HOW TO ACHIEVE A RAPID, FAIR, AND EFFICIENT TRANSFORMATION TO NET ZERO EMISSIONS

Policy findings from the NAVIGATE project

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The NAVIGATE consortium

THE NAVIGATE PROJECT AND INTEGRATED ASSESSMENT MODELS

Integrated assessment models (IAMs) integrate energy, economy, land, water and climate into a consistent modelling framework that provides regionally and sectorally differentiated climate-change-mitigation pathways. IAMs provide valuable information to support the design and evaluation of climate change policies. More information on IAMs is available at the website of the Integrated Assessment Modeling Consortium: www.iamconsortium.org/what-are-iams

The EU-funded NAVIGATE project aims to develop the next generation of advanced integrated assessment models to support climate policy making.

NAVIGATE improves the capabilities of IAMs by targeting advancements in two areas: describing transformative changes in the economy, technology and consumer goods and services; and describing the distributional impacts of climate change and climate policy. By addressing existing weaknesses and shortcomings of the current generation of IAMs, NAVIGATE provides new insights into how long-term climate goals can translate into short-term policy actions.

NAVIGATE also aims to increase the usability, transparency, legitimacy and hence uptake of IAM results. To this end, a stakeholder dialogue identifies user needs, methodologies are developed to better assess the robustness of IAM results, model documentation is expanded and new communication tools developed. Capacity building efforts aim to lower the entry barrier to IAM activities for other research around the world. NAVIGATE partners actively promote the uptake of project results by policy makers and international assessments.

The NAVIGATE project was coordinated by the Potsdam Institute for Climate Impact Research and conducted by 16 research institutions from the European Union and two institutions from Brazil and China. The NAVIGATE consortium is listed in the Annex.

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For more information on NAVIGATE please visit www.navigate-h2020.eu

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ACRONYMS AND ABBREVIATIONS

AR6	Sixth Assessment Report of the IPCC
CCS	carbon dioxide capture and storage
CCUS	carbon capture and storage and utilization
CDR	carbon dioxide removal
CGE	computable general equilibrium (models)
CH4	methane
CLEW	climate, land, energy and water
CO_2	carbon dioxide
CO_2eq	carbon dioxide equivalent
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DIC	developed and industrialised countries
GDP	gross domestic product
GHG	greenhouse gas
Gt	gigatonnes
$GtCO_2$	tonnes of carbon dioxide
HVAC	Heating, Ventilation, and Air Conditioning
IAMC	Integrated Assessment Modeling Consortium
IAMs	Integrated Assessment Models
ICAO	International Civil Aviation Organisation
IEA	International Energy Agency
IMO	International Maritime Organisation
IPCC	Intergovernmental Panel on Climate Change
LCA	life cycle assessment
MACC	Marginal abatement cost curve
N2O	nitrous oxide
OECD	Organisation for Economic Co-operation and Development
SDGs	Sustainable Development Goals
SSP	Shared Socio-Economic Pathways

CONTENTS

KEY INSIGHTS

1 ADVANCING THE TRANSFORMATION TOWARDS NET ZERO EMISSIONS AND LIMITING GLOBAL WARMING TO 1.5°C

ADVANCED MITIGATION OPTIONS CAN ACCELERATE NEAR TO MEDIUM TERM EMISSION REDUCTIONS

Key policy entry points exist for achieving rapid and deep reductions in greenhouse gas emissions by both producers and consumers. On the energy side, these entry points are rapid decarbonisation of electricity generation; direct and indirect electrification of industry, transport, and buildings; deployment of carbon dioxide capture and storage (CCS) in industry and for carbon dioxide removal (CDR); substantial increases in energy efficiency in all sectors; high building renovation rates alongside stringent insulation requirements for new buildings; a shift in transport modes; and reduced demand for floorspace, passenger and freight transport. On the land use side, they include deep reduction of non-CO_2 greenhouse gas (GHG) emissions, particularly methane; forest and peatland protection and restoration; land-based CDR measures; reduction of food waste; and dietary change.

The simultaneous and immediate use of all these policy entry points by targeted measures can substantially accelerate action and close the gap between a pathway limiting warming to well below 2°C and a pathway compatible with limiting warming to 1.5°C by 2100. A rapid supply-side transformation is essential to decarbonise energy use and industrial production, an early transformation of energy consumption reduces additional emissions in the short term, and land-use measures contribute enhanced carbon uptake and reduction of non-CO_2 GHGs. Modelling results show that in combination they can slash global CO_2 emissions until the time of net zero CO_2 by an additional 300 GtCO_2 compared to a well below 2°C scenario that does not fully activate these entry points.

The combination of all energy and land use measures can almost close the gap to achieving net zero greenhouse gas emissions in the EU by 2050. Advanced land use measures have to be an integral part of the EU's net zero strategy as they help to push EU GHG emissions reductions beyond 80% towards 90% in 2040 and beyond 90% towards 100% in 2050.

Only the combination of producer- and consumer-oriented policies can realise the full emission reduction potential in all sectors. The combination ensures that both emissions intensity of production and energy and land use intensity of consumption are targeted simultaneously.

→ Section 1

ADVANCING DEEP MITIGATION IN PRODUCTION SECTORS

With enhanced representation of industry and technology innovations, most integrated assessment models can still achieve the goal of limiting warming to 1.5°C in the 21st century. The rapid energy and industry transition is based on strong uptake of renewable energy, electrification of end-uses, and emergence of clean fuels. Global CO_2 emissions from the energy supply sector need to go net-negative by 2050 to compensate for some residual fossil fuel use in energy demand sectors without over-reliance on CDR. CCS is an important mitigation option in the industry sector and for carbon dioxide removal from the atmosphere, especially for limiting warming to 1.5°C, but it raises feasibility concerns and increases mitigation costs.

→ Section 4.2

ADVANCING DEEP MITIGATION ON THE ENERGY DEMAND SIDE

The full portfolio of emissions and energy demand reduction strategies is needed to eliminate the increase in global final energy demand in the buildings and transport sectors, and cut their global emissions in half by 2050 using demand-side measures alone. The portfolio includes activity-reducing measures, technology-oriented efficiency-improving measures and electrification measures. While all three strategies contribute substantially to the reduction of final energy demand, electrification stands out as the strongest contributor to the reduction of direct CO_2 emissions in both sectors. However, this approach also leads to a considerably higher electricity demand than in the other scenarios. A combination of all three strategies can reduce the global electricity demand from buildings and transport substantially. Adopting a comprehensive approach not only yields the most substantial emissions reductions but also reduces the potential stress on the energy system that may arise from focusing on a single demand-side strategy.

In the EU, the combination of all three strategies can accelerate the reduction of final energy demand to around 40% (buildings) and 60% (transport) by 2050 relative to 2015, and cut direct CO_2 emissions from both sectors by 70% using demand-side measures alone. The combination of the strategies also ensures that despite strong electrification of both sectors, the EU's electricity demand in 2050 is around 45% lower for transportation and around 25% lower for buildings compared to the electrification-focused strategy.

→ Section 3.1

THE ROLE OF LIFESTYLE CHANGE FOR CLIMATE CHANGE MITIGATION

Policymakers have many different entry points for enabling low-carbon lifestyle change which interacts with – and can potentially amplify – the mitigation benefits of technological change. But this is not deterministic: lifestyle change as an amplifier needs to be enabled by targeted policy and infrastructure measures that widen access, skills, capabilities and opportunities for engaging with climate action.

Lifestyle groups with lower inherent propensities towards low-carbon lifestyles should not be 'left behind' by mitigation policies with strong co-benefits. Lifestyle change is highly variable across different population segments and 'disengaged' groups risk being marginalised in the absence of strong social learning on climate action. 'Engaged' lifestyle types experience faster and higher reductions in final energy demand compared to 'Disengaged' types in our modelling analysis. This gap is closed under the assumptions of a universal shift to low-carbon values leading to a convergence in 'Improve' behaviours (e.g. efficiency investments) over time and a stronger uptake of 'Avoid' behaviours (e.g. thermostat adjustments) in the formerly 'disengaged' groups.

→ Section 3.2

THE INTERACTION OF STRUCTURAL CHANGE WITH CLIMATE CHANGE MITIGATION

The magnitude and pace of future structural change, understood as the reallocation of activity and employment across economic sectors, is highly uncertain, but can have substantial implications for total energy consumption and GHG emission trajectories of countries. Initial model results suggest that the specific impact of well below 2°C mitigation policies on structural changes at the macroeconomic level can be expected to be small compared to the uncertainty about future structural transformations in baseline scenarios. However, climate policies will have deep structural implications within sectors, particularly in the energy sector but also in other sectors such as agriculture, construction, and industry.

