PBL Netherlands Environmental
Assessment Agency

MITIGATING GREENHOUSE GAS EMISSIONS IN HARD-TO-ABATE SECTORS

July 2022

Utrecht
University

Colophon

Mitigating greenhouse gas emissions in hard-to-abate sectors

© PBL Netherlands Environmental Assessment Agency
The Hague, 2022
PBL publication number: 4901

Corresponding authors

o.y.edelenbosch@uu.nl, maarten.vandenberg@pbl.nl, andries.hof@pbl.nl

Authors

Oreane Edelenbosch (UU), Maarten van den Berg, Harmen-Sytze de Boer, HsingHsuan Chen (UU), Vassilis Daioglou, Mark Dekker, Jonathan Doelman, Michel den Elzen, Valentijn Frinking (UU), Mathijs Harmsen, Andries Hof (PBL and UU), Efstratios Mikropoulos (UU), Mariesse van Sluisveld, Isabela Tagomori and Detlef van Vuuren (PBL and UU)

Acknowledgements

We would like to thank Pieter Boot, Martine Uyterlinde, Tom Kram, Henk Westhoek, Eduardo Müller Casseres and Sebastiaan Deetman for their valuable input. We would also like to thank Willem-Jan van Zeist (WEcR) and Elke Stehfest for their contribution to the development of the land-use scenarios.

This work was supported by the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 821124 (NAVIGATE project) and benefited from the SHAPE project, part of AXIS, an ERA-NET project initiated by JPI Climate and funded by NWO (NL) with co-funding from the European Union (Grant No. 776608).

Visualisations

PBL Visualisation Team

Production coordination

PBL Publishers

Accessibility

PBL attaches great importance to the accessibility of its products. Should you encounter any access-related problems when reading them, please contact us at info@pbl.nl, stating the title of the publication and the issue you are experiencing.

Parts of this publication may be reproduced, providing the source is stated, in the form:
O.Y. Edelenbosch (2022), Mitigating greenhouse gas emissions in hard-to-abate sectors, PBL Netherlands Environmental Assessment Agency, The Hague.

PBL Netherlands Environmental Assessment Agency is the national institute for strategic policy analysis in the fields of the environment, nature and spatial planning. We contribute to improving the quality of political and administrative decision-making by conducting outlook studies, analyses and evaluations in which an integrated approach is considered paramount. Policy relevance is the prime concern in all of our studies. We conduct solicited and unsolicited research that is both independent and scientifically sound.

Contents

Mitigating greenhouse gas emissions in hard-to-abate sectors 4

1 Introduction 10

2 Background 12

3 Methods 14
3.1 Literature study on hard-to-abate emissions: complexities, measures and policies 14
3.2 Sector analysis by scenario implementation in IMAGE 15
3.3 Achieving 1.5 °C 18

4 Abatement challenges in hard-to-abate sectors 19
4.1 Transport: aviation and shipping 19
4.2 Industry and materials 23
4.3 Buildings 27
4.4 Agriculture and non-CO_2 emissions 30
4.5 Similarities and differences between the hard-to-abate sectors 33

5 Scenario analysis 34
5.1 Scenario assumptions 34
5.2 Reducing greenhouse gas emissions in the hard-to-abate sectors 38
5.3 Deep emission reduction in the four pathways 54

6 Impact of additional measures in hard-to-abate sectors on 1.5 °C pathways 57

References 63

Appendix. Decomposition formulas 69

FINDINGS

Mitigating greenhouse gas emissions in hard-to-abate sectors

In some sectors, achieving net-zero emissions by mid century is expected to be very difficult. We refer to these sectors as 'hard to abate'. To achieve the climate targets of the Paris Agreement, the remaining emissions in these sectors, in default mitigation scenarios, are compensated via carbon dioxide removal (CDR) measures. However, such measures involve technical, environmental and social concerns. Many scenario studies show that, to achieve net-zero emissions, large-scale application of carbon dioxide removal measures is necessary to offset the residual emissions remaining in the hard-to-abate sectors. However, the feasibility of large-scale use of carbon dioxide removal measures is often questioned. For instance, for biofuels in combination with carbon capture and storage, the cultivation of bioenergy crops requires large amounts of water and land, which can impact food production, water scarcity and biodiversity. There are also concerns about the availability of storage capacity and the enormous scale of carbon dioxide removal operations. Finally, if CDR is used later in time to offset current emissions from hard-to-abate sectors, this would lead to a temperature overshoot with related risks. Therefore, it is useful to reduce mitigation barriers in hard-to-abate sectors.

Industry, aviation, shipping and agriculture are typically regarded as hard-to-abate sectors, but reducing emissions in buildings has also proved to be difficult. Reasons for the difficulty in reducing emissions in these sectors include rapid activity growth, lack of low-cost commercially available mitigation technologies and implementation challenges. Deep and rapid emission reductions are possible in electricity generation, land transport and land use. In contrast, aviation, shipping, agriculture, industry and buildings are characterised by their relatively slow-paced emission reductions in 1.5 °C scenarios. We therefore regard these sectors as hard-to-abate in this report. The aviation and shipping sectors, in the past, have shown strong growth in activity levels. Despite the drastic drop resulting from the COVID-19 pandemic, the activity levels of the aviation sector are expected to bounce back and continue to grow. The growing demand for materials and goods is expected to drive industrial demand, while the agricultural sector is expected to grow further due to population growth and increased consumption of animal products. The hard-to-abate sectors also face technical and structural challenges to mitigate greenhouse gas emissions. The lack of commercially available mitigation technologies plays a critical role in aviation, shipping, agriculture, and some industrial sectors. In industry, aviation and shipping, large upfront costs combined with slow capital turnover rates and market competitiveness can create major barriers to rapid change. In the buildings and agriculture sectors, the diversity of users, often with limited access to capital, knowledge and training as well as site-specific conditions, hampers the adoption of innovative mitigation practices.

Critical measures are needed to overcome mitigation barriers in hard-to-abate sectors. The most important ones according to the literature are summarised per sector in Table 1. Overall, important measures include technological advancements, structural changes leading to more circularity and efficient waste handling, and lifestyle changes that impact demand. These measures could be stimulated by various policies, including financial instruments, regulation and direct investments in R&D and training. Financial instruments (e.g. taxes and subsidies) can be applied at the level of the consumer end products (e.g. airline tickets and meat) or earlier in the supply chain (e.g. sustainable transport fuel and process emissions). These policy instruments can break the impasse of investments being commercially non-viable or risky in competitive markets. To avoid carbon leakage, internationally harmonised policy is an important ingredient of successful mitigation in the hard-to-abate sectors, specifically in industry, aviation and shipping. Finally, it may be effective for some products and services to enforce standards using legislation, for example, in the case of energy efficiency in buildings or emissions from agriculture, which rely more on national policies.

Table 1
Measures connected to achieving deep reductions towards zero emissions in hard-to-abate sectors

Aviation and shipping	Industry	Buildings	Agriculture
Sustainable aviation fuels: In the medium term power-to-liquid fuel and biofuels; In the long-term: alternative fuelling (e.g. hydrogen in aviation); Alternative modes of transport, such as high-speed rail; Alternative tourism, increased teleworking; Adapted aircraft design; More efficient operations and air traffic control; Earlier retirement of conventional planes; Alternative shipping fuels; Operational measures (slow steaming); Efficient ship design	Technological advancement in process industry (electrification, clean fuel, CCS); Alternative feedstocks (clinker, cement); Circularity of materials and extended product lifetimes; Material retention, substitution and efficiency; Integration of processes via scale and interlinkage of sub-sectors, also in the form of energy and carbon storage; Lifestyle change and changes to current product standards and traditions; Early retirement of current production infrastructure	Insulation and renovation; Local electricity and energy generation; Higher efficiency technologies; Reduced energy waste via occupancy sensors, stand-by mode for appliances; Behavioural change concerning appliance ownership and demand for energy services; Communal spaces and shared energy services (e.g. cooking and other appliances); Less floorspace per capita (e.g. smaller houses, increased household sizes); Energy-efficient architectural design; Switch from traditional biomass for cooking to cleaner alternatives	Technological solutions: more efficient livestock farming: genetic selection, feed additives; In rice production: techniques to reduce flooding, reduced use of fertilizer and less runoff: higher fertilizer efficiency, nitrification inhibitors; Land management techniques: higher water tables on peat soils, different agricultural management to increase soil carbon; Alternative products (e.g. cultured meat); Structural changes required to build knowledge, investment profitability, improved manure and livestock management systems; Dietary changes; Decreases in food waste in farm processing, retail and households

The additional measures to reduce emissions in hard-to-abate sectors can be classified as being demand- and technology-oriented and as non-structural or more structural in nature. In this study, we developed a set of scenarios based on these distinctions. Demand-side changes are related to the consumption of services, compared to the reference situation, while technology-related changes concern different technology deployment in the provision of services. Demand-side changes in buildings, for example, concern heat reduction, cooling, appliances and lighting waste, using occupancy sensors, avoiding stand-by mode, shifting towards more co-living where living space is shared, reduced appliance ownership and smaller houses. Technology-side changes, for example, include the promotion of heat pumps, more efficient refurbishment, use of net-metering, and residential PV. In the agricultural sector, demand-side changes include less meat consumption, lower calorie intake and less food waste, while technology changes include a shift toward cultured meat and measures to reduce non-CO_2 emissions from agriculture. Air-travel demand could be reduced by implementing an air passenger tax, promoting alternative tourism, teleworking and shifting to alternative transport modes, while technology innovation could lead to the deployment of alternative fuel technologies.

The technology- and demand-oriented pathways can effectively reduce emissions, but face different challenges. In principle, demand-oriented pathways can be implemented relatively rapidly, although this depends on the degree and rate of societal change. The technology-oriented pathways rely on certain technologies which are not yet commercially available on a large scale and depend on technology turnover. In the short term, this could lead to relatively slow emission reductions, but the pace could increase when novel technologies are adopted on a large scale. In buildings, technology options show great potential to reduce emissions already in the short term. Although industrial demand management can cut the decarbonisation challenge in half, leading to less CCS required, the deepest industrial reductions follow structural technology changes, such as the rapid transition to electric arc furnaces and hydrogen in steel production.

Drastic changes are needed in the hard-to-abate sectors to reduce emissions to almost zero. Some of the demand and technology measures can be implemented in current sectoral operating mode, while others require structural changes. This leads to further reductions, especially in the industrial and the buildings sectors. In the industrial sector, global net zero-emission pathways by 2050 are deemed possible if negative emissions can be achieved in the cement and pulp and paper industries, combined with the availability of zero-carbon energy in other industrial sectors. In the building sector, remaining emissions primarily originate from cooking with traditional biomass (primarily in Sub-Saharan Africa and South Asia), which in the technology-oriented pathway have nearly been eliminated. In aviation, shipping, and agriculture, the scenarios suggest that the largest changes can be achieved through demand-oriented measures. The reduced use of aircraft for short-distance travel and reduction in long-distance flights could reduce emissions by as much as 40% by 2060. Especially, the structural demand-side solutions (e.g. dietary changes) are projected to be effective in the agricultural sector and lead to substantial decreases in non-CO_2 emissions.

The additional measures in the hard-to-abate sectors can reduce reliance on CDR measures. The scenarios show that the measures also allow for more rapid reductions, reducing the need for CDR measures in offsetting emissions both early on and later in time to achieve the 1.5 °C target. This is illustrated by the finding that, with structural demand-oriented measures, a 1.5 °C scenario can be constructed in which crop-based bioenergy use is limited to well below sustainable levels and afforestation is limited to abandoned cropland and grassland only. The structural technology-oriented measures lead to slightly lower emission reductions, in the short term. Therefore, with the structural technology-oriented measures, some additional afforestation will be needed to achieve the 1.5 °C target, but crop-based bioenergy can remain well below sustainable levels.

Agriculture plays a crucial role in achieving net-zero emissions, given the large potential to reduce emissions directly and indirectly through demand and technology measures. Of all hard-to-abate sectors, scenario analysis shows that the highest emissions remain in agriculture and consist of non-CO_2 greenhouse gases. Therefore, measures targeting the remaining emissions from this sector may have a strong direct impact, notably those on dietary changes or cultured meat and lower caloric intake that lower emissions from enteric fermentation and manure. In addition, these measures reduce the amount of land used for grazing and feed and, therefore, indirectly, allow for more afforestation.

Although this report explores technology- and demand-oriented measures separately, the potential of these measures can be increased if combined. Moreover, many demand-side options can be supported by technology, and vice versa. Replacing short-distance flights by high-speed rail, for instance, will only be possible if the required rail infrastructure is in place. For industry, more effective recycling may reduce the need for primary inputs and support a transition towards carbon-neutral production technologies. In the end, however, none of the measures proposed in this report will be easy to implement as they all come with specific challenges and costs. The challenge of achieving net-zero emissions within a few decades is simply enormous and will require difficult and sometimes costly measures.

FULL RESULTS

1 Introduction

With the adoption of the Paris Agreement, 192 countries agreed to hold the increase in global average temperature to well below 2 ℃ above pre-industrial levels and pursue further efforts to limit the temperature increase to 1.5 ℃. Greenhouse gas emissions need to be significantly reduced to achieve these goals. In fact, in most scenarios in the literature that aim to achieve a 1.5 ℃ goal, carbon dioxide emissions reach a level of net zero around 2050 (IPCC, 2018). In the well below 2 ℃ scenarios, this is delayed by approximately two decades. Consistently, over the past few years, 136 countries, 235 cities (each with a population of half a million or more), and almost 700 of the 2000 largest companies in the world have set net-zero emission targets (Hale et al, 2021).

Achieving net-zero emission targets is a huge task. Most scenario studies show that, in several sectors, a cost-effective trajectory to net-zero greenhouse gas emissions does leave residual emissions, which are compensated for by so-called *carbon dioxide removal* (CDR) measures, either simultaneously or later in time. The same scenarios indicate that it is very difficult to reduce greenhouse gas emissions to zero in the sectors of agriculture, aviation, shipping, industry, and buildings, compared to those from other sources. For the last sector, the difficulty lies mainly in the granularity of the sector with many actors involved and site-specific conditions, while, in the other sectors, there are technical limitations in bringing emissions to zero on a sectoral level.

Text box 1.1: Hard-to-Abate sectors

Commonly, heavy industry and international transport are referred to as ‘hard-to-abate sectors’, as they lack the technological mitigation options needed to enable reductions towards zero greenhouse gas emissions. In this study, we broadened the scope and considered not only the technical barriers but also the demand and structural barriers. Under most model-based 1.5 °C scenarios, the agricultural and buildings sectors typically also do not achieve net-zero emissions. Furthermore, in all four sectors, the pace of emission reductions under the 1.5 °C scenarios is relatively slow, while emissions are reduced rapidly in electricity generation, land transport and land use. In this study, we refer to industry, buildings, aviation, shipping and agriculture as ‘hard-to-abate’ sectors.

Compensating for residual emissions in these hard-to-abate sectors by implementing CDR measures to achieve net-zero emissions does come at a price. Such measures include large-scale afforestation, the use of bioenergy in combination with carbon capture and storage, and direct air capture. Relying heavily on these CDR measures is risky, as bioenergy crops and afforestation require large amounts of land with possible impacts on food security and biodiversity, which raises questions around the feasibility of some of these measures (van Vuuren et al., 2017; Smith et al., 2016). Moreover, their potential is only limited.

In order to reduce the reliance on CDR measures, deep emission reductions are necessary in hard-to-abate sectors. This raises the question of why this is so difficult in these sectors and what possible additional measures and policies could help overcome these difficulties. These issues form the basis of this report, answering the following questions:

i) What are the main challenges in reducing emissions in the hard-to-abate sectors of agriculture, aviation, shipping, industry and buildings, and what measures could address these challenges? (Chapter 4)

ii) What could be the additional impact of these measures on reducing emissions in hard-to-abate sectors? (Chapter 5)
iii) What are the consequences of these additional measures for the required reduction efforts in other sectors and their reliance on CDR measures? (Chapter 6)

Chapter 2 first provides background information on current 1.5 °C pathways and the role of hard-to-abate sectors. Subsequently, Chapter 3 discusses the methodology used. The answer to the first research question is discussed in Chapter 4, based on a literature review. Chapter 5 describes how we used the Integrated Assessment model IMAGE to explore the impact of some of the identified measures on sectoral emissions. We applied decomposition analysis to identify the main determinants of emission reductions. IMAGE was also used to explore economy-wide emissions and the reliance on CDR, which is described in Chapter 6.

2 Background

In addition to the stated temperature goals (well below 2 °C and pursuing efforts to limit the increase to 1.5 °C), the Paris Agreement notes that, in the second half of this century, a balance needs to be achieved between anthropogenic emission sources and greenhouse gas sinks. This is consistent with the findings of many scenario studies that show that, to keep the increase in global mean temperature below 1.5 °C by 2100 with at least a 66% chance, CO_2 emissions will need to reach net zero around 2050 (with an interquartile range of 2045–2055) (IPCC, 2018b), and that, for the well below 2 °C target, this should be achieved by 2070 (interquartile range of 2065–2080). Since it is more difficult to achieve net-zero emissions for non-CO_2 greenhouse gases, the year by which this can be achieved is about 10 years later than for CO_2 emissions, according to the scenarios. The exact net-zero year depends, amongst other things, on the exact mitigation strategy (e.g. the timing of mitigation).

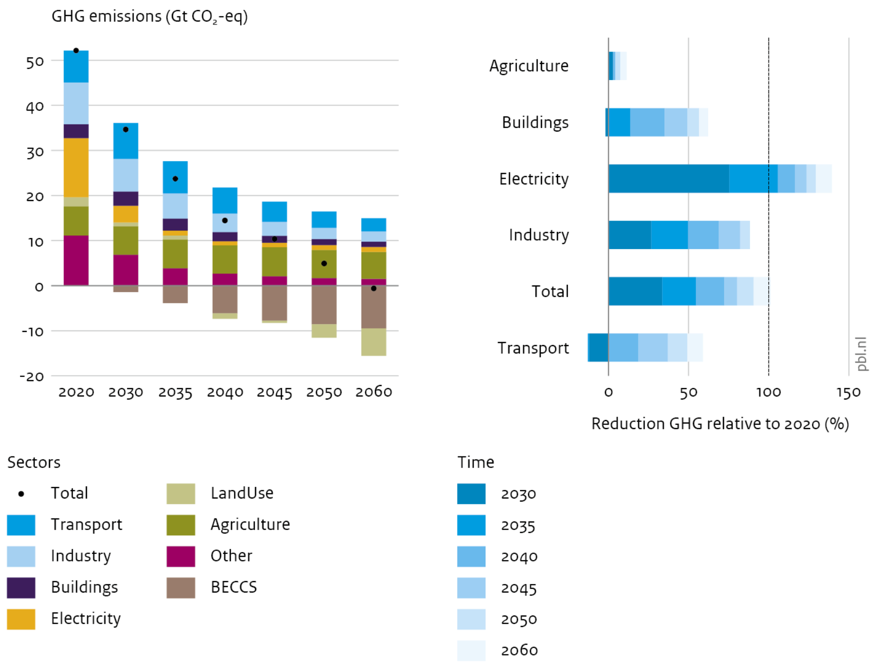
As discussed in Chapter 1, achieving net-zero greenhouse gas emissions economy-wide does not imply that emissions must be zero in every sector. Some measures, referred to as CDR measures, can capture CO_2 from the atmosphere and store it. The two most applied CDR measures in scenarios are afforestation, which leads to additional carbon storage in trees, and *bioenergy with carbon capture and storage* (BECCS). BECCS leads to negative CO_2 emissions as the cultivation of bioenergy crops removes CO_2 from the atmosphere, and these CO_2 molecules are captured when bioenergy is used as fuel, generating electricity or heat, and stored underground in geological storage reservoirs.

Most scenarios show that it is easier to achieve net-zero emissions when allowing some residual emissions in certain hard-to-abate sectors and applying CDR measures to offset those residual emissions, rather than aiming for completely decarbonising all sectors. The left panel of Figure 1 shows how, under the scenarios, net-zero emissions are typically achieved. Significant greenhouse gas emissions that remain largely consist of non-CO_2 emissions from agriculture (i.e. cattle, rice cultivation), while residual CO_2 emissions also originate from industry, buildings and transport (i.e. over land, shipping & aviation). These positive emissions are almost completely offset by negative emissions due to afforestation and BECCS.

The hard-to-abate sectors are also easily identified by the pace of their emission reductions, as shown in the right-hand panel of Figure 1. In the selected, quite typical, 1.5 °C scenario, the fastest emission reduction takes place in electricity generation, where most is already achieved by 2030. In buildings and transport, almost all reduction occurs after 2030 and in agriculture even from 2045 onwards.

Figure 1

Projected global greenhouse gas emissions using the IMAGE model, in a scenario that keeps global temperature at 1.5 °C, by the end of the century (left); and global greenhouse gas emission reductions, over time and per sector (including those from BECCS), by 2060, compared to 2020 (right).



Note: industry includes cement process emissions and emissions from cokes production. Land-use change emissions are not included in the total greenhouse gas emissions.

There are important questions regarding the feasibility of large-scale CDR measures, as there are only very few operating BECCS projects, today (Bui et al., 2018). Moreover, there are technical, social, and environmental concerns related to a large-scale application of BECCS (Smith et al., 2016). Cultivating bioenergy crops requires large amounts of land and water, which may impact food production, water scarcity, and biodiversity. There are also concerns about carbon leakage from storage reservoirs (Anderson and Peters, 2016; Bui et al., 2018; Giampietro et al., 2009). Afforestation as a CDR technology raises similar concerns, as large-scale implementation could negatively affect food security, water availability and biodiversity. Additionally, the permanence of carbon storage in forests is uncertain, amongst other things, with the increased fire risk due to climate change. Alternative CDR options, typically, have similar concerns. Soil carbon enhancement, for instance, is related to concerns of permanency and the actual potential. Direct air capture and sequestration is still expensive and energy-intensive.

However, minimising the reliance on CDR measures and associated risks requires achieving more reductions in the other sectors. As depicted in Figure 1, under current scenarios, net-zero emissions are generally not achieved in the sectors of agriculture, buildings, transport (aviation and shipping), and industry. Each of these sectors is associated with significant challenges in mitigating emissions. Chapter 4 discusses these challenges by sector, and suggests measures that could overcome them. It also provides examples of policy instruments that could help implement these measures. Next, scenarios were developed in which the identified measures were implemented — either directly or through policy instruments — to determine the effectiveness of these measures for mitigating the hard-to-abate sectors.

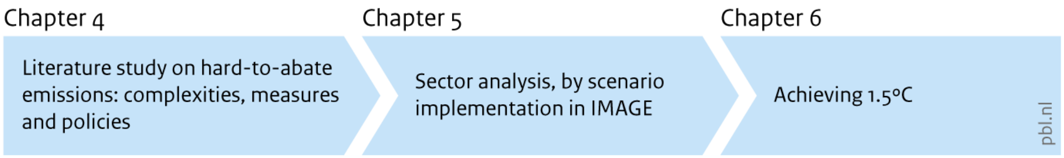
3 Methods

The method in this report consists of three steps:

1. For each hard-to-abate sector, this study first provides an overview of its characteristics and of why it is so difficult to achieve net-zero targets in these sectors. This is based on a literature review that provides an overview of the hard-to-abate sectors, their complexities and the obstacles to mitigating emissions in these sectors. This part of the methods addresses the first research question of this report.
2. We developed a set of scenarios organised in a matrix that looks into measures for hard-to-abate sectors, a) identifying demand and supply-side measures, and b) non-structural versus structural measures. These scenarios were implemented in the IMAGE model framework, and were subsequently used to examine the impact on reducing sectoral emissions, and as such address the second research question of this report.
3. Finally, we investigated how these additional measures in the hard-to-abate sectors impact the overall challenge of limiting global warming to 1.5 °C while limiting bioenergy use to sustainable levels. This part of the methods addresses the third research question of this report.

