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A review of successful climate change mitigation policies in major emitting economies and the potential of global replication

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ABSTRACT

This article reviews climate change mitigation policies implemented in five major emitting economies: China, the European Union, India, Japan and the United States. It analyses their historical performance in terms of energy system and greenhouse gas emissions indicators. In cases where policies aim to reduce future emissions, their target performance levels are assessed. The review centres on the sectors of electricity generation, passenger vehicles, freight transport, forestry, industry, buildings, agriculture, and oil and gas production. Most focus countries have implemented successful policies for renewable energy, fuel efficiency, electrification of passenger vehicles, and forestry. For other sectors, information is limited or very heterogeneous (e.g. buildings, appliances, agriculture) or there are few comprehensive policies in place (e.g. industry). The article further presents an explorative emissions scenario developed under the assumption that all countries will replicate both the observed trends in sector-level indicators and the trends that policies for future emissions reductions aspire to achieve. It shows that the global replication of sector progress would reduce greenhouse gas emissions by 2030 by about 20% compared to a current policies scenario. All countries analysed would overachieve the emissions reduction targets in their post-2020 climate targets. However, the resulting reduction in global emissions by 2030 would still not be sufficient to keep the world on track for a global cost-effective pathway that keeps temperature increase below 2°C. The findings of this study emphasise the need for transformative policies to keep the Paris Agreement temperature limit within reach.

1. Introduction

With the adoption of the Paris Agreement in 2015 [1], countries have committed to keeping the average global warming increase well below 2°C above pre-industrial levels and to pursuing efforts to limit it to 1.5°C to prevent dangerous impacts of climate change. Full implementation of countries' contributions to GHG emissions reduction targets under the Paris Agreement, also known as Nationally Determined Contributions (NDCs), is estimated to cover only half of the emissions reductions that

would be required under a no-policy baseline by 2030 to stay on a global least-cost pathway consistent with keeping warming levels well below 2°C [2]. Further, emissions projections suggest that many countries, including several G20 members, will not achieve their NDCs, unless they implement additional policies [3]. Current policies are projected to reduce global emissions by only a third of that necessary for a least-cost, well-below-two-degrees pathway, compared to a no-policy baseline scenario assuming no new policies are put in place from around 2005 onwards [2]. It is thus essential that national governments and other actors increase their climate change mitigation efforts.

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List of abbreviations and units

CCS	carbon capture and storage	IPCC	Intergovernmental Panel on Climate Change
CO ₂ e	carbon dioxide equivalent	kt	kilotonne = 10 ³ metric ton
EED	Energy Efficiency Directive	LULUCF	Land use, land-use change and forestry
EPBD	Energy Performance Buildings Directive	LDV	light-duty vehicle
EPA	Environmental Protection Agency	Mt	megatonne = 10 ⁶ metric ton
EU	European Union	NDC	Nationally Determined Contribution
EU ETS	European Union Emissions Trading System	NYDF	New York Declaration on Forests
EV	electric vehicles	ODEX	Energy efficiency index from ODYSSEE-MURE project
FAO	Food and Agriculture Organization of the United Nations	oe	oil equivalent
GHG	greenhouse gas	PAT	Perform, Achieve, Trade
GWP	global warming potential	RE	renewable energy
HCFC	hydrochlorofluorocarbon	RPS	renewable portfolio standard
HDV	heavy-duty vehicle	SNAP	Significant New Alternatives Policy
HFC	hydrofluorocarbon	METI	Ministry of Economy, Trade and Industry of Japan
IED	Industrial Emissions Directive	UK	United Kingdom
ICCT	International Council on Clean Transportation	EIA	Energy Information Administration
IEA	International Energy Agency	VAP	Voluntary Action Plan
		yr	year

For this process, it is essential to know by how much individual countries and the world as a whole are able to reduce their GHG emissions. The official procedures established under the climate negotiations do not provide country-specific data on emissions reductions requirements. Nevertheless, governments will need such information to heighten their ambition with regard to targets.

Several studies have looked into the GHG emissions trajectories of major economies as projected by integrated assessment models for least-cost 2°C scenarios, and quantified those emissions under the assumption of minimised global aggregate economic costs [4,5]. Fekete et al., Krieglger et al. and Roelfsema et al. quantified the impact on GHG emissions reductions of a global roll-out of successful policies and transitions toward decarbonisation at national and regional levels [6–8]. Climate Action Tracker provides country-specific mitigation scenarios under scaled-up climate action, including “good practice scenarios” [9]. However, the *ex post* assessment of policy impact conducted in the aforementioned studies were either not systematically conducted or not comprehensive in terms of the coverage of countries and sectors.

This article conducts an extensive review of policies that have had an impact on GHG emissions in the past in major emitting economies and explores the potential impact on GHG emissions of replicating them globally at a similar level of ambition. The exercise presented in this article aims to investigate whether there is a correlation between policy interventions and GHG emissions reductions in the current political economy, and obtain insights into how countries could enhance mitigation action in the short-term by learning from other countries' experiences. The review looks at individual policies in the context of a sector, rather than taking a higher level, statistical approach as done by Eskander et al. [10].

This article builds on existing literature by making the policy review more comprehensive and providing an updated set of explorative scenarios. It examines implemented policies related to energy and climate change mitigation on a sector-level in key economies that are major emitters and it describes the historical performance of energy and GHG indicators influenced by such policies. Where relevant for the discussion, this article also reflects on forward-looking policies, such as those concerning renewable energy, energy efficiency targets and the goals of international initiatives. The article then presents an explorative emissions scenario devised under the assumption that all countries will follow the observed trends in sector-level indicators on energy use or GHG emissions after successful policy implementation. These quantitative results are based on the assumption that it is possible to replicate

successful sector policies and their impact observed in a few countries around the world [8]. The approach only allows regional variations in the roll-out of selected policies to occur in cases where measures are likely to come at a high public cost [11]. The underlying idea is that countries learn from each other and transfer knowledge on policy implementation between political settings, although not by direct copying of legislation [12]. An example of such policy transfers is the implementation of feed-in tariffs adjusted to local circumstances in Uganda and Thailand, based on the German experience [13].

The policy review focuses on the following five major emitting economies: China, the European Union (EU), India, Japan and the United States. Collectively, they accounted for 55% of global GHG emissions in 2018, including those caused by land use, land-use change and forestry (LULUCF) [14,15]. Besides their size in terms of emissions, criteria for selecting those countries were the relevance in global climate change politics, the potential to serve as flagships, the presence of advanced policy packages, stages of economic development, and data availability. Policies in other countries were also considered based on their importance in specific sectors (e.g. policies for energy efficiency of appliances in the Republic of Korea and LULUCF sector policies in Brazil) as well as on the findings of other policy reviews. Finally, an explorative quantitative assessment presents the calculated impact of global replication of successful sector policies on emissions at both the global level and the level of 12 major emitting countries.

2. Data and methods

The analysis consisted of two main elements: (1) the review of policies and their historical or projected impact on sector-level indicators, and (2) the explorative analysis of a GHG emissions scenario that uses the values of sector-level performance indicators achieved under successful policies and applies those indicator values to other countries around the world. The study focusses on two scenarios: the current policies scenario and the replication of successful policies scenario. The former assumes that no additional mitigation action is taken beyond currently implemented climate policies. Current policies trajectories reflect the main adopted and implemented national policies, both economy-wide and for all sectors, as defined in Kuramochi et al. [16]. The latter assumes the global replication of successful sector and sub-sector progress, implied by policies.

The analysis of sector and subsector progress and the construction of the global replication scenario consisted of the five steps illustrated in

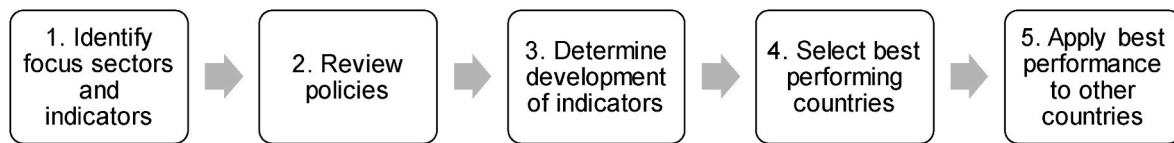


Fig. 1. Overview of the five-step approach.

Fig. 1.

The first step was to identify focus sectors and select indicators for progress in those sectors. A literature review provided insights into the importance and policy relevance of specific subsectors and areas, as well as their contribution to meeting the goals of the Paris Agreement. For example, the promotion of renewable electricity generation and the regulation of coal-fired power plants were identified as two *separate* policy areas. The policy review builds on and adds to the approach taken in Kriegler et al. and Roelfsema et al. and aims to further strengthen the evidence base on whether, and to what extent, policies implemented in the five major emitting economies have contributed to GHG emissions reductions [7,8]. Consulted sources include the Climate Policy Database and Kuramochi et al. [17,18]. The selected sectors covered 85% of global total GHG emissions in 2018 [19]: electricity generation, fossil fuel extraction, manufacturing industry, buildings, transport, F-gases (cross-sectoral), and LULUCF.

The second step was to identify existing policies per sector, per subsector and per country for each of the focus countries. Where relevant, the review was expanded to include other countries with insightful policies in specific sectors. The starting point for this review was Kuramochi et al., who compiled information on existing sector-level policies in 25 countries as of mid-2018, including the five major emitting economies that this study focuses on [20]. Another source of information was the European CD-LINKS project, which performed surveys among national policy experts in order to identify key implemented policies for GHG emissions reductions, without limiting itself to those that primarily address energy and climate issues [21]. Several other reviews and studies were also examined, including the World Energy Outlook reports, an earlier study on good practice for GHG emissions reduction policies, a report on the impact of climate change action in the short term, and the Climate Action Tracker project with GHG emissions projections under implemented policies for about 40 countries [6, 22–26]. Where required, this study complemented and updated existing studies by reviewing legislative texts. For some sectors, it was not possible to compile a comprehensive overview of policies within the scope of this study. In such cases, the review focused on those countries with a set of strong policies in those particular sectors.