The macroeconomic impacts of a global net-zero transition differ between countries, partly due to differences in the sectoral composition and international trade position of their economies. Modelling results indicate that fossil fuel-exporting nations experience the highest macroeconomic impacts, while high-income fossil fuel-importing countries the lowest. The most uncertain macroeconomic effects are found in middle-income countries that are both carbon-intensive and reliant on fossil fuel imports, such as China and India.

→ Section 4.1

EXPLOITING SYNERGIES BETWEEN ENERGY SECURITY AND CLIMATE CHANGE MITIGATION

The volumes of gas and oil imports to Europe are expected to decrease substantially with ambitious 1.5°C compatible climate policies (25–60% during 2025–2040 based on a model comparison study), greatly enhancing European energy security in the near to medium term.

European gas and oil imports can be reduced the strongest if consumer-oriented policies such as increasing energy efficiency and reducing energy-intensive activity levels feature prominently in the mix. Depending on the model, the difference can be between more than 70% reduction in oil and gas imports in 2050 and just around 40% reduction if only producer-oriented policies are pursued.

→ Section 2.1

EXPLOITING SYNERGIES BETWEEN CLIMATE, LAND, ENERGY AND WATER RELATED SUSTAINABLE DEVELOPMENT GOALS

There are clear synergies in near-term action to achieve the sustainable development goals and climate mitigation. Notably, the shift in diets towards healthier, less carbon-intensive diets, combined with a more equal distribution of food has positive impacts over multiple dimensions of the sustainability agenda, such as food security, the environment and biodiversity, sustainable water management and the climate goals.

Policy implementation must consider the alignment of climate and sustainable development policies, maximizing their benefits and minimizing the trade-offs. The expansion of access to clean energy and lifestyle changes (e.g. dietary changes and sustainable consumption, reducing waste) remains a challenging transformation. Trade-offs between climate policy and energy and food access policies are observed, such as an increase in energy and food prices due to higher pressure in the land system, requiring ancillary measures to address these trade-offs. These include policies to improve clean energy and nutritious food access to the poor and policies advocating less energy intensive lifestyles and healthier diets.
→ Section 2.2

2 ADVANCING THE TRANSFORMATION IN INDIVIDUAL SECTORS

INDUSTRY

Industry sector emissions are expected to increase without additional policies, particularly due to heavy industry expansion, continued fossil fuel use and industrial process emissions. Emission reductions can be achieved by a broad portfolio of options that are commercially available or can be developed over the next ten years.

A broad set of mitigation options is required to overcome decarbonization bottlenecks in the sector. Key mitigation options include supply of clean energy and its integration into the industry sector, particularly electricity, bioenergy and hydrogen, improving material efficiency and recycling, carbon capture with utilization and storage and the use of bioenergy as a feedstock source.

To limit warming to 1.5°C by 2100, rapid and deep industry sector decarbonization is required until 2050, particularly in developed and industrialized countries. This requires the rapid deployment of all key mitigation options leading to a reduction of global industry sector CO_2 emissions to around 3 $GtCO_2$ by 2050 (about 2 $GtCO_2$ lower than in the well below 2°C scenario). Otherwise, decarbonization bottlenecks in the countries' industry sectors put the achievability of limiting warming to 1.5°C at risk.

For the EU industry sector, models with the largest industry decarbonization potential project CO_2 emissions reductions of 73 to 82% by 2040 and 83 to 95% by 2050 relative to 2020. This includes energy efficiency improvements, substitution of fossil fuels by electricity, hydrogen and biofuels (e.g. coal use is reduced by 90% until 2050 in one model), demand reduction, increased recycling, particularly of scrap metal, and CCS. CCS in the EU industry sector is projected to be ramped up to several hundred megatons of CO_2 by 2050, with major fractions used in combination with biomass and for capturing CO_2 from the calcination process in the cement industry.

Efficient use of electricity for industry sector decarbonization is critical. Subsidies on electricity prices for incumbent industries and technologies will likely cause misallocations and slow the rapid decarbonization of industry processes. The decarbonization options are closely intertwined. For example, increased recycling of scrap metal increases energy efficiency and electrification rates. High demand for electricity from electrification in all sectors discourages the deployment of e-fuels rather than biofuels in the industry sector.
→ Section 4.3

ROAD TRANSPORT

Disadvantaged population groups have the lowest flexibility in adjusting their mobility range, and should therefore be a focus of more equitable transport and health policies. The COVID-19 pandemic caused a significant worldwide reduction in human mobility. Our case study for Sweden found that socially disadvantaged groups had the lowest reduction in mobility range, while the wealthiest groups had the largest. The findings highlight the importance of integrating socio-economic and minority considerations into transport policy analysis, including the analysis of net zero emissions strategies for road transport.

New mobility services and innovations like car clubs, peer-to-peer car sharing, ridesharing, shared

ride hailing, electric vehicles, and e-bikes can reduce GHG emission from passenger transport if designed properly. Proper design is critical to avoid disincentives for, e.g., increased car use and higher energy demand that could increase emissions. Early adoption by consumers is motivated by a combination of functional, symbolic and societal considerations.

A multi-faceted approach involving carbon pricing, phase-out policies for international combustion engines, and infrastructure build-up for e-mobility, can offer the most effective route to decarbonize Europe's road transport. Using an integrated assessment model for the EU, it is found that the combination of carbon pricing and phase out policies could bring EU road transport emissions close to zero by 2050. A carbon price significantly reduces indirect emissions like those from electricity production, while phase-out policies slash direct emissions from vehicles.

Further evidence from a transport model suggests that by 2050, around 60% of passenger cars in the EU could be electrified, necessitating an investment of 44 to 80 billion euros in infrastructure from 2031-2050. In the study, a well-developed fast-charging network is found to be pivotal to this transition.

→ Section 3.3

INTERNATIONAL TRANSPORT

A multi-model study of 1.5–2°C mitigation scenarios shows declining (1.5°C) to stabilizing (2°C) CO_2 emissions from international shipping by 2050. This compares to a roughly 50% increase of shipping emissions in line with the projected increase in shipping activity in a scenario extrapolating the NDCs. The additional reductions in the 1.5°-2°C scenarios are achieved by fuel switching and to a lesser degree efficiency improvement. Biofuels and alcohols seem the most promising short-term candidates, while ammonia and synthetic energy carriers become essential towards 2050. The International Maritime Organisation (IMO) 2018 emission reduction target for the sector (-50% by 2050) remains on the ambitious side of the 1.5°C scenarios in the study.

International aviation seems harder to decarbonise than shipping as most of the models show increasing emissions after 2050 even under a 1.5°C compatible carbon budget. The rise in emissions is driven by a large increase in aviation demand (3–5 times higher in 2050 than in 2010 depending on the scenario) and the limited efficiency gains and fuel switch options available. Biokerosene is taken up rapidly, but may be constrained by biomass availability, while e-fuel uptake is slower.

→ Section 3.4

BUILDINGS

Combining stringent decarbonisation of energy supply with building sector policies including activity reduction and shift, electrification and fuel shifts, and technological improvements and energy efficiency can reduce total (direct and indirect) CO_2 emissions in the global and European building sectors by up to 95% in 2050 compared to a reference scenario without stringent decarbonisation and building sector policies. The building sector policies are critical to fully capitalize on the decarbonisation of energy supply in the sector.

In absence of stringent climate policies, building sectoral policies alone can reduce total (direct and indirect) CO_2 emissions in the building sector by 25% globally and by 35% for Europe (averages across models) in 2050 compared to a reference scenario.

→ Section 3.5

AGRICULTURE

Substituting 20 percent of per-capita ruminant meat consumption with microbial protein by 2050 could halve annual global deforestation and related CO_2 emissions from land-use change. This switch also lowers methane emissions from ruminant enteric fermentation and reduces nitrous oxide emissions from fertilizers. In summary, microbial protein production for the same protein supply is more environmentally friendly, requiring less land and resulting in fewer greenhouse gas emissions than ruminant meat production.

Non-CO_2 greenhouse gas mitigation potentials, most of which are in the agricultural sector, play a key role for limiting warming to 1.5–2°C. Under pessimistic non-CO_2 mitigation assumptions, limiting warming to 1.5°C by 2100 is found to be infeasible and combined with an unfavourable socio-economic outlook might even put holding warming to below 2°C at risk. In a 2°C scenario, the variation in non-CO_2 mitigation potentials translates into a large projected range in non-CO_2 emissions reduction (40–58% in 2100 relative to a baseline without climate policy), cumulative CO_2 emissions until 2100 (±120 $GtCO_2$) and policy costs (±16%).