Figure 2

The three steps of the method used in this study



Source: PBL

3.1 Literature study on hard-to-abate emissions: complexities, measures and policies

The literature study first provides an overview of the characteristics of each hard-to-abate sector. We also discuss what makes it difficult to achieve net-zero targets in these sectors. The second part of the review focuses on the possible policies and measures to address these obstacles. The review serves two purposes. It presents the state-of-the-art knowledge on the characteristics of the sectors relevant for climate change mitigation and possible future developments that could impact their mitigation potential. In addition, it provides context to the model analysis, by using the identified policies and measures in developing the scenarios and in the interpretation of the model projections.

3.2 Sector analysis by scenario implementation in IMAGE

3.2.1 IMAGE modelling framework

To understand the role of the development in hard-to-abate sectors in trying to limit global warming to 1.5 °C, the IMAGE model was used. IMAGE is an integrated assessment modelling framework that simulates the interaction between human activity and economic development, on the one hand, and the environment, on the other. The model has been frequently used to explore comprehensive scenarios on global climate change mitigation, such as used for IPCC's Sixth Assessment Report (IPCC, 2022) and the UNEP Emissions Gap Report (UNEP, 2021).

IMAGE is a process-oriented integrated assessment model (IAM), providing an intermediate complexity representation of human and earth systems. The key components of the human system that largely contribute to greenhouse gas emissions are the energy system and the agricultural and land systems. The main drivers for the human system are demographic, economic and technological developments, as well as resource availability, lifestyle changes and policy. For the earth system, the modelling framework is used to describe land cover, crop growth, carbon and water cycles and climate. The human and earth systems are interconnected by emissions and land use. The socio-economic processes and most of the human system parameters are described at the level of 26 world regions, while the earth system is modelled on a 5x5 minute grid for land use and land-use changes and on a 30x30 minute grid for plant growth and the carbon and water cycles. IMAGE operates in annual time steps and, as such, is suitable for long-term climate mitigation assessments up to 2100.

IMAGE describes, in detail, the development of all five hard-to-abate sectors considered in this report. Based on historical trends, the demand for travel, housing, specific materials and agricultural products are described and related to regional economic and price developments, cultural factors and demographic development. These services can be provided or produced in various ways, depending on resource availability, technology development, operation and availability, amongst other things. Passenger transport modes include buses, bicycles, motorcycles, walking, trains, passenger vehicles and aircraft, and which mode people choose may depend on personal preferences, as well as on costs. If, for example, air travel would become more expensive due to the implementation of air passenger tax, or conversely would become cheaper due to technological developments, the kilometres travelled by air may decrease or increase, respectively. The energy consumption in buildings follows the demand for cooking appliances, space heating and cooling, water heating and lighting. The model distinguishes between urban and rural housing and five income groups. Demand for agricultural products is determined by food demand driven by increases in population and income. To fulfil demand, agricultural land use can be expanded or intensified leading to the conversion of natural land, more water and fertilizer use, and increasing non-CO_2 emissions. Measures to reduce emissions include the protection of natural land, afforestation, technological measures to reduce non-CO_2 emissions, or preference shifts in food consumption towards fewer animal-based products that have less environmental impact. The industry distinguishes between the iron and steel sector, clinker and cement, paper and pulp, food processing, non-energy and other industry. Non-energy industry includes olefins, methanol,

Table 2
Overview of modelling of hard-to-abate sectors in the IMAGE model framework

Sector	Drivers	Service provided	Technology detail
Aviation and shipping	Income, fuel price, technology development	Passenger kilometre travel, tonne kilometre transported	Aviation: 16 technologies with varying levels of efficiency, depending on production year, using bio-jet fuel or conventional jet fuel, electric aircraft and hydrogen-fuelled aircraft; Shipping: 8 technologies with varying levels of efficiency, using fuel oil, biofuel or hydrogen.
Industry and Materials	Income, population, fuel price, feedstock availability, (simplified) technology development	Material produced (e.g. in tonnes of steel, cement, paper and pulp)	Iron and steel: 13 combinations for iron ore reduction and steel production, including primary and secondary production routes; Clinker and cement: 4 different lime kiln configurations; Paper and pulp: 16 combinations for heat production across 6 heating technologies, including primary and secondary production routes; Food processing: 12 combinations for heat production across 5 heating technologies and two temperature grades (> and < 100 °C); Non-energy industry, olefins include 6 different primary feedstock production routes with 2 simplified steam cracker types and 3 secondary feedstock production routes; Other industry: simplified representations of improved energy efficiency, electrification and CCS that are correlated with the carbon price.
Buildings	Income, temperature, fuel price, technology development, electrification. Income influences floorspace and household size, which act as secondary drivers	Cooking, heating (space and water), cooling, appliances	Fossil (solid, liquid and gaseous), biomass (modern and traditional) and electricity technologies compete for market shares for space heating, water heating and cooking. For traditional biomass, we assume that 60% can be considered to be fully renewable. For the remaining 40%, the carbon content (26kg-C/GJ) is assumed to contribute to emissions. Space heating can also be provided from district heating, and electric heating is further disaggregated to resistance heating and heat pumps. Three cooling technologies (fan, air cooling, air conditioning), nine household appliance groups, and lighting increase electricity demand.
Agriculture and non-CO_2	Income, food preferences, food prices, land availability	Food	16 food crops, 5 animal products and 5 bio-energy crops; Rainfed and irrigated agriculture.

ammonia and other refinery products, and other industry consists of the non-ferrous metals, non-metallic minerals, petrochemical sector (excl. feedstock), transport equipment, machinery, mining and quarrying, construction, textile and leather and other non-specified industries.

Text box 3.1: Default climate scenarios (SSPs)
The framework of Shared Socio-Economic Pathways (SSPs) comprises five storylines for long-term global development, correlating with various challenges with respect to mitigation and/or adaptation within the context of climate change. The SSP1 scenario describes a pathway of sustainable development. The SSP2 scenario is a middle-of-the-road pathway, with intermediate challenges. The SSP3 scenario depicts a fragmented world, with large challenges for economic growth and technology development. The SSP4 scenario indicates a world of substantial inequality. Finally, the SSP5 scenario describes a conventional development pathway, where rapid growth is achieved based on fossil fuel expansion. The most recent IMAGE SSPs scenarios follow the SSPs narratives and include the impacts of the COVID-19 pandemic (van Vuuren et al., 2018a). In this report, the reference scenario is the IMAGE middle-of-the-road SSP2 scenario.

3.2.2 Sector analysis through scenario framework

To analyse what the effect could be of the additional measures identified in the literature review on the emissions originating from hard-to-abate sectors, various scenarios are developed and compared. This includes a reference scenario without climate policy, a reference scenario with a fixed carbon price that rapidly increases to high levels, and a set of scenarios in which, besides the carbon price, specific measures directed towards the hard-to-abate sectors are implemented. Chapter 5 presents the details of these additional measures, which build on the literature review described in Chapter 4.

With a rapidly increasing carbon price, this study aims to assess how much mitigation could be achieved, theoretically, in the hard-to-abate sectors. For this set of scenarios, the carbon price profile follows the following pathway :

- 2025: regionally differentiated carbon price, based on the pledged Nationally Determined Contributions (NDCs)
- 2035: convergence to a global uniform carbon price of USD 1750/tC
- 2050 onwards: global carbon price of USD 4000/tC

These carbon prices do not need to be implemented in practice to achieve the reductions shown in Chapter 5; carbon prices are simply the way mitigation policy is modelled. In reality, a diverse set of mitigation policies will lead to lower required carbon prices, as emissions are already reduced via these other policies.

This trajectory closely follows the 90th percentile of carbon price pathways of all 1.5 °C scenarios in the AR6 IPCC database. Climate policy is implemented in IMAGE through the introduction of a carbon price, which induces the system to transition from higher to lower greenhouse gas emitting technologies as investments in energy efficiency, fossil fuel substitution and additional investments in non-fossil options increase. Other policy instruments, such as energy-efficiency standards, feed-in tariffs and vehicle-efficiency standards, can also be introduced in the model via target-setting. The scenarios are compared to each other through decomposition analysis, which allows to disentangle the different developments within the sector contributing to emission changes.

Text box 3.2: Decomposition analysis

Decomposition analysis is used to analyse the impact of the additional policies and measures on sectoral emissions. The analysis decomposes the contribution of different trends on emissions. The trends consist of population, service or activity levels, structural change, energy or land intensity and carbon intensity. Generally speaking, each of these elements contribute to changes in sectoral emissions according to this equation:

$$Direct\ emissions = Pop * \frac{Activity}{Pop} * \sum_{n=1} \frac{Activity_n}{Activity} * \frac{Resource_n}{Activity_n} * \frac{Emission_n}{Resource_n}$$

The activity or service component differs per sector. For passenger transport, passenger kilometres travelled is used to measure activity; for freight, this is tonne kilometres; for the agricultural sector this is consumption of crops and livestock expressed in kcal; for industry, this is Mt in material produced; for buildings, this is floorspace in square meters. The structural change component indicates the distribution of the activity over various categories. In transport, the categories consist of transport modes, while in the residential services, these consist of the functions for which energy is used (e.g. space heating, water heating, space cooling, cooking, lighting). The exact formulation of the decomposition equation differs per sector, as each sector has different characteristics, but the concept is the same for each sector.

3.3 Achieving 1.5 °C

The final part of the analysis is aimed at better understanding how the additional policies and measures in the hard-to-abate sectors affect economy-wide 1.5 °C mitigation strategies. Specifically, it is to understand whether, with these additional measures, global warming can be limited to 1.5 °C while keeping BECCS at a sustainable level. For this set of scenarios, a global emission pathway that limits global warming to 1.5 °C is determined by minimising cumulative discounted mitigation costs, and, as such, following a cost-effective carbon price pathway.

Text box 3.3: Bioenergy deployment

A maximum limit of 60 EJ/yr was set for the deployment of bioenergy from energy crops, based on maximum levels of what can be sustainably harvested (Fuss et al., 2018). As such, the mitigation challenges in the hard-to-abate sectors can be evaluated while enforcing a sustainable use of biomass. The limit on bioenergy was not applied to agriculture and forestry residues and municipal solid waste.

4 Abatement challenges in hard-to-abate sectors

This section presents an overview of the characteristics of the hard-to-abate sectors (transport, focusing on aviation and shipping (4.1), industry and materials (4.2), buildings (4.3) and agriculture and non-CO_2 emissions (4.4)), based on literature review. The purpose is to gain some understanding of why it so difficult in these sectors to achieve net-zero emissions and to identify possible policies and measures that can address these obstacles.

4.1 Transport: aviation and shipping

4.1.1 Overview of the sector and its complexities

Aviation

Air transport is a modern means of travel characterised by strong growth over the last decades. The total number of passengers travelling by air grew from 100 million in 1960 to 4.5 billion in 2019 (IPCC, 2018b). Globally, the aviation sector emitted 1027 $MtCO_2$ in 2019, which was approximately 2.9 % of total CO_2 emissions (Crippa et al. 2019; IEA, 2021). Despite the impact of COVID-19, the growth in air passenger travel is expected to continue, leading to an estimated doubling of emissions by 2050, if no specific mitigation measures are implemented (IEA, 2021; OECD, 2019a, Esmeijer et al. 2020; ICAO, 2019). In contrast to these projections, the International Air Transport Association (IATA), representing more than 80% of all international air traffic, recently agreed to achieve net-zero carbon emissions by 2050 (IATA, 2021a), following earlier commitments to carbon-neutral growth starting in 2020 and halving emissions by 2050, compared to 2005 levels (IATA, 2009).

While activity levels have drastically dropped as a result of the COVID-19 pandemic, with, in 2020, an overall reduction in the number of passengers of 74% in international flights and 50% in domestic flights (ICAO, 2020), and a 40% decrease in CO_2 emissions (IEA, 2021), the industry expects a rebound (ICAO, 2020; Gösseling and Humpe, 2020) as observed in previous crises, such as the global financial crisis in 2008 (IATA, 2021b). The size and expected growth in the aviation sector differ across the globe. Over half of the passenger-related carbon emissions from aviation in 2019 (domestic plus international) originated from flights departing from the United States (23%), EU-28 (19%) and China (13%) (Brandon Graver, 2020). However, the European and North American growth rates of annual levels of air travel (5%–5.7% over the past 20 years) are superseded by those of Asia Pacific (8.8%) and the Middle East (13%) (Hasan et al., 2021).

There are also technical and structural challenges that make the aviation sector particularly hard to abate. Most importantly, the sector is dependent on carbon-intensive petroleum fuels, such as kerosene, kerosine-petrol mixture or aviation fuel and this dependence will likely remain in the near future due to the early development stage and limitations of alternatives (Gray et al., 2021). A major barrier to large-scale biofuel use is the required large amounts of land and water (Peeters, 2017) and there are important technical challenges in the development of electric aircraft and the requirement for battery-specific energies (Viswanathan and Knapp, 2019). Second, the sector is characterised by a relatively low fuel price elasticity, as the fuel price only consists of a limited share of its operating expenses (approximately 23.7% in 2019 (IATA, 2019) and there are only few alternatives. A third major hurdle to the introduction of new less carbon-intensive aircraft is the high life expectancy of aircrafts, resulting in a longer turnover time (Hasan et al., 2021). Fourth, from a policy perspective, the international character of the aviation sector forms a barrier for policymakers to set certain standards, due to fear of carbon leakage, and to implement an efficient carbon price mechanism. In fact, currently, apart from the European Union, international aviation emissions are not part of the Nationally Determined Commitments (NDCs).

Shipping

Maritime transport plays a major role in goods transportation. International maritime transport has seen a steady growth over the past decades and was responsible for the transport of 11,000 Mt in goods, worldwide, in 2019 (UNCTAD, 2021). Globally, the shipping sector emitted 866 $MtCO_2$ in 2019, which constituted approximately 2.4% of total CO_2 emissions (IEA, 2021). International shipping is responsible for roughly 80% of total shipping CO_2 emissions, while domestic shipping and fishing account for the remaining 20%. Emissions in international shipping have increased from 187 $MtCO_2$ in 1950 (Eyring et al., 2005) with an average growth of 2.4% per year, while, in recent years, growth has slowed down to 1.6% per year (2012–2018 period). The sector saw a stark increase (87%, 2012–2018 period) in methane (CH_4) emissions driven by an increase in the consumption of Liquified Natural Gas (LNG). Specifically, the change in dual-fuel machinery associated with LNG causes a growth in CH_4 emissions. There is a large range in future emission projections from shipping, from remaining relatively constant (IMO, 2019) until 2050 to more than a doubling of emissions (Esmeijer et al., 2020).

The shipping sector is considered hard to abate, both through the tight coupling between shipping demand increases and the growth in the global economy, as well as due to a number of techno-economic challenges. In addition, due to its international character, the global shipping sector can be a challenge to regulate. The International Maritime Organization (IMO) projects increases in demand by 2050 of 40% to 100%, relative to 2008 (IMO, 2019). Although the COVID-19 pandemic has affected the international transport sector, substantially, in the first half of 2020, transport volumes recovered by the third quarter of 2020 (UNCTAD, 2021; IMO, 2019). The international character of the sector and an associated favourable taxation regime makes it difficult to implement substantial policies in reducing emissions, similar to those of aviation. Structurally, the shipping sector has a symbiotic relationship with the fossil fuel sector. Not only does it depend on the sector for cheap bunker fuel as a by-product from oil refineries, but also as a service provider in trade of fossils. Fuel-switching requires substantial investments in new infrastructure required for low-carbon alternative fuels. The extreme difficulties of electrification and its current high dependence on cheap fuel presents a major obstacle in mitigating carbon emissions. A switch to alternative and more expensive fuels represents a considerable challenge to the shipping system, especially in the case of low-value-added products (dry bulk, liquid bulk). At the same time, the existence of many potential alternative fuels could create a problem, in terms of standards.

4.1.2 Measures and policies

Aviation

Continued research and development present several new technological opportunities, in the near future, of which some may have significant impact. IATA estimates that most emission reductions can be achieved through technological advancement in fuels (IATA, 2021a), in particular from Sustainable Aviation Fuels (SAF), a certification that ensures no degradation to or competition with existing food and water systems. It is important to distinguish alternative fuels that use existing combustion engine technology and infrastructure, and those that use electric motors, powered by either fuel cells or batteries (Gray et al., 2021). The last may only become viable in the distant future, and likely not in time for the 2050 net-zero goals (Peeters, 2017). Fuels that are compatible with existing aircraft and infrastructure are near-term solutions and partially overcome the problem of long aircraft lifetimes. They concern drop-in biofuels, possibly in blends (this is already operational in a small fraction of the sector), and Power-to-Liquid (PtL) fuels — also known as e-fuels — such as liquid hydrocarbons generated from green hydrogen. In their roadmap for full decarbonisation of the aviation sector by 2050, the European Federation for Transport and Environment (T&E) expects there will be a relatively minor share of fuel (11.4%) from biofuels, while the role of PtL is expected to be much larger (Murphy et al., 2018).

Other measures to reduce aviation demand concern incentives for increased use of teleworking to replace physical work meetings and travelling to less far away tourist destinations. High speed rail could provide an alternative for short haul travel, but, in the short run, only for those destinations where rail infrastructure is in place. Potentially less limited by speed requirements is shifting from air freight to maritime freight transport, which can be more energy efficient by a factor 10 or more (Dahlmann et al., 2016).

Other emission reductions could be achieved by adjusting operational efficiency through changing airline operation or air traffic control. Adjustments in aircraft design, such as weight reduction, improved aerodynamics and improvement in engine fuel efficiency, have been effective in the last years, but further improvements are still possible. For example, Dahlmann et al. (2016) argue that replacing the A330–200 fleet with redesigned aircraft could reduce the climate impact of the existing fleet by 32%. However, because of the long lifetime of aircraft, the current rate of fuel efficiency increase is only 1% per year. As part of the roadmap for achieving 2050 emission reduction targets, T&E incorporates an additional, but still limited, 0.5% (Murphy et al., 2018).

It has been argued that the aforementioned technological measures may only limit the growth in emissions, rather than bringing them to zero, if left without proper pricing of carbon and air travel tickets (Peeters, 2017). The required technological transitions to achieve net-zero emissions include new generations of aircraft and fuels, which require substantial financial support to develop, become competitive and allow for widespread adoption. This is especially true when considering the timing of their adoption; under current conditions, hydrogen fuel cell or electric aircrafts may become available for short distance air travel, due to additional weight requirements, by approximately mid-century (Gray et al., 2021). Technological stimuli, as well as acceptance by the industry and the general public, crucially depend on formulating globally harmonised measures. A policy measure to target demand response could be the implementation of distance-based air passenger taxes, which would compensate for the VAT exemption of international airline tickets, but also result in a more equalised approach between different transportation modes (road and rail transport do pay fuel tax while aviation does not). Harmonisation of tax levels between countries would allow them to increase, substantially. A proposal to gain public acceptance is to tax every additional passenger flight taken per year (Larsson et al., 2019), which affects frequent flyers proportionally more: approximately 71% of flights are made by commercial air travellers and 10% of fliers account for 30% to 50% of all flights taken (Gösseling and Humpe, 2020).

Aviation emissions have been included in the EU ETS since 2012 and by the ICAO initiated Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA, in 2016). The EU ETS legislation was initially made to affect emissions caused by flights to, from and within the European

Economic Area (EEA), but implementation currently only covers flights *within* the EEA. Under current policies, the EU ETS system is projected to lead to a 4% reduction in global aviation emissions, by 2036, which would be 16% if the policy would apply to the whole world (Scheelhaase et al., 2018). The CORSIA system started in 2021 and dictates the purchasing of carbon credits or investing in emission reduction projects based on a company's emissions. The global coverage is larger (71 states, 88% of global t-kms) and its effect is projected at 18% reductions, by 2039 (Scheelhaase et al., 2018).

Shipping

IMO, in its Initial Greenhouse Gas Strategy, aims to abate international shipping emissions by 50%, by 2050 (with respect to 2008) and reduce carbon intensity by 40%, by 2030 (IMO, 2018). Most measures adopted by the IMO to work towards achieving these targets focus on energy-efficiency improvements. Policies proposed to improve efficiency include the Energy Efficiency Design Index (EEDI), the Energy Efficiency Existing Ship Index (EEXI) and the Ship Energy Efficiency Management Plan (SEEMP). The EEDI makes it mandatory to increase the efficiency of new vessels in successive phases. The EEXI is required to be calculated for vessels of 400 Gt or more, indicating their energy efficiency when compared to the Energy Efficiency Design Index baseline (i.e. new vessels). Finally, the SEEMP is a plan designed to optimise the operational and technical management of shipping activities, improving their energy efficiency. The plan applies to both new vessels and those already in operation (IMO, 2018; Müller-Casseres et al., 2021).

There is a number of notable approaches to achieving abatement targets in the shipping sector. Measures to increase efficiency include more efficient ship design, such as the use of lightweight materials, the increase in vessel sizes (economies of scale) and the improvement in propulsion efficiency and waste heat recovery. The use of alternative energy sources, for instance in the form of wind energy through kites and sails, and hybrid power systems can help reduce the demand for energy from fossil fuel sources (UNCTAD, 2021; Müller-Casseres et al., 2021; Bouman et al., 2017).

One of the key measures to reduce shipping emissions is the use of alternative fuels. Alternative fuels for shipping are similar to those used in aviation. These fuels can be produced together, depending on the production process (hydrotreated vegetable oils, bio/electric Fischer-Tropsch liquids). This presents an opportunity to provide drop-in fuels to both sectors. Alternative fuels for shipping include distillates suitable for compressed ignition engines, such as biofuels produced from vegetable oils and from lignocellulosic biomass, alcohols and liquefied gases suitable for spark ignition engines, such as liquefied biomethane and biomass-based methanol and ethanol, as well as ammonia, hydrogen and, similar to aviation, electricity-produced synthetic fuels (PtL or e-fuels) (Carvalho et al., 2021). International standards and norms for the use of alternative fuels for shipping are needed to guarantee their suitability and, especially in case of biofuels, sustainability — similarly to what has been done regarding alternative fuels for aviation (Carvalho et al., 2021; IATA, 2022).

Measures aimed at shipping operations, such as optimising shipping capacity and voyages, could further reduce carbon intensity. Also, slow steaming policies can play an important role in reducing energy use in the shipping sector, because moderate reductions in speed lead to significant fuel savings. This measure does not depend on new technology, but the economics of slow steaming are complex; there is competition between financial gains from increased delivery speed on the one hand, and higher fuel efficiency at lower movement speeds on the other. Reductions in demand can also contribute to lowering emissions in the shipping sector, for instance by lowering fossil fuel demand (Müller-Casseres et al., 2021) or by allowing more localised production closer to where the demand is (UNCTAD, 2021).

Table 3
Overview of the challenges in the transport sector, and the measures and policies connected to achieving net zero emissions.