The third step was a review of literature and data sources to determine the net historical impact of the identified policies on GHG emissions, and the relevant metrics. This revealed the historical trends in sector- and subsector-level GHG and energy indicators for a period of five to ten years, which then served as proxies to evaluate the performance of the energy and climate policies in question. The analysis also considered forward-looking policies that aspire to achieve future emissions reductions, such as sector and subsector targets and their support schemes. By comparing those to current values, it was possible to estimate the progress of sector indicators in the future. The use of proxy indicators does not allow for distinguishing the policy impact from the impact exerted by other drivers, such as changes in the industrial structure. The data sources used include IEA [27,28], national GHG inventories, other national inventories, the ODYSSEE energy efficiency index (ODEX) [29], and documentation on individual policies and their impact assessments. A five-to ten-year period may not always be considered long enough to constitute strong evidence for the historical impact of policies, but it seems reasonable for climate change mitigation efforts, as, for many sectors, the implementation of policies to support the deployment of key low-carbon technologies and other drastic GHG emissions reduction measures only started around the 2009 Copenhagen

climate conference (15th Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC)).

It is also important to note that the assessment period of the performance indicators and the implementation period of the policies reviewed do not always match. In some cases, enforcement of the policy started before the assessment period, in others during the assessment period. Another relevant observation is that it was not always possible to assess the performance of the policies in recent years, given that the available scientific literature is often a few years behind the latest statistical data. In some cases, it was not possible to provide figures or give a qualitative assessment of the impact because corresponding data was not available.

The fourth step involved identifying the countries where the indicators at the sector and subsector levels have improved quickest, and the associated policies that are likely to have contributed to the observed performance. This step compares the quantified indicators from step 3 for the countries where data is available. The research does not decompose the impacts of individual policies.

The fifth step was to provide projections of the historical sector trends and apply them to all other countries around the world, using two different models: a bottom-up spreadsheet calculation [20] and the energy model TIMER as part of the integrated assessment model IMAGE 3.0 [30,31]. Energy- and industry-related GHG emissions and emissions of F-gases were projected by bottom-up calculations based on existing external scenarios [6] and by the TIMER model [8] (Appendix A). The GHG emissions of the LULUCF sector and agriculture sector were projected by GLOBIOM and G4M models (Appendix A).

All projections in this study were harmonised to the historical emissions data for 2014. For Annex I countries, the data point is the GHG emissions inventory data reported to the UNFCCC [32], and for non-Annex I countries, data reported to the EDGAR database (all GHG excluding land use) and the FAO (land use emissions) [14,15]. The projections are expressed in terms of 100-year global warming potentials (GWPs) from the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC; IPCC-SAR GWPs) (for further details, see Appendix A and Supporting Information). More specifically, the impact of successful sector policies on GHG emissions was translated into parameters for use in both models.

3. Review of existing sector-level policies and their performance indicators

Table 1 presents an overview of the selected sector-level performance benchmarks. The following sections review the sector-level policies implemented in the focus countries of this study, summarise the rationale for the selection of good practice policies and the quantification of their performance indicators. They discuss the feasibility of achieving levels of performance in other countries in line with those indicators. The policy review centres on measures that explicitly target a specific sector. Policy measures that indirectly or implicitly influence sector indicators, such as emissions trading schemes or carbon or energy taxes, are in most cases not considered. Where the literature review reveals important and successful policies in countries other than those examined here, they are included in this section for completeness.

The literature review showed that there is more information available on OECD countries than on emerging economies and developing countries, and that, in many cases, OECD countries have historically achieved higher performance levels and implement forward-looking

Table 1
Overview of good-practice policy indicators.

Sector (share in 2018 global GHG emissions) [15]	Subsector, policy area or policy action	Indicator	Historical global average performance	Best performers among major emitting economies	
				Historical performance and future policy target used for explorative scenario analysis	Countries and examples of policies that contributed to good performance
Electricity generation (25%)	Electricity generation: Share of electricity generated through renewables	Increase of the share of renewables in total electricity generation per year (percentage points)	0.5% points increase in share per year (2005–2015)	1.35% points increase in share per year excluding hydro (2005–2015)	EU (Renewable Directive and Roadmap; Member States support schemes)
	Electricity generation: limits on coal-fired power plants	Various: Cap on coal consumption or capacity; target year for phase out	189 GW coal power (global) output from plants under construction (as of July 2020)	[Historical] Cancellation of several construction plans (China, Japan); forced closures of old and inefficient plants (China) [Forward-looking] No new coal-fired power plants after 2025 for OECD countries, and after 2035 for developing countries	[Historical] Coal consumption cap (China); environmental impact assessment (Japan) [Forward-looking] Canada, China, United Kingdom, India, several EU Member States (coal consumption cap, emission performance standards)
Industry (fuel combustion and process emissions) and fossil fuel production (29%)	Energy efficiency	Final energy consumption per physical output	Approximately 1%/yr energy intensity improvement	[Historical] Up to 0.5% annual additional improvement (limited information available)	EU (energy efficiency standards, air pollutant emission standards, emissions trading scheme); Japan (voluntary agreements)
	Oil and gas production: venting and flaring	Implied CH ₄ emission factor per unit of oil and gas production	Oil production: 1.8%/yr reduction of flaring CO ₂ intensity (1996–2019) and 2.9%/yr reduction of CH ₄ intensity (1992–2012); Gas production: 0.5%/yr reduction of CH ₄ intensity (1992–2012)	[Historical] 4.8% annual reduction in emission intensity between 2008 and 2015 (United States) [Forward-looking] Limited information available	[Historical] United States (EPA Natural Gas STAR Program to encourage reductions; Waste Prevention Rule of the Bureau of Land Management to reduce flaring of gas)
Buildings (7%)	Energy efficiency in space heating and cooling	Final gross energy consumption per square meter for new residential and commercial buildings (kWh/m ²)	Limited information available	[Historical] Limited information available [Forward-looking] all new buildings to be nearly zero-energy by 2020 (EU) and 2030 (Japan)	[Historical/forward-looking] EU (Energy Performance Buildings Directive: EPBD)
		Renovation rate for existing buildings	Approximately 1%/yr	[Historical] Limited comparable information available [Forward-looking] renovation rate 3% per year for public buildings; rate used in analysis for all residential buildings: 2.1% per year (OECD countries) 1.6% per year (China, Russia) 1.5% per year (other regions)	EU (EPBD)
Transport (13%)	Efficiency standards for appliances	Annual improvement in appliance efficiency (%)	1%/yr efficiency improvement for appliances and lighting	[Historical] About 0.5% annual additional to autonomous improvement; limited comparable information available [Forward-looking] Limited comparable information available	[Historical] Japan (Top Runner Standards); EU (Energy Efficiency Directive, Ecodesign Directive, Energy Labelling Directive)
	Passenger vehicles: fuel efficiency standards	Average km/l for new registrations	Light-duty vehicles fuel efficiency: 20 km/l (Japan, 2013, test mode)	[Historical] 13.7 km/l to 20.5 km/l between 2001 and 2016 (Japan) [Forward-looking] 32 km/l by 2030 (EU) Figure used in analysis: 27 km/l by 2030	[Historical] Japan, EU [Forward-looking] EU
F-gases (3%)	Passenger vehicles: market penetration of zero-emission vehicles	Share of electric cars in new registrations (%)	Share of new Electric vehicles: <1%	[Historical] 0.3%–56% between 2010 and 2019 (Norway) [Forward-looking] 100% zero-carbon vehicles in 2025 Figures used in analysis: 25% share of new electric vehicles to be achieved in 2025 for OECD countries, and in 2035 for developing countries	[Historical] Norway (subsidies, incentives for parking) [Forward-looking] Norway
	Freight transport: fuel efficiency standards	Final energy consumption per tonne-km	Limited data available	[Historical] Limited comparable information available [Forward-looking] Limited comparable information available Figure used in analysis: new vehicle efficiency to improve between 2017 and 2030 at the rate previously suggested by the United States Standards Strategy	[Historical] China, EU, Japan, United States [Earlier proposal] United States (fuel economy standards)

(continued on next page)

Table 1 (continued)

Sector (share in 2018 global GHG emissions) [15]	Subsector, policy area or policy action	Indicator	Historical global average performance	Best performers among major emitting economies	
				Historical performance and future policy target used for explorative scenario analysis	Countries and examples of policies that contributed to good performance
	F-gas consumption (industry, buildings and transport)	F-gas emissions reductions induced by policies (%)		[Historical] Limited comparable information available [Forward-looking] 85% reduction to be achieved between 2035 and 2045, compared to 2010 levels	[Forward-looking] Kigali Amendment to the Montreal Protocol
Land use, land-use change and forestry (7%)	Zero net deforestation	Annual net deforestation area	6 million ha/yr net forest loss	[Historical] 83% reduction between 2004 and 2012 (Brazilian Amazon) [Forward-looking] End natural forest loss by 2030	[Historical] Brazil, China, EU [Forward-looking] International: New York Declaration on Forests (endorsed by a large number of national governments)
Other: Agriculture and waste (15%)	Anaerobic digesters			50% of manure from livestock treated with anaerobic digesters by 2030	[Historical] Germany, Denmark
	Rice paddies			Efficiency gains in GHG reduction of 2% per year by 2030	[Historical] Vietnam

policies with more stringent targets. For major emitting countries such as India and China, however, a less stringent target level often results in higher absolute numbers, for example in terms of electric vehicle sales or capacity additions for renewables.

3.1. Electricity generation

3.1.1. Increase in renewable electricity

Table 2 presents support policies for the deployment of renewable electricity, and the historical growth of its share in total electricity generation between 2007 and 2017 in the focus countries. Globally, the share of renewables in electricity generation increased from 18% in 2007 to 24% in 2017 (including hydro), which translates into an average increase of 0.6% points per year [28].