→ Sections 4.4 · 4.5

3 TOWARDS AN EFFICIENT AND JUST TRANSITION

DISTRIBUTIONAL IMPACTS OF CLIMATE CHANGE AND CLIMATE CHANGE MITIGATION MEASURES

Stringent mitigation policies are found to be regressive in many regions, i.e. they impact the income of poorer households more than the income of richer ones. For example, we found for Europe that a carbon price of 25 euro per tonne of CO_2 would result in a 3% increase of household expenditures for the poorest 10% of households, whereas richer households would only see an increase of 1.5% of their expenditures.

Climate change impacts affect poorer households disproportionally. For example, we found that climate impacts in the case of largely unabated climate change could cause the Gini index, a measure of domestic income inequality ranging from 0 (perfectly equal) to 100 (one person with all income) (EU Gini index in 2021: 52), to rise by up to six points, particularly in Sub-Saharan African countries, resulting in substantial worsening of income inequality.

In the longer term, strong climate action will benefit poorer households, while in the near-term additional policies may be required to ensure a just transition. Mitigation pathway analysis reveals the countervailing distributional impacts of mitigation action and avoided climate damages over time. In the short term, avoided climate damages are still small and the adverse distributional impacts of mitigation dominate. In the long term, the impact of mitigation policies has abated and a large distributional benefit from avoided climate damages clearly prevails.

→ Section 5.1

REDISTRIBUTIVE POLICIES TO ENHANCE EQUITY OF THE TRANSITION

The redistribution of carbon revenues in form of a “climate dividend”, i.e. an annual uniform payment to households, can effectively address the regressive impact of carbon pricing, and can even lead to a reduction in income inequality compared to the reference case without carbon pricing. We have shown in a model study that global carbon pricing combined with a climate dividend in a well-below 2°C pathway can make the poorer 60% of the world population already better off by 2030, rising to 96% of the world population in 2100 due to the avoided climate impacts.

Inequality is consistently reduced in 1.5°–2°C mitigation pathways from a combination of redistributive policies using carbon pricing revenues and the avoided increase in inequality from climate damages. Based on a first-of-its-kind integrated assessment model comparison study of distributional implications of mitigation pathways we found consistent reductions in income inequality across a set of countries from all continents and throughout time (2030–2100) compared to the case of unabated climate change. The inequality reducing effect of redistributive policies dominates in the near term while the effect of avoided climate damages dominates in the long term.

→ Section 5.1

ENHANCING EQUITY AND EFFICIENCY OF GLOBAL COLLECTIVE ACTION

Global collective action is subject to equity, efficiency and sovereignty considerations that often conflict with each other. Equitable burden sharing and efficient use of mitigation options are important and conflicting goals and the use of international transfers to mediate between the two is limited for political reasons. International climate policies need to find compromises that balance different interests.

We show in a modeling study of equity-oriented mitigation pathways limiting warming to well below 2°C that equitable effort sharing can be achieved by a combination of limited international financial transfers and moderate spread of domestic mitigation action. For instance, without any transfers equalizing effort would require the most mitigation-constrained region to adopt a carbon price that is around 100 times higher than the lowest regional carbon price, and increases global mitigation costs by 2.6 trillion US$ (2020–2100). Reducing the carbon price spread by 75% lessens the global inefficiency by 56%, but requires only around 20% of transfers that would be needed under a globally uniform carbon price to equalize effort. This achieves the distributional objectives with neither straining the socioeconomic nor the fiscal sovereignty of nations.

If the differences in climate policy stringency remain large because international transfers are strongly constrained by sovereignty concerns, market distortions can lead to adverse outcomes for sustainability objectives. Prominent examples are increased bioenergy trade from low to high carbon price countries and increased need for CDR to offset additional emissions from regions with low carbon prices.

→ Section 5.4

IMPACTS OF CARBON REVENUE RECYCLING ON EQUITY AND EFFICIENCY

Using a set of well-established macro-economic models, we demonstrate the socio-economic benefits of using revenues from carbon pricing in a 1.5°C mitigation scenario to reduce distortive labour taxes leading to significant reduction of the losses in gross domestic product (GDP) and employment caused by deep decarbonisation. In addition, lump-sum transfers to households can improve income equity despite the lower GDP than in the labour tax reduction scenario, illustrating a potential trade-off between different carbon revenue recycling schemes in terms of efficiency and equity.

→ Section 5.2

EMPLOYMENT EFFECTS OF THE TRANSITION IN THE EU

Despite limited mitigation costs, the 1.5°C transition is expected to create about 1.3–1.4 million new jobs in the EU in 2040 and 2050, if carbon revenues are used to reduce labour costs. Job losses are registered only in fossil production sectors and in heavy manufacturing, while jobs are created in sectors related to the transition (and their supply chains), including electricity supply, clean energy manufacturing, construction services needed for the build-up of low-carbon technologies and infrastructure, and agriculture to produce advanced biofuels.

When focussing on the energy sector, we estimate the largest increase in direct energy jobs in the EU in the most ambitious net zero scenario, from about 1.3 million jobs today to about 2.5 to 3 million jobs by mid-century. Underneath is a shift in energy sector employment, with around 300 thousand jobs lost in the fossil fuel industry and the majority of new jobs related to renewable energy, reaching 80% of total energy employment by 2050. Regional hot spots, notably Poland, exist, and just transition policies will be crucial to ensure a just transition.

→ Section 5.3

1

ADVANCED MITIGATION OPTIONS CAN ACCELERATE NEAR TO MEDIUM TERM EMISSION REDUCTIONS

MOTIVATION

Current climate policies are not consistent with the 1.5°C limit in almost all countries. Where carbon prices are implemented at all, they are too low, and there appears to be reluctance to raise carbon prices to levels that would lead to a 1.5°C pathway. However, early and rapid emission reductions as required by the Paris Agreement and national and regional targets such as the EU Green Deal, require to draw on advanced emission reduction measures across the board. Here, we investigate how early policies[1] leveraging advanced emissions reduction measures on the industry and energy supply side, the energy consumption side, as well as in the land use sector can close the gap between well below 2°C and 1.5°C pathways without increasing the carbon price. Our analysis is based on a comparison of five integrated assessment models (IAMs) that have been improved in a number of aspects within the NAVIGATE project, including enhanced sector representation, updated GDP and population projections, and new marginal abatement cost curves (MACCs) for non-CO_2 greenhouse gas (GHG) emissions.

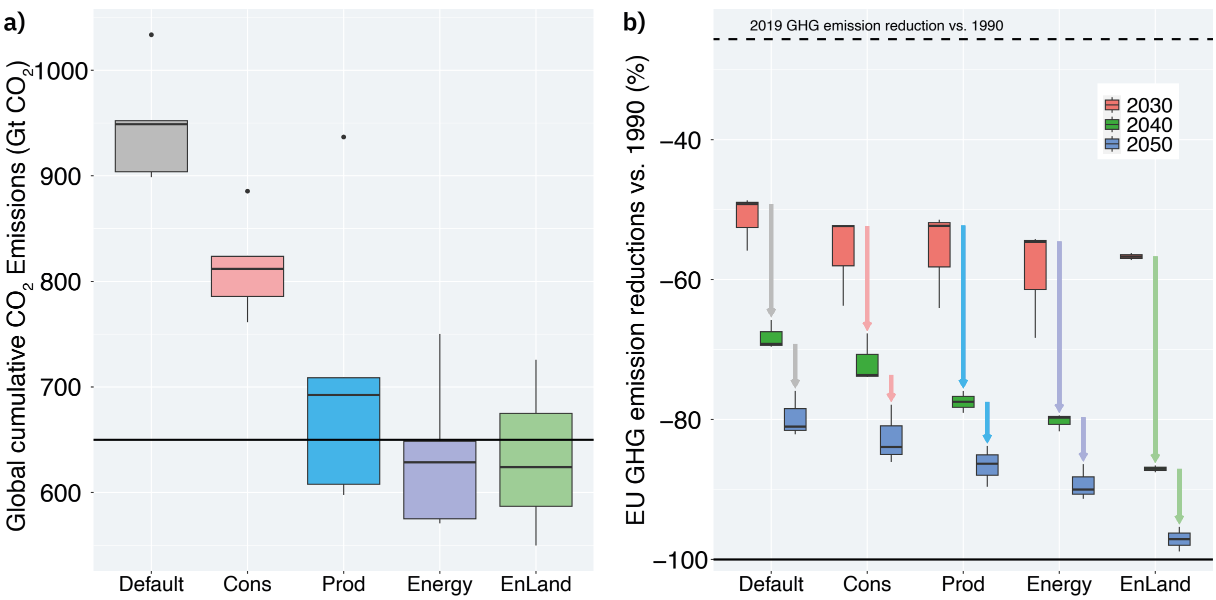
METHODS

We focus on three dimensions of advanced emission reduction measures as entry points for early action to be realised through targeted policies to accelerate their deployment: transformation of energy consumption in the buildings and transport sector, including efficiency

FIGURE 1.1: Scenario design.