	Challenges	Measures	Policies
Aviation	Rapidly increasing demand'; Carbon-intensive fuel, with no 'off the shelf technology alternatives; Low fuel price elasticity due to fuel at a fraction of the cost price and limited alternatives; Long fleet lifetimes and slow infrastructure turnover; International sector	Sustainable Aviation Fuels; In the medium term, power-to-liquid fuel and biofuels; Long-term alternative fuelling (e.g. hydrogen in aviation); Alternative modes of transport, such as high-speed rail; Alternative tourism, increased teleworking; Adapted aircraft design; More efficient operations; Earlier retirement of conventional planes	Carbon pricing; Ticket pricing; Improved alternative transportation infrastructure; Harmonisation of policy; Investment in R&D
Shipping	International character Market competitiveness and dependence on low fuel prices; Technological problems (difficulties in electrification, no near-term alternative fuels); Demand increases, linked with economic growth; Already highly efficient marine engines	Alternative fuels; Energy Efficiency Operational measures (slow steaming); Efficient ship design	Slow steaming policy; Ship Energy Efficiency Management Plan (SEEMP); Energy Efficiency Design Index (EEDI); Energy Efficiency Existing Ship Index (EEXI); Investment in R&D

4.2 Industry and materials

4.2.1 Overview of sector and its complexities

Globally, the industrial sector contributes to about 24% of all anthropogenic direct CO_2 emissions (IEA, 2022) and is the largest energy-demanding sector, consuming 29% of the total final energy consumption (Birol et al., 2015). The bulk of direct emissions is emitted by only a few key basic industries comprising of clinker and cement (27%), iron and steel (25% in 2018), and chemicals (14%) (IEA, 2022). If historical trends are continued, the OECD (2018) anticipates that the current global primary material demand will double by mid century (OECD, 2019b). Greater growth is expected for metals and non-metallic minerals (construction materials), particularly in emerging and developing economies, while fossil fuels and biomass resources follow an overall slower trend. Environmental effects from new material demand (e.g. for steel and cement products) are projected to exceed the gains from circularity (recycling) and energy-efficiency improvements, leading to a net increase in the environmental pressure emerging from the industry sector (OECD, 2019b; van Ruijven, 2016).

Next to an increase in material demand, industry faces a number of technical challenges at the same time, making the emissions from this sector hard to abate. Unlike other demand sectors, the challenge industry is not only about decarbonising energy emissions, as many emission-intensive industries also emit a high share of process emissions. Process emissions are a result of changes made to the chemical composition of composites during processing; for example, as found in the separation of oxygen from iron ore, or the extraction of calcium from limestone. Subsequently, several heavy industries also operate under very specific conditions (e.g. high temperatures) that are not easily substituted. Given how these process emissions and industrial specificities are intrinsic to certain production processes, it requires tailored knowledge and adoption of low-carbon alternatives. Often, this implies radical changes to current production sites or a need for a new type of industry to arise.

Stimulating a new industry, or remodelling a current one requires ability and opportunity. Already under normal conditions, the heavy industries can experience difficulties as they operate in highly competitive markets with high variations in profit margins (Crompton and Lesourd, 2008; Luiten et al., 2006). Common practice, particular in industrialised countries, is for example to make investments to refurbish existing plants (brownfield investments) instead of building new plants. Compared to bulk material, the specialised, high-quality materials find themselves in a somewhat different market, where the importance of quality, reliability and timing results in a lower price elasticity and a less volatile market.

From an operational point of view, additional barriers for investments in low-carbon solutions exist as a consequence of uncertainties, in the long run. Particularly, the absence of regulatory certainty (affecting future operational costs), required infrastructure (e.g. for anticipated use or supply of hydrogen, CO_2 or electricity) or demand for the new but pricier low-carbon end product or its secondary market add uncertainty to long-term planning that needs to be bridged.

4.2.2 Measures and policies

Strategies to mitigate the climate impact of industry require a change across all value chains in society; from extraction and mining to processing, manufacturing, the end-user and back. For processing and manufacturing, the proposed solutions cover mostly fuel and feedstock switching and adopting innovative new production technologies that either enable capturing or reducing direct emissions from production. However, which strategy is to be chosen very much depends on the sector and region involved and the policy context that is put in place. For example, Gerres et al. (2019), who look into a variety of European industrial roadmaps from 2009 to 2017, show that core discussion topics amongst the industries themselves were on the conversion of energy to heat amongst the iron and steel, pulp and paper, ceramics and food sectors. Specific interests have also been placed on electrolysis (iron and steel), alternative feedstock (clinker and cement sector) and chemical, electro-chemical and mechanical separation processes (chemical and petrochemical sector). Johnson et al. (2021), repeating a similar roadmap analysis for the 2015–2020 period, show that the focus shifted to carbon capture and storage, electrification and the enabling conditions for these transformations to occur. With increasing efforts to comply with ever tightening climate objectives and conditions, more robust pathways of change per industrial sector are expected to form and materialise. A clear example is found with the steel industry, showing a strong worldwide mobilization towards a particular zero-carbon technology (hydrogen-based Direct Reduced Iron, H-DRI) since the 2020s (Vogl et al., 2021; Agora Energiewende, 2022). However, although operation starting dates have been set for some of the announced projects within the next decade, to date, only a limited number of actual investment decisions towards green production have been formalised.

A common and long-term industrial policy is frequently mentioned as a means of breaking a stalemate and providing stronger footing for the adoption of radical innovation in industry. Although countries with higher emission levels explicitly included industry in their NDCs, since COP26 in Glasgow (2021), two thirds of them still lack any specification for their industrial sub-sectors (Sanchez and Nilsson, 2021). Most remarkably, the European Union does not explicitly mention the industrial sector as a whole, despite its leading position in formulating climate ambition. From an EU standpoint, policies have remained mostly technology-neutral and focused on setting conditions and boundaries for the internal market. Particularly, the recent European Green Deal (Fetting, 2019) and the Fit for 55 package (European Commission, 2021) offer supporting guidelines and nudges into the desired direction. Policy instruments have therefore focused on making carbon-intensive production processes and imports less attractive (respectively, by increasing the carbon price in the emissions trading system (ETS), and the Carbon Border Adjustment Mechanism, CBAM, currently under discussion) on a sectoral level, while direct investment support schemes are implemented on project level to subsidise parts of the total investment costs for low-carbon innovations (e.g. EU funding programmes), or their operational costs (e.g. via Carbon Contracts for Difference). Public support is also provided to innovation projects that are considered too big for one Member State or one company alone.

More downstream, circular economy principles apply when considering strategies for mitigating the impact of the industrial value chain. Strategies include new design standards for durability, enhanced reuse and recycling. Other examples are material substitution (e.g. cross-laminated timber replacing steel) and material and value retention (e.g. through sharing economic initiatives, repair shops). Although the mitigation potential of some circularity measures that slow down, narrow or close the material flux through the economy are still contested, it is assumed that they will cause a shift away from, or restrict the need for, high-carbon production processes (McCarthy et al., 2018). Dedicated, regulatory circular economy policy packages, especially those related to industry, are considered to be effective in implementing the waste hierarchy (reduce, recover, recycle) (Fitch-Roy et al., 2021). Most activities are in an experimental phase, with a focus on a specific product or resource rather than on the entire value chain, without a clear prioritisation and timing of when concepts can be implemented.

Table 4
Overview of the challenges in the industrial sector, and the measures and policies connected to achieving net zero emissions.

Challenges	Measures	Policies
Complexity of the sector (product-wise and regionally) requires tailored policy; High competitiveness due to high energy intensity and capital costs; Intrinsic emissions in high-temperature and process industry; Demand inelastic and growing, due to linkages with other sectors, economic growth and infrastructure demand; Long lifetimes of products and factories in combination with high costs of change	Technological advancement in process industry (electrification, clean fuel, CCS); Alternative feedstock; Circularity of materials and extended product lifetimes; Material retention, substitution and efficiency; Integration of processes via scale and interlinkage of sub-sectors, also in the form of energy and carbon storage; Lifestyle change and changes to current product standards and traditions; Early retirement of current production infrastructure	Improvement in the global governance of industrial / whole value-chain transitions; Promotion of circular economy principles (product requirements, warranty times, tax on goods); Market-based policy instruments to move away from high carbon production (carbon price) and imports/exports (carbon border adjustment mechanism); Direct investment support schemes for capital-intensive equipment (e.g. Investment fund); Market development policies for low-carbon or secondary materials (e.g. green public procurement, Contracts-for-Difference); International harmonisation to avoid carbon leakage

Proposing solutions that either add a price premium to a primary product that is produced in a highly competitive environment, or that do not award an appropriate value and quality to a product and its lifecycle, hampers the creation of viable business cases or new viable markets. There are various options for creating markets for carbon-free primary or secondary production. One that is frequently mentioned is green public procurement (GPP) (Hasanbeig et al.,2021), which creates a substantial volume in demand. A market can also be specifically engineered through private partnerships. Recent collaboration initiatives include those that close part of the value chain (mostly centred around low-carbon steel use in the automotive industry or the entire value chain amongst aspiring supply chain partners (Ørsted, 2022).

Finally, many industrial value chains operate on international markets. In the current landscape, they are subjected to a wide variety of policy frameworks and national and international legislation, which make the sector potentially prone to carbon leakage. Currently, however, mostly transnational initiatives and institutions (e.g. leadership groups, climate clubs, bilateral cooperation) have taken the lead in generating momentum for a broader global governance of the industrial transition. Further mainstreaming and harmonisation could help advance the green industrial transition in line with the Paris Agreement objectives (Oberthür et al., 2021).

4.3 Buildings

4.3.1 Overview of the sector and its complexities

Energy consumed in residential and non-residential buildings combined accounts for 40% of total EU energy consumption (Li et al., 2019) and approximately a third of global final energy (IEA, 2019). Increased use of electrical appliances in combination with increasing demand for space cooling equipment resulted in an increased demand for electricity in the buildings sector between 2000 and 2017, growing by an average 2.2% per year — twice the rate of total building-related energy consumption (IEA, 2019). The largest source of end-use energy consumption in relation to buildings is space heating, representing about one third of total building-related energy consumption. Increased building envelope efficiency, as a result of improved insulation, renovations, building code enforcement, and improved efficiency have stabilised heating energy consumption, globally, over the last years, despite increasing population, wealth and changing lifestyles leading to increased demand (Lucon et al., 2014). Still, low-efficiency heating technologies, including coal, oil, and natural gas boilers, and electric resistance heating, take up the largest market share (IEA, 2019).

In 2017, the buildings sector accounted for 28% of global energy and process-related greenhouse gas emissions. Direct emissions from the combustion of coal, oil and natural gas in buildings accounted for 9% of global greenhouse gas emissions, the remainder originating from indirect emissions related to electricity consumption (IEA, 2019). In addition, poor households, particularly those in Sub-Saharan Africa and South and Southeast Asia, use significant volumes of traditional biomass for cooking and heating. Emissions arising from the use of traditional biomass are typically not included in emissions accounting, since the type of biomass used varies (firewood, dung, residues, charcoal), and it is unclear to what extent the provision of traditional biomass leads to deforestation and land-use emissions. We do, however, take these emissions into account in our scenarios, as described in Chapters 5 and 6.

In the absence of climate policy, increasing floorspace and demand for energy services (particularly for cooling and appliances) are projected to increase direct and indirect building-related emissions by 5%, by 2050, compared to 2020, and to level off thereafter. This emission increase is primarily driven by indirect emissions, whereas direct emissions are projected to decrease with increased electrification of energy services (IEA, 2019; Daioglou et al., 2022) The application of climate policy, unless complimented by energy-access policies, may lead to poor households being unable to transition to modern cooking and heating fuels due to the inflationary effect of climate policy on energy prices (Steckel et al, 2021).

By reducing energy demand through technology improvements, such as insulation, improved energy efficiency of appliances and buildings systems, and using renewable energy in the form of rooftop photovoltaics (moving buildings from energy consumers to so-called prosumers), it is technically possible to achieve zero or very low energy consumption buildings, known as a ZEBs (Yang et al., 2019; Lund, 2007). There are various definitions of ZEBs, including net zero energy and net zero emission buildings, depending on specific national targets and conditions. If the building produces more than it consumes, it can even become a so-called energy-plus building.

While reaching zero emissions for the entire building sector is technically possible, there are several challenges along the way. The buildings sector is a heterogeneous sector, involving various types of people and demographics, household structures, building archetypes and conditions that are site-specific or intersect with private, business or cultural value systems. This is why one of the first challenges concerns the fact that profitability of investments depends on local circumstances. For instance, the costs and benefits of investments, such as building insulation, photovoltaics (PV) systems or heat pumps depend on the location, the building itself, energy prices, access to capital/finance, and future cost development of installed technologies. Related to this, even if such investments turn out to be profitable, the affordability will depend on household circumstances. In fact, upgrading existing homes to achieve the zero-energy target can be exceedingly expensive, depending also on the age of the building. This point is particularly pertinent for rented housing where landlords and tenants are not willing to invest in efficiency measures, due to limited personal benefits and lack of long-term returns, respectively (Daioglou et al., 2022). The dependence of these innovations on private value judgement can be regarded as a challenge in its own right, also beyond financial aspects and associated with the perception of comfort, for example. A third challenge concerns the lifetime of buildings; the renovation of the entire building stock will take a significant amount of time, at current renovation rates of approximately 1% to 2% per year), which implies that there is a significant lock-in effect, especially in the absence of building codes tackling existing buildings and promoting renovations. Fourth, the availability of unobstructed surface areas in dense urban environments on which to install PV systems is limited. The final challenge concerns the increased electrification of energy services in buildings, combined with the high electrical load required for sub-sectorial buildings, such as hospitals. Thus, the potential of reaching net-zero emissions in building energy demand is closely related to developments in the power sector and its challenges for decarbonisation.

A review of policy practices across countries shows that a barrier to delivering the expected energy savings is the lack of local capacity to inspect and review buildings during construction for code compliance, which requires also dedicated training programmes and tools for inspecting agents as well as builders and developers. This is becoming also more important because of the trend to move to more complex buildings energy codes. Moreover, rated, tested and labelled building materials are required, in order to make implementation easier, and programme evaluation should help policymakers to identify gaps in compliance (Evans et al., 2017).

4.3.2 Measures and policies

A number of measures exist that help reduce the energy demand and associated emissions in the buildings sector. A first set of measures aims to reduce the demand for useful energy (e.g. for heating or cooling). These measures involve increased efficiency, including the thermal efficiency of buildings via insulation and renovation of building stocks, and improved efficiency of heating, cooling, cooking, and other appliances. Another way of reducing the demand for useful energy revolves around reducing wasted energy via the use of occupancy sensors and other types of sensors. Other measures concern the way building users consume energy within these spaces. This intersects with behavioural and value judgments in the residential sector, where personal choices around comfort, communalism, and foregoing of certain amenities can reduce energy demand. Specific measures include lowering thermostat settings, reducing the demand for hot water, sharing spaces and energy-consuming activities (e.g. cooking, laundry, appliance use). Net energy demand of buildings can also be reduced by fostering local energy production; for instance, via rooftop PV systems, geothermal heating, solar water heating, and small-scale district heating. A final measure that incorporates all of these elements concerns improved architectural design. This includes the promotion of spaces and facades in which passive heating, cooling, ventilation, and lighting, local energy production is incorporated, as well as design that encourages occupants to change their behaviour to reduce energy demand.

The implementation of building energy code policies has proven an effective policy measure to reduce carbon emissions, for example, in Europe and the United States. In 2015, more than 40 national governments had building energy codes in place (Cox, 2016), and they are an important instrument that countries pledged to use as part of their NDCs (Evans et al., 2017). The extent of the energy coverage by energy code policies, however, varies significantly per country. In some cases, the policy covers all buildings and various building systems, such as lighting, envelope, heating, ventilation and air conditioning (HVAC), while others specifically apply to, for example, the envelope of newly constructed buildings. It is increasingly understood that effectiveness strongly depends on policy implementation. It has been argued that big data techniques and building smart readiness indicators could provide more reliable information of the achieved energy savings (Li et al., 2019).

Regulatory policy instruments that enforce implementation of efficiency gains may generate welfare loss and exacerbate inequalities, especially for those that gain less from improved efficiency. Moreover, they target mainly the investment sector while energy curtailment is not addressed and could result in a rebound effect. In that sense, implementation of information, financial or economic policies leading to behavioural change can be more effective than tackling specific energy demand aspects within the sector. For example, an energy tax could not only lead to an increase in the use of LED lightbulbs, but may also reduce unnecessary lighting. Informational instruments disclosing information on potential savings through product labelling or energy audits, peer comparison as well as presenting real-time energy consumption can also have a positive effect on energy conservation (Cattaneo, 2019). Targeted policies and access to financing could also help overcome certain inequalities concerning capacity to mitigate, particularly on the landlord–tenant effect and insurmountable upfront costs faced by some households, as mentioned above. These could include building codes as well as access to cheap loads and mortgages.

Table 5
Overview of the challenges in the buildings sector, and the measures and policies connected to achieving net zero emissions.

Challenges	Measures	Policies
Heterogeneity across locations, building archetypes, local conditions; High costs of investments make profitability and affordability non-trivial; Conflicting motivations to take on investment costs across landlords and tenants; Household decisions dependent on private value judgments; Long lifetime and slow renovation pace, stock lock-in; Limited availability of unobstructed surface for PV systems in urban areas; High required electricity load for particular sub-sectorial buildings; Limited capacity for evaluation of compliance	Insulation and renovation; Local electricity and energy generation; Higher efficiency technologies; Reduced waste via occupancy sensors, stand-by mode for appliances; Behavioural change concerning appliance ownership and demand for energy services; Communal spaces and shared energy services (e.g. cooking, appliances); Lower floorspace per capital (e.g. smaller houses, increased household sizes); Energy-efficient architectural design; Switch from traditional biomass for cooking to cleaner alternatives	Energy or emissions tax; Information and awareness; Increased access to funding for poorer households (e.g. subsidies, low interest loans/mortgages); Building energy performance standards and certification; Subsidies on cleaner cookstoves

4.4 Agriculture and non-CO_2 emissions

4.4.1 Overview of sector and its complexities

Anthropogenic emissions originating from agriculture, forestry and other land use (AFOLU) are estimated to comprise approximately 23% of global anthropogenic greenhouse gas emissions (Crippa et al., 2019). Between 2007 and 2016, AFOLU net emissions amounted to an estimated average of 12 $GtCO_2$ eq, 6.2 $GtCO_2$ eq of which originated from the agricultural sector and 5.8 $GtCO_2$ eq from land use, land-use change and forestry sector (LULUCF) (IPCC, 2019). The net 6.2 $GtCO_2$ eq emissions from agriculture can be split into 4.0 $GtCO_2$ eq methane (CH_4) and 2.2 $GtCO_2$ eq nitrous oxide (N_2O) (IPCC, 2019). Model-based projections show that CH_4 and N_2O emissions from agriculture will steadily increase towards 2100, in the absence of climate policy (roughly 50% on average compared to the present day, but with large uncertainties) (Harmsen et al., 2020; Gidden et al., 2019).

The continuing intensification and expansion of the agricultural sector, associated with increases in the use of synthetic fertilizer and manure production, is the primary driver of the increase in N_2O emissions. Grazing covers about 70% of global agricultural land use, which also impacts the carbon cycle, due to deforestation and land degradation. Moreover, 34% of global cropland is used to produce feed for livestock (Stehfest et al., 2019). Agricultural CH_4 emissions predominantly originate from enteric fermentation in the digestive systems of ruminant animals, and from rice cultivation. Livestock production contributes 66% of the total agricultural CH_4 emissions, mainly from ruminants (cattle, sheep and goats) that due to their physiology produce much more CH_4 than do pigs and poultry. Manure management also contributes smaller but significant amounts of CH_4 emissions (IPCC, 2019).

The direct relationship between the sector's greenhouse gas emissions and food brings us to the first challenge along the way to abate emissions in this sector; population growth is generally associated with higher demand for agricultural products, and GDP growth correlates with an increased consumption of animal products. Dietary changes would change this relationship, but involve barriers associated with consumer behaviour, marketing and the cultural position of food. Besides problems on the demand side, a second challenge concerns technological solutions (examples are given below) that target the same emissions and thus lead to diminishing returns when implemented simultaneously. In fact, it has been found technically impossible to reduce agricultural emissions to zero, even if all identified measures are applied (Harmsen et al., 2019). Unlike with CO_2 emissions, negative non-CO_2 emissions via biological or chemical capture are either impractical or impossible. However, removal via photocatalysis in large chimneys has been proposed as an option for negative non-CO_2 emissions (de Richter et al., 2018). This option is not included in this study, because pilot projects have only recently started (CORDIS, 2020), making costs and benefits speculative. A third challenge to abating emissions in this sector concerns the competitiveness of the agricultural market and, in some cases, the high investment costs for mitigation measures. The high investment costs form barriers particularly for smallholder farms, who account for approximately one third of the world's food (Ricciardi et al., 2018). Besides the financial aspects of agricultural innovation, certain measures, such as emission-efficient tillage and residue management require knowledge and training. In general, there are two sides to the high competitiveness and resulting innovation; it stimulates the productivity of the sector, but may also reduce the revenue margin (and, in turn, the investment potential), increase pollution and threaten animal welfare.

4.4.2 Measures and policies

As with other sectors, there are both technological and behavioural or demand-based measures to mitigate emissions in the agricultural sector. On the technological side, there are several changes to the production process that farmers could apply, in order to significantly reduce direct CH_4 and N_2O emissions. Promising practices for CH_4 include genetic selection and breeding of ruminants, feed management to reduce CH_4 emissions from enteric fermentation (e.g. changing feed composition and the use of feed additives) (Roe et al., 2020), alternate flooding and draining to reduce CH_4 emissions from paddy fields, the application of anaerobic digesters and decreased exposure of manure that would limit CH_4 emissions from animal waste. Similarly, the use of more efficient fertilizer application levels, improved land manure applications or nitrification inhibitors can reduce N_2O emissions from manure and fertilise use. Although these measures will not completely reduce all emissions (see the second challenge), they are expected to have a significant effect. For example, alternate flooding and draining of the land in rice production may lead to an estimated reduction efficiency of 57% (Harmsen et al., 2019). Agricultural activities largely take place in the open air and, therefore, fully capturing emissions directly is largely impossible, given that plants require nitrogen and ruminants will always produce CH_4. Agricultural land can also be managed differently, such as by limiting the amount of land used (reducing deforestation), limiting the use of peatlands or raising the water table, preventing soil carbon loss or increase soil carbon stocks by reduced tillage or biochar, or by increasing tree cover as part of the agricultural landscape which increases carbon storage (agroforestry and silvopastoralism). While the potential of such measures is high, according to the literature (Roe et al.,2020; van de Esch et al., 2021), it is also surrounded by large uncertainties regarding interactions with the food system. Therefore, we did not include them in this study.

A fast-growing yet costly technology to reduce food and feed consumption is the production of cultured meat (The Good Food Institute, 2019). This technology involves the cultivation of animal cells in a laboratory environment, thus, producing meat without the need for animal husbandry. Social acceptability of the technology forms an adoption challenge, although a trend towards public acceptance has been observed (Post et al.,2020). Although cultivated meat is suggested to be more efficient than conventional meat, in terms of greenhouse gas emissions, water consumption and land use, it may be more energy intensive (Mattick et al., 2015; Tuomisto et al., 2011), which means the environmental benefits depend on the availability of clean energy.

In addition, several studies show that measures affecting the demand side, such as dietary change towards less animal-based diets, may help mitigate the expected growth in livestock-related emissions[71,83]. For instance, a global shift towards a plant-based diet would reduce agricultural greenhouse gas emissions by 56%, by 2050, compared to under baseline scenarios (Springmann et al., 2018). In the proposed diet, red meat would be limited to one portion per week, and white meat to a half portion per day. While the impact of such changes would be very large, there are behavioural change barriers (Eker et al., 2019), as this would require billions of people to change their dietary behaviour, which, in turn, points to a potential role for plant-based meat alternatives and artificial meat. Food demand can also be reduced by reducing food loss and waste, and by improved management of supply chains, transport and processing. Currently, about a third of the food (mostly staple crops, fruits and vegetables) is either lost before it is sold or wasted in households (FAO, 2011). Halving this waste and loss (in line with Sustainable Development Goal pledges) is estimated to reduce environmental pressures from this sector by 6% to 16%, by 2050, compared to under baseline scenarios (Springmann et al., 2018).