Of the major emitting countries and regions, the EU performed the strongest, thanks to support from both the EU Renewable Energy Directive and national-level policies. Between 2007 and 2017, the average yearly increase was 1.5% points with hydro included, and 1.35% points, excluding hydro [33]. At Member State level, Germany, the UK and Denmark showed average yearly increases of 1.9%, 2.5% and 4.5% points respectively, for the same period. For China, the figure was 1% point, while it recorded an increase of more than 40% in total electricity demand over the same period. During those years, China set ambitious capacity targets and implemented financial incentives to increase the production and deployment of renewable energy technologies. Japan and the United States also showed performance on par with or better than the world average. By contrast, India experienced a slight decrease in the share of Renewable Energy (RE) electricity over the observed period, while installed renewable technology capacities increased. The impact of falling technology costs and the 2016 National Electricity Plan was rather limited. Roelfsema et al. list a few other small countries that have achieved RE share growth rates well above the global average [8]. The size of the country impacts the indicator: RE capacity additions are the highest in China, but, because of the size of the country, the relative share changes only marginally [34].

3.1.2. Limits on coal-fired power plants

In July 2020, there was 189 GW of coal-fired power plant capacity under construction globally [46]. Several economies have policies already in place or plans to limit electricity generation from coal-fired power plants (Table 3), and an increasing number of countries has set phase-out dates, or is in the process of doing so [3,47]. Some countries not covered by this study have already phased coal out of their energy systems. This section focuses on forward-looking policies, i.e. policies targeted at phasing out coal at a certain point in the future.

None of the focus countries has set an explicit phase-out year for

Table 2

Most relevant policies for the deployment of technologies for electricity generation through renewable energy (RE).

Country/region	Main policy measures effective from 2007 to 2017	Historical growth of electricity generation through RE from 2007 to 2017 [28]	Share of electricity generation through RE in 2017 [28]
China	Energy Development Strategy Action Plan 2014–2020 [35]; Renewable Energy Development Five Year Plan with non-fossil and capacity targets for RE technologies [36]; 13th Five Year Plan for Energy Development [37]; several financial instruments for RE technology support (tax reliefs, feed-in tariffs) [38]	1% point per year	25%
EU	Renewable Energy Roadmap (Directive 2009/28/EC) [33]; Member States support policies and targets	1.5% points per year including hydro and 1.35% points per year excluding hydro	30%
Japan	Long-term Energy Supply and Demand Outlook [39]; Feed-in tariff scheme (2012) [40]	0.7% points per year	17%
India	National Solar and Wind Missions (2010) and various related support schemes [41]; National Electricity Plan [42]	–0.1% points per year	16%
United States	State-level renewable portfolio standards (RPS) [43]; tax relief for renewable energy technologies [44,45]	0.9% points per year	17%

coal-fired electricity production. While some EU Member States plan to phase out coal-fired power plants [48], no target exists on the level of the EU as a whole. The target years set by Member States to phase out coal vary between 2020 in Austria and Sweden, and 2038 in Germany; Belgium shut down its last coal-fired plant in 2016 [49].

In China, the Energy Development Strategy Action Plan 2014–2020 aims to cap coal consumption in 2020 at 4.2 billion tonnes of coal equivalent [50]. Government-affiliated research organisations project

Table 3
Most relevant policies on limiting coal-fired power plants.

Country/region	Policy measures	Indicator value	Share of coal-fired electricity generation in 2017 [28]
China	Energy Development Strategy Action Plan 2014–2020 [35]; 13th Five Year Plan for Energy Development [37]	Cap on coal consumption in 2020 at 4.2 billion tce	68%
EU	No policy on EU level directly targeted at coal-fired power plants. Some Member State policies have coal phase-out plans [61].	Varying target years for phasing out coal in Member States between 2022 and 2038	21%
India	National Electricity Plan [42].	N/A	74%
Japan	Environmental impact assessments [52]	Best Available Technology benchmarks and consistency with the national GHG mitigation targets	33%
United States	No policies	N/A	28%

that China's coal capacity would peak in 2025 under current policies (including the cap on coal) [51]. The Japanese environment ministry regulates new coal-fired power plant constructions by examining their consistency with the national GHG mitigation targets under mandatory environmental impact assessments [52]. This policy has led to cancellations of several new construction plans [53,54] while other projects were allowed to continue [55,56]. India's National Electricity Plan expects a further net increase of coal-fired power capacity by 46 GW between 2022 and 2027 [57].

There are several examples of coal phase-out plans in countries not covered by this study. Canada has committed to phasing out its coal-fired power plants not equipped with carbon capture and storage (CCS) technology by 2030 [58]. At sub-national levels, the Canadian province of Ontario phased coal out in 2014 [58], followed by the state of South Australia in 2016 [59]. In January 2018, Chile announced it would stop developing new coal-fired power plants and establish a calendar for the phasing out of coal [60].

3.2. Fossil fuel extraction: fugitive emissions

This section covers policies that address methane (CH₄) emissions from venting and flaring in oil and gas production. It also looks at reduced CH₄ emissions from coal mining.

3.2.1. Reduction of venting and flaring in oil and gas production

While large GHG emissions reductions can be achieved in the oil and gas extraction sector [62,63], only a few countries have implemented policies to control this kind of emissions [24]. Data on fugitive emissions from oil and gas production is highly uncertain and is not available for all countries [65]. Historically, global average CO₂ emission intensity of flaring per unit oil production reduced at 1.8%/yr on average between 1996 and 2019 [64], while global average CH₄ emission intensity per unit of oil and gas production reduced at 2.9%/yr for oil production and 0.5%/yr for gas production on average between 1992 and 2012 [65].

Table 4 presents an overview of policies on venting and flaring in the oil and gas production sector. Among the policies implemented in the focus countries, the US approach to methane reductions is the only comprehensive policy package in this area. It covers the entire sector and attempts to achieve reductions that are significantly greater than the historical trends between 1990 and 2008. The United States aims to cut

Table 4
Most relevant policies for GHG emissions reductions from venting and flaring in oil and gas production * (adapted from Roelfsema et al. [8]).

Country/region	Policy measure	Indicators value
China	Law on the Prevention and Control of Atmospheric Pollution [70,77]	N/A.
EU	No regulation at the EU level	N/A.
United States	USA methane target to reduce methane emissions by 40–45% from 2012 levels by 2025 (EPA proposal, included in Obama Climate Plan) [78]. EPA Natural gas START Program that encourages methane emissions reductions in the oil and gas sector [79]. Implementation of the Waste Prevention Rule [80] to reduce flaring of gas by capturing or use for production.	77.4 ktCO ₂ e/Mtoe oil and gas produced in 2025 or 4.7% per year intensity improvement. Historical average annual CH ₄ and CO ₂ intensity improvement of 4.8% from 2008 to 2015.
Russia	Reduce flaring by 5% [74]. Companies are fined when not adhering to the defined limits. In addition, improvements of regulatory and legal framework, including market liberalisation and improving market access [75].	874 ktCO ₂ e/Mtoe oil and gas produced in 2015, but no significant change in emission factor in the past ten years.
Norway	A CO ₂ tax on oil and gas production (starting in 1991) promoting carbon capture and storage options [76].	5.5 ktCO ₂ e/Mtoe oil and gas produced in 2015, but no significant change in emission factor in the past ten years. CH ₄ and CO ₂ intensity improvement of 2.3% per year from 1990 to 2020.
Canada	Regulations Respecting Reduction in the Release of Methane and Certain Volatile Organic Compounds (Upstream Oil and Gas Sector) [81].	N/A
Nigeria	Flare Gas (Prevention of Waste and Pollution) Regulations 2018 [82].	N/A

*Japan and India are not included here because they do not produce relevant amounts of oil or gas. On the other hand, various countries that do not belong to the focus group of this study are included, given the relevance of their policies.

CH₄ emissions from oil and gas production by 40–45% from 2012 levels by 2025. Although the US Environmental Protection Agency under the Trump administration proposed to change methane emission standards on oil and gas wells [66], no new regulations have not been introduced yet.

Under the current rules, the US Energy Information Administration projected that the country would decrease its emission intensity to 77.4 ktCO₂e per Mtoe fuel produced by 2025 [67], which translates to an annual reduction of 4.7% [6]. The contribution of flaring to the GHG emissions of the US oil and gas sector is less than one-fifth of the total. The average annual reduction of the historical CH₄ and CO₂ emissions intensities from oil and gas operations between 2008 and 2015 was 4.8%, according to data reported for that period [68].

In the EU, there are no union-wide policies directly targeted at reducing emissions from venting and flaring. The European Commission, however, does participate in networks for knowledge exchange on methane emissions reductions from oil and gas production [69].

In China, the Law on the Prevention and Control of Atmospheric Pollution regulates fugitive emissions from the production of fuels, but only focuses on coal [70]. For the purposes of this study, it is assumed that the impact of this policy on methane emissions in the oil and gas production is limited. Those emissions have been stable in the past decade [71].

Countries that are not included in the focus group of this study and have relevant policies in the area of fugitive emissions from venting and flaring are Canada and Nigeria. Canada controls leakage and limits venting in upstream facilities [72]. Nigeria limits the flaring of gas and taxes the volumes of gas that facilities continue to flare under those limits [73]. Countries where policies exert less impact in this area are Russia and Norway. Russia aims at reducing flaring by 5% [74,75]. Norway has taxed CO₂ emissions from oil and gas production since 1991 [76].

3.3. Manufacturing industry

3.3.1. Enhanced energy efficiency

Table 5 presents the most relevant energy efficiency policies that have been implemented in the manufacturing industry. In 2008, India adopted the National Plan on Climate Change, which includes the National Mission for Enhanced Energy Efficiency. The latter contains a market-based energy efficiency improvement programme called the Perform, Achieve and Trade (PAT) scheme, under which industries are required to meet energy saving targets by either implementing energy efficiency measures or offsetting their excess energy consumption through the purchase of energy saving certificates. A recent study that reviewed the effectiveness of the PAT scheme during its first cycle (2012–2015) concludes that the energy saving targets were no more stringent than those set for the business-as-usual scenarios [83].