	Default Industry & Energy Supply	**Advanced Industry & Energy Supply**	**Advanced Industry & Energy Supply & Land**
Default Energy Consumption	Default	Prod	
Advanced Transformation of Energy Consumption	Cons	Energy	
Advanced Transformation of Energy Consumption and Land			EnLand

FIGURE 1.2: a) Global cumulative CO_2 budget from 2020 until the time of net zero CO_2 emissions. The black line indicates the global CO_2 peak budget consistent with 1.5°C with low overshoot (650 $GtCO_2$). b) Reductions in annual EU27+UK GHG emissions with respect to 1990 in 2030 (orange), 2040 (green), and 2050 (blue). The dashed line indicates emission reductions in 2019, the solid line indicates the net-zero target.



1 These policies include policies to shift consumer preferences, early development of technologies, as well as regulatory measures, which do come at a cost though it is less visible than an increased carbon price.

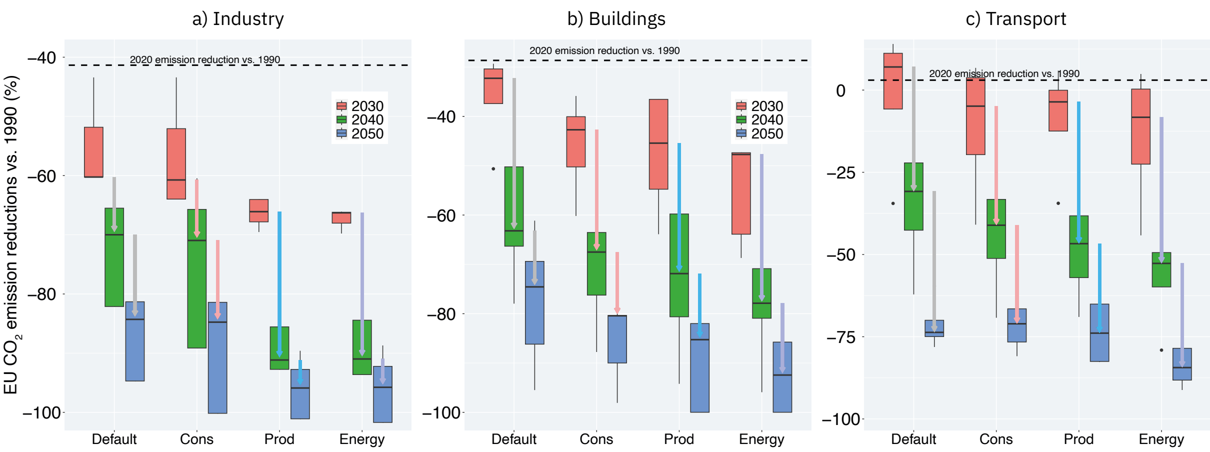
measures; transformation of industry and energy supply, including electrification measures in all sectors; and mitigation in the land use sector, including both production and consumption measures.[2] We combine these three dimensions into five scenarios (see Figure 1.2): a *Default* without advanced mitigation measures, advanced transformation of energy consumption (*Cons*), advanced transformation of industry and energy supply (*Prod*), the combination of both (*Energy*), and the combination plus advanced transformation in the land use sector (*EnLand*). All scenarios follow the same carbon price trajectory, which in the *Default* scenario leads to a high probability (>80%) of staying below 2°C (IPCC, 2021; Forster et al. 2023). In the following we analyse the extent to which early deployment of advanced mitigation measures can close the gap to 1.5°C without further increasing the carbon price.

KEY FINDINGS

Only the combination of all Energy system measures reduces global cumulative CO_2 emissions (Figure 1.2a) to a level compatible with the 1.5°C budget. Both dimensions are needed because supply-side transformation is essential to decarbonise the industrial sector, and all sectors in the long term, while the transformation of energy consumption can reduce emissions especially in the short term, when the energy system is not yet decarbonised. This also allows for more ambitious short term targets and leads to lower cumulative emissions. Land use policies can contribute to enhanced carbon storage on land, thereby further reducing cumulative CO_2 emissions. In addition, land policies are the most effective option for reducing non-CO_2 GHG emissions, leading to a further reduction of peak warming and overshoot of 1.5°C by 0.03–0.12°C.

The combination of all energy system and land use measures can almost close the gap to achieving greenhouse gas neutrality in the EU[3] by 2050. Consumer- and producer-oriented policies complement each other, with the combination enabling emission reductions of around 90% in 2050 compared to 1990 (Figure 1.2b). Advanced land use measures (EnLand) are crucial to push EU GHG emissions reductions beyond 90% towards 100% in 2050 and are therefore essential for achieving the EU 2050 target in combination with the other advanced mitigation measures. The inclusion of land use measures is already crucial for more ambitious 2040 targets. While advanced supply-side measures are more important in the long term, the energy demand reductions through changes in consumption (*Cons*) have a notable impact especially on 2030 emissions, and therefore play an important role in meeting short-term targets.

FIGURE 1.3: Reductions in annual EU27+UK CO_2 emissions with respect to 1990 in 2030 (orange), 2040 (green), and 2050 (blue) for a) industry, b) buildings, c) transport. The dashed line indicates emission reductions in 2020 with respect to 1990.



2 Demand side measures include consumer-oriented measures relating to both efficiency improvements and behavioral changes towards lower energy demand, e.g. faster buildings renovation and better insulation for new constructions, efficiency improvements in the transport sector, but also reduced passenger and freight transport, transport modal shifts, lower floorspace per capita, and a shift in setpoint temperatures. On the production and energy supply side, the measures include a rapid decarbonization of electricity generation, a push for more direct and indirect electrification in all sectors, and significant deployment of CCS. Measures in the land use sector range from advanced measures in reducing non-CO_2 GHG emissions modelled via more optimistic MACCs and inclusion of peatland protection and restoration as well as additional land-sharing CDR methods to dietary changes and reduced food waste both at household levels and farms or processing retail.

3 All results relate to EU27 + UK

Both producer- and consumer-oriented policies are needed to realise the full emission reduction potential in all sectors (Figure 1.3). Industry and energy supply measures halve the emission intensity by 2050 compared to the *Default* by reducing fossil energy and increasing renewable energy and electrification. Consumption measures, on the other hand, lead to larger reductions in energy intensity, in particular in the buildings and residential sector. Total final energy in the EU in 2050 is reduced from 42 (34–49) EJ/yr in the *Default* scenario to 37 (28–44) EJ/yr in the *Cons* scenario (globally from 410 (370–440) EJ/yr to 330 (300–400) EJ/yr).

Early policies targeting industry and energy supply, energy consumption, as well as land use can close the gap between a pathway that limits warming to well below 2°C and one that is compatible with limiting warming to 1.5°C by 2100. On the energy supply side, early policies are important to drive investment in direct electrification and the scale-up of technologies such as CCS to enable deep emission reductions in the coming decades. The rapid reductions in energy demand observed in the scenarios may be difficult to achieve in the real world, where behavior can be very inert. Although these changes result from individual consumer choices and are difficult to influence at sufficient breadth across society through policy, policy can support consumption choices through structural changes and political action to enable the uptake of low-carbon choices, for example by reducing barriers such as lack of information (Creutzig et al., 2022). To ensure a successful land use transformation, a process to gain support of affected farmers as well as consumers needs to start now.

THE IMPORTANCE OF THE LAND USE SECTOR IN BRAZIL

Regional context matters for the analysis of deep mitigation pathways. Different geographies have different energy and land resources and their economies are adapted accordingly. The Brazilian context accentuates the profound significance of the land use sector in terms of both GHG emissions and the national economy. The integration of measures to mitigate emissions from agriculture and the management of non-CO_2 gases has emerged as a significant strategy in Brazil for achieving emissions reductions while advancing economic goals.