A number of policy instruments that are aimed at reducing emissions in this sector make it easier for smallholders to adopt technological innovations or land management techniques. Such policies involve training courses for farmers or the provision of the required capital through subsidies and support schemes. More sustainable farming practices can also be encouraged through better legislation on manure management, capping livestock numbers, prohibitions on burning residues, and setting emission standards. In line with the Glasgow Agreement, banning deforestation and products derived from deforested areas or other ways of reducing emissions from land-use change are important measures to abate emissions from this sector. For policy to be effective, it is important to highlight and target the role of food retailers and companies, as they can manipulate demand through marketing and pricing of a selection of products, and via their indirect emissions in the value chains (i.e. scope 3 emissions). A commonly mentioned policy for inducing behavioural change is that of taxation — either on the demand side (meat tax) or the supply side (CH_4 tax). These policies would of course lead to food price increases, which would particularly affect the poor (see the first challenge mentioned above). Lessening these inequalities could be addressed by generic income policies.

Table 6
Overview of the challenges in the agricultural sector, and the measures and policies connected to achieving net zero emissions.

Challenges	Measures	Policies
Continued increases in food demand and behavioural barriers to dietary change; Technological solutions overlap and are not enough to go to zero; In some cases, high up-front investments for farmers and lack of incentives; Competitive market; Majority of emissions are from smallholder farms; Non-financial barriers for farmers refer to knowledge and training.	Technological solutions: more efficient livestock farming: genetic selection, feed additives; In rice production: reduced flooding techniques, reduced fertilizer and runoff: higher fertilizer efficiency, nitrification inhibitors; Land management techniques: higher water tables on peat soils, different agricultural management to increase soil carbon, increased tree cover in agricultural landscapes; Alternative products (e.g. artificial meat); Structural changes required to build knowledge, investment profitability, improved manure and livestock management systems; Dietary changes; Decreases in food waste in farm processing, retail and households.	Incite innovation: R&D, subsidies, training; Stronger legislation for farmers: e.g. manure management, burning residue prohibition, emission standards; Stronger legislation for food retailers and companies; Taxes.

4.5 Similarities and differences between the hard-to-abate sectors

Summarising the above, there are a number of similarities with respect to the challenges that make the emissions in the four sectors hard to abate. For most of them, emission abatement is impeded by the expected substantial growth in demand for services and products provided by these sectors, such as housing, industrial goods, food and long-distance travel. Another similarity between the sectors is their dependence on commercially available mitigation technologies or the presence of critical challenges to implement them. This can be the result of, for example, international, competitive markets that form a barrier to the implementation of mitigation policies, or large upfront costs combined with the long lifetime of structures and infrastructures, which can create a major barrier to rapid change (Gray et al., 2021; Wesseling et al., 2017). For some sectors, their output directly affects important economic benefits, such as in industry and transport, or is close to people's personal lives and individual choices, such as in cases of travel, housing and food consumption, therefore policies might lack public support. The diversity of users, possibly with limited financial means, knowledge and training, or site-specific conditions are also common factors that hamper the adoption of innovative practices (Bui et al., 2018; Giampietro, 2009) notably in agriculture and the buildings sector.

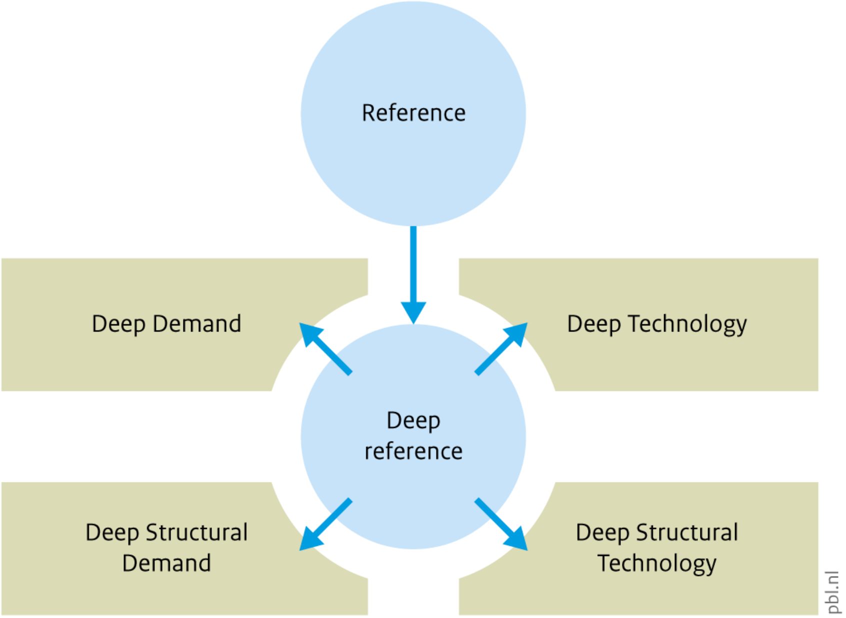
This chapter discusses the proposed measures and policies to address these challenges which also contain similarities and can be placed into a few categories. In most of the sectors, technological advancements associated with sustainable fuels, electrification and efficiency-improving techniques are an important part of the potential measures, followed by procedural advancements regarding operations, circularity and waste, some of which tackle the long lifetimes and slow adoption of technological advancement. Especially in the agriculture and building sector, effective measures can also be found on the demand side in the form of lifestyle changes. Common aspects of policy concern pricing, taxation of high-emission services and products and subsidies on low-emission alternatives, either regarding the end product for consumers (e.g. airline tickets or meat) or earlier in the supply chain (e.g. sustainable transport fuel and process emissions). To avoid carbon leakage, internationally harmonised policy has also been mentioned as an important ingredient of emission abatement in these sectors — specifically in industry and transport. As mentioned before, abatement challenges due to technological dependence can be addressed through direct investments in R&D and training, which can break the impasse of investments being commercially non-viable or risky in competitive markets in industry, transport and agriculture. Finally, for some products and services, it may be effective to enforce standards and verification mechanisms by means of legislation — for example, in cases of building-related energy efficiency standards or emissions from agriculture.

5 Scenario analysis

5.1 Scenario assumptions

The literature review in Chapter 4 shows that the challenges to mitigate emissions in the hard-to-abate sectors can be divided into those related to either demand or technology. To understand the role of changes in demand and technology when it comes to mitigation in the hard-to-abate sectors, four new scenarios were developed that distinguish between measures that address technological and demand-side changes (see Figure 3). Demand-side changes are defined as those in the consumption of services, compared to the *Reference* (i.e. baseline without climate policy), while, on the technology side, changes concern technology deployment in the provision of services, and relate to innovation, operation and technology diffusion. A second distinction can be made between fundamental, structural and non-structural changes to the way a sector operates. These four distinct pathways (Deep Demand, Deep Technology, Deep Structural Demand and Deep Structural Technology), which were newly developed for the analysis of this report, examine the additional mitigation potential of the identified policies and measures, and study the required effort and feasibility of reaching lower emission levels in these hard-to-abate sectors. The framework also helps understand the role of changes in technology and demand in overcoming the obstacles and what it would take to achieve net zero emissions in the hard-to-abate sectors.

Figure 3
Overview of the mitigation scenarios



Source: PBL

Deep Demand scenario

Under the *Deep Demand scenario,* the demand for services is reduced, compared to under the *Reference* scenario. The hard-to-abate sectors are characterised by substantial growth in demand, if current trends continue, which is closely linked to economic growth and personal welfare, making it more difficult to mitigate emissions. The changes in demand under this scenario do not require fundamental changes in how sectors operate but do push them to their limits within current operation modes. In the buildings sector, the demand for energy is reduced in various ways, such as by people lowering the thermostat setting, taking shorter showers, and using occupancy sensors to minimise energy waste. The demand for steel, cement, paper and pulp, non-energy products and other industrial products is assumed to remain at the 2023 level. This assumption can be considered at a level in-between that under the *Deep Structural Demand* scenario (see next paragraph) and the *Reference* scenario. For the agricultural sector, a lower demand for animal products is assumed, as 60% of the global population is expected to transition towards a less meat-intensive diet. Measures that prevent higher food prices as a result of mitigation measures are removed, which gives more priority to the implementation of non-CO_2 emissions than is the case under the *Reference* scenario. Note that this is applied in all scenarios of the framework. In addition, food waste throughout the supply chain is significantly reduced. In the transport sector, there is a lower increase in the money spent on transportation with increased income, leading to less transport growth in high-income countries. Furthermore, a global taxation on airline tickets is also implemented.

Deep Structural Demand scenario

Under the *Deep Structural Demand scenario,* the sectors are required to implement changes in their operating methods, resulting in a strong reduction in demand. These changes are additional to other changes to reduce demand. Demand for aviation transport will decrease due to increases in teleworking and local rather than international tourism. Short-distance flights are replaced by high-speed rail in regions where such infrastructure is either available, under construction or planned. Over the course of the century, a full transition to a low-meat, healthy diet is expected to take place, which will impact the agricultural sector. With respect to the buildings sector, co-living will become common practice, increasing occupancy rates and reduced appliance ownership and floorspace used per capita. In the industrial sector, material demand decreases at the same rate as projected under the Low Energy Demand (LED) scenario presented in the Resource Efficiency and Climate Change (RECC) report by the International Resource Panel (IRP) (Hertwich et al., 2020). The 43.5% reduction in material by 2060, compared to 2016 levels, as is seen under the LED scenario, is applied in the *Deep Structural Demand* scenario from 2023 onwards and can be considered a rather extreme reduction in the demand for material.

Deep Technology scenario

Under the *Deep Technology* scenario, fast diffusion of innovative low-carbon technologies takes place, assuming an optimistic outlook on technology development and adoption. In the industrial sector, only efficient production technologies are available to produce cement and steel. The paper and pulp sector is increasingly electrified, and fossil fuels are only used by CHP (combined heat and power) technologies. In buildings, fossil fuel space heating will be completely phased out after 2050, with increased use of heat pumps and faster technology turnovers. Increased access to loans and low interest rates, amplifying households credit will allow for more adoption of efficient yet expensive technologies, including the renovation of building envelopes. Urban households who use traditional biomass for cooking switch to cleaner alternatives. The aviation sector sees faster development and adoption of efficient aircraft. The aviation fuel infrastructure is adjusted so that bio-jet fuel can easily be blended with fossil fuels. Moreover, the state of the art in operational efficiency is implemented, worldwide. In the agricultural sector, the demand for livestock decreases due to a moderate shift towards the consumption of artificial meat. The assumption being that the feedstock of artificial meat is maize, which has a 42% caloric conversion efficiency (Mattick et al., 2015).

Deep Structural Technology scenario

Under the *Deep Structural Technology* scenario, technological changes require fundamental changes in the current mode of operation. Electric aircraft are available for short-distance travel, and hydrogen, or e-fuelled aircraft are used for the short-to-medium distances. The transition towards these alternative propulsion techniques is accelerated due to early retirement of traditionally fuelled equipment. New architectural designs, in the building sector, lead to a lower demand for heating, and promote alternative residential paradigms, resulting in more efficient use of space and facilities. Traditional biomass is being phased out for cooking for both urban and rural households. In the steel sector, only electric arc furnace (EAF), hydrogen steel making and electrowinning are available, resulting in rapid phase-out of fossil fuels. Also, for cement and paper and pulp, electrification is highly stimulated. In addition, for paper and pulp, only non-fossil energy inputs are available. Artificial meat becomes the dominant market player, resulting in 60% reduction in meat by 2050, and 80% by the end of the century. Moreover, the maximum reduction potential for agricultural CH_4 and N_2O sources is increased. This is most impactful for enteric fermentation, where there is a widespread use of novel techniques, such as the seaweed Asparagopsis taxiformis as a feed additive.

Table 7
The specific assumptions made in the Deep Demand (a.), Deep Structural Demand (b.), Deep Technology (c.), and Deep Structural Technology (d.) scenarios, for the four sectors
a. Deep Demand

Transport	Buildings	Industry	Agriculture
Airline ticket tax of USD 4 per flight; Faster saturation of increasing money spend on travelling with increased income; Faster saturation of freight demand-IVA elasticities.	Reduction in Cooling Degree Days/Heating Degree Days; Reduced ownership of household appliances; Reduced heating, cooling, appliances and lighting waste via e.g. occupancy sensors, avoiding stand-by mode; 25% reduction in hot water demand (shorter showers).	Steel, paper and pulp, cement, non-energy and other industry: Keep material demand at 2023 level until 2067. After 2067, the default (*Reference*) assumptions on material demand development are applied; These assumptions are considered somewhat in between the assumptions under the *Reference* and Structural Demand scenarios.	Reduction in meat consumption towards a maximum of 40% of healthy diet levels[88] by 2050 and 50% by 2100 Reduction in food waste at farm, processing, retail and household levels by 20% by 2050 and 25% by 2100. Non-CO_2 emission factors: No disincentive to mitigate in agriculture (i.e. no measures to prevent higher food prices).

b. Deep Structural Demand

Transport	Buildings	Industry	Agriculture
Transition between 2025 and 2035 to shift from short-distance aviation to high speed rail; Teleworking and alternative tourism, reducing travel-distances result in a 25% reduction in activity.	Converge regional per-capita floorspace to 45 m²; Increase in household occupancy rate by 20% in more affluent regions, thus reducing the per-capita ownership of appliances.	Steel, paper and pulp, cement, non-energy and other industry reduce material demand according to the LED scenario in the IRP RECC report (Hertwich et al., 2020). This scenario shows an average 43.5% decrease in demand by 2060 compared to 2016. This decrease rate is applied on material demand from 2023 up to 2067. After 2067, standard default assumptions on material demand development are applied.	Transition towards healthy diets (following Willet et al. (2019)), transition implemented by 80% by 2050 and 100% by 2100; Reduction in food waste at farm, processing, retail and household levels by 40% by 2050 and 50% by 2100; Non-CO_2 emission factors: No disincentive to mitigate in agriculture (i.e. no measures to prevent higher food prices)

c. Deep Technology

Transport	Buildings	Industry	Agriculture
More fuel-efficient aircraft on the market; Light weight and retrofitted; Drop in Bio-jet fuel can replace kerosine in existing aircraft.	No fossil fuels in space heating after 2050 and promote use of heat pumps; Accelerate transition away from traditional biomass in urban households; Promoting refurbishment of heating technologies and appliances with newer / more efficient versions; Increase share of air-coolers as space cooling technology from 10% to 30%; Increase credit to households for adoption of efficient yet expensive technologies, including building envelope renovation; Increase efficiency of cooking, cooling, and heating technologies; Use net-metering, promoting the use of residential PV.	Steel: Inefficient blast furnace technologies not available from 2021 onwards; Cement: Inefficient technologies not available from 2021 onwards; paper and pulp: Premium factor for the use of biomass, electricity and hydrogen. For fuel types having a CHP (combined heat and power) option available, only the CHP option is active from 2025 onwards.	Moderate reduction in meat consumption due increase in the consumption of artificial meat: implemented as a 20% reduction by 2050 and 30% reduction by 2100; Non-CO_2 emission factors: No disincentive to mitigate in agriculture (i.e. no measures to prevent higher food prices).

d. Deep Structural Technology

Transport	Buildings	Industry	Agriculture
Electric aircraft for short-distance aviation; Hydrogen fuelled aircraft for short- and medium-distance aviation; Faster market turnover.	Increased use of architectural designs that have lower heating demand (i.e. appartements as opposed to detached housing); Promote alternative residential paradigms (i.e. increased communal spaces and sharing of cooking stoves and other household appliances); Accelerate transition away from traditional biomass in urban and rural households.	Steel: Only EAF, hydrogen used in steel making (from 2030 onwards) and electrowinning (from 2040 onwards); Cement: Inefficient technologies not available ; Premium stimulating electricity use; paper and pulp: Only non-fossil technologies; Premium stimulating electricity, biomass and hydrogen use.	Strong reduction in meat consumption due to an increase in the consumption of artificial meat: implemented as a 60% reduction by 2050 and an 80% reduction by 2100; Non-CO_2 emission factors: 1) No disincentive to mitigate in agriculture (i.e. no measures to prevent higher food prices); 2) Increased maximum reduction potential by 2100 for CH_4 and N_2O: Rice production: 80% Enteric fermentation: 60% Fertilizer use: 70% Animal waste/manure CH_4: 80%, N_2O: 70%

5.2 Reducing greenhouse gas emissions in the hard-to-abate sectors

This section presents the impact of the measures listed in Table 7 on the achieved emission reduction, per sector. A comparison is made between the *Reference* scenario without climate policy, a reference scenario with climate policy (referred to as *Deep Reference*) and the four additional newly developed scenarios with climate policy (indicated by '*Deep Demand*', '*Deep Technology*', '*Deep Structural Demand*' and '*Deep Structural Technology*'). In all climate policy scenarios, very stringent climate policy is assumed to be in place, represented by a steep rising carbon price. This also means that some of the measures listed in Table 7 could already be (party) adopted in the *Deep* Reference scenario. In other words, not all of the measures listed in Table 7 are additional to the *Deep Reference* scenario. The results allow to reflect on how the measures that are additional could help to achieve net zero emissions in the hard-to-abate sectors, and the effort that it would take to reach net-zero on a sectoral level. This section discusses the four hard-to-abate sectors, aviation and shipping (5.1), industry and materials (5.2), buildings (5.3), and agriculture and non-CO_2 emissions (5.4)). The emission developments are analysed through decomposition analysis, of which the underlying formulas can be found in the Appendix.

5.2.1 Aviation and shipping

Figure 4 shows the decomposition of the emission development in the passenger transport sector in population, activity growth, modal shift, energy efficiency and fuel shift. For passenger transport, the activity levels (A) are expressed in passenger-kilometres (pkm), whereas for freight, tonne-kilometres (tkm) are used. The latter reflect the amount of transported goods multiplied by the distance over which they have been transported. For both freight and passenger transport, the decomposition includes shifts in the transport modes expressed as mode shares. Energy efficiency is given in energy use (FE) per activity level (tkm and pkm) per mode and carbon intensity as the ratio of CO_2 emissions over energy use per mode.

Table 8
Components in the decomposition of passenger and freight transport emissions

Component	Population (P)	Activity (A)	Modal shift (M)	Energy efficiency (E)	Carbon Intensity (I)
Passenger	Pop	$\frac{Pkm}{Pop}$	$\sum_{n=1}^{Mode} \frac{Pkm_n}{Pkm}$	$\frac{FE_n}{Pkm_n}$	$\frac{CO2_n}{FE_n}$
Freight	Pop	$\frac{Tkm}{Pop}$	$\sum_{n=1}^{Mode} \frac{Tkm_n}{Tkm}$	$\frac{FE_n}{Tkm_n}$	$\frac{CO2_n}{FE_n}$

Under the *Reference* scenario, globally emissions are expected to grow to a little over 7 Gt per year, by 2050. This is the result of the combined effect of population growth, activity growth and a modal shift towards the more carbon-intensive transport modes, such as aircraft and cars. Improved efficiency of passenger vehicles, largely due to electrification and the resulting reduction in carbon intensity, partly compensates the increasing demand. As a result, aviation emissions have an increasing share in total transport CO_2 emissions by 2050. Under the reference climate policy scenario (*Deep Reference*), transport activity reduces with respect to reference levels, resulting in decreasing emissions from passenger vehicles, aviation and buses. Compared to the *Reference* scenario, there is a modal shift away from aviation, further reducing transport emissions. However, the large-scale electrification of passenger vehicles and busses, globally, leading to energy efficiency and carbon intensity improvements, is the dominant factor in mitigating transport emissions. While the aviation sector sees efficiency improvements, due to a shift towards next-generation technologies, and fuel intensity decreases as a result of the use of biofuels, the achieved emission reduction in the aviation sector is limited compared to the changes observed in the other modes. As a result, the aviation sector is taking up the majority share of emissions remaining in 2050.

The airline ticket tax, under the *Deep Demand* scenario, combined with a faster saturation of transport demand, decreases the aviation activity and further amplifies the shift from aviation to other modes, compared to the *Deep Reference* scenario. Under the *Deep Structural Demand* scenario, as a result of the increased teleworking and alternative tourism to local areas, the activity reduction is amplified. Moreover, this scenario assumes the use of high-speed rail for short-distance travel in those regions where infrastructure is either currently in place or planned, resulting in a shift away from aircraft. The result is that, under the *Deep Structural Demand* scenario, aviation emissions are decreased by almost 50% (~0.4 $GtCO_2$ reduction by 2050), compared to the *Deep Reference* scenario. Under the *Technology* scenarios, more efficient technologies are on the market, such as blended wing body aircraft. Drop-in biofuels, under this scenario, are used, which means that they are a complete substitute for conventional jet fuel, and respond directly to biofuel availability and price. Under both the *Deep Technology* and *Deep Structural Technology* scenarios, in the first decades, there is a large increase in use of biofuels. However, as biofuels are more in demand in other sectors resulting in increased fuel prices, they become less attractive to use in the aviation sector. The *Deep Structural Technology* scenario sees increased electrification and a shift to hydrogen, but this does not start to kick in until after 2050 and really picks up speed in 2070, when this technology start to mature, despite the faster technological development and market turnover.

Figure 4
Decomposition of passenger transport CO_2 emissions over the factors Population (P), Activity (A), Modal shift (M), Energy efficiency (E) and Fuel shift (I). The top left panel shows the reference emissions by 2050, compared to 2015. The five other panels show the mitigation scenario by 2050, compared to the reference emissions by 2050.