In the EU, the main policies that address industrial energy efficiency are: (1) the EU Emissions Trading Scheme (ETS; 2003/87/EC); (2) the Energy Efficiency Directive (EED; 2012/27/EU), which encourages the EU Member States to make use of various financing channels for measures that serve to meet the EU-wide target of a 20% improvement in energy efficiency by 2020; and (3) the Industrial Emissions Directive (IED; 2010/75/EU), which principally addresses pollutant emissions, but also requires industrial operators to consider the overall environmental performance of their plants by covering energy efficiency, material use and several other elements [84]. An extensive review study suggested that CO₂ emissions from sectors covered by the EU Emissions Trading System (EU ETS) declined compared to estimated business-as-usual emissions during its first two phases but the study could not determine a causal relationship between the scheme and emissions reductions [85]. Another review also pointed out that large overlaps may exist between the three EU initiatives with regard to reductions in greenhouse gas emissions [86].

The ODYSSEE energy efficiency index (ODEX) is used to measure progress in energy efficiency by sector. It is a weighted average of subsector physical output-based energy efficiency indices. According to

Table 5
Most relevant policies for energy efficiency in the industrial sector.

Country/region	Policy measures	Historical energy efficiency improvement (physical output-based)
China	Various measures under the 12th and 13th Five Year Plans (2010–2015, 2015–2020) [35]; Made in China 2025 (2015) [100]	N/A
EU	Energy Efficiency Directive (2012) [101]; Industrial Emissions Directive (2010) [84]; Emissions Trading Scheme (2003) [102]	1.8% per year from 1990 to 2014 (1.3% per year from 2005 to 2014)
India	PAT scheme [41] under Mission for Enhanced Energy Efficiency (2008)	N/A
Japan	The Keidanren VAP (1997) [103] Sector benchmarks (2010 amendment of the Energy Conservation Act) [104]	0.4% per year from 1991 to 2008 0.9% per year from 2000 to 2008
United States	Superior Energy Performance (SEP) 50001 Program [99] Better Plants Program [105]	N/A

this index, energy efficiency in the EU industry sector improved at an average yearly rate of 1.8% between 1990 and 2014 and 1.3% between 2005 and 2014 [29]. Compared to the typical value of about 1% per year for autonomous energy efficiency improvement [87,88], the historical trends suggest that the policies that were in place constituted an additional energy efficiency improvement. These results, however, should be interpreted cautiously as the ODEX is considered to be less scientifically robust than other established energy efficiency indices [89–91].

China's current high-level policy for industry energy efficiency is the Climate Change Action Plan (2014), which aims to reduce industrial CO₂ emissions per unit of added value by 50% by 2020 compared to 2005 levels. Moreover, the China Manufacturing 2025 initiative aims to reduce energy intensity per unit of added value for enterprises above a designated size by 18% in 2020 and 34% in 2025, compared to 2015 levels. To achieve these targets, it identifies ten key policy tools, including standards, subsidies, financial policies and government-backed investment funds [92].

In Japan, the main energy efficiency measures in the industry are Keidanren's Voluntary Commitment to a Low-Carbon Society, and the sector benchmarks introduced in 2010 under the amended Energy Conservation Act. The former is an extension of the Voluntary Action Plan (VAP) that started in 1997 as part of the government plan to achieve the mitigation target under the first commitment period of the Kyoto Protocol. As with the VAP, the targets under the Commitment are set unilaterally by the industry and oversight is also carried out by the industry, leading to questions on compliance, transparency and ambition levels [93]. To date, the benchmarks have not been effective, partly due to the lack of a penalty for non-compliance. In 2015 none of the four integrated steelmakers and only five of seventeen cement companies achieved the benchmarks [94]. Energy efficiency in the Japanese industry sector, measured on a physical output-basis, improved at an average yearly rate of 0.4% between 1991 and 2008 and 0.9% between 2000 and 2008 [95].

Although there is limited evidence available, the case of the EU suggests that an additional energy efficiency improvement of roughly 0.5% per year would be possible by introducing a comprehensive policy package. The figure is comparable to others that have been established in bottom-up scenario studies. An aggressive energy efficiency scenario based on the technical potential of energy efficiency improvement presented in the Global Energy Assessment [96] foresees a 2% per year improvement. On the other hand, the United Nations Industrial Development Organization [97] projected that replacing all plants with current best available technologies in the next 25 years (base year: 2005) would only lead to an efficiency improvement of 1.7% per year.

The United States has a few, mostly non-regulatory, policies to enhance industrial energy efficiency [98]. One of these is the Superior Energy Performance (SEP) 50001 Program, which certifies industrial operators that implement an energy management system that meets the ISO 50001 standard, and demonstrate they have actually improved their energy efficiency [99]. The Better Plants Program is a voluntary partnership under which industrial actors set specific energy efficiency goals and receive support from the government to achieve their goals.

3.4. Buildings

3.4.1. Enhanced efficiency of space heating and cooling

There are not many examples of policies that address renovation rates and energy performance of existing buildings (Table 6). For new buildings, the EU Energy Performance of Buildings Directive [106] is among the most ambitious measures, requiring all new buildings to be nearly zero-energy by 2020 [106]. The exact definition of nearly zero-energy varies across EU Member States [107]. Germany has requirements for the refurbishment of existing buildings and mandatory standards for new ones [108]; new buildings consuming less than 40 kWh/m² per year in primary energy terms receive additional financial support.

Table 6
Most relevant policies for low-carbon installations in buildings (adapted from Roelfsema et al. [8]).

Country/region	Existing policy measures	Indicator value
China	The 13th Five-Year Plan for Energy and Resource Conservation by Public Institutions [116]; Green Building Evaluation Standard [117]	N/A
EU	Evaluation Standard for Green Retrofit of Existing Buildings [118]; Energy Performance of Buildings Directive (2010) [119]	All new buildings to be nearly zero-energy by 2020
India	Energy Conservation Building Code Rules, 2018 [120]	N/A
Japan	Basic Energy Plan (2014) [113]; Zero-Energy House/Building Roadmap (2015) [121]	All new buildings to be on average net zero-energy in primary energy terms by 2030
United States	Federal level: Energy efficiency codes and labels [111,112]; California: Building Efficiency Standards [109,110]	Federal level: Not assessed; California: All new residential buildings to be zero net energy by 2020; All new commercial buildings to be zero net energy by 2030

The Energy Performance of Buildings Directive also requires Member States to create national plans for promoting the conversion of existing dwellings to nearly zero-energy, but there are no clear targets. The Energy Efficiency Directive [101] further requires Member States to annually renovate 3% of the total floor area of buildings owned and occupied by the central government, but there are no renovation targets for other buildings.

In the United States, the state of California also aims for all new residential and commercial buildings to be zero net energy by 2020 and 2030, respectively [109]. The term zero net energy is defined as the situation that occurs when “the value of the net amount of energy produced by on-site renewable energy resources is equal to the value of the energy consumed annually by the building” [110]. At the federal level, building codes and labels are the dominating tools to support efficiency in buildings [111,112].

Japan has set the target of reducing the average net primary energy use of all new commercial buildings and dwellings to zero by 2030 under the 2014 Basic Energy Plan, with an interim 2020 target of the same reduction applying to 50% of all new commercial buildings and dwellings [113]. Japan includes both fully zero-energy and nearly zero-energy dwellings in its targets, with nearly zero being defined as achieving a reduction of 75% or more in net primary energy use. In 2017, the share of zero-energy and nearly zero-energy dwellings in new residential buildings was 10.5% [114].

China promotes the construction of nearly zero-energy buildings through large-scale demonstration projects and the development of new standards. The country’s definition of nearly-zero depends on the climate zone: heating demand must be below 18 kWh/(m²*yr) in the severely cold climate zone, below 15 kWh/(m²*yr) in the cold climate zone and below 5 kWh/(m²*yr) in other climate zones [115]. While China has mandatory building codes, there is no requirement for all new buildings to be classified as nearly zero-energy.

3.4.2. Energy efficiency standards for appliances

Table 7 summarises good practice policies on energy efficiency of appliances in the focus countries of this study and the Republic of Korea. Japan adopted the Top Runner Program in 1998 to establish energy efficiency standards for machinery, equipment and other items as part of the national plan to achieve the GHG mitigation target within the first commitment period of the Kyoto Protocol [122]. Under this programme, manufacturers are required to achieve the energy efficiency targets

Table 7
Most relevant policies on the energy efficiency of appliances (adapted from Roelfsema et al. [8]).

Country/region	Policy measure(s)	Indicator value
China	Mandatory standards; One Hundred Energy Efficiency Standards Promotion Program [128]	N/A
EU	Energy Efficiency Directive (2012/27/EU); Ecodesign Directive (2009/125/EC); Energy Labelling Directive (2010/30/EU) [29]	Stock average: average efficiency improvement of 1.7% per year between 1990 and 2014
India	BEE Standards & Labelling Programme [129]	N/A
Japan	Top Runner Program efficiency standards (1998) [122]	New products: average efficiency improvement (median of 24 products) of 3.7% per year over varying periods (4–9 years)
United States	Standards and labels for multiple technologies [127]	N/A
Republic of Korea	Energy efficiency label and standard programme (1992); High-efficiency appliance certification (1996); e-Standby program (1999); High efficiency product subsidies (2001) [124]	N/A

based on the most efficient products available on the market at the time they are set. With regard to target stringency, Tojo [123] concludes that manufacturers “must be at least as well-equipped with technologies as their counterparts abroad” to meet and exceed the Top Runner standards.