KEY FINDINGS

Advanced transformation of the land use system including food demand changes and reduction of food waste is of great importance for Brazilian deep decarbonization. These measures help the agricultural sector to assume a fundamental role both in producing food with lower levels of GHG emissions, and in producing energy, from electricity to producing biofuels, with fewer direct and indirect emissions. This reduces the GHG footprint of biofuel production without reducing the supply. These measures not only mitigate emissions related to land use, but also reduce food losses, and improve agricultural efficiency – for food and energy crops – which helps to relieve pressure on new areas for agricultural production.

Expansion of agricultural production systems to areas with a high level of degradation becomes essential to enable the production of agricultural products – food or energy – with lower GHG footprints. The migration of crops, particularly energy crops, to areas with initially low productivity, such as areas with a high degree of degradation, is also a priority. The recovery of these areas allows for an increase in carbon stock levels below the ground, which helps to mitigate agricultural emissions from the input of hydrogenated fertilizers.

It is necessary to develop comprehensive climate policies that include a broad spectrum of GHGs that extend beyond CO_2. Policymakers are tasked with recognizing the substantial contribution of non-CO_2 gases to climate change, making emissions reduction targets for non-CO_2 emissions indispensable. This would help the agricultural sector develop and implement new production systems, more advanced, disruptive and with fewer non-CO_2 emissions than those used in traditional systems. In Brazil, the most significant GHG emitter in agriculture and the sector with the highest volume of CH_4 emissions is the cattle sector – which is the sector with the highest methane emissions in the country – which can reduce its emissions through more intensive production systems.

In essence, the Brazilian land use sector presents itself as a pivotal domain for curbing GHG emissions while simultaneously stimulating economic progress, both in terms of AFOLU emissions and energy emissions. Strategies encompassing a range of non-CO_2 gases, anchored in sector-specific approaches, serve as the foundation for achieving ambitious emissions reduction targets. To expeditiously traverse the trajectory towards net-zero CO_2 emissions and address the overarching climate challenge, policymakers must prioritize a combination of measures that enhance energy efficiency, champion electrification initiatives, and foster sustainable practices within the AFOLU sector. In harnessing these diverse opportunities, Brazil stands poised to lead as a model of sustainable land use paradigms, thus significantly contributing to the global trajectory of emissions abatement.

2

SYNERGIES BETWEEN ADVANCED MITIGATION OPTIONS AND SUSTAINABLE DEVELOPMENT

Different mitigation strategies can have different impacts for sustainable development and other societal goals. For example, a strong focus on demand reduction would help limit the size of the overall energy system and keep the need for energy production low, which could reduce resource demand and energy trade. In this section, we examine the implications of mitigation strategies on energy security, on the water-energy-land nexus, and on the implications for welfare distribution.

2.1 EXPLOITING SYNERGIES BETWEEN ENERGY SECURITY AND CLIMATE CHANGE MITIGATION

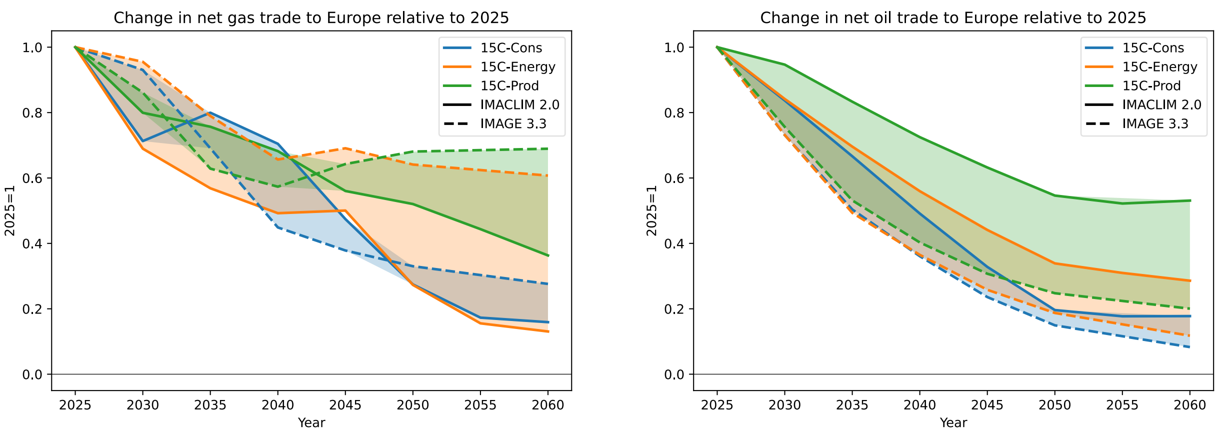
MOTIVATION

A key pillar of the European Union's policy agenda revolves around energy security. The way in which future fossil energy imports develop may depend on the mitigation strategy. We used two IAMs to assess the energy security implications of GHG mitigation policies focused on the consumption or production side. We focus on energy imports of oil and natural gas, which have dominated the energy security debate in Europe in recent years. As Europe's domestic oil and gas production is small and declining, and geopolitical developments strongly influence international oil and gas markets, the synergy between mitigation policies and energy security becomes more apparent.

METHODS

The IAMs have been applied to four scenarios, all of which limit global warming to 1.5°C with low overshoot: default assumptions for the transformation of industry, energy supply, and energy consumption (15C-Default), advanced measures for the transformation of industry and energy supply but default assumptions for the transformation of energy consumption (15C-Prod), advanced transformation of energy consumption but default assumptions for the transformation of industry and energy supply (15C-Cons) and the combination of advanced measures in all production and consumption sectors (15C-Energy). Consumption-oriented measures include efficiency and sufficiency options in buildings and transport, such as increased insulation and vehicle efficiency, and reduction in floor space and transport demand. Production-oriented measures include rapid and high levels of electrification, combined with hydrogen and CCS technologies. The climate targets in all scenarios limit warming to 1.5°C with low overshoot. To achieve this, a peak carbon budget of 650 $GtCO_2$ (as of 2020) and an end of century carbon budget of 400 $GtCO_2$ have been enforced in all scenarios. The scenarios are implemented globally, but analysed here only for the European region in two IAMs: IMAGE and IMACLIM. The trade variables are not constrained by the scenario implementation, but nevertheless, a distinction between the trade impacts across scenarios emerges from these scenarios.

FIGURE 2.1: Net trade trajectories for oil and gas fuels to the European region relative to 2025 in the IMACLIM and IMAGE models.



KEY FINDINGS

The volumes of gas and oil imports to Europe are expected to decrease substantially (25–60% during 2025–2040) with ambitious 1.5°C compatible climate policies, which will significantly improve Europe's energy security in the short to medium term.

Gas imports to Europe are expected to decrease the most in the longer term due to the implementation of policies to reduce energy demand. This is a finding for the long-term trends in both models (Figure 2.1) albeit with large fluctuation in the short term. Although the gas trade projections differ between the models, both show a slower decline in gas imports in the 15C-*Prod* scenario and ultimately the lowest import levels in the 15C-*Cons* scenario. In the combined case of the 15C-*Energy* scenario, including both consumer and producer policies, the models diverge: the IMAGE model converges to higher imports than under 15C-*Prod* and the IMACLIM model converges to the lower import levels of 15C-*Cons*.

European oil imports are projected to fall sharply by mid-century across models and scenarios. Again, imports are lowest when demand-side mitigation measures are implemented, while production-side measures maintain higher levels of oil imports in both models.

These findings show that an ambitious climate policy would significantly reduce Europe's dependence on fossil fuel imports and enhance energy security as a co-benefit of climate policy. The scenarios suggest that mitigation measures on the consumption side would achieve largest reduction in oil and gas imports, but in order to reap the benefits of both approaches, a balanced mitigation approach including both production and consumption side measures would be beneficial.

2.2 EXPLOITING SYNERGIES BETWEEN CLIMATE, LAND, ENERGY AND WATER RELATED SUSTAINABLE DEVELOPMENT GOALS

MOTIVATION

In 2015, the 2030 Agenda on Sustainable Development was agreed upon. This agenda introduced the Sustainable Development Goals (SDGs), which set a global ambition to accelerate sustainable development around the world. The SDGs set targets across many dimensions, including the human systems (e.g. poverty reduction, social well-being and economic development) and the environment (e.g. environmental protection, biodiversity and climate). Implicit in this combined agenda is the need for massive transformations across society, both in terms of soft measures such as health, education and governance, as well as physical infrastructure systems to support clean and modern economies (Soergel et al., 2021; Doelman et al., 2022; Kulkarni et al., 2022). Several SDGs are directly related to climate change and policies to mitigate it. These include the set of SDGs related to the climate, land, energy and water (CLEW) nexus (SDG2, SDG6, SDG7, SDG13 and SDG15). In NAVIGATE, we aim to understand the synergies and trade-offs between climate policy and the SDGs agenda: how do near-term actions on the SDGs influence the long-term climate goals?