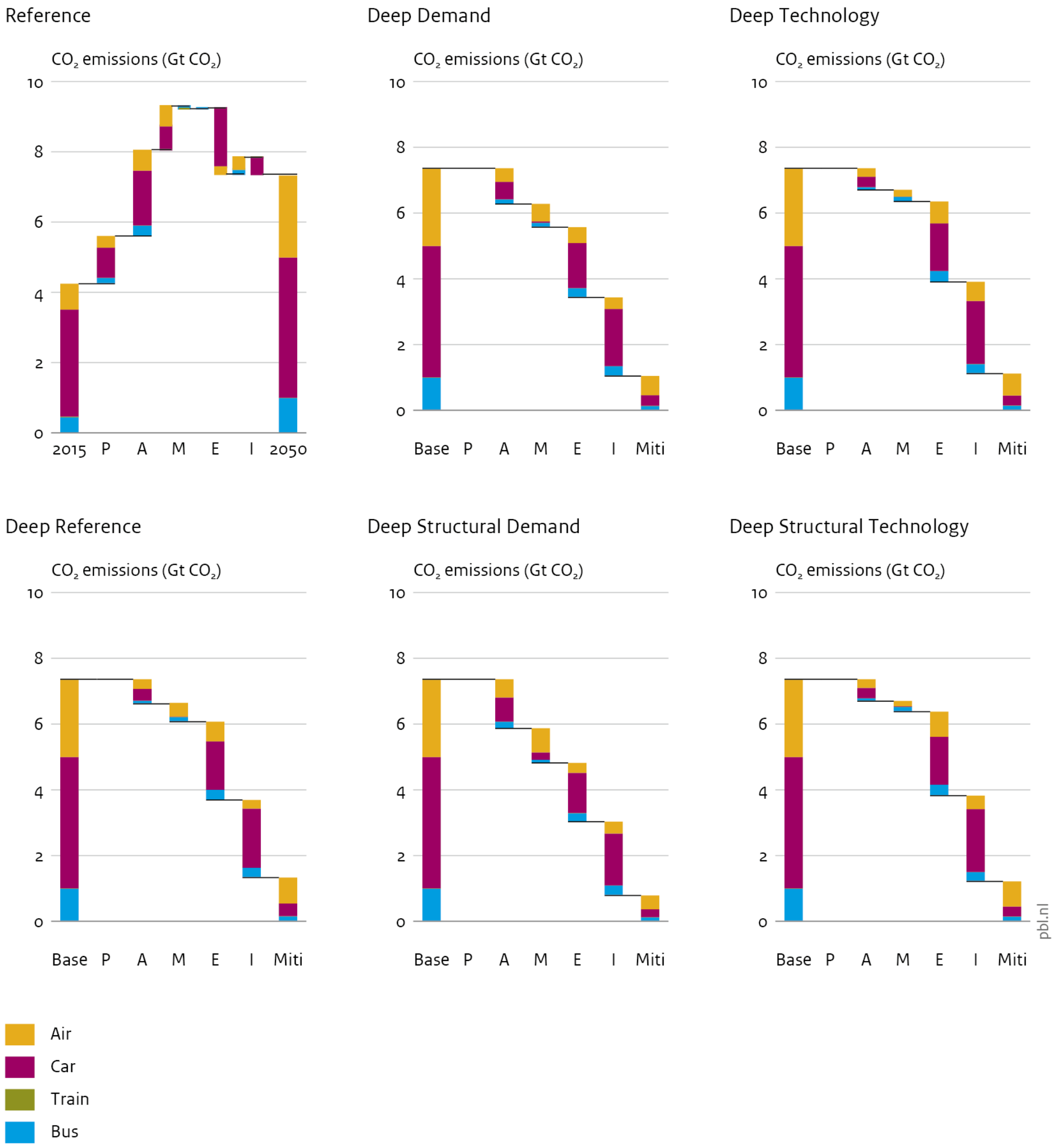
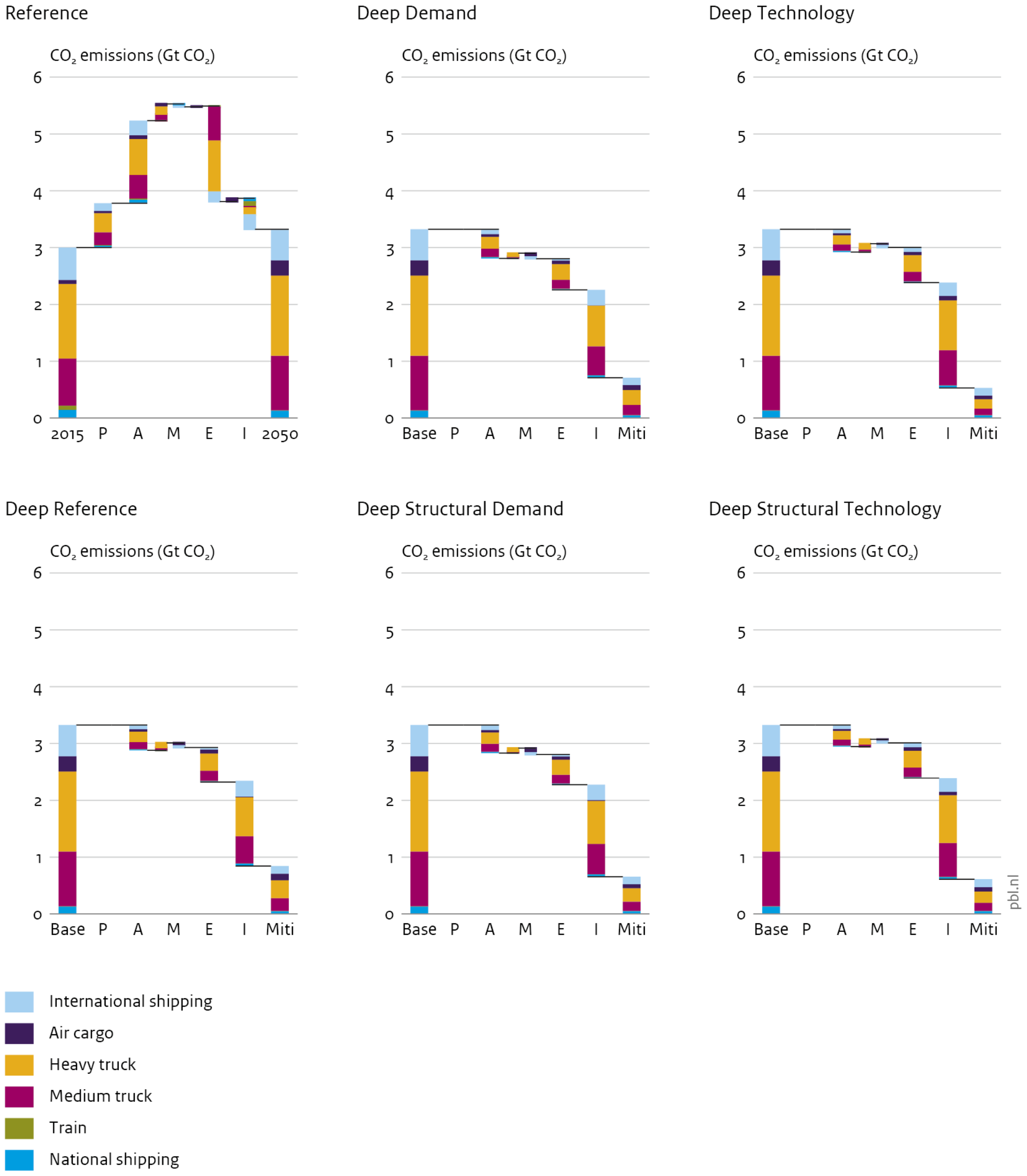


Figure 5
Decomposition of freight transport CO_2 emissions over the factors Population (P), Activity (A), Modal shift (M), Energy efficiency (E) and Fuel shift (I). The top left panel shows the reference emissions by 2050, compared to 2015. The five other panels show the mitigation scenario for 2050, with carbon price, compared to the reference emissions by 2050.

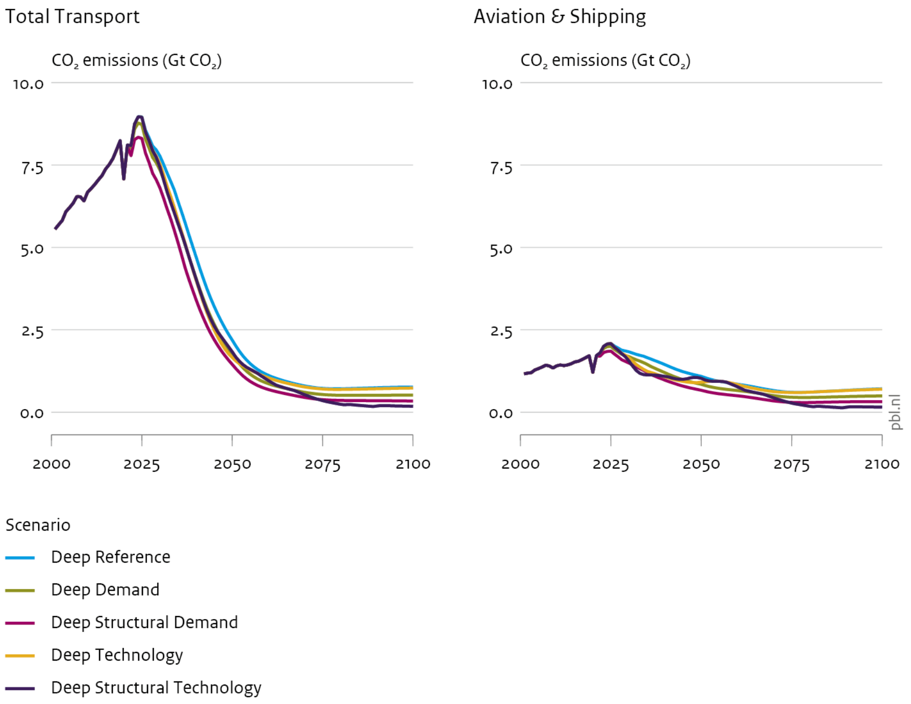


The freight sector sees a strong growth in demand, under the *Reference* scenario, which, similar to passenger transport, is largely offset by efficiency improvements (Figure 5). Therefore, under the assumption of no climate policy, by 2050, freight emissions are comparable to current emission levels. Although the shares in international shipping and air freight are increasing, the majority of CO_2 emissions continue to originate from freight trucks. Under the *Deep Reference* scenario, activity reduction, energy efficiency and fuel shifting, depicted by the changes in the E and I component, allow to reduce CO_2 emissions that originate from trucks by more than 75%, compared to the

Reference scenario, by 2050. There is a small modal shift to trucks, as new truck technologies that allow to reduce their carbon emissions make them less vulnerable to price increases following the carbon price implementation, compared to for example freight aircraft. The *Deep Demand* and *Deep Structural Demand* scenario show reduced shipping and air traffic activity, shown by the A component, while the technological change scenarios have a slight impact on efficiency and carbon intensity improvements of both modes.

Figure 6 shows that, in response to the greatly increasing carbon price, the majority of the carbon emissions that remain by 2050 originate from aviation. While currently aviation is responsible for approximately 12% of transport emissions, under the *Deep Reference* scenario, this would be 41%. For other transport modes, in particularly road and rail, the high carbon price leads to strong electrification, and efficiency improvements (see decomposition Figure 4). The aviation and shipping sectors, however, continue to rely on fossil fuels. Both the technological change and demand side change scenarios allow on the one hand for a faster transition, and in the long term reach deeper emission reductions. Under the deep demand and deep structural demand scenarios, the high peak of emissions is averted and emissions decline faster and stay lower. As a result of the reduction in demand due to more teleworking, alternative tourism, higher airline ticket tax, under the *Deep Structural Demand* scenario, in the period from 2020 to 2050, has emitted cumulatively 8 $GtCO_2$ less, compared the *Deep Reference* scenario.

Figure 6
Total CO_2 emissions from transport (left panel), compared to aviation and shipping (right panel), under the mitigation scenarios of Deep Reference, Deep Demand, Deep Structural Demand, Deep Technology and Deep Structural Technology.



5.2.2 Industry and materials

The industrial emission development projected by the different scenarios are depicted in Figure 7. This decomposition distinguishes between the effect of P: population growth; A: activity development, expressed in Mt of materials produced per capita; E: energy efficiency in final energy per Mt; S: structural change indicating the fuel shift to electricity and hydrogen; I: carbon intensity, which is the amount of CO_2 emissions before carbon capture is applied per non electric final energy use; and finally C: CCS, indicating the total amount of emissions captured.

Table 9
Components of the decomposition of industrial emissions

Component	Population (P)	Activity (A)	Energy efficiency (E)	Structure change (S)	Carbon Intensity (I)	CCS (C)
Industry	Pop	$\frac{Mt_n}{Pop}$	$\frac{FE_n}{Mt_n}$	$\frac{FE\ NE_n}{FE_n}$	$\frac{CO_{2n}}{FE\ NE_n}$	$CO_2captured$

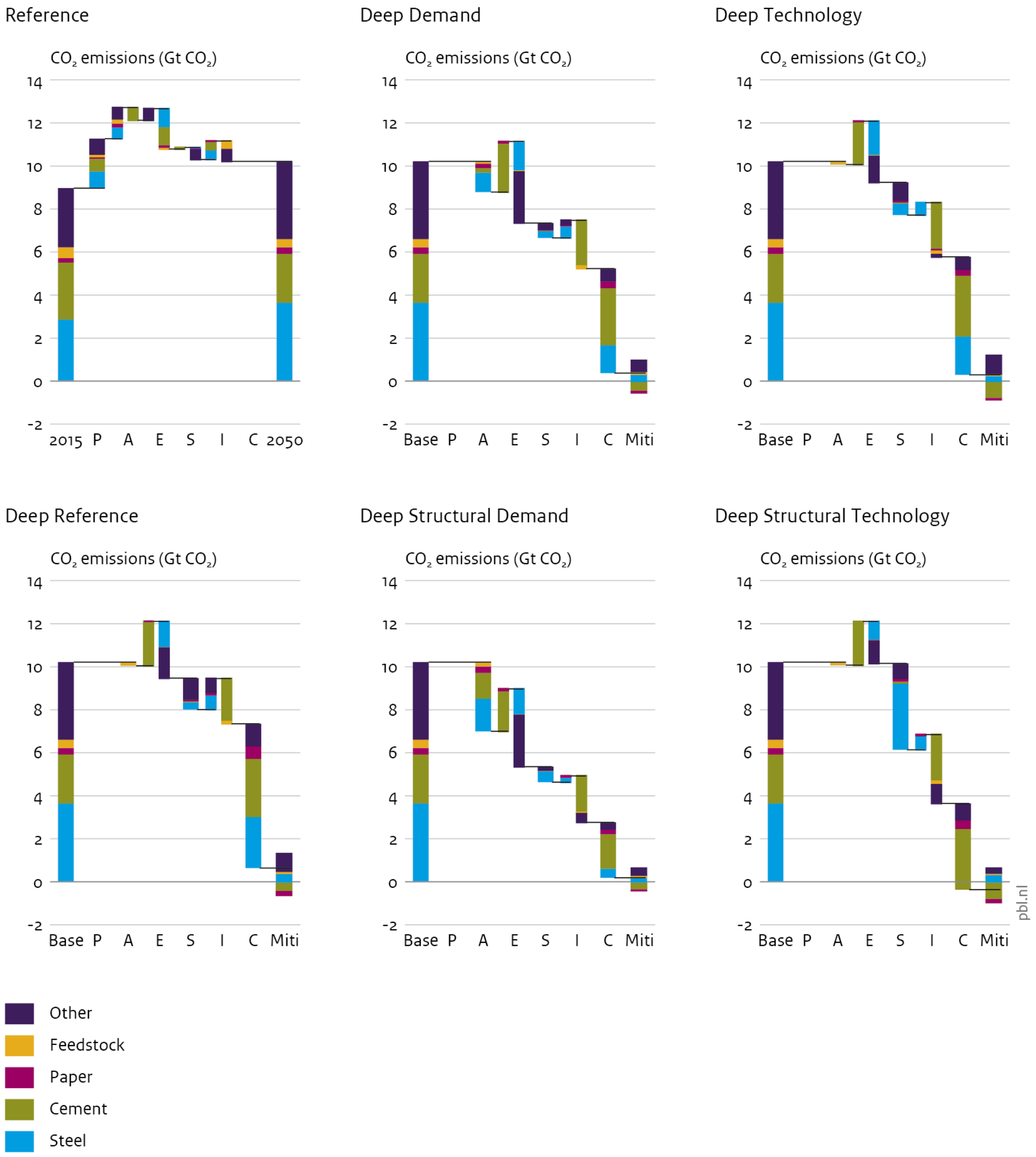
Without any policy intervention, under the *Reference* scenario, global industrial carbon emissions are expected to increase under the pressure of growing global population and material demand (see Figure 7). The level and composition will remain largely similar to the 2015 situation, although the contribution from the steel sector and other industry becomes slightly more prominent. The growth in emission will partly be offset by several autonomous improvements in material efficiency (A)(cement) and energy efficiency (E) (steel, cement and paper), or fuel switching (I) activities in the non-energy sector and other industries.

To bend the curve on industrial emissions, several pathways have been analysed. A cost-effective approach (*Deep Reference*) reinforces the existing efficiency approaches, but shows a notable preference for carbon capture and storage (C) as a solution strategy across the majority of industrial sectors. The alternative scenarios show that any additional policy intervention to a least-cost strategy can have a strong influence on the degree of required mitigation and the rate of dependence on CCS (C). Net zero emissions by 2050, within the industry, appear to be possible across the range of scenarios, but only under the premise that industries in the clinker and cement and pulp and paper sectors can structurally deliver negative emissions as residual emissions remain in the steel and other industrial sectors.

Furthermore, in the current formulation of the demand management scenarios, it shows that immediate demand reduction measures may have a dual mitigating effect of both a lower total peak emission level and up to nearly halving total emissions that need to be mitigated (P, A, E in *Deep Demand and Deep Structural Demand*). The remaining emission reductions are projected to come from clean technology and fuel deployment, with still a relatively large dependence on CCS (particularly for cement). The level of change in material demand mostly affects the level of CCS applied, given how the strategic responses of the model remain broadly similar (for E, I and S between *Deep Demand and Deep Structural Demand*). As a result of the greater demand reductions observed under the *Deep Structural Demand* scenario, compared to under the *Deep Demand* scenario, the industrial sector in the *Deep Structural Demand* scenario requires far less CCS to achieve similar emission targets.

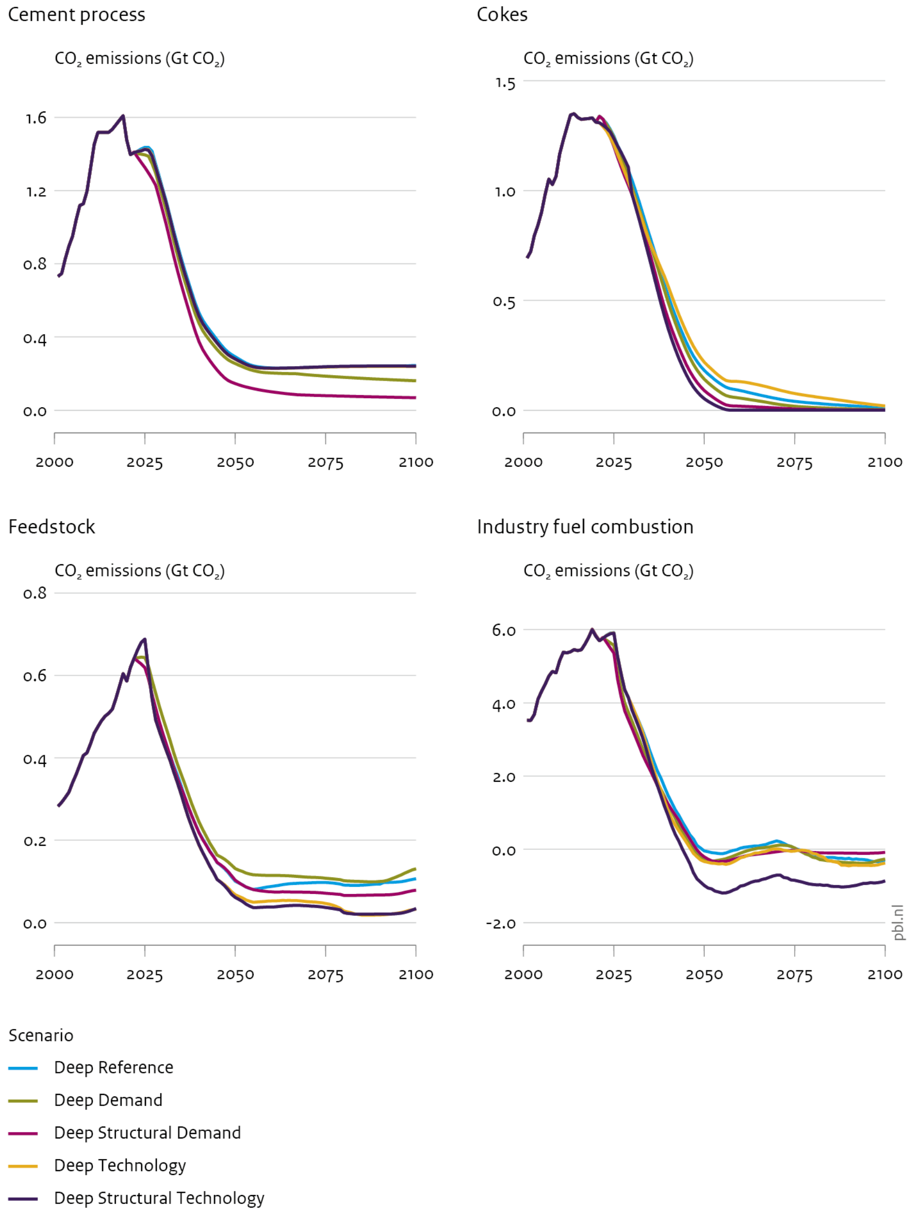
Figure 7

Decomposition of industry CO$_2$ emissions over the factors Population (P), Activity (A), Energy efficiency (E) and carbon intensity (I), and structural change (electrification and hydrogen shift) (S) and application of CCS (C). The top left panel shows reference emissions by 2050, compared to 2015. The five other panels show the mitigation scenario for 2050, compared to reference emissions by 2050.



A dual effect also occurs when designed policy interventions have a technology-oriented focus. The effect, however, moves into an opposite direction than under the demand-oriented scenarios. A growing demand for materials shows to lead to a higher emission level, while additionally the devised technology portfolio leads to a higher total energy requirement. Banning inefficient technologies under the *Deep Structural Technology* scenario has only a small impact on the mitigation pathway, compared to under the regular *Deep Reference* scenario. This is mainly due to automatically reduced use of inefficient technologies when introducing climate policy in the form of a carbon price, making inefficient technologies less cost-competitive. In the second place, banning or promoting a certain technology pathway has notable implications for the remaining residual emissions, with particular effect on the residual emissions in the other industry. Advancing direct and indirect electrification results into both deeper emission reductions and a lower dependence on CCS.

Figure 8
Total CO_2 emissions from cement processes, cokes production, non-energy feedstock and industry energy combustion, under the Deep Technology, Deep Structural Technology, Deep Demand, Deep Structural Demand scenarios, compared to the Deep Reference scenario.



5.2.3 Buildings

The results for the building sector are shown in Figure 9 (Residential buildings emission decomposition), Figure 10 (Non-residential buildings emission decomposition) and Figure 11 (total direct and indirect emissions from residential and non-residential buildings). The decomposition consists of population growth (P), the change in floorspace per capita (F), the activity change which is in useful energy per floorspace for residential buildings, and useful energy per capita for the non-residential buildings , End use change (M), indicating the shift toward different end uses, energy efficiency (E), and the carbon intensity (I) in emissions per final energy use.

Table 10
Components in the decomposition of emissions from residential and non-residential buildings

Component	Population (P)	Floorspace (F)	Activity (A)	End use change (M)	Energy efficiency (E)	Carbon Intensity (I)
Residential	Pop	$\frac{Floorspace}{Pop}$	$\frac{UE}{Floorspace}$	$\sum_{n=1}^{Enduse} \frac{UE_n}{UE}$	$\frac{FE_n}{UE_n}$	$\frac{CO_{2_n}}{FE_n}$
Non-residential	Pop		$\frac{UE}{Pop}$	$\sum_{n=1}^{Enduse} \frac{UE_n}{UE}$	$\frac{FE_n}{UE_n}$	$\frac{CO_{2_n}}{FE_n}$

As shown in Figures 9 and 10, under the *Reference* scenario, the global emissions in these sectors are projected to increase driven by a growing population, increased activity, and, to a lesser extent, increasing floorspace (for residential buildings). Efficiency improvements and fuel switching (particularly towards electricity) offer a counterforce, but are not enough to negate the pressures that drive up energy demand.