The Top Runner Program is successful in enhancing the energy efficiency of appliances. The median of compound average improvement rates for 24 appliances (including heating, cooling and cooking devices) over periods of 4–9 years was 3.7% per year (authors’ own calculation based on data published by the Japanese Ministry of Economy, Trade and Industry [122]). On average, these 24 appliances overachieved their efficiency targets by 0.9% per year (ibid.).

In the EU, energy efficiency of appliances is promoted by a number of Directives, including the Energy Performance of Buildings Directive (2010/31/EU), the Energy Efficiency Directive (2012/27/EU), the Ecodesign Directive (2009/125/EC), and the Energy Labelling Directive (2010/30/EU). The Ecodesign Directive sets minimum requirements on energy efficiency for appliances to be introduced in the European market [29].

Between 1990 and 2014, energy efficiency in the EU household sector increased at an average rate of 1.7% per year based on the ODEX (see Section 3.3.1 on industrial energy efficiency). Similar energy efficiency improvement rates were observed for large electric appliances, such as dishwashers, refrigerators and freezers, televisions and washing machines. As pointed out in the section on industrial energy efficiency, the results from the ODEX need to be interpreted with caution.

The Republic of Korea, another major manufacturer of electric appliances, has four key energy efficiency policies: energy labelling, high-efficiency equipment certification, standby power reduction, and subsidies for high-efficiency products [124]. No information was found on the effectiveness of these policy measures.

The policies based on performance standards of both Japan and the EU are assessed to have delivered similar levels of energy efficiency improvement for appliances [125]. Based on the assessments of the Top Runner Program, and assuming that the efficiency improvement targets are at least at the level of autonomous efficiency improvement, historical observations for new products show that an additional efficiency improvement of about 1% per year can be realised. This roughly

translates into a figure of 0.5% per year for stock average, which is consistent with a scenario under moderately strengthened policies developed by the Japanese Ministry of the Environment [126]. The historical trends observed in the ODEX of the EU suggest a similar magnitude of policy impact.

In the USA, the Department of Energy works under the Energy Policy and Conservation Act to develop standards that regulate the maximum energy consumption of all main appliances. In this regard, “Energy Star” is the most prominent label for electric devices [127]. China has mandatory standards as the backbone of efficiency improvements in appliances. This area is being further developed through the One Hundred Energy Efficiency Standards Promotion Program [128].

3.5. Transport

3.5.1. Light-duty vehicles: standards for fuel efficiency and GHG emissions

Fuel efficiency standards for light-duty vehicles (LDVs) are well developed in many economies. All the focus countries of this study have implemented fuel efficiency standards or GHG emission standards for passenger cars. In the shift towards zero-carbon mobility, the efficiency of the combustion engine becomes irrelevant. This policy review therefore refrains from providing an in-depth discussion of this subsector and acknowledges the importance of efficiency of electric vehicles.

In 2017, the International Council on Clean Transportation (ICCT) published an up-to-date overview of implemented standards for cars [130]. See Table 8 for relevant details.

The EU policies represent good practice, having set the most ambitious standards currently in force. Annual efficiency improvement up to 2030 is set to go slightly beyond the maximum figure of 4% required by the Transportation Roadmap [131]. Furthermore, with regard to fuel economy, a significant gap exists between official figures (established under test conditions) and on-road figures, which are 30% lower [132]. Using the target of 4% per year improvement and making an adjustment of 30% for on-road performance, the good practice policy target (for on-road performance) in this study is 105 gCO₂/km or 26.6 km/l by 2030 for new cars (Table 1).

3.5.2. Light-duty vehicles: support for electric vehicles (EVs)

Support for EVs is increasing in many countries, including the focus countries of this study (see Table 9).

In September 2017, China passed quotas on new vehicle sales for

Table 8
Overview of fuel efficiency or GHG emissions standards for passenger cars.

Country/region	Policy measures	Target Year	Unadjusted Fleet target
China	Light duty fuel efficiency standard	2020	20 km/l
		2025	25 km/l
EU	Light-duty CO ₂ emissions standard	2021	95 gCO ₂ /km
		2025	81 gCO ₂ /km
		2030	59 gCO ₂ /km
India	Light-duty CO ₂ emissions standard [133]	2022	113 gCO ₂ /km
Japan	Light duty fuel efficiency standard	2020	20.3 km/l
		2030	25.4 km/l
United States	Light duty fuel efficiency and emissions standard	2025	23.5 km/l or 91 gCO ₂ /km

Source: Adapted from Refs. [130,134]. The fuel efficiency and GHG targets are based on different test cycles and specifications, which means they are not fully comparable. For a few countries the values from the original source were converted for comparability reasons. The original values are: 5 l/100 km for China, 55.2 mpg and 147 gCO₂/mi for United States. To obtain the EU figures, relative reductions were applied compared to the 2021 limits: 15% for 2025, and 37.5% for 2030. The Trump administration aims to replace the current regulation and freeze the efficiency requirements at 2020 levels [135]. This change is still going through legislative processes and in the meantime, the 2025 target remains in place.

large car manufacturers and importers [136]. The quotas, 10% for 2019 and 12% for 2020, can also be met by purchasing credits, which is why the actual share of electric vehicles will be lower than the quota [137]. In 2019, the Ministry of Industry and Information Technology released its 15-year EV plan for public commenting, aiming for 25% of new light-vehicle sales to be electric models by 2025 [138].

In its National Electric Mobility Mission, India set a sales target of 6–7 million electric vehicles for 2020. This translates into 2–4% of the total vehicle stock, depending on different demand forecasts. India has been discussing targets for 2030, with possible options being abandoning the sale of fossil fuel combustion engines, and requiring that a 30% share of the vehicle stock be electric [139]. Singh et al. [140] estimate that India will reach this target with the successful implementation of various policies currently on the table.

In the EU, there is no union-wide regulation directly targeted at increasing the share of EVs. However, they count as zero-emission vehicles and as such can be used to meet the emissions standards. France and the UK aim to have no fossil fuel vehicles by 2040, the Netherlands by 2030.

Japan has a long history of support for EVs, going back to 1996 [141]. Since then it has had subsidies in place for the purchase of EVs. It further provides tax rebates and has installed a dense charging infrastructure [142]. The long-term goal and strategy of Japan’s automotive industry for tackling global climate change is to reduce passenger car emissions by 90% by 2050. The strategy includes interim targets for electric mobility: by 2030, the diffusion rate of battery and plug-in electric vehicles is to reach 20%–30% of new sales, and that of hybrid vehicles is to reach 30%–40% [143].

As for the United States, there is federal level support for EVs in the form of tax rebates. EVs can also be used to comply with the fuel efficiency standards (see Section 3.5.1). Many states provide additional support, with the most comprehensive and ambitious policy package being California’s Zero-Emission Vehicle Program. Its goal is to reach a stock of 5 million EVs by 2030 and to install 250,000 charging stations. Besides other measures, this programme requires manufacturers to ensure a specific share of their sales is in fully electric or plug-in hybrid vehicles. The support policies also provide financial incentives for zero-emission vehicles [144]. The federal agency EPA projects that, with the policies implemented today, the EV share of overall vehicle sales will increase to 9% in the USA as a whole by 2030 [145].

Interesting policy packages exist beyond the study’s focus countries: the governments of Norway, the Netherlands, and California have implemented comprehensive packages to support the uptake of electric cars. These consist of financial incentives, along with investments in

Table 9
Overview of policies to support electric passenger cars.

Country/region	Policy measures	Market penetration of zero-emission vehicles
China	Quota for sales of new vehicles; financial incentives	10% in 2019 and 12% in 2020 Planned: 25% in 2025
EU	No EU-level regulation:	100% by 2040
	Phase out combustion engine at member state level:	100% by 2030
India	France	
	The Netherlands	
India	National Electric Mobility Mission Plan 2020 [146]	6–7 million vehicles by 2020 (roughly 2–4% of market according to demand estimates)
Japan	Tax incentives and subsidies; long-term target for increase of electric vehicles [143]	20–30% by 2030 for battery and plug-in EVs; roughly 3% for fuel cell electric vehicles
United States	Tax incentives on federal level; various states have additional support programmes and targets;	9% by 2030
	California Zero-Emission Vehicle Program [144], Clean Cars 2040 Act	California: 5 million zero-emissions vehicles by 2030; planned: 100% zero-emission vehicle sales as of 2040

charging infrastructure and incentives for behavioural change, such as the right to drive on bus lanes, and free public parking.

Assessments of this multi-layered policy package confirm that it effectively contributes to higher levels of EV sales [147]. Norway, for instance, achieved an EV market share of 56%, including plug-in hybrids, in 2019 [148] and aims at increasing this to 100% zero-carbon vehicles in sales of new cars in 2025 [149].

Costa Rica has not yet set targets for electric vehicles but is comprehensively supporting purchase and use through tax incentives, charging infrastructure, and changes to the fleets of public institutions [150]. Many cities, including Copenhagen, Oxford, Paris and numerous Chinese cities, have decided to ban fossil-fuel combustion engines from their streets by 2030 at the latest [151].

3.5.3. Heavy-duty vehicles: fuel efficiency standards

Given that freight transport is heterogeneous and adjusted to the circumstances of individual countries, this study refrains from giving a comprehensive overview and provides several examples of interesting policies instead. Fuel efficiency for heavy-duty vehicles (HDVs) has been much less regulated than for LDVs, but an increasing number of countries has implemented fuel economy standards in the past ten years [152]. Canada, China, Japan and the United States are forerunners towards more fuel-efficient HDVs, with China and the United States being the only ones whose standards extend beyond 2020 [152]. In particular, the United States has comprehensive and ambitious standards in place [153]. These apply to the period 2021 to 2030 and seek to achieve an average yearly efficiency improvement of 1.7%¹ for new HDVs [153]. China has implemented stages I and II of a fuel consumption standard for new heavy commercial vehicles. Stage I was in force from 2012 to 2015, and stage II affects HDVs as of 2015. In addition, China is now working on stage III, which is to apply to new lorries as of 2021 [154]. While the current fuel efficiency is lower than that of, for example, the United States, the rates of improvement implied by the standards are higher: the shift from stage II to stage III involves a yearly improvement of 2.4%.