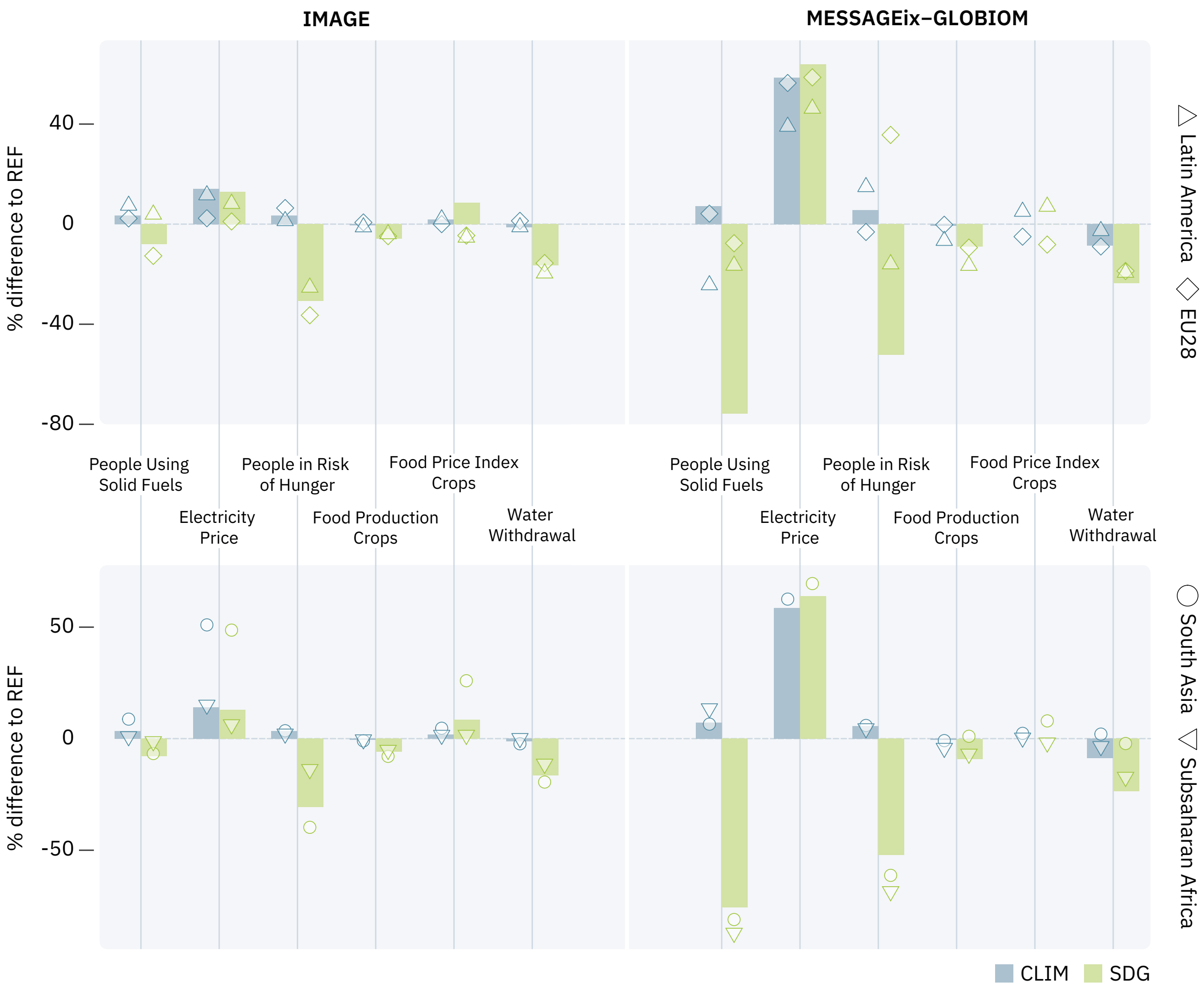
METHODS

Based on a model comparison (IMAGE and MESSAGEix-GLOBIOM), we evaluate three scenarios: i) a reference scenario, without new climate policies (REF); ii) a well-below 2°C scenario (CLIM); and iii) a CLEW nexus SDGs scenario, targeting the CLEW nexus (SDG). All scenarios include climate impacts (e.g. impacts on precipitation patterns and drought intensity, crop yields, renewable energy supply, and cooling and heating demand).

KEY FINDINGS

We see clear positive impacts from combining the achievement of climate goals with the SDG agenda (Figure 2.2**).** In particular, combining a more equitable distribution of food with a shift towards healthier, less carbon-intensive diets, as well as reducing food waste, has positive effects across multiple SDGs, increasing food security (SDG2), protecting natural areas and biodiversity (SDG15), the climate goals (SDG13) and sustainable water management (SDG6).

FIGURE 2.2: Effectiveness of implemented SDGs measures, per region, per model (2030), % difference when compared to the reference scenario. Bars represent global results, points represent different regions. Outliers: electricity prices increase over 100% in Sub Saharan Africa for the MESSAGEix-GLOBIOM model (122% and 149%, for CLIM and SDG, respectively).



Near-term action on the sustainability agenda results in less temperature overshoot, and therefore less need for net negative emissions by the end of the century to meet the global warming mitigation targets.

However, important trade-offs such as higher food prices exist as well, which may require additional policies to mitigate impacts on poorer households. For example, both models show an increase in food prices due to increased competition for land as a result of land-based mitigation and the protection of natural areas. Without accompanying policies to ensure access to and distribution of food, as well as the adoption of healthier diets (lower meat consumption and calorie intake), an increase in prices could lead to higher risks of food insecurity. These findings underlines the extreme challenge of such a system transformation and the importance of coordinating policies and balancing their benefits and trade-offs.

2.3 WELFARE GAINS THROUGH CLIMATE POLICY

MOTIVATION

Climate policy can affect human welfare through climate change and mitigation in a number of ways, including but not limited to changes in economic performance, the natural environment, human health, and food and energy supply. For some of these dimensions, there are trade-offs between better performance on welfare-related dimensions and achieving more ambitious climate targets.

METHODS

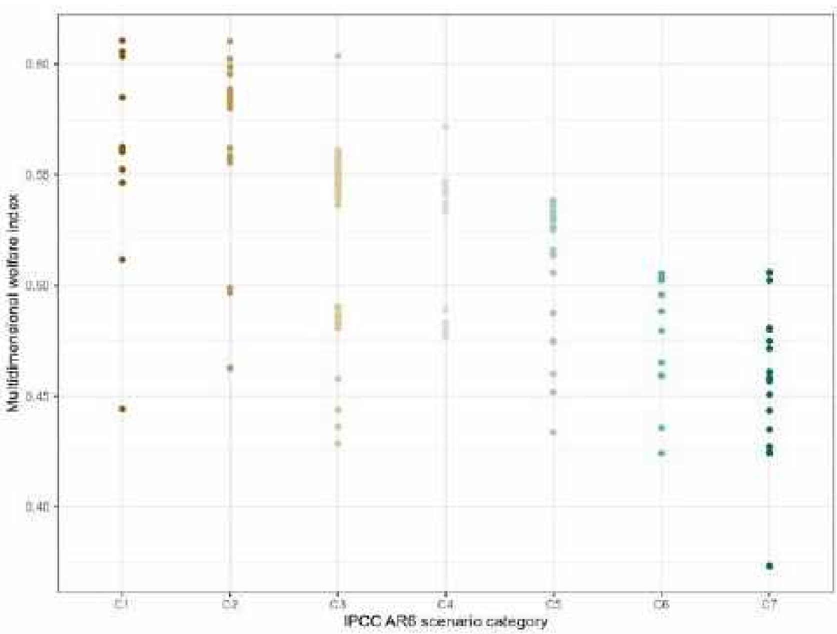
A comprehensive multidimensional measure of welfare, generalising the Human Development Index, can attempt to weigh and synthesise these effects. We develop such an index based on seven indicators reflecting the quality of human health (including food supply), education, economic performance and also environmental quality and temperature. The index depends on two key sets of parameters: 1) how difficult it is to compensate for losses in one dimension, e.g. lower health, by gains in another dimension, e.g. education (this is a parameter of "substitutability"); and 2) how much weight is given to each dimension.