Under all of the ’*Deep*’ mitigation scenarios, emissions decrease drastically over the 2020–2050 period, in line with the stringent climate policy implementation and the steeply rising carbon price. The results show that by far the most important component of emission mitigation comes from Fuel Shift (I in Figures 9 and 10), which reflects a movement towards electrification of energy services. As Figures 9 and 10 include both the direct and indirect emissions in this sector, an increase in the electrification of building energy services as well as a general improvement in the emission intensity of electricity production is reflected in the ‘Fuel Shift’ component (I). This explains the ’Fuel Shift’ emission mitigation of electricity-only services such as appliances. This also explains some negative emissions arising from space cooling and lighting (residential) and water and space heating (services), as negative emissions achieved in the power sector (due to the use of some BECCS) appear in the indirect emissions in these sectors. The main remaining source of emissions from residential building in mitigation scenarios is cooking. The remaining emissions from cooking arise from the continued use of traditional biomass by poor households, primarily in Sub-Saharan Africa and South Asia. Since traditional fuels are not taxed, and climate policy leads to an inflationary effect on modern energy carriers, traditional fuels remain important for poor households, also in a world with strong climate policies. The emission factor of traditional biomass is highly uncertain due to uncertainties around the type of biomass used (e.g. fuel wood, residues, dung, charcoal), and the effect traditional biomass provision has on land-use emissions. In both Deep Technology scenarios, traditional biomass is replaced by cleaner alternatives, including modern biomass, which explain the far lower emissions from cooking in these scenarios.

Specifically for non-residential buildings, besides fuel shift, ‘End use change’ also helps reduce emissions, particularly in the *Deep Technology* and *Deep Structural Technology* scenarios. This reflects a general reduction in the demand for energy services in this sector compared to the *Reference*. It is important to note that, even in the *Deep Reference* scenario, the non-residential buildings approach extremely low emissions (see Figure 9), so the main contribution from the *Demand* and *Technology* scenarios is to shift the burden of emission mitigation from Fuel Use (I) to End Use Change (M).

For residential buildings, as shown in Figure 11, the technology change scenarios achieve an almost complete elimination of direct emissions. This is done via a complete electrification of space and water heating. Furthermore, this scenario also assumes increased action towards clean energy access, thereby also reducing but not eliminating emissions arising from the use of traditional biomass in cooking (primarily by poor households in Sub-Saharan Africa and South Asia). The demand scenarios also show some residual emissions from continued use of fossil fuels for space heating and water heating, especially in North America, Europe, China, Central Asia, and, to a lesser extent, also in Latin America, Africa, and South Asia. The structural demand scenario, in which co-living becomes a common practice, shows the potential contribution of reduced floorspace per capita, as well as increasing household sizes. This reduces the energy demand across all services, by reducing the heating/cooled floorspace, or by energy demand services such as cooking and other appliances shared by multiple residents. It is important to note that the reduced floorspace has an effect mostly on OECD regions and more affluent households, in general. Thus, on a global level, limiting floorspace and increasing household size has a muted effect. The same can be said for reduced activity, as poorer regions are expected to increase most of their activity, because they gain access to a minimum level of appliances and heating and cooling opportunities.

Figure 9

Decomposition of residential CO_2 emissions over the factors Population (P), Floorspace change (F), Activity (A), End use change (M), Energy efficiency (E) and Fuel shift (I). The top left panel shows reference emissions by 2050, compared to 2015. The five other panels show the mitigation scenario for 2050, compared to reference emissions by 2050.

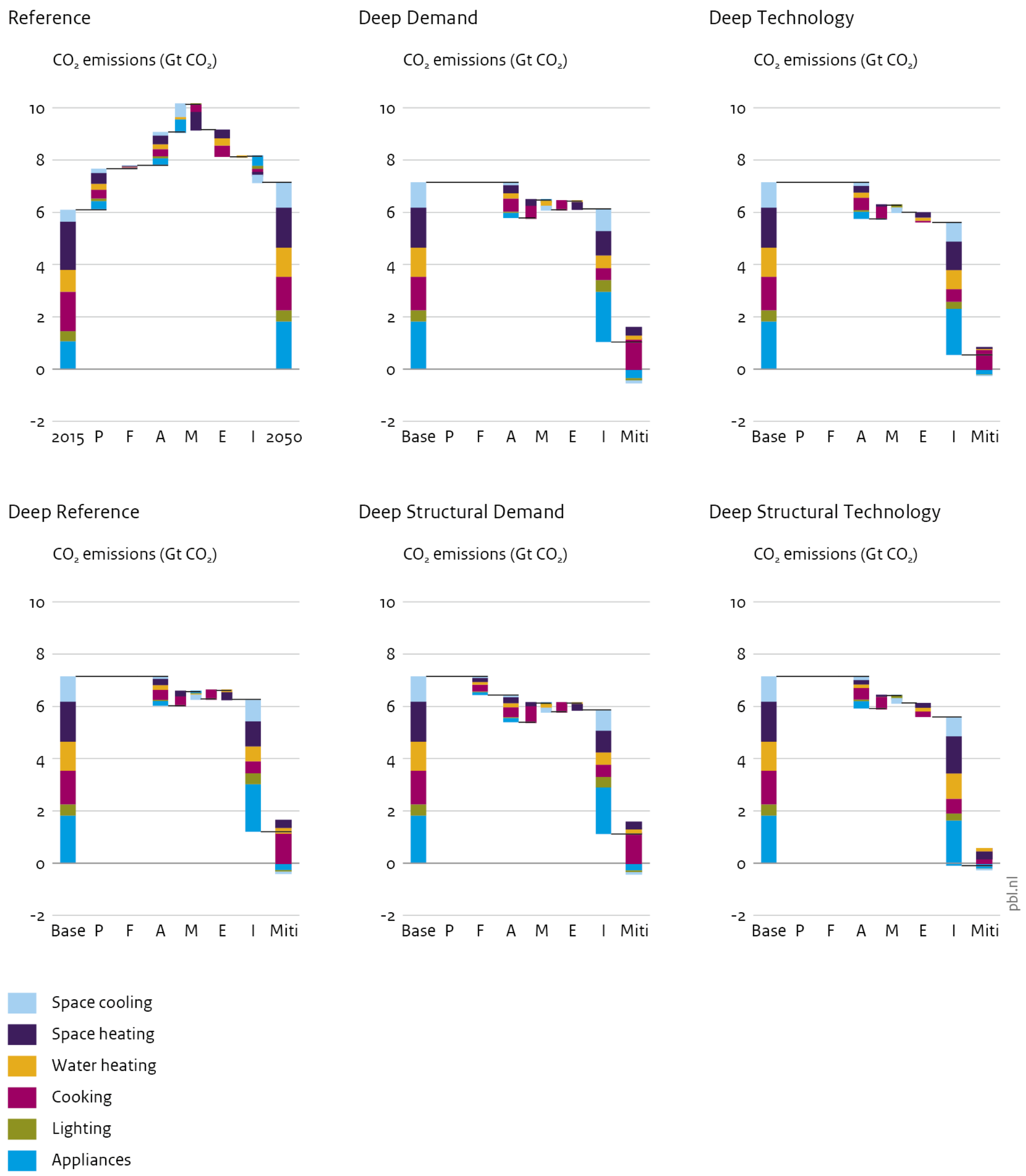


Figure 10

Decomposition of CO_2 emissions from non-residential buildings into the factors population (P), activity (A), end-use changes (M), energy efficiency (E) and fuel shift (I). The top left panel shows the reference emissions by 2050, compared to 2015. The five other panels show the mitigation scenario for 2050, compared to the reference emissions by 2050.

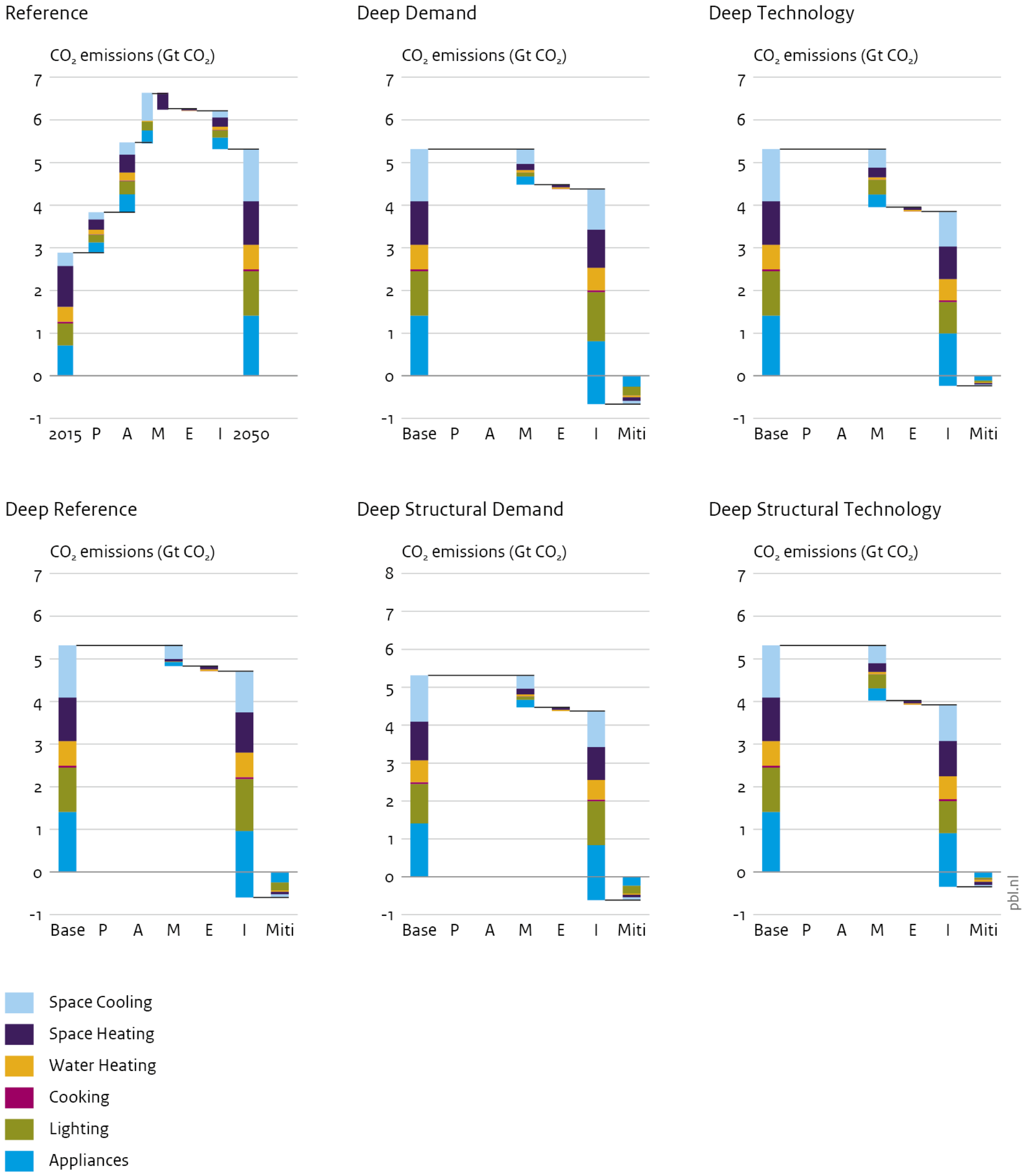
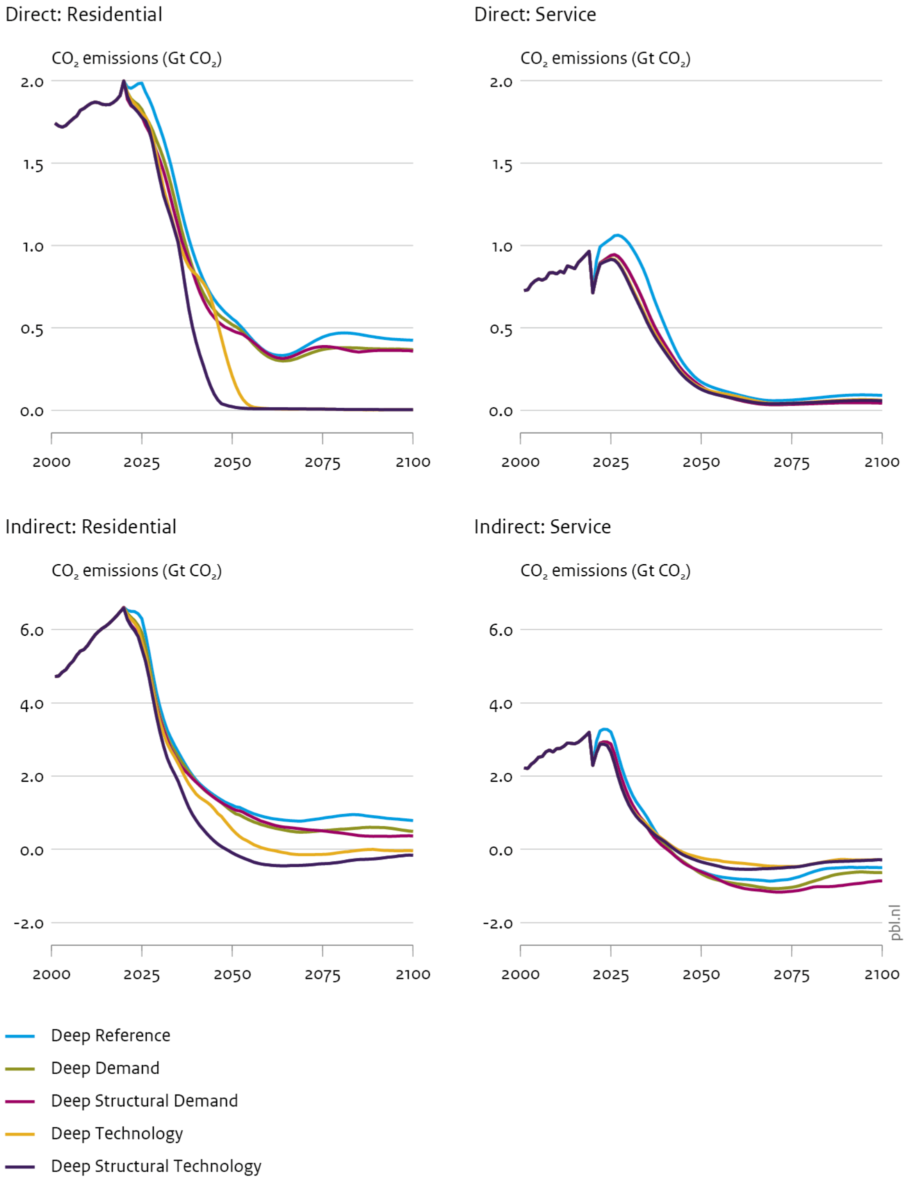


Figure 11
Total direct CO_2 emissions (top) and indirect CO_2 emissions (bottom) from residential and non-residential buildings, under the Deep Technology, Deep Structural Technology, Deep Demand, Deep Structural Demand scenarios, compared to the Deep Reference scenario.



5.2.4 Agriculture

The decomposition of the greenhouse gas emissions in the agricultural sector is shown in Figure 12, with the *Reference* breakdown for the 2015–2050 period, in the upper left corner. The other panels show the difference with the *Reference* by 2050. In the agricultural sector, the non-CO_2 emissions from livestock and crops are particularly hard to abate. This is demonstrated by the *Deep Reference* results where the remaining greenhouse gas emissions in 2050 are CH_4 and N_2O emissions. Besides the direct non-CO_2 emissions, the figure also shows those from land-use change (LUC-CO_2), which are indirectly affected by the developments taking place in the agricultural sector. For example, dietary change and yield improvements lead to less land use. LUC-CO_2 emissions are projected to be negative, in the *Deep Reference* case, due to active forest protection and afforestation policies, but become more negative due to additional reductions in agricultural land from dietary change.

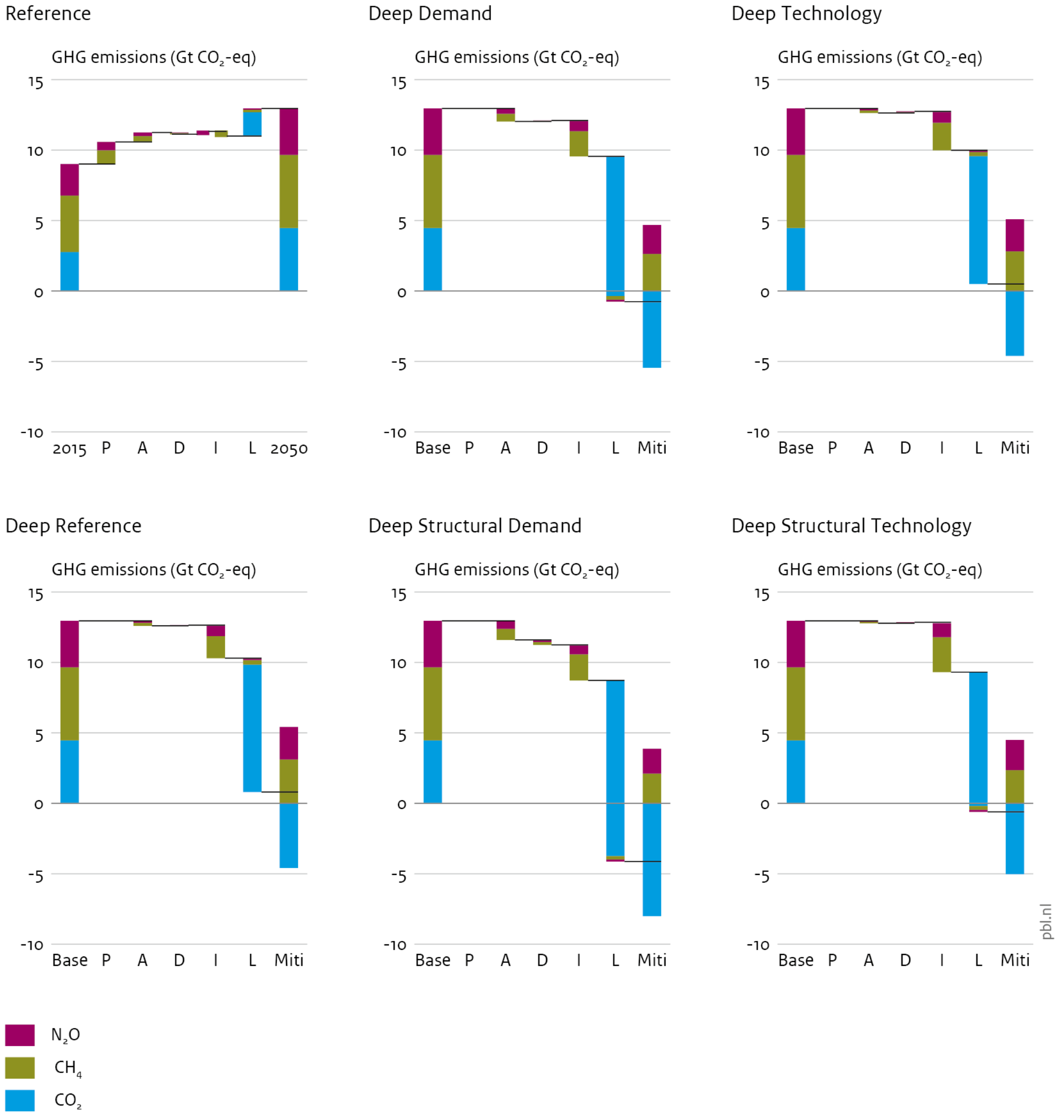
In short, the components in Figure 12 show P: Population, which does not vary across mitigation scenarios for 2050. A: Activity, in kilo-calories per capita, which is mainly lower in the Dem scenarios as a result of dietary change); D: Resource efficiency, showing how much crop/feed is produced per kcal food (this is lower with less food waste and more plant-based diets); I: Emission intensity of agricultural goods, which is lower as a result of ‘end-of-pipe’ reduction measures, mainly affecting non-CO_2 emissions, where n indicates either N_2O or CH_4; and L: the CO_2 originating from land-use change which is lower in a more plant-based production system. Note that the measures in the *Demand* and *Technology* scenarios do not relate to a single component, but can have a mixed effect. For example, in the case of dietary change and the introduction of cultured meat, the components (A, D) do not show all benefits, only the direct effect of eating less meat and using less crop/feed as a basis for plant-based diets. The larger indirect effects; less methane from lower livestock numbers and less CO_2 from lower levels of deforestation are shown under the components I and L, respectively.

Table 11
Components in the decomposition of agricultural sector emissions

Component	**Population (P)**	**Activity (A)**	**Resource use (D)**	**GHG intensity (I)**	**Land-use change emissions (L)**
non CO_2	Pop	$\frac{kcal}{Pop}$	$\frac{prod}{kcal}$	$\frac{GHG_n}{prod}$	
CO_2					CO_2

The *Deep Structural Demand* scenario shows the strongest reduction in greenhouse gas emissions (to a level of -5 $GtCO_2$ eq by 2050, when including LUC CO_2). Total agricultural production is substantially reduced under this scenario, due to reduced animal product consumption, which also leads to lower feed requirements and lower total food demand, as people consume healthier amounts of food (predominantly lower intake in more affluent regions), and because of less food waste. Lower total agricultural production results in lower greenhouse gas emission levels, where the strongest effect is seen in LUC-CO_2 emissions. These are strongly negative as a result of less demand for agricultural land, in turn, allowing for increased reforestation which increases carbon uptake. Moreover, *Deep Structural Demand* also shows the largest net non-CO_2 reduction (by 2050: 52% compared to the *Reference* scenario, with 36% in the *Deep Reference* case), due to the largest relative reduction in livestock production, leading to lower emissions from enteric fermentation and manure.

Figure 12
Decomposition of agricultural greenhouse gas emissions over the factors Population (P), Activity (A), resource Efficiency (E), GHG intensity (I) and Land-use change (L). The top left panel shows the reference emissions by 2050, compared to 2015. The five other panels show the mitigation scenario for 2050, compared to the reference emissions by 2050.

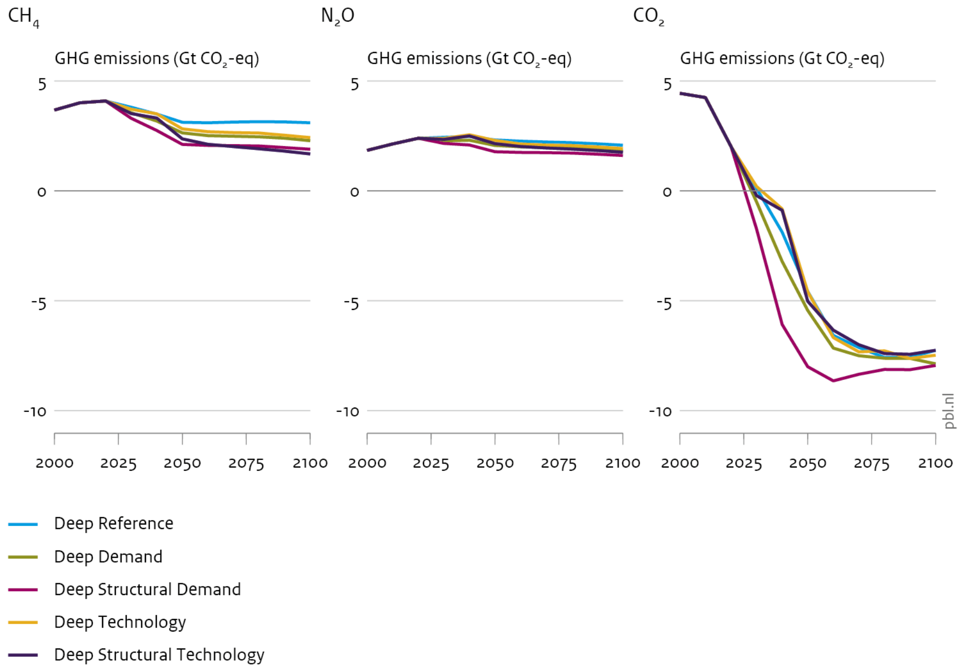


The *Deep Demand* scenario also shows a substantial reduction in greenhouse gas emissions (to a level of -1 $GtCO_2$ eq by 2050, when including LUC CO_2). However, as only meat consumption is reduced as well as a moderate reduction in food waste, this leads to more moderate reductions than under the *Deep Structural Demand* scenario. This shows that there is a substantial difference between 40% or 80% of the population shifting to a less meat intensive diet. Additionally, the shift towards healthy levels of food intake (i.e. avoiding overconsumption) also plays an important role.