The electrification of on-road freight transport will play a crucial role in decarbonising the transport sector. Today, technologies are also available to fuel buses with electricity while running, in addition to on-board batteries. While installations have been created to test these technologies, no large-scale sites for commercial production have been built yet, nor do policies exist to promote production. Due to the lack of examples of good practice, this analysis does not examine HDV energy efficiency initiatives in further detail, and leaves them out of the enhanced policy scenarios.

3.6. Reduction of emissions of fluorinated greenhouse gases (F-gases)

With the Kigali Amendment to the Montreal Protocol, governments agreed to a global phasing out of the consumption of hydro-fluorocarbons (HFCs). The schedule varies by country group, with developed countries required to decrease HFC consumption sooner and to lower levels than developing countries (see Table S3 in the Supporting Information). Several countries have implemented national legislation to regulate F-gases (see Purohit et al. [155] and Table 10 for an overview): the EU introduced the F-gas regulation in 2014 [156]; the United States has updated its Significant New Alternatives Policy (SNAP) Program, which designates alternative uses for ozone-depleting substances [157]. The EU might be able to achieve its Kigali target with existing policies, while there are differing views on whether Japan and the United States could achieve theirs with the policies they have in place

¹ Calculation based on the required efficiency of new lorries in tonnes-km/1 across Class 7 and Class 8, using the average of the values for lorries with low, medium and high roofs.

Table 10
Overview of policies to reduce F-gas emissions.

Country/region	Policy measures	Target reduction rate and year
China	Inspection of enterprises and subsidies for destruction of HFCs [161]	N/A
EU	F-gas regulation [167]	66% reduction of all F-gases relative to 2010 by 2030
India	HCFC Phase Out Management Plan	reduction of HCFC production and consumption to 50% below 2009–2010 levels in 2020, and 60% in 2023
Japan	Act on Rational Use and Proper Management of Fluorocarbons [168]; Ozone Layer Protection Act [169]	N/A
United States	Significant New Alternatives Policy (SNAP) [157]	N/A

[158,159].

The EU F-gas regulation aims for a 66% reduction of all F-gas emissions relative to 2010. The legislation includes limiting the total amount of F-gases sold, banning the use of F-gases in specific appliances, preventing emissions from equipment during their service life, and introducing recycling or disposal measures [160].

China is a major emitter of F-gases and has started to regulate its emissions by tightening the control of enterprises which generate F-gases as by-products [161]. India has implemented an hydrochloro-fluorocarbon (HCFC) Phase Out Management Plan, currently at stage 2, which aims at reducing HCFC production and consumption. According to the Indian government, this plan will bring about reductions faster than required under the Kigali Amendment [162].

Japan implemented the Act on Rational Use and Proper Management of Fluorocarbons to better control the F-gas chain in 2015. Specific measures are GWP targets for certain types of equipment and the obligation to destroy F-gas for entities re-using recovered F-gases [163]. The Ozone Layer Protection Act states that the Kigali Amendment applies to Japan (ibid.).

The 2019 amendment establishes several obligatory measures and penalties on non-compliance to increase the F-gas recovery rates to the targeted 50% by 2030 from 38% in 2017.

The global replication of successful policies scenario assumes reductions of HFC emissions according to the Kigali Amendment schedule (Table S3 in the Supporting Information) and expands these reductions to the use of other F-gases (PFCs and SF6), as significant reductions are technically possible and already being implemented. Most PFC emissions from aluminium production could be reduced by 85% if producers changed to the processes with the lowest emission factors [164], and 43% of business-as-usual emissions from semiconductor manufacturing could be abated at breakeven costs [165]. SF6 used in electrical equipment has a practical recovery rate of 80%, and SF6 in the production of magnesium can be replaced by HFC-143, which has a shorter atmospheric lifetime [166].

3.7. Agriculture

The agricultural sector is highly heterogeneous in its structures and resulting GHG mitigation strategies, and depends strongly on the demand side. For example, the reduction of meat consumption is an important lever. This study was not able to address the sector as a whole in a comprehensive manner, and therefore centres on two areas in which several countries have implemented successful policies and measures that can be replicated elsewhere. While these countries do not belong to the study's focus group, the examined policies are relevant to this research.

3.7.1. Widespread use of anaerobic digesters

In 2000, Germany passed its Renewable Energy Act, which provides incentives for electricity generation from renewable energy by offering above market feed-in tariffs. Subsequently, the number of biogas installations rose from around 1000 to more than 9000 in the period between 2000 and 2016. In 2015, the installed capacity totalled 4200 MW [170]. The first feed-in tariffs and bonuses for biogas paid under the Act – and a revised version of the legislation in 2004 – were as high as EUR 22 cent/kWh [171]. Manure is one of the feedstocks used in anaerobic digesters to produce methane, and the CH₄ emissions reduction from proper manure management can reach 90% [172]. A 2014 reform of the Renewable Energy Act aimed to reduce overall costs of the policy by slowing down growth in renewable energy technologies through a reduction of feed-in tariffs, and also to encourage the use of organic and farming waste as feedstocks [173]. In the EU, around 5% of manure from pigs was treated in anaerobic digesters in 2010. Denmark even managed to process more than 30%.

The study draws on the policies above to set the following benchmark: 50% of manure from the livestock sector is assumed to be treated in anaerobic digesters by 2030. This benchmark is in line with the assessment of the technical potential within the EU, which is estimated to be 50% and can, in the case of individual countries, go up to 80%, depending on current average farm size and structure [174]. Under favourable policy conditions, an even more widespread adoption of anaerobic digesters could be anticipated, in particular on small-scale farms [175,176].

3.7.2. Limiting emissions from rice paddies

Among the rice-producing countries, Vietnam stands out thanks to its long-term efforts. Following several initial economic reforms in the early 1980s, which enabled individual farmers to gain some degree of market access, and brought about the first jump in rice yield, Vietnam adopted the Doi Moi plan in 1986. This market-oriented policy reform allowed markets to play a greater role in the allocation of economic resources and caused a decentralisation of production from collectives to individual farm households [177]. Over the next decades, following additional reforms, such as investment in infrastructure and irrigation, land reform, and subsidies, Vietnam transformed itself from a rice importer to one of the world's leading exporters [178]. Sustained yield growth through the adoption of new varieties (the adoption rate was around 90% by 2000), increased irrigation and improved fertilisation [177,179,180] recently resulted in a stabilisation of harvested area [181]. According to FAOSTAT, this development coincided with a stabilisation of CH₄ emissions from rice production in the period from 2000 to 2010, but in contrast, the country itself still reported to the UNFCCC an increase in emissions from 37.5 to 44.5 MtCO₂e per year during the same period [182].

Based on the policies presented above, the study sets the following benchmark: a doubling of efficiency gains in GHG reduction from the historical global yearly average of 1%–2% by 2030. The scenario thereby foresees a reduction in the emissions of CH₄ from the agricultural sector.

3.8. The land use, land use-change and forestry (LULUCF) sector: zero deforestation

The change in forest area is one of the key indicators to understand developments in the ecological and environmental services that forests provide. According to Keenan et al. [183], the world's forest area is still declining, but the rate of global net loss of forest area did decrease by over 50% in the periods between 1990 and 2000, and between 2010 and 2015. The focus countries of this study play a limited role in the sector, but other countries have implemented comprehensive policy packages (see Table 11). They intend to increase their forest area by putting

forward policies to reduce deforestation, increase afforestation and protect areas at risk of being converted.

Brazil has historically shown the strongest performance in reducing deforestation. Data from its National Institute for Space Research indicates a reduction of the deforestation rate in the Amazon biome from a peak year with 29,059 km² of forest loss to a historical low in 2012 when 4571 km² was lost [184]. The reduction is due to the implementation of the government's regulatory measures, such as the Brazil Forest Code, and the improvement of supply chains [185]. The private sector has also played a major role in tackling deforestation issues in Brazil. An example is the implementation of the 2006 Soy Moratorium in the Amazon. This agreement between civil society, industry, and government prohibits the purchase of soy grown on recently deforested land, thereby helping to reduce the deforestation rate. If it was expanded to the Cerrado biome, it could also serve to slow down the deforestation of this area and thereby contribute to further reductions in deforestation rates at the national level [186]. Nevertheless, at present the deforestation rate in Brazil is rising and if legal treaties are not enforced the trend may continue [187].

The experience of Brazil suggests that a strong reduction in the deforestation rate can be achieved when civil society, industries and governments work together to implement and enforce relevant policies. In the period between 2004 and 2012, Brazil achieved an average 5%

Table 11
Most relevant policies to increase the national forest area.

Country/ region	Existing policy measure	Indicator value
China	Nationally appropriate mitigation actions (2016) [192]; the 13th Five-year plan [189]	Increasing the forest area by 40 million hectares and the forest stock volume by 1.3 billion m ³ from 2005 levels by 2020. Increase the forest cover to 23% and increase the forest growing stock to 16.5 billion m ³ .
EU	EU Biodiversity Strategy (2020) [191]	Three billion new trees are planted in the EU, fully adhering to ecological principles.
India	Green India Mission (2011) [193]	Increase the forest cover in moderately dense forests: 5 million hectares. Improve forest cover of forest areas: 5 million hectares
Japan	No relevant policies found	N/A
United States	No relevant policies found	N/A
Argentina	Environmental and Insurance Sustainability Program [194]; investments for cultivated forests [195]	Increase forest plantations from 1.3 million hectares to 2 million hectares by 2030. Development of afforestation projects on a total of 500,000 ha.
Brazil	The Brazilian Forest code (2012) [196]	Restoring and reforesting 12 million hectares of forests by 2030.
	Plan for Prevention and Control of Deforestation in the Amazon (2004) [197]	Zero illegal deforestation by 2030 in the Amazon biome.
	Action Plan for the Prevention and Control of Deforestation and Forest Fires in the Cerrado biome (2010) [198]	N/A
Colombia	Increase of the area of protected forest land in the Amazon [199]	Increase area of protected forest land in the Amazon to 38 million hectares.
Chile	National Strategy for Climate Change and Vegetation Resources (2010) [200]	Afforest 100,000 ha of land with mainly native tree species.
Indonesia	Presidential instruction, August 2018 [201]	Three-year moratorium on the expansion of palm oil plantations.

reduction per year, resulting in a drop in its national deforestation rate of as much as 84%. If the country manages to reverse the current trend and return to pre-2012 developments, it will see its deforestation rate reaching zero before 2030.

