (AFOLU) *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed O Edenhofer et al (Cambridge: Cambridge University Press) pp 811–922
- Spencer T et al 2017 Tracking sectoral progress in the deep decarbonisation of energy systems in Europe *Energy Policy* **110** 509–17
- Steckel J C, Edenhofer O and Jakob M 2015 Drivers for the renaissance of coal *Proc. Natl Acad. Sci. USA* **112** E3775–81
- Steckel J C, Hilaire J, Jakob M and Edenhofer O 2020 Coal and carbonization in sub-saharan Africa *Nat. Clim. Change* **10** 83–88
- Stern D I 2011 The role of energy in economic growth *Ann. N. Y. Acad. Sci.* **1219** 26–51
- Stern D I 2020 How large is the economy-wide rebound effect? *Energy Policy* **147** 111870
- Stern D I, Gerlagh R and Burke P J 2017 Modeling the emissions–income relationship using long-run growth rates *Environ. Dev. Econ.* **22** 699–724
- Stern D 2019 *Energy and economic growth* *Routledge Handbook of Energy Economics* ed U Soytaş and R Sarı (London: Routledge)
- Stokes L C and Breetz H L 2018 Politics in the U.S. energy transition: case studies of solar, wind, biofuels and electric vehicles policy *Energy Policy* **113** 76–86
- Taiebat M and Xu M 2019 Synergies of four emerging technologies for accelerated adoption of electric vehicles: shared mobility, wireless charging, vehicle-to-grid, and vehicle automation *J. Cleaner Prod.* **230** 794–7
- Talaei A, Ahiduzzaman M and Kumar A 2018 Assessment of long-term energy efficiency improvement and greenhouse gas emissions mitigation potentials in the chemical sector *Energy* **153** 231–47
- Thoday K, Benjamin P, Gan M and Puzzolo E 2018 The mega conversion program from kerosene to LPG in Indonesia: lessons learned and recommendations for future clean cooking energy expansion *Energy Sustain. Dev.* **46** 71–81
- Tian H et al 2020 A comprehensive quantification of global nitrous oxide sources and sinks *Nature* **586** 248–56
- Tilman D and Clark M 2014 Global diets link environmental sustainability and human health *Nature* **515** 518–22
- UNDESA 2019 2019 revision of world population prospects (available at: <https://population.un.org/wpp/>)
- UNEP 2017 *The Emissions Gap Report 2017* (Nairobi: United Nations Environment Program) (available at: www.unep.org/pdf/2012gapreport.pdf)
- UNWTO 2019 *Transport-Related CO₂ Emissions of the Tourism Sector—Modelling Results* (United Nations World Tourism

- Organisation) (available at: www.e-unwto.org/doi/book/10.18111/9789284416660)
- Ürge-Vorsatz D, Cabeza L F, Serrano S, Barreneche C and Petrichenko K 2015 Heating and cooling energy trends and drivers in buildings *Energy* **41** 85–98
- Ürge-Vorsatz D, Khosla R, Bernhardt R, Chan Y C, Vérez D, Hu S and Cabeza L F 2020 Advances toward a net-zero global building sector *Annu. Rev. Environ. Resour.* **45** 227–69
- van der Werf G R *et al* 2017 Global fire emissions estimates during 1997–2016 *Earth Syst. Sci. Data* **9** 697–720
- Vasconcelos A, Bernasconi P, Guidotti V, Silgueiro V, Valdiones A, Carvalho T, Bellfield H and Pinto L F G 2020 *Illegal Deforestation and Brazilian Soy Exports: The Case of Mato Grosso* (available at: www.icv.org.br/website/wp-content/uploads/2020/06/traseissuebrief4-en.pdf)
- Vermeulen S J, Campbell B M and Ingram J S I 2012 Climate change and food systems *Annu. Rev. Environ. Resour.* **37** 195–222
- Waite M, Cohen E, Torbey H, Piccirilli M, Tian Y and Modi V 2017 Global trends in urban electricity demands for cooling and heating *Energy* **127** 786–802
- Wang J, Rodrigues J F D, Hu M, Behrens P and Tukker A 2019a The evolution of Chinese industrial CO₂ emissions 2000–2050: a review and meta-analysis of historical drivers, projections and policy goals *Renew. Sustain. Energy Rev.* **116** 109433
- Wang Q, Li S and Pisarenko Z 2020a Heterogeneous effects of energy efficiency, oil price, environmental pressure, R&D investment, and policy on renewable energy—evidence from the G20 countries *Energy* **209** 118322
- Wang Q and Zhou Y 2020 Evolution and drivers of production-based carbon emissions in China and India: differences and similarities *J. Cleaner Prod.* **277** 123958
- Wang R, Assenova V A and Hertwich E 2019b Empirical explanations of carbon mitigation during periods of economic growth *SocArXiv*
- Wang Z, Meng J and Guan D 2020b Dynamic driving forces of india's emissions from production and consumption perspectives *Earth's Futur.* **8** e2020EF001485
- Weller Z D, Hamburg S P and Von Fischer J C 2020 A national estimate of methane leakage from pipeline mains in natural gas local distribution systems *Environ. Sci. Technol.* **54** 8958–67
- Wiedenhofer D *et al* 2020 A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part I: bibliometric and conceptual mapping *Environ. Res. Lett.* **15** 063002
- Wiedenhofer D, Fishman T, Lauk C, Haas W and Krausmann F 2019 Integrating material stock dynamics into economy-wide material flow accounting: concepts, modelling, and global application for 1900–2050 *Ecol. Econ.* **156** 121–33
- Wiedenhofer D, Steinberger J K, Eisenmenger N and Haas W 2015 Maintenance and expansion: modeling material stocks and flows for residential buildings and transportation networks in the EU25 *J. Ind. Ecol.* **19** 538–51
- Wiedmann T, Lenzen M, Keyßer L T and Steinberger J K 2020 Scientists' warning on affluence *Nat. Commun.* **11** 1–10
- Wood R, Stadler K, Simas M, Bulavskaya T, Giljum S, Lutter S and Tukker A 2018 Growth in environmental footprints and environmental impacts embodied in trade: resource efficiency indicators from EXIOBASE3 *J. Ind. Ecol.* **22** 553–64
- Xin Y, Sun L and Hansen M C 2021 Biophysical and socioeconomic drivers of oil palm expansion in Indonesia *Environ. Res. Lett.* **16** 034048
- Yang J, Cai W, Ma M, Li L, Liu C, Ma X, Li L and Chen X 2020 Driving forces of China's CO₂ emissions from energy consumption based on Kaya-LMDI methods *Sci. Total Environ.* **711** 134569
- Yao C, Feng K and Hubacek K 2015 Driving forces of CO₂ emissions in the G20 countries: an index decomposition analysis from 1971 to 2010 *Ecol. Inform.* **26** 93–100
- Yu Y, Feng K and Hubacek K 2013 Tele-connecting local consumption to global land use *Glob. Environ. Change* **23** 1178–86
- Zheng X, Lu Y, Yuan J, Baninla Y, Zhang S, Stenseth N C, Hessen D O, Tian H, Obersteiner M and Chen D 2020 Drivers of change in China's energy-related CO₂ emissions *Proc. Natl Acad. Sci.* **117** 29 LP–36
- Zink T and Geyer R 2017 Circular economy rebound *J. Ind. Ecol.* **21** 593–602
- zu Ermgassen E K H J *et al* 2020 Using supply chain data to monitor zero deforestation commitments: an assessment of progress in the Brazilian soy sector *Environ. Res. Lett.* **15** 35003