The emission reductions under the *Deep Technology* and *Deep Structural Technology* scenarios are lower than under the *Demand* scenarios (with emissions reaching 0 and -1 $GtCO_2$ eq by 2050, respectively, when including LUC CO_2). Both *Technology* scenarios assume substitution of meat by artificial meat, resulting in greenhouse gas emission reductions from lower enteric fermentation and manure emissions. In addition, less grazing land for animal production is required resulting in reforestation, but at a smaller scale than under the *Deep Demand* and *Deep Structural Demand* scenarios, because a relative increase in cropland is required to provide sufficient feedstocks (maize) for the production of cultured meat. In *Deep Structural Technology*, there is an increased non-CO_2 reduction, due to more optimistic assumptions on emission intensity-reducing measures (indicated as a larger 'end-of-pipe' reduction under 'I'), as well as reduced emissions from meat production, such as enteric fermentation and manure. Despite this larger reduction, the net additional non-CO_2 reduction under *Deep Structural Demand* is larger than under *Deep Structural Technology*, due to the large added benefit of demand-side mitigation, compared to under the *Deep Reference* scenario. However, note that energy-intensity reduction is already quite substantial in the default *Deep Reference* case and is assumed to contribute most to net non-CO_2 reduction under all scenarios (indicated by larger reductions under 'I' than under 'A').

Figure 13 shows the net agriculture CH_4, N_2O and CO_2 emissions in the mitigation scenarios. It clearly shows that reduction measures can strongly and indirectly affect LUC-CO_2 emissions, beyond the hard-to-abate non-CO_2 emissions. This is particularly relevant under the *Deep Structural Demand* scenario, where demand-side effects allow for substantially more reforestation. However, in the long term, non-CO_2 emission reduction becomes more dominant and also goes substantially further than in the *Deep Reference* case. By 2100, methane emissions are projected to decrease by about half in both the *Deep Structural Demand* and *Deep Structural Technology* cases (for N_2O, this is about a quarter). Here, both demand- and technology-oriented solutions can lead to strong additional reductions.

Figure 13
Total CH_4, N_2O and CO_2 emissions from the agricultural sector of Deep Technology, Deep Structural Technology, Deep Demand, Deep Structural Demand, compared to the Deep Reference scenario.



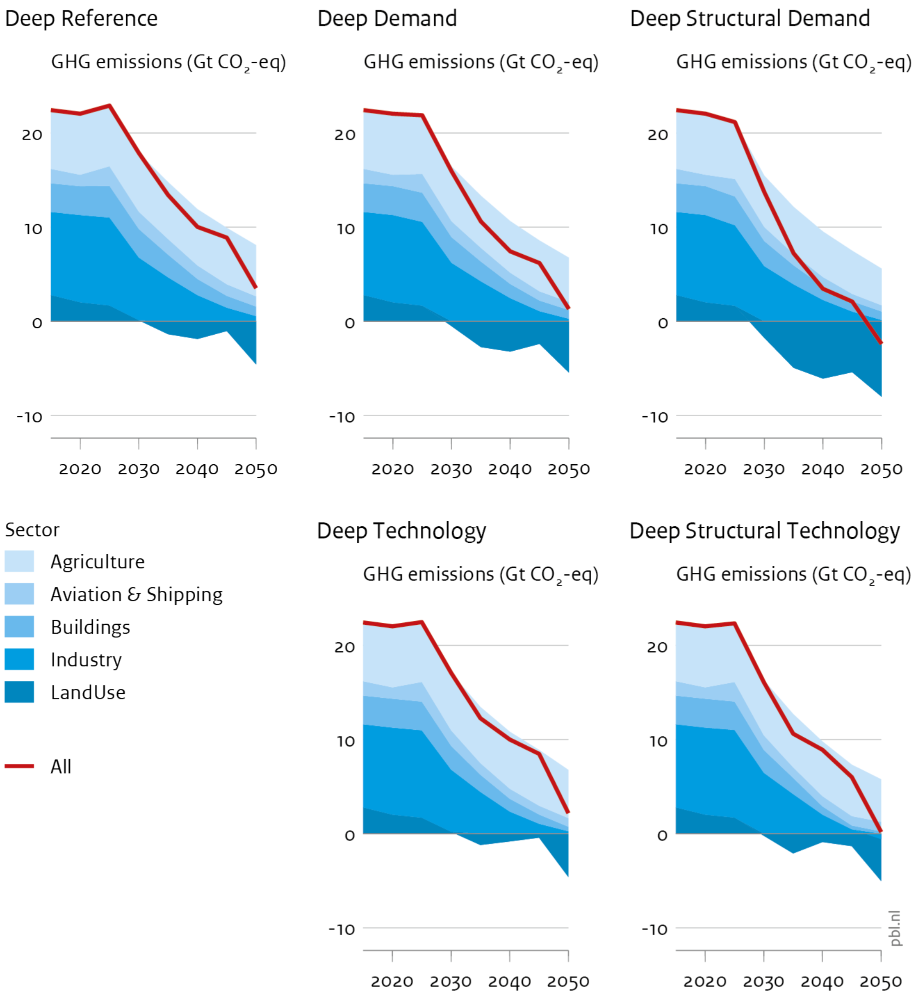
5.3 Deep emission reduction in the four pathways

The previous sections of Chapter 5 show how additional measures (next to a universal carbon price) in the hard-to-abate sectors of agriculture, industry, buildings, aviation and shipping could help further reduce emissions from these sectors. The measures implemented under the *Deep Demand* and *Deep Technology* scenarios lead to quite significant additional emission reductions, reducing the remaining emissions from the hard-to-abate sectors to 1.3 and 2.2 $GtCO_2$ eq, respectively, by 2050 (see Figure 14). Under the technology scenario, in the buildings sector, the electrification of space and water heating and phase-out of traditional biomass use by urban households leads to remaining low emission levels, mainly from traditional biomass used by rural poor households in Sub-Saharan Africa and South Asia. In the agricultural sector, under both the deep demand and technology sectors show a substantial decrease in non-CO_2 emissions as a result of less meat consumption — either as a result of substitution by artificial meat, or due to dietary change. Emissions from the aviation and shipping sectors show, in the short term, a stronger response to implementation of the airline ticket tax, implemented under the demand scenario, than increased development and availability of fuel and technology alternatives, implemented under the deep technology scenario.

The structural measures — either demand- or technology-oriented — further reduce sectoral emissions, with remaining emission levels of 0.2 and -2.4 $GtCO_2$ eq, respectively (see Figure 14). In both the industry and the buildings sector, the largest emission reduction occurs under the *Deep*

Structural Technology scenario. Although industrial demand management can cut the decarbonisation challenge in half, leading to less CCS being required, the deepest industrial reductions follow structural technology changes, such as rapid transition to electric arc furnace hydrogen to produce steel. As a result, global net zero-emission pathways by 2050 for industry (scope 1) are deemed possible in the *Deep Structural Technology* scenario, if negative emissions can be delivered by cement and pulp and paper and given the availability of loads of zero-carbon energy for other industrial sectors. In the aviation, shipping and agricultural sectors, the largest changes can be seen under the *Deep Structural Demand* scenarios. The reduced use of aircraft for short-distance travel and reduction in longer distance flights reduce emissions by 40%. In the agriculture sector, it matters a lot if 40% or 80% of the global population shifts to a more healthy diet by 2050 (as assumed under the *Deep Demand* scenario and *Deep Structural Demand* scenario, respectively). This can be seen in the reduction in non-CO_2 emissions (indicated by agriculture), and in the indirect effect of land-use change, which is dominating in absolute emission reduction values (-8.0 $GtCO_2$ eq in *Deep Structural Demand* compared to -5.4 $GtCO_2$ eq in *Deep Demand*). The difference between the non-structural and the structural scenarios demonstrates that drastic changes are needed, if emissions in the hard-to-abate sectors are to be reduced to almost zero.

Figure 14
Total emissions from the hard-to-abate sectors, over time, under the Deep Demand, Deep Structural Demand, Deep Technology, and Deep Structural Technology scenarios, compared to the Deep Reference scenario.



6 Impact of additional measures in hard-to-abate sectors on 1.5 °C pathways

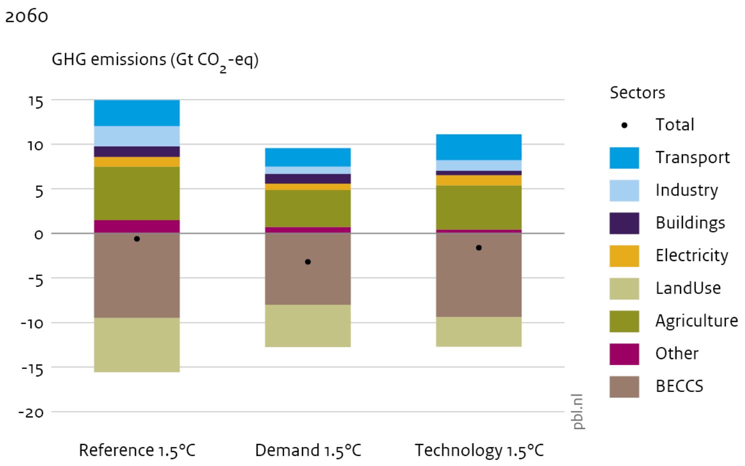
This chapter illustrates the potential impact on system-wide 1.5 °C pathways of the additional demand and technology measures in *hard-to-abate* sectors. In principle, the additional mitigation potential in hard-to-abate sectors would help to meet the 1.5 °C target. This can be used in several ways. For instance, scenarios can rely less on the use of negative emissions through CDR measures to compensate for residual emissions (van Vuuren et al., 2018b). This also reduces the negative consequences of some CDR measures, such as for land use (i.e. afforestation and BECCS), and it reduces the risks of non-permanence, most notably in afforestation. Alternatively, the additional mitigation potential can also be used to remove other high-costs mitigation options. Given the available choices in this regard, we only illustrate what the impact of the additional measures in the hard-to-abate sectors may look like.
For this, we focus on three scenarios:

- *Reference 1.5 °C*: This scenario reaches a radiative forcing of 1.9 W/m^2 by 2100 (corresponding to a 1.5 °C temperature target), using default SSP2 assumptions and by implementing a uniform carbon price. This carbon price trajectory is lower than the carbon prices applied in Chapter 5, reaching USD 800/tC by 2035 and about USD 1000/tC by 2050, compared to USD 1750/tC by 2035 and USD 4000/tC;
- *Demand 1.5 °C*: This scenario uses the same carbon price trajectory as *Reference 1.5 °C* and additional measures in the *hard-to-abate* sectors following the *Structural Demand* scenario. Afforestation and bioenergy are restricted (see below).
- *Technology 1.5 °C*: This scenario uses the same carbon price trajectory as *Reference 1.5 °C* and additional measures in the *hard-to-abate* sectors according to the *Structural Technology* scenario. Afforestation and bioenergy are restricted (see below).

The additional measures in both the *Demand* and *Technology 1.5 °C* scenarios, thus, imply that the scenario achieves deeper reductions in the *hard-to-abate* sectors. In these scenarios, we used this to limit the annual crop-based bioenergy use to a sustainable level of 60 EJ (Fuss et al., 2018). Moreover, in the *Demand 1.5 °C* scenario, only afforestation on abandoned croplands and grasslands is permitted; i.e. carbon-price driven afforestation was excluded to avoid competition with food supply and biodiversity (please note that there is considerable reforestation in both scenarios anyway, as a result of the lower meat demand). In the *Technology 1.5 °C* scenario, some carbon-price driven afforestation was still allowed to achieve the temperature target. The amount of carbon-price driven afforestation is reduced, however, to half of the default potential (about 500 Mha instead of about 1000 Mha). The radiative forcing levels of all three scenarios are comparable and correspond to achieving the 1.5 °C temperature target.

Figure 1 showed that, in the reference 1.5 °C scenario, net-zero greenhouse gas emissions are achieved by offsetting positive emissions from the hard-to-abate sectors with negative emissions from BECCS and land use (mainly afforestation). Emissions from agriculture are especially difficult to reduce, and therefore, significant agricultural emissions of approximately 6 GtCO$_2$ eq remain in our reference 1.5 °C scenario around mid-century (see also Figure 1; Figure 15 provides a time slice for 2060).

Figure 15
Global annual GHG emissions per sector in the reference 1.5 °C scenario compared to the Demand and Technology 1.5 °C scenarios by 2060.

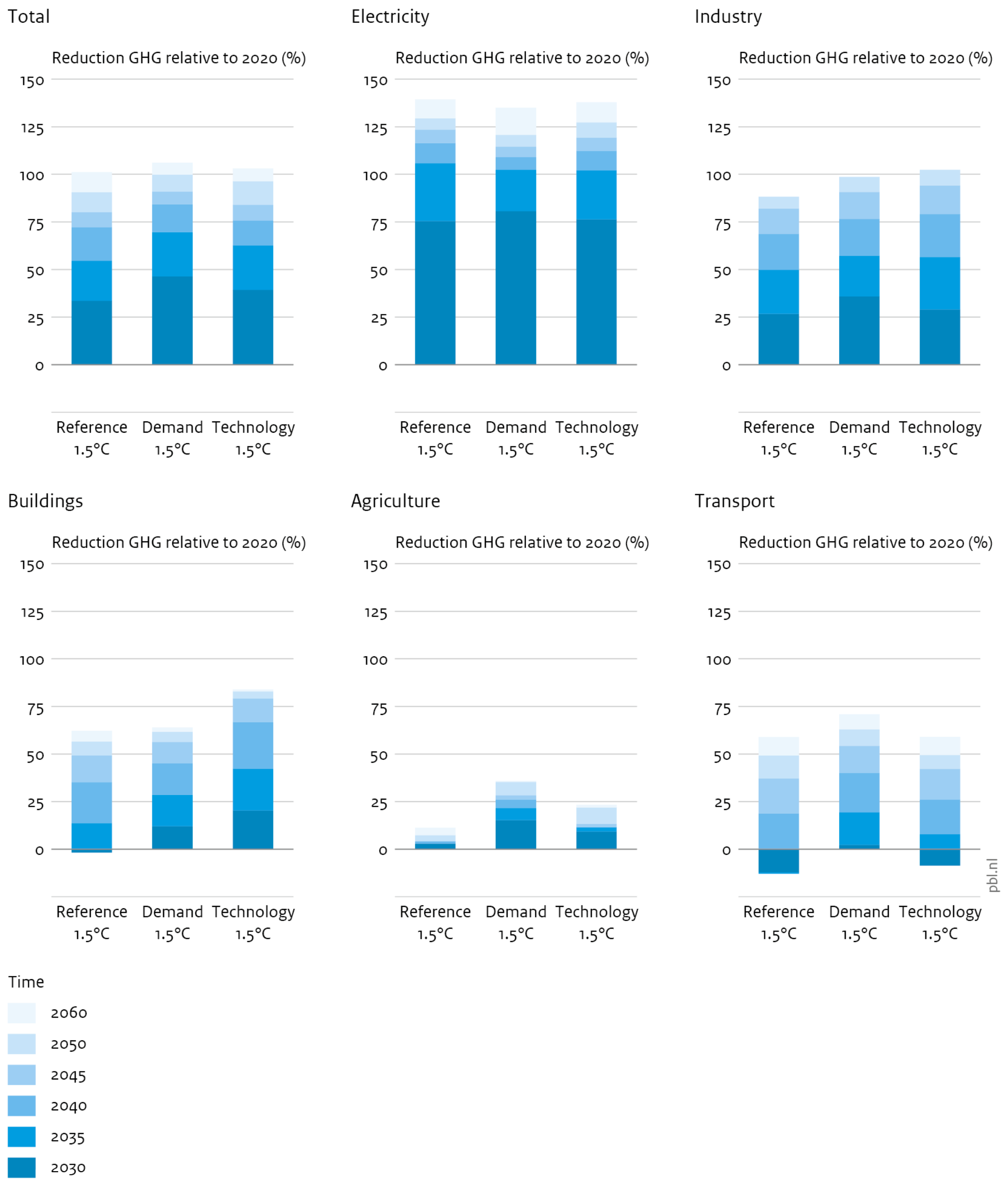


Note: 'Other' consists mainly of heat, hydrogen and flaring.

In the scenarios with additional measures in the hard-to-abate sectors, annual emissions from agriculture are strongly reduced to about 4 $GtCO_2$ eq in the *Demand* 1.5 °C and to 5 $GtCO_2$ eq in the *Technology* 1.5 °C scenario by 2050. In the *Demand* 1.5 °C scenario, this is achieved by a shift towards more healthy diets (i.e. less meat consumption and lower calorie intake) and food waste reduction. In the *Technology* 1.5 °C scenario, meat is largely replaced by artificial meat, and novel techniques significantly reduce non-CO_2 agricultural greenhouse emissions (e.g. from rice cultivation). In both scenarios, less agricultural land is required for food production, and the abandoned land is subsequently reforested. This means that the additional measures in agriculture have i) a strong direct impact, lowering emissions from enteric fermentation and manure, and ii) an indirect impact, as the reduction in land used for grazing and feed leads to an increased amount of land that is available for afforestation purposes. Still, for the full century, the total CO_2 uptake as a result of afforestation is lower in both the *Demand* and *Technology* 1.5 °C scenarios than under the *Reference* 1.5 °C scenario due to the restriction of additional afforestation. Cumulatively, from 2020 onwards, CO_2 uptake via land use is 227 $GtCO_2$ under the *Demand* 1.5 °C *scenario* and 151 $GtCO_2$ under the *Technology* 1.5 °C *scenario*, compared to 305 $GtCO_2$ under the *Reference scenario*,, see also Figure 17.

Industry is the second-largest hard-to-abate sector, in terms of remaining emissions in the net-zero year. In both the *Technology* 1.5 °C and the *Demand* 1.5 °C scenario, the additional measures lead to significantly lower residual industrial emissions; with only about 1 $GtCO_2$ eq annual emissions remaining, compared to 2.3 $GtCO_2$ eq under the *Reference* 1.5 °C scenario (Figure 15). These remaining emissions are even compensated by BECCS applied in industry, resulting in net-zero industrial emissions by 2060, under the *Demand* and *Technology* 1.5 °C scenarios (Figure 16).

Figure 16
GHG emission reductions over time, compared to the year 2020 for different sectors.



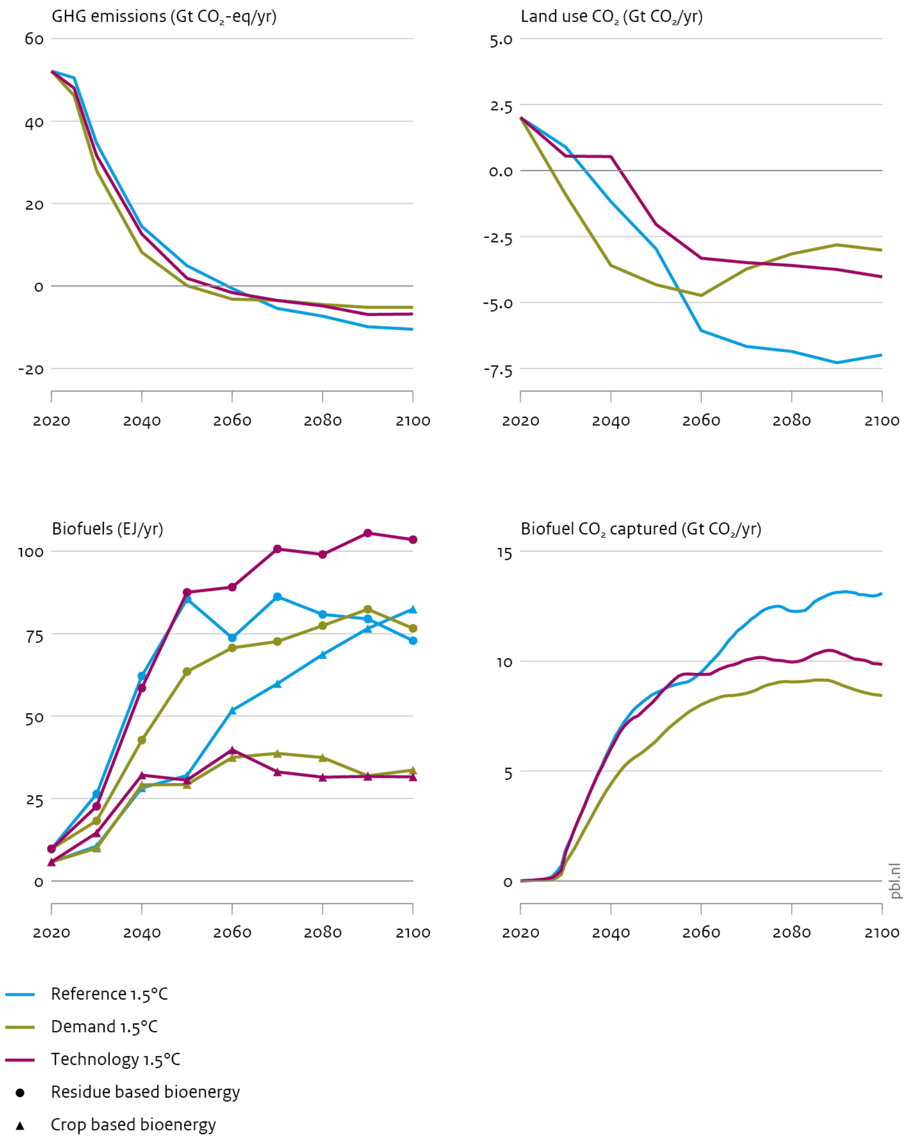
The impact of the additional demand-side measures on emissions from agricultural, transport and industry is rapid, under the *Demand* 1.5 °C scenario. While social change also might require time, significant emission reductions could already be achieved by 2030, in these sectors (Figure 16). In contrast, under the *Technology* 1.5 °C scenario, some new technologies are not yet available at a large scale, in the short term, but kick in only after 2040 (Figure 16). There are also strong sectoral differences: emissions from buildings, for instance, are being reduced much faster in the *Technology* 1.5 °C scenario than in the *Demand* 1.5 °C scenario. Here, technologies such as heat pumps are readily available, while shifting to different ways of living with more shared uses and spaces is dependent on construction cycles. In both scenarios, less of the emission budget is spent by 2060, and deeper reductions have been reached than in the *Reference* 1.5 °C scenario.

Compared to the *Reference* 1.5 °C scenario, the *Demand* and *Technology* 1.5 °C scenarios achieve faster reductions in the buildings and transport sectors as a result of the additional measures. The reduction rate in these sectors slow down between 2040 and 2050, and the sectors will not achieve net-zero emissions by 2060. Similarly, despite the additional reduction in non-CO_2 emissions, the agricultural sector does not reach net-zero greenhouse gas emissions by 2060 if the indirect effect of land-use change is not taken into account.