China has a long history of implementing ambitious policies to increase the area and the quality of their national forests. These have led to an increase in forest cover from 8.6% in 1949 to 18.21% in 2003 [188]. The 13th five-year plan sets the target of increasing the national forest cover to 23% [189]. This is in line with the longer-term Chinese plans for afforestation projects to increase the total forest cover by about 40 million hectares from 2005 to 2020 [190].

In the EU, there are no union-wide policies directly targeted at reducing the level of legally permitted deforestation carried out within the Member States. However, the 2020 EU Biodiversity Strategy sets clear and quantitative targets for afforestation and the protection of land within Europe [191].

There are several countries that do not belong to the focus group of this study but do have relevant policies for increasing forest area and reducing deforestation. Those include Argentina, Brazil, Colombia, Chile and Indonesia.

In addition to individual national legislations, there is the New York Declaration on Forests (NYDF) which was signed by governments, companies, non-governmental organisations and indigenous organisations [202] Aiming to halt the global net loss of forest area while simultaneously enhancing food security, the NYDF presents 10 action points, or goals, including targets for deforestation and land restoration by 2020 and 2030. In terms of deforestation, one of its key actions points is to end naturally occurring forest loss by 2030, with a 50% reduction by 2020 as a milestone toward full achievement [203]. The 2019 assessment report indicates that achieving the 2020 target is “likely impossible” and that larger scale, more coordinated action is needed to bring the 2030 target within reach [204].

4. Explorative scenario analysis: impact on emissions of replicating sector progress globally

The sector progress achieved by successful past policies and aimed at by forward-looking policies (see Table 1) was applied to all countries by changing the parameters in both models for projections about the period 2015 to 2030 relative to the current policies scenario. This resulted in an estimation of global GHG emissions that peak around 2020 and decline

afterwards (Fig. 2). By 2030, emissions would decrease to 46.6–48.6 GtCO₂e per year from 51.5 GtCO₂e in 2015. This corresponds to reductions of 11.7–12.1 GtCO₂e, or 19–21%, by 2030, compared to the current policies scenario

At the global level, the largest emissions reductions in 2030 come from the power sector (5.3–5.6 GtCO₂e per year), followed by the sectors LULUCF (2.2 GtCO₂e per year), transport (0.8–1.2 GtCO₂e per year) and industry (0.9–1.1 GtCO₂e per year). The reductions in emissions stemming from electricity generation are partly due a fall in the demand for electricity, caused by factors such as efficiency improvement of devices. On the other hand, the growth of electrified transport leads to an increase in demand. Overall, the change in electricity consumption after replicating sectoral progress is small: the demand in 2030 results in 1% less than in the scenario under current policies in the bottom-up calculations (data point not available for TIMER/IMAGE).

In all the analysed countries, the most stringent NDC targets would be overachieved under a scenario that globally replicates successful policies (see Table 12). The largest reductions are achieved in the electricity production sector in nearly all major economies, except Mexico, where the current share of coal-fired power generation is already low (11% in 2015). Similarly, in Brazil the reduction in the LULUCF sector amounts to up to 190 MtCO₂e per year by 2030, accounting for up to half of the total possible reduction for Brazil identified in this study. The application of successful energy and GHG policies has a clear impact on Russia, achieving emissions reductions of 26%–35% relative to current policies scenario projections. The country has significant mitigation potential with regard to fugitive emissions from oil and gas production (200 MtCO₂e per year in 2030) and F-gas emissions.

As for developing countries, the effect of reductions in F-gas emissions under the Kigali Amendment by 2030 is found to be relatively small because stringent consumption caps will not be in place until after 2030, and there will be a time lag until the impact of caps becomes visible in terms of reduced emissions.

Table 12 provides ranges of emissions projections that reflect the uncertainty of the results for all countries. For example, emissions projections for India are subject to considerable uncertainty related to economic growth assumptions. In Japan, decisions on the future of nuclear energy will strongly influence the development of emissions in the power sector. In Brazil, projected emissions from land use are unsure. The global results and most of the sectoral results are comparable to outcomes produced by other studies (see SI 4).

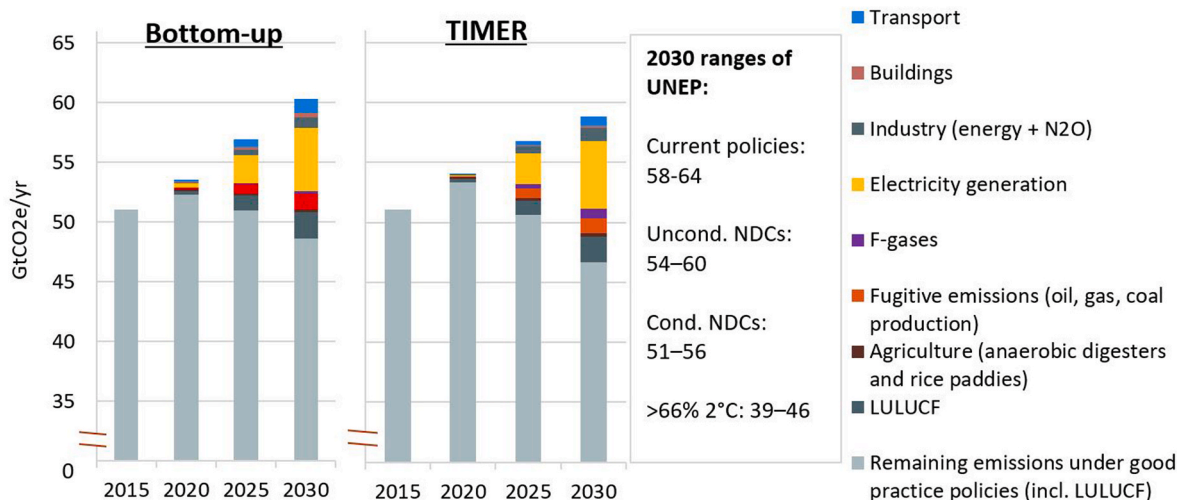


Fig. 2. Global GHG emissions (including those from LULUCF). The grey segment of each bar represents emissions forecasts under the scenario of replicated sectoral progress in 2030; the coloured segment represents emissions reductions stemming from the implemented policies. Note: For comparison, the graph includes the emission ranges for 2030 of the UNEP Emissions Gap Report [3]. These are, more specifically, the 10th to 90th percentile estimates of the total GHG emissions by 2030 under three different scenarios: the current policies scenario, the unconditional and conditional NDC scenario, and the below 2°C and 1.5°C scenario.

Table 12

GHG emissions projections (including emissions from LULUCF) by 2030 under the current policies scenario and under the good practice policies scenario in major emitting economies. Emissions values are based on IPCC-SAR GWPs. Unit: MtCO_{2e} per year.

	Brazil	Canada	China	EU	India	Japan	Mexico	Russia	South Africa	USA
Current policies scenario										
GHG emissions (MtCO _{2e} /yr)	1110–1470	530–590	13,000–14,100	3280–3530	4510–5100	930–1050	760–790	2120–2130	650–760	4790–5730
Replicated sector progress scenario										
GHG emissions (MtCO _{2e} /yr)	780–1010	380–480	10,600–11,280	2430–2780	3390–4100	770–840	670–730	1470–1660	520–590	3640–4530
Reductions relative to the current policies scenario	30%–31%	19%–29%	18%–20%	21%–26%	19%–25%	17%–19%	8%–12%	21%–31%	20%–22%	21%–24%
Emissions change vs. 2015 levels	–40% to –22%	–34% to –16%	–5% to –1%	–38% to –29%	+26% to +53%	–39% to –33%	+3% to +12%	–21% to –11%	–7% to +6%	–36% to –20%
NDC scenario (For comparison: NDC target range in IPCC-SAR GWPs based on UNEP [205])										
Unconditional (conditional)	1200	520	13,400–14,800	2960–3290	4050–6220	950–1040	730–760 (600–620)	2410–2740	610 (400–610)	4740–4870 (in 2025)
NDC (MtCO _{2e} /yr)										

5. Discussion

5.1. Significance of this study

The review of policies in this study shows that the historical performance and expected outcomes of future measures vary significantly across countries. This is not only explained by the degree of policy implementation, but also by other factors, such as the pace of economic development in the years observed and market forces. This study has found that in the past, OECD countries such as the EU Member States, Japan, Norway and the United States, tended to implement policy packages that led to more rapid progress in improvements to energy intensity and GHG intensity, in comparison to emerging economies and developing countries. However, major emitting developing countries are now catching up and are increasingly implementing similar packages (for example for fuel efficiency of passenger cars), which in some cases are more aggressive than those of many OECD countries; a case in question is China's policy on electric vehicles. It is further important to consider that in major emitting economies, such as India or China, even if relative values develop more slowly, the absolute increase of mitigation technologies is more substantive than in smaller countries. At several points, the analysis presents comparisons of relative and absolute figures. Examples of substantive gains are capacity additions for renewable energy and the numbers of electric vehicles introduced in certain countries. These developments influence global markets and drive down costs in other countries as well.