KEY FINDINGS

We find that **higher multidimensional welfare is very often associated with a lower temperature target** described by the categorization of scenarios in terms of their warming outcome used by the IPCC Sixth Assessment Report (AR6). This is illustrated in Figure 2.3 which shows welfare levels in 2100 for scenarios in the warming categories. The finding that welfare in 2100 increases with more stringent climate targets is robust to a wide variety of assumptions about the substitutability parameter and also to a wide variety of weights on all indicators.

The main exception is human health. We find that when food security is a high priority, welfare increases when less stringent climate targets are met. Our findings suggest that **climate policies should be accompanied by policies to mitigate adverse effects on food production**. Furthermore, welfare does not always increase with more ambitious climate policies in the short to medium term, reflecting an intertemporal trade-off.

FIGURE 2.3: Value of the welfare index in 2100 for different scenarios in the AR6 database depending on the climate assessment categories of the IPCC (categories C1 to C7 from lowest to highest warming outcomes, where C1 corresponds to limiting warming to 1.5°C, while C7 corresponds to warming greater than 4°C).



3

ADVANCING DEMAND SIDE MITIGATION

It has become increasingly clear that demand-side mitigation is a critical part of strategies to meet the Paris climate goals (IPCC, 2022; Mundaca et al., 2019). Demand side changes, including lifestyle choices, consumer technology choices, and energy-saving behavior, can aid in mitigating climate change in the short term and reduce the need for carbon dioxide removal technologies in the long term. Reduced energy demand also allows for more flexibility in technology choice in the supply sectors (IPCC, 2022). Furthermore, electrification of energy end uses can contribute substantially to emission reductions on the demand side and has synergies with the transition to renewables-based power systems (Luderer et al., 2022).[4]

3.1 THE ROLE OF DEMAND-SIDE MEASURES IN CLIMATE MITIGATION PATHWAYS

MOTIVATION

Recent estimates (IPCC, 2022) suggest that shifting and reducing activities, together with efficiency improvements in end-use sectors, could potentially lead to sectoral emission reductions of 40–70% by 2050. However, uncertainties remain about the demand-side contributions to emissions reductions, as well as the optimal emission reduction strategies in each sector and the interactions between different sectors. Therefore, we aim to provide a comprehensive perspective on the emission reduction potential of demand-side strategies.

METHODS

The study uses several IAMs (COFFEE, IMACLIM-R, IMAGE, MESSAGE, PROMETHEUS, REMIND and WITCH) to analyse a set of demand-side intervention scenarios, looking specifically at the buildings and transport sectors. Each scenario represents a distinct intervention strategy: the activity-focused strategy (ACT) includes the promotion of methods to reduce activity levels, such as active transport and flexible workspaces in buildings; the technology-focused strategy (TEC) focuses on increasing efficiency through measures such as improved building insulation and heating, ventilation and air conditioning (HVAC) systems, as well as the introduction of fuel-efficient technologies in vehicles; the electrification-focused strategy (ELE) includes the introduction of various low-carbon technologies, including heat pumps in buildings and electric vehicles in transport, among others. Current policies serve as the reference (REF) against which the intervention strategies are applied within each scenario.

KEY FINDINGS

The models project that the current trend of emission growth in the transport and buildings sectors can be reversed into emission reductions when combining all the measures.

In the reference current policy scenario, global transport emissions are projected to increase on average by 23% (17–32%) in 2030 and 31% (18–48%) in 2050 compared to 2015 levels. Emissions in the buildings sector are projected to increase on average by 20% (-1–36%) in 2030 and 21% (-8–38%) in 2050. In the EU, a different trend is expected. Transport emissions are projected to decrease by 27% (-5–51%) in 2030 and by 44% (6–73%) in 2050 compared to 2015 levels, while emissions in the buildings sector are projected to decrease by 3% (-9–22%) in 2030 and 23% (-4–52%) in 2050. All intervention strategies lead to global emissions reductions compared to 2015 levels (Figure 3.1) and further contribute to lowering EU emissions (Figure 3.2).

Electrification and fuel shifts can play a pivotal role in reducing demand-side CO_2 emissions in both sectors, but they also result in a substantial surge in electricity demand. Among most models the electrification-focused strategy is the most effective in reducing direct CO_2 emissions in the transport and buildings sector by 2050, even resulting in a decrease compared to 2015 levels. Conversely, global electricity demand more than doubles by 2050 compared to 2015 in this scenario, whereas EU electricity demand increases by 60%.

4 Note that electrification is treated here slightly different than in the Chapters above. Here, electrification is analysed as a consumption-side measure, whereas in the scenarios in Chapters 1 and 2 electrification was lumped with production-side measures.

FIGURE 3.1: Growth of global Final Energy (top) and (direct) global CO_2 emissions from fuel combustion (bottom) in energy demand sectors in 2030 and 2050 with respect to 2015. All scenarios have current policies implemented. Bars indicate model-averages and black lines depict the model ranges.

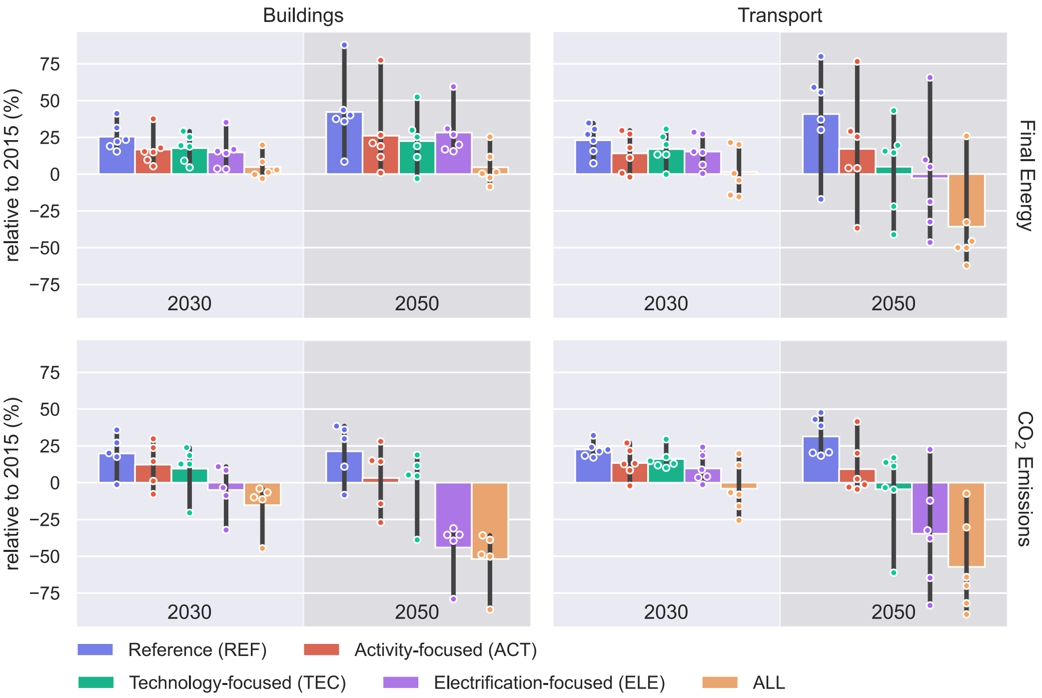
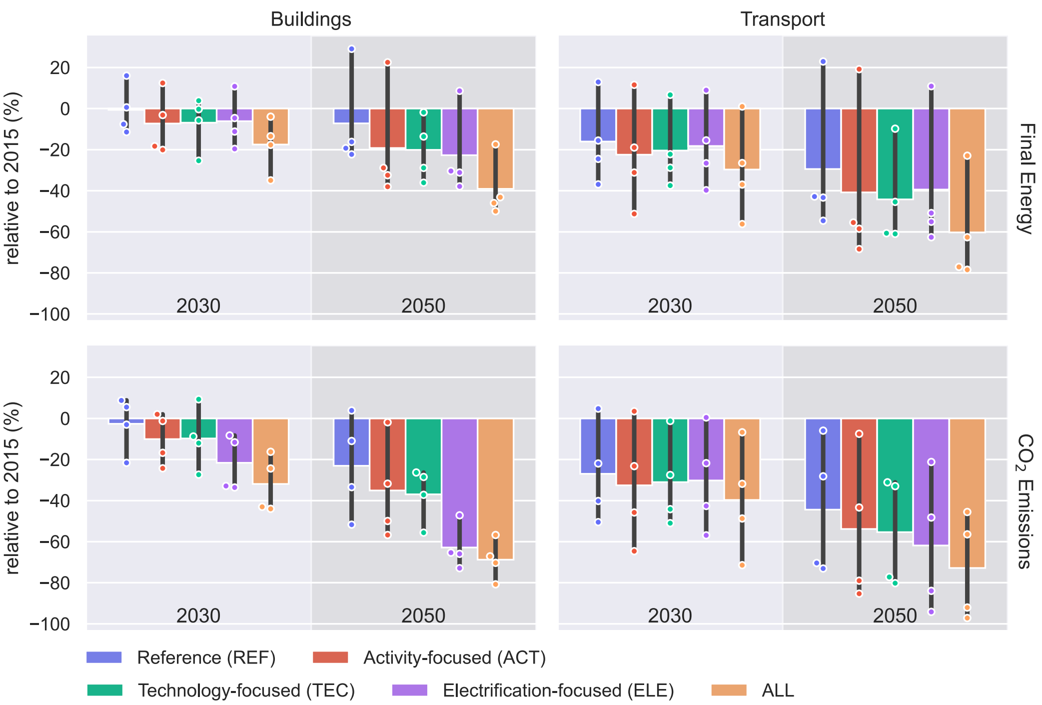


FIGURE 3.2: Growth of Final Energy in the EU (top) and (direct) CO_2 emissions from fuel combustion in the EU (bottom) in energy demand sectors in 2030 and 2050 with respect to 2015. All scenarios have current policies implemented. Bars indicate model-averages and black lines depict the model ranges.



Combined approaches not only lead to the greatest reduction in emissions but also help alleviate the stress on the energy system that may arise from individual demand-side changes, such as an increase in electricity demand due to electrification. Activity reductions and technological improvements can help to decrease electricity demand. In 2050, the combined intervention scenario (ALL) results in a 35% (13–58%) lower global electricity demand for transportation compared to the electrification-focused scenario (ELE). For buildings, global electricity demand is 20% (14–28%) lower in the ALL scenario. Similarly, the EU's 2050 electricity demand is 44% (33–56%) lower for transportation and 23% (14–31%) lower for buildings in the ALL scenario. This implies that a comprehensive approach can reduce the pressure on the supply side.

3.2 HE ROLE OF LIFESTYLE CHANGE FOR CLIMATE CHANGE MITIGATION

MOTIVATION

Lifestyle change is an inescapable feature of future climate mitigation pathways, particularly under stringent 1.5–2°C climate stabilisation assumptions. Policymakers have many entry points for enabling low-carbon lifestyle change but policy analysis tools privilege economic and technological insights, and fail to represent lifestyle variation across population segments. New empirical research and model development in the NAVIGATE project has enabled us to comprehensively analyse low-carbon lifestyle change drivers and outcomes, generating important policy messages.

METHODS

First, we did a comparative synthesis of how lifestyles are understood and analysed across health, marketing, and pro-environmental fields (Agnew et al., 2023).

Second, based on this synthesis we built a universal, global typology of low-carbon lifestyles drawing on data from large-scale social survey data in four countries from the Global North and South (Pettifor, Agenew & Wilson, 2023). We identified four low-carbon lifestyle types – 'Resourceful' and 'Active' (collectively: 'Engaged'), 'Constrained' and 'Cautious' (collectively: 'Disengaged'). These lifestyle types are consistent across countries, and are characterised by varying low-carbon cognitions, by distinctive propensities towards low-carbon behaviours, and by certain contextual markers, like digital skills. We incorporated these data and analysis in a new open access 'LIFE' model of low-carbon lifestyles (made available through the NAVIGATE project's NAVIGATOR portal).

Third, we coupled the LIFE model with a global IAM, MESSAGEiX, to dynamically simulate low-carbon lifestyle change as a second order effect in a reference scenario and a value-shift scenario, alongside the first order effect resulting from technical and economic processes captured by the IAM (Pettifor et al., 2023). This first-of-its-kind model application focused on lifestyle change in the buildings sector, and included both 'Avoid' type behaviours (e.g. changing thermostat setpoints) and 'Improve' type behaviours (e.g. installing energy efficiency measures or solar PV).

KEY FINDINGS

Low-carbon lifestyles should be understood and modelled as the interplay between behaviours and cognitions in material and social contexts that shape how we live. Low-carbon lifestyle change is the result not just of strengthening pro-environmental values, but also the result of changes in physical and social context,and in response to experiences with new technologies or behaviours. This gives policymakers many different entry points for enabling and supporting low-carbon lifestyle change.

Low-carbon lifestyle change interacts with – and can potentially amplify – the mitigation benefits of technological change. But this is not deterministic: lifestyle change as an amplifier needs to be enabled by targeted policy and infrastructure measures to enable access, opportunity and social learning on climate action.

Low-carbon lifestyle change occurs at different speeds among population segments as a result of variation in means, motivation, and opportunity.

FIGURE 3.3: Proportion of Households Adopting Improve and Avoid Behaviours within Each of Four Lifestyle Types. 'Engaged' lifestyle types are Resourceful or Active; 'Disengaged' types are Constrained or Cautious. SSP2 (Reference) is a middle-of-the-road reference scenario with no stringent climate policy and no representation of lifestyle or lifestyle heterogeneity (dotted line, left panels). SSP2+LIFE includes the newly developed LIFE Model for simulating lifestyle heterogeneity and low-carbon lifestyle change over time (four coloured lines, middle panels). SSP2+LIFE+Values additionally simulates a universal shift to low-carbon values, but without additional climate policy assumptions (four coloured lines, right panels). The impact of this universal shift to low-carbon values is seen for the Constrained and Cautious lifestyle types who 'catch up' in their adoption of Improve behaviours (top panels) and race ahead in their adoption of Avoid behaviours (bottom panels).

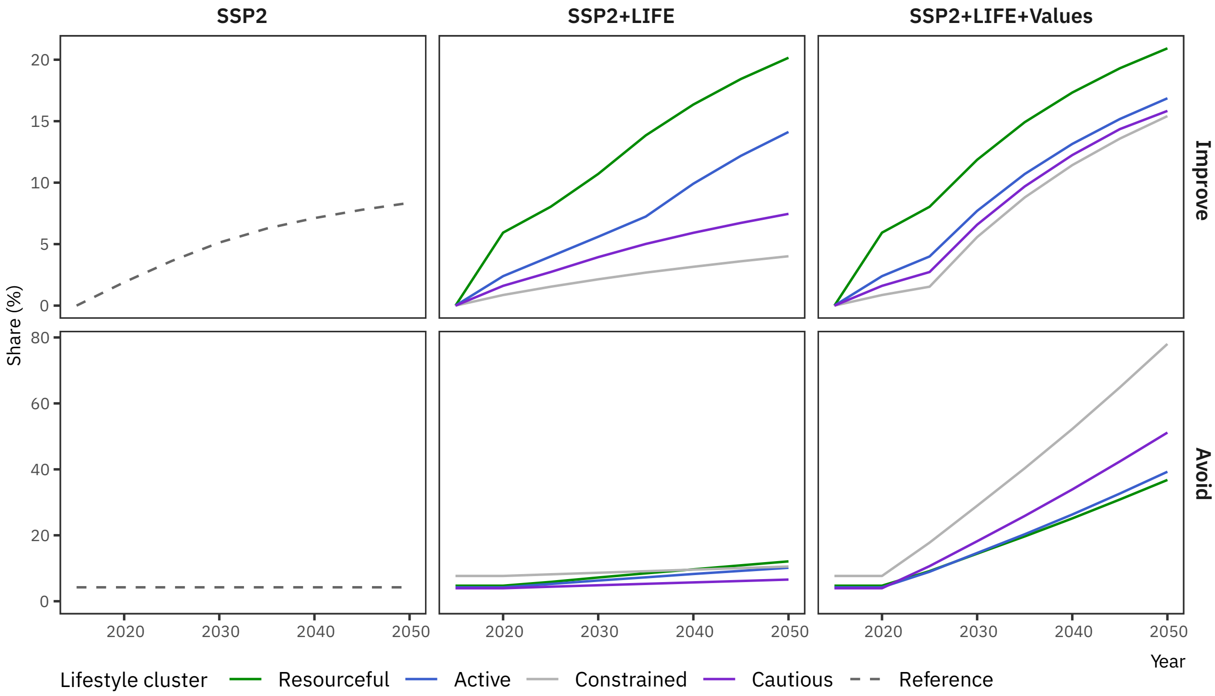