In both *Demand* and *Technology* 1.5 °C scenarios, the reliance on bioenergy from crops is considerably lower and stays well below the limit of 60 EJ. In both the *Demand* 1.5 °C and the *Technology* 1.5 °C scenario, annual crop-based bioenergy will stay below 40 EJ, throughout the century. Under the *Technology* 1.5 °C scenario, crop-based bioenergy use will however peak earlier, namely in 2060 (Figure 17). The higher short-term use of bioenergy in the *Technology* 1.5 °C scenario is due to their use in aviation. The reasons why the *Demand* and *Technology* 1.5 °C scenarios stay well below the bioenergy limit throughout the century are i) less demand for bioenergy from transport due to lower total transport activity, and ii) the reduced use of BECCS (given the lower residual emissions).

Interestingly, despite the lower use of crop-based bioenergy, there is still a strong reliance on BECCS in both *Demand* and *Technology* 1.5 °C scenarios. This is mainly because residues can also be used as a feedstock besides crop-based biomass. In our assumptions, we did not restrict residue supply (given that it does not lead to additional land use). For the *Technology* 1.5 °C scenario, residue bioenergy use even increases compared to the *reference scenario*, but total bioenergy use is still lower. Still, even though the reliance on bioenergy crops is reduced in the scenarios with additional measures, a substantial amount is still used, particularly in the *Technology* 1.5 °C scenario. This means that the scenarios strongly depend on the availability of residues for bioenergy, the actual availability of which is quite uncertain (Fuss et al., 2018; Daioglou et al., 2018).

Figure 17
Global greenhouse gas emissions, bioenergy use, BECCS and land-use CO_2 over the course of the 21st century.



The top left panel of Figure 17 shows the global greenhouse gas emissions pathways of the three scenarios over the century. The figure shows how reduced residual emissions in the first half of the century reduce the extent to which CDR measures need to be implemented in the second half of the century, in order to remain within 1.5 °C warming. The deeper reductions achieved earlier on, particularly under the *Demand* 1.5 °C scenario, reduce the need for negative emissions, and therefore the scale at which CDR measures are implemented at the end of the century. This can be seen in both the amount of BECCS (bottom right) and the level of afforestation (top right) at the end of the century. As such, the scenarios clearly show that the required adoption of CDR measures depends on the level of residual emissions in the hard-to-abate sectors. Despite the obstacles that the hard-to-abate sectors face in reaching net-zero emissions this study shows that, with drastic demand and technology measures, hard-to-abate sectors can reach lower, near-zero emission levels within a shorter amount of time. The result is that the exceedance of the carbon budget is lower, reducing the reliance on CDR in the second half of the century.

References

Agora Energiewende (2022). Global Steel Transformation Tracker. https://www.agora-energiewende.de/en/service/global-steel-transformation-tracker/. Accessed on 9 February 2022.

Anderson K and Peters G. (2016). The trouble with negative emissions. Science 354, 182–183.

Birol F, Cozzi L, Gould T, Bromhead A and Priddle R. (2015). https://www.iea.org/reports/world-energy-outlook-2015. World Energy Outlook.

Bouman EA, Lindstad E, Rialland AI and Strømman AH. (2017). State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping – A review. Transportation Research Part D: Transport and Environment 52, 408–421.

Graver B, Rutherford D and Zheng S. (2020). CO_2 emissions from commercial aviation: 2013, 2018, and 2019. International Council on Clean Transportation (ICCT) 1–25.

Bui M, Adjiman CS, Bardow A, Anthony EJ, Boston A, Brown S, Fennell PS, Fuss S, Galindo A, Hackett LA, Hallett JP, Herzog HJ, Jackson G, Kemper J, Krevor S, Maitland GC, Matuszewski M, Metcalfe IS, Petit C, Puxty G, Reimer J, Reiner DM, Rubin ES, Scott SA, Shah N, Smit B, Martin Trusler JP, Webley P, Wilcox J and Dowell NM. (2018). Carbon capture and storage (CCS): The way forward. Energy and Environmental Science 11, 1062–1176.

Carvalho F, Müller-Casseres E, Poggio M, Nogueira T, Fonte C, Wei HK, Portugal-Pereira J, Rochedo PRR, Szklo A and Schaeffer R. (2021). Prospects for carbon-neutral maritime fuels production in Brazil. Journal of Cleaner Production 326, 129385.

Cattaneo C. (2019). Internal and external barriers to energy efficiency: which role for policy interventions? Energy Efficiency 12, 1293–1311.

CORDIS (2020). Solar up-draft tower to enable atmospheric photocatalysis for non-CO_2 greenhouse gases removal: an emerging negative emission technology. https://cordis.europa.eu/project/id/871998. Accessed on 3 February 2022.

Cox S. (2016). Building Energy Codes: Policy Overview and Good Practices. US Department of Energy.

Crippa M, Guizzardi D, Solazzo E, Muntean M, Schaaf E, Monforti-Ferrario F, Banja M, Olivier JGJ, Grassi G, Rossi S and Vignati E. (2019). GHG emissions of all world countries. Publications Office of the European Union.

Crompton P and Lesourd JB. (2008). Economies of scale in global iron-making. Resources Policy 33, 74–82.

Dahlmann K, Koch A, Linke F, Lührs B, Grewe V, Otten T, Seider D, Gollnick V and Schumann U. (2016). Climate-Compatible Air Transport System - Climate Impact Mitigation Potential for Actual and Future Aircraft. Aerospace 3, 38.

Daioglou V, Doelman J, Wicke B, Faaij A and Van Vuuren DP. (2018). Integrated assessment of biomass supply and demand in climate change mitigation scenarios. Global Environmental Change.

Daioglou V, Mikropoulos E, Gernaat D and Van Vuuren DP. (2022). Efficiency improvement and technology choice for energy and emission reductions of the residential sector. Energy 243, 122994.

De Richter R, Ming T, Davies P, Liu W and Caillol S. (2017). Removal of non-CO_2 greenhouse gases by large-scale atmospheric solar photocatalysis. Progress in Energy and Combustion Science 60, 68–96.

European Commission (2021). Fit for 55 — Delivering the EU's 2030 climate target on the way to climate neutrality. European Commission.

Eker S, Reese G and Obersteiner M. (2019). Modelling the drivers of a widespread shift to sustainable diets. Nature Sustainability 2, 725–735.

Esmeijer K, Den Elzen M and Van Soest H. (2020). Analysing international shipping and aviation emission projections. PBL Netherlands Environmental Assessment Agency, The Hague.

Evans M, Roshchanka V and Graham P. (2017). An international survey of building energy codes and their implementation. Journal of Cleaner Production 158, 382–389.

Eyring V, Köhler HW, Van Aardenne J and Lauer A. (2005). Emissions from international shipping: 1. The last 50 years. Journal of Geophysical Research: Atmospheres 110, 171–182.

FAO (2011). Global Food Losses and Food Waste. Food and Agriculture Organization.

Fetting C. (2019). The European Green Deal. European Commission, Brussels.

Fitch-Roy O, Benson D and Monciardini D. (2021). All around the world: Assessing optimality in comparative circular economy policy packages. Journal of Cleaner Production 286, 125493.

Fuss S, Lamb WF, Callaghan MW, Hilaire J, Creutzig F, Amann T, Beringer T, de Oliveira Garcia W, Hartmann J, Khanna T and Luderer G. (2018). Negative emissions—Part 2: Costs, potentials and side effects. Environmental Research Letters 13.

Gerres T, Chaves Ávila JP, Llamas PL and San Román TG. (2019). A review of cross-sector decarbonisation potentials in the European energy intensive industry. Journal of Cleaner Production 210, 585–601.

Giampietro M and Mayumi K. (2009). The biofuel delusion: The fallacy of large scale agro-biofuels production. The Biofuel Delusion: The Fallacy of Large Scale Agro-Biofuels Production. Taylor and Francis Inc.

Gidden MJ, Riahi K, Smith SJ, Fujimori S, Luderer G, Kriegler E, Van Vuuren DP, Van den Berg M, Feng L, Klein D, Calvin K, Doelman JC, Frank S, Fricko O, Harmsen M, Hasegawa T, Havlik P, Hilaire J, Hoesly R, Horing J, Popp A, Stehfest E and Takahashi K. (2019). Global emissions pathways under different socioeconomic scenarios for use in CMIP6: A dataset of harmonized emissions trajectories through the end of the century. Geoscientific Model Development 12, 1443–1475.

Gössling S and Humpe A. (2020). The global scale, distribution and growth of aviation: Implications for climate change. Global Environmental Change 65, 102194.

Gray N, McDonagh S, O'Shea R, Smyth B and Murphy JD. (2021). Decarbonising ships, planes and trucks: An analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors. Advances in Applied Energy 1, 100008.

Hale T, Kuramochi T, Lang J, Mapes B, Smith S, Aiyer R, Black R, Boot M, Chalkley P, Hans F, Hay N, Hsu A, Höhne N, Mooldijk S and Walsh T. (2021). Net Zero Tracker. https://www.zerotracker.net/.

Harmsen JHM, Van Vuuren DP, Nayak DR, Hof AF, Höglund-Isaksson L, Lucas PL, Nielsen JB, Smith P and Stehfest E. (2019). Long-term marginal abatement cost curves of non-CO2 greenhouse gases. Environmental Science & Policy 99, 136–149.

Harmsen M, Van Vuuren DP, Bodirsky BL, Chateau J, Durand-Lasserve O, Drouet L, Fricko O, Fujimori S, Gernaat DEHJ, Hanaoka T, Hilaire J, Keramidas K, Luderer G, Moura MCP, Sano F, Smith SJ and Wada K. (2020). The role of methane in future climate strategies: mitigation potentials and climate impacts. Climatic Change 163, 1409–1425.

Hasan MA, Mamun A al, Rahman SM, Malik K, al Amran M, Uddin I, Khondaker AN, Reshi O, Tiwari SP and Alismail FS. (2021). Climate Change Mitigation Pathways for the Aviation Sector. Sustainability 13, 3656.

Hasanbeig A, Nilsson A, Mete G, Fontenit G and Shi D. (2021). Fostering industry transition through green public procurement: A “how to” guide for the cement and steel sectors. United Nations Industrial Development Organization (UNIDO) and Leadership Group for Industry Transition (LeadIT).

Hertwich E, Lifset R, Pauliuk S, Heeren N, Ali S and Tu Q. (2020). Resource efficiency and climate change: Material efficiency strategies for a low-carbon future. International Resource Panel.

IATA (2009). Halving Emissions by 2050 - Aviation Brings its Targets to Copenhagen. International Air Transport Association.

IATA (2019). Fact Sheet on Fuel. International Air Transport Association.

IATA (2020). Fact Sheet 2: Sustainable Aviation Fuel: Technical Certification. International Air Transport Association.

IATA (2021a). Net-Zero Carbon Emissions by 2050. Press Release No: 66 3–4. International Air Transport Association.

IATA (2021b). World Air Transport Statistics. International Air Transport Association.

ICAO (2019). Trends in Emissions that affect Climate Change. International Civil Aviation Organization.

ICAO (2020). Economic Impacts of COVID-19 on Civil Aviation. International Civil Aviation Organization.

IEA (2019). The Critical Role of Buildings. Perspectives for the Clean Energy Transition. International Energy Agency.

IEA (2021). World Energy Outlook 2021. International Energy Agency.

IEA (2022). Tracking Industry 2021. International Energy Agency.

IMO (2018). Initial IMO GHG Strategy. International Maritime Organization.

IMO (2019). Fourth Greenhouse Gas Study 2020. International Maritime Organization.

IPCC (2018a). Global Warming of 1.5 °C. An IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. International Panel on Climate Change.

IPCC (2018b). Summary for Policymakers. In: Global Warming of 1.5 °C. An IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. International Panel on Climate Change.

IPCC (2019). Summary for Policymakers. In: Climate Change and Land: An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. International Panel on Climate Change.

IPCC (2022). Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

Johnson OW, Mete G, Sanchez F, Shawoo Z and Talebian S. (2021). Toward climate-neutral heavy industry: An analysis of industry transition roadmaps. Applied Sciences (Switzerland) 11.

Kinley RD, Martinez-Fernandez G, Matthews MK, De Nys R, Magnusson M and Tomkins NW. (2020). Mitigating the carbon footprint and improving productivity of ruminant livestock agriculture using a red seaweed. Journal of Cleaner Production 259, 120836.

Klein A, Hilster D, Scholten P, Van Wijngaarden L, Tol E and Otten M. (2020). Goederenvervoer STREAM 2020 Emissies van modaliteiten in het goederenvervoer. CE Delft.

Larsson J, Elofsson A, Sterner T and Åkerman J. (2019). International and national climate policies for aviation: a review. Climate Policy 19, 787–799.

Li Y, Kubicki S, Guerriero A and Rezgui Y. (2019). Review of building energy performance certification schemes towards future improvement. Renewable and Sustainable Energy Reviews 113, 109244.

Lucon O, Zain Ahmed A, Akbari USA H, Bertoldi P, Cabeza LF, Graham P, Brown M, Henry Abanda F, Korytarova K, Ürge-Vorsatz D, Zain Ahmed A, Akbari H, Bertoldi P, Cabeza LF, Eyre N, Gadgil A, Danny Harvey LD, Jiang Y, Liphoto E, Mirasgedis S, Murakami S, Parikh J, Pyke C and Vilariño MV. (2014). Buildings. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. International Panel on Climate Change.

Luiten E, Van Lente H and Blok K. (2006). Slow technologies and government intervention: Energy efficiency in industrial process technologies. Technovation 26, 1029–1044.

Lund H. (2007). Renewable energy strategies for sustainable development. Energy 32, 912–919.

Mattick CS, Landis AE and Allenby BR. (2015). A case for systemic environmental analysis of cultured meat. Journal of Integrative Agriculture 14, 249–254.

McCarthy A, Dellink R and Bibas R. (2018). The macroeconomics of the circular economy transition. OECD Environment Working Papers 33, 1–50.

Millefiori LM, Braca P, Zissis D, Spiliopoulos G, Marano S, Willett PK and Carniel S. (2021). COVID-19 impact on global maritime mobility. Scientific Reports 11, 1–16.

Müller-Casseres E, Carvalho F, Nogueira T, Fonte C, Império M, Poggio M, Wei HK, Portugal-Pereira J, Rochedo PRR, Szklo A and Schaeffer R. (2021). Production of alternative marine fuels in Brazil: An integrated assessment perspective. Energy 219, 119444.

Murphy A, Earl T, Hemmings B, Calvo Ambel C, Buffet L, Gilliam L and Sihvonen J. (2018). Roadmap to decarbonising European aviation - Campaigning for cleaner transport in Europe. Transport & Environment, Brussels.

Oberthür S, Khandekar G and Wyns T. (2021). Global governance for the decarbonization of energy-intensive industries: Great potential underexploited. Earth System Governance 8, 100072.

OECD (2019a). ITF Transport Outlook 2019. Organization of Economic Cooperation and Development.

OECD (2019b). Global Material Resources Outlook to 2060. Organization of Economic Cooperation and Development.

Ørsted (2022). Heading for a circular economy – Salzgitter AG and Ørsted launch strategic partnership. https://orsted.com/en/media/newsroom/news/2022/01/20220125471111. Accessed on 9 February 2022.

Peeters P. (2017). Tourism's impact on climate change and its mitigation challenges How can tourism become 'climatically sustainable'? TU Delft University, Delft.

Post MJ, Levenberg S, Kaplan DL, Genovese N, Fu J, Bryant CJ, Negowetti N, Verzijden K and Moutsatsou P. (2020). Scientific, sustainability and regulatory challenges of cultured meat. Nature Food 1, 403–415.

Ricciardi V, Ramankutty N, Mehrabi Z, Jarvis L and Chookolingo B. (2018). How much of the world's food do smallholders produce? Global Food Security 17, 64–72.

Roe S, Streck C, Beach R, Busch J, Chapman M, Daioglou V, Deppermann A, Doelman J, Emmet-Booth J, Engelmann J, Fricko O, Frischmann C, Funk J, Grassi G, Griscom B, Havlik P, Hanssen S, Humpenöder F, Landholm D, Lomax G, Lehmann J, Mesnildrey L, Nabuurs G, Popp A, Rivard C, Sanderman J, Sohngen B, Smith P, Stehfest E, Woolf D and Lawrence D. (2021). Land-based measures to mitigate climate change: Potential and feasibility by country. Global Change Biology 27, 6025–6058.

Sanchez F and Nilsson A. (2021) Is industry transition now a priority in the latest round of NDCs? https://www.industrytransition.org/insights/industry-transition-and-ndcs/. Accessed on 9 February 2022.

Scheelhaase J, Maertens S, Grimme W and Jung M. (2018). EU ETS versus CORSIA – A critical assessment of two approaches to limit air transport's CO2 emissions by market-based measures. Journal of Air Transport Management 67, 55–62.

Smith P, Davis SJ, Creutzig F, Fuss S, Minx J, Gabrielle B, Kato E, Jackson RB, Cowie A, Kriegler E, Van Vuuren DP, Rogelj J, Ciais P, Milne J, Canadell JG, McCollum D, Peters G, Andrew R, Krey V, Shrestha G, Friedlingstein P, Gasser T, Grübler A, Heidug WK, Jonas M, Jones CD, Kraxner F, Littleton E, Lowe J, Moreira JR, Nakicenovic N, Obersteiner M, Patwardhan A, Rogner M, Rubin E, Sharifi A, Torvanger A, Yamagata Y, Edmonds J and Yongsung C. (2016). Biophysical and economic limits to negative CO2 emissions. Nature Climate Change 6, 42–50.

Springmann M, Clark M, Mason-D'Croz D, Wiebe K, Bodirsky BL, Lassaletta L, De Vries W, Vermeulen SJ, Herrero M, Carlson KM, Jonell M, Troell M, DeClerck F, Gordon LJ, Zurayk R, Scarborough P, Rayner M, Loken B, Fanzo J, Godfray HCJ, Tilman D, Rockström J and Willet W. (2018). Options for keeping the food system within environmental limits. Nature 562, 519–525.

Steckel JC, Dorband II, Montrone L, Ward H, Missbach L, Hafner F, ... and Renner S. (2021). Distributional impacts of carbon pricing in developing Asia. Nature Sustainability, 4, 1005–1014.

Stehfest E, Bouwman L, Van Vuuren DP, Den Elzen MGJ, Eickhout B and Kabat P. (2009). Climate benefits of changing diet. Climatic Change 95, 83–102.

The Good Food Institute (2019). State of the Industry Report Cultivated Meat. https://gfi.org/resource/cultivated-meat-eggs-and-dairy-state-of-the-industry-report/. Accessed on 3 February 2022.

Tuomisto HL and Teixeira De Mattos MJ. (2011). Environmental impacts of cultured meat production. Environmental Science and Technology 45, 6117–6123.

UNCTAD (2021). Review of Maritime Transport 2021. United Nations Conference on Trade and Development.

UNEP (2021). The Emissions Gap Report 2021: The Heat Is On – A World of Climate Promises Not Yet Delivered, Nairobi.

Van der Esch S, Sewell A, Bakkenes M, Berkhout E, Doelman J, Stehfest E, Langhans C, Fleskens L, Bouwman A and Ten Brink B. (2021). The global potential for land restoration: scenarios for the global land outlook. PBL Netherlands Environmental Assessment Agency, The Hague.

Van Ruijven BJ, Van Vuuren DP, Boskaljon W, Neelis ML, Saygin D and Patel MK. (2016). Long-term model-based projections of energy use and CO2 emissions from the global steel and cement industries. Resources, Conservation and Recycling 112, 15–36.

Van Vuuren DP, Hof AF, Van Sluisveld MAE and Riahi K. (2017). Open discussion of negative emissions is urgently needed. Nature Energy 2, 902–904.

Van Vuuren DP, Stehfest E, Gernaat D, De Boer H-S, Daioglou V, Doelman J, Edelenbosch O, Harmsen M, Van Zeist W-J, Van den Berg M, Dafnomilis I, Van Sluisveld M, Tabeau A, De Vos L, De Waal L, Van den Berg N, Beusen A, Bos A, Biemans H, Bouwman L, Chen H, Deetman S, Dagnachew A, Hof A, Van Meijl H, Meyer J, Mikropoulos S, Roelfsema M, Schipper A, Van Soest H, Tagomori I and Zapata V. (2018a). The 2021 SSP scenarios of the IMAGE 3.2 model. EarthArXiv.

Van Vuuren DP, Stehfest E, Gernaat DE, Van Den Berg M, Bijl DL, De Boer HS, Daioglou V, Doelman JC, Edelenbosch OY, Harmsen M and Hof AF. (2018b). Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. Nature Climate Change 8, 391–397.

Viswanathan V and Knapp BM. (2019). Potential for electric aircraft. Nature Sustainability 2, 88–89.

Vogl V, Sanchez F, Gerres T, Lettow F, Bhaskar A, Swalec C, Mete G, Åhman M, Lehne J, Schenk S, Witecka W, Olsson O and Rootzén J. (2021). Green Steel Tracker - Leadership Group for Industry Transition. Green Steel Tracker.

Wesseling JH, Lechtenböhmer S, Åhman M, Nilsson LJ, Worrell E and Coenen L. (2017). The transition of energy intensive processing industries towards deep decarbonization: Characteristics and implications for future research. Renewable and Sustainable Energy Reviews 79, 1303–1313.

Willett W, Rockström J, Loken B, Springmann M, Lang T, Vermeulen S, Garnett T, Tilman D, DeClerck F, Wood A, Jonell M, Clark M, Gordon LJ, Fanzo J, Hawkes C, Zurayk R, Rivera JA, De Vries W, Majele Sibanda L, Afshin A, Chaudhary A, Herrero M, Agustina R, Branca F, Lartey A, Fan S, Crona B, Fox E, Bignet V, Troell M, Lindahl T, Singh S, Cornell SE, Reddy KS, Narain S, Nishtar S and Murray CJL. (2019). Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. The Lancet 393, 447–492.

Yang X, Zhang S and Xu W. (2019). Impact of zero energy buildings on medium-to-long term building energy consumption in China. Energy Policy 129, 574–586.

Appendix. Decomposition formulas

Passenger transport

$$CO_2 = Pop * \frac{Pkm}{Pop} * \sum_{n=1}^{Mode} \frac{Pkm_n}{Pkm} * \frac{FE_n}{Pkm_n} * \frac{CO_{2_n}}{FE_n}$$

Freight transport

$$CO_2 = Pop * \frac{Tkm}{Pop} * \sum_{n=1}^{Mode} \frac{Tkm_n}{Tkm} * \frac{FE_n}{Tkm_n} * \frac{CO_{2_n}}{FE_n}$$

Industry

$$\sum_{n=1}^{Sector} (CO_{2_n} = Pop * \frac{material\ prod}{Pop} * \frac{FE}{material\ prod} * \frac{FEnonelec}{FE} * \frac{CO2 + CCS}{FEnonelec} - CCS$$

Residential buildings

$$CO_2 = Pop * \frac{Floorspace}{Pop} * \frac{UE}{Floorspace} * \sum_{n=1}^{Enduse} \frac{UE_n}{UE} * \frac{FE_n}{UE_n} * \frac{CO_{2_n}}{FE_n}$$

Non-residential buildings

$$CO_2 = Pop * \frac{UE}{Pop} * \sum_{n=1}^{Enduse} \frac{UE_n}{UE} * \frac{FE_n}{UE_n} * \frac{CO_{2_n}}{FE_n}$$

Agriculture

$$N2O = Pop * \frac{kcal}{Pop} * \frac{prod}{kcal} * \frac{N2O}{prod}$$

$$CH4 = Pop * \frac{kcal}{Pop} * \frac{prod}{kcal} * \frac{CH4}{prod}$$

$$CO2 = LUCCO2$$