The analysis performed here has identified examples of successful policies that have led to clear deviation from business-as-usual trends in energy use and GHG emissions in the following sectors: renewable electricity, passenger vehicles (fuel efficiency and promotion of zero-emission vehicles), and forestry. For other sectors such as industry and buildings, which are often considered as *hard-to-abate* sectors, the comparable information available is too limited to allow any conclusions to be drawn. For the industry and freight transport sectors, no relevant historical policies or forward-looking policies were identified in the five major emitting economies.

Of the examples observed in this paper, some have clearly changed trends in the sectors. Policy makers in other countries could learn from these good examples and use them as benchmarks for their own ambition. For a complete picture, policy making should further consider national circumstances and ensure compatibility with the mitigation requirements of the Paris Agreement.

The results of the explorative quantitative assessment show that replicating sector progress globally (see Section 4) can significantly change the current trend in global emissions. However, the resulting level of progress in each sector is still insufficient for respecting the

temperature limits of the Paris Agreement.

5.2. Limitations and uncertainties of this study

The research methods used in this study have faced some limitations. First, the policy review focuses on major emitting economies, and even among those, inadequate availability of information narrows the analysis. The analysis focuses mostly on national-level policies, but more ambitious or more effective schemes may exist on a subnational or city level.

Second, there is not always a direct link between the implemented policies and progress in the studied sectors. Many other developments influence the trends in the sectors.

Third, the quantitative analysis is based on the assumption that the historically observed performance of a country can be replicated around the world and over a long time. Some successful policies identified in this study are in part driven by political objectives that are unrelated to climate change mitigation (e.g. reducing air pollution or enhancing energy security). Countries with similar ambitions for their sectoral indicators may be driven by widely varying reasons. There are, for example, many different arguments that support an increase in the market share of electric vehicles. One key element is having the power to actually execute policies, and this varies, depending on factors such as the level of community organization, culture and levels of educational attainment. This study does not provide a recipe for countries on how to effectively implement ambitious climate policies and achieve the level of performance observed in exemplary cases. It does not either consider the political developments in the countries, such as the withdrawal of the US from the Paris Agreement.

Fourth, this study has not assessed whether the identified policies and their performance are cost-effective, fully account for national circumstances, are compatible with national processes and priorities, and are in the interest of stakeholders in the countries where they are replicated. The replication of good practice policies in other countries around the world requires careful consideration of national circumstances and criteria that go further than emissions reductions alone. This also includes differentiating the mitigative capacity of countries based on their level of development. In this regard, this study has taken a simplified approach of differentiating the time horizon of policy implementation in cases where the policy area is heavily influenced by the level of income of the population affected by the policy.

The fifth limitation relates to the time horizon of this study. It is assumed that the good practice policies can be implemented without significant delays in countries around the world, starting in 2018. The starting year is a critical assumption: the development of effective policy packages can be complex and require a significant amount of research,

and therefore it can take years of preparation for policies to be fully implemented. Further, the study set 2030 as the target year and does not consider the longer-term implications which are important for a transition to net-zero-CO₂ emissions by around 2050. The study does not assess the transformation impact of the policies in the long-term. The policies need to be complemented with cost-effective instruments with a long-term vision [7]. Examples are a price on carbon, or specific support for negative emissions technologies, e.g. through reforestation.

Sixth, the article does not delve into various sectors that may be critical for some countries and are essential to consider in the global transition to Paris-compatible pathways: waste, international shipping and aviation, and aspects of industrial processes other than F-gases and efficiency.

Lastly, as in all attempts to estimate future trends, there is uncertainty in the projected emissions. The two models used for this research make different assumptions about economic and sector-specific technological developments and about policy implementation rates. In addition, there are several country-specific conditions which add to the uncertainty (see Section 4). The estimates of countries' GHG emissions relative to 2015 levels vary between the two models: in five cases, the variations are less than 10%, and in five others they range from 10% to 20%. Overall, the emissions projections under the current policies scenarios of this study are compatible to emissions projections from other national and global models (for a comparison, see Ref. [3,206]).

6. Conclusions and policy implications

This article reviews climate change mitigation policies that lead to reduced GHG emissions, compared to scenarios without such policies. Focusing on the largest emitting economies, it describes the policies and illustrates the expected or actual sector progress they bring about. Indicators for energy intensity and GHG intensity illustrate and compare progress in the sectors. In a second step, the research makes the assumption that all countries are able to replicate the most ambitious progress in each sector. Explorative scenarios use the IMAGE model and bottom-up calculations to provide per-sector estimates of GHG emissions under their own particular conditions.

Historical performance and expected outcomes of future targets vary across countries. This study has found that in the past, OECD countries such as the EU Member States, Japan, Norway and the United States, tended to implement policy packages that led to more rapid progress in improvements to energy intensity and GHG intensity, in comparison to emerging economies and developing countries. However, major emitting developing countries are now catching up and are increasingly implementing similar or even more aggressive packages than those of many OECD countries.

The level of implementation of mitigation policies varies also per sector. There are many policies that have led to clear deviation from business-as-usual trends in energy use and GHG emissions related to renewable electricity, passenger vehicles and forestry. For industry and buildings, the comparable information available is too limited to allow any conclusions to be drawn. For the industry and freight transport sectors, no ambitious historical policies or forward-looking policies were identified in the five major emitting economies.

Global replication of successful sector-level policies and their performance will definitely reduce greenhouse gas emissions by 2030 compared to levels achieved under current policies. Even so, the resulting level of sector progress still does not keep the world on track to measure up to the challenge of meeting the temperature limits of the Paris Agreement by 2030. To fulfil the Paris goals, countries therefore need to very rapidly expand their actions over and beyond historical efforts. The findings of this study include the following recommendations thereto:

- develop comprehensive policy packages with financial incentives, which address user behaviour and limit administrative barriers;

- provide long-term security to actors in the sector;
- focus on underdeveloped sectors (in terms of technology or coverage by the policy framework), where countries have the capacity to do so; building up transformative policy frameworks for those sectors can drive corresponding climate action around the world and is therefore also a responsibility of OECD countries.

CRedit authorship contribution statement

Hanna Fekete: Conceptualization, Methodology, Writing - original draft, Data curation, Formal analysis, Investigation, Project administration. **Takeshi Kuramochi:** Conceptualization, Methodology, Writing - original draft, Data curation, Formal analysis, Investigation, Project administration. **Mark Roelfsema:** Formal analysis, Investigation. **Michel den Elzen:** Funding acquisition, Conceptualization, Writing - review & editing, Supervision. **Nicklas Forsell:** Formal analysis, Investigation, Writing - review & editing. **Niklas Höhne:** Funding acquisition, Conceptualization, Supervision. **Lisa Luna:** Formal analysis. **Frederic Hans:** Formal analysis. **Sebastian Sterl:** Formal analysis. **Jos Olivier:** Formal analysis. **Heleen van Soest:** Formal analysis. **Stefan Frank:** Formal analysis. **Mykola Gusti:** Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A Tools used and methods applied for emissions projections

Two different quantification frameworks were used to make the projections of energy- and process-related GHG emissions (except those from the agriculture sector) and F-gases emissions under the current policies scenario and the good practices scenario: the IMAGE model and bottom-up calculations based on existing external scenarios (see below and [Supporting Information](#)). The GHG emissions from the LULUCF sector as well as the agriculture sector were projected using GLOBIOM and G4M models (see below and the [Supporting Information](#)). The projections are expressed in terms of IPCC-SAR GWPs.

A.1. IMAGE integrated assessment modelling framework

The first set of projections calculated the impact of individual policies in different subsectors using the IMAGE integrated assessment modelling framework [30], which includes models for energy systems (TIMER) and land use. The starting point for the calculations of the impact of climate policies was the SSP2 baseline (i.e. no climate policy) as implemented in the IMAGE model [30]. The impact of current climate and energy policies in G20 countries, as identified in the CD-LINKS project [16], was fed into the model and resulted in additional GHG emission reductions to the baseline [31]. For this projection, current policies were translated into quantitative policy indicators that could be used in the model. The methodology for calculating the impact of the policies and targets on emissions for the global replication of successful policies scenario for the IMAGE model (including the TIMER energy

model) is described in detail in [Section S1 of the Supporting Information](#).

A.2. Bottom-up calculations based on existing external scenarios

The second set of emissions projections was made by applying a bottom-up quantification of individual policy impacts using publicly available sector-level reference emissions projections as a starting point.

The development of projections under the current policies scenario is described in Kuramochi et al. [16], and is here also outlined in detail in [Section S2 of the Supporting Information](#). The starting point for the calculation of current policies emissions projections is a publicly available baseline policy scenario for economy-wide GHG emissions and energy-related CO₂ emissions, that draws on government documents and projections made by international organisations such as the IEA. After making the projections, the study examined whether the baseline scenario considered all the important policies implemented to date. If a specific policy exerting a substantial impact was found to have been left out, the emission and energy use projections were adjusted to reflect this.

To calculate the impact of replicating progress globally, the authors adapted sector-specific, simplified stock turnover models developed for the power, buildings and transport sectors. These adapted versions were derived from the models used and described in Kriegler et al. [7]. The tool developed for F-gas emissions projections collected historical data from three databases [207–209] and the development of the current policies scenario projections was based on work by the US EPA [172] and government submissions to the UNFCCC. See [Section S1.2 of the Supporting Information](#) for a detailed description of the tools.

A.3. GLOBIOM and G4M models for land-use sector calculations

Both the bottom-up calculations and the IMAGE scenario calculations were supplemented with others on LULUCF CO₂ and agricultural policies, using the IIASA global land-use model GLOBIOM [210] and the global forest model G4M [211]. To ensure consistency between model scenarios, the SSP2 baseline was selected as the starting point for the calculations by GLOBIOM and G4M [212]. To illustrate comprehensive results, IIASA's LULUCF CO₂ and agriculture emissions projections were added to the GHG emission projections made by IMAGE and the bottom-up calculations.

A detailed description of the tools presented above, including the description of quantification of individual policy impacts, can be found in [section S3 of the Supporting Information](#).

Appendix B. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.rser.2020.110602>.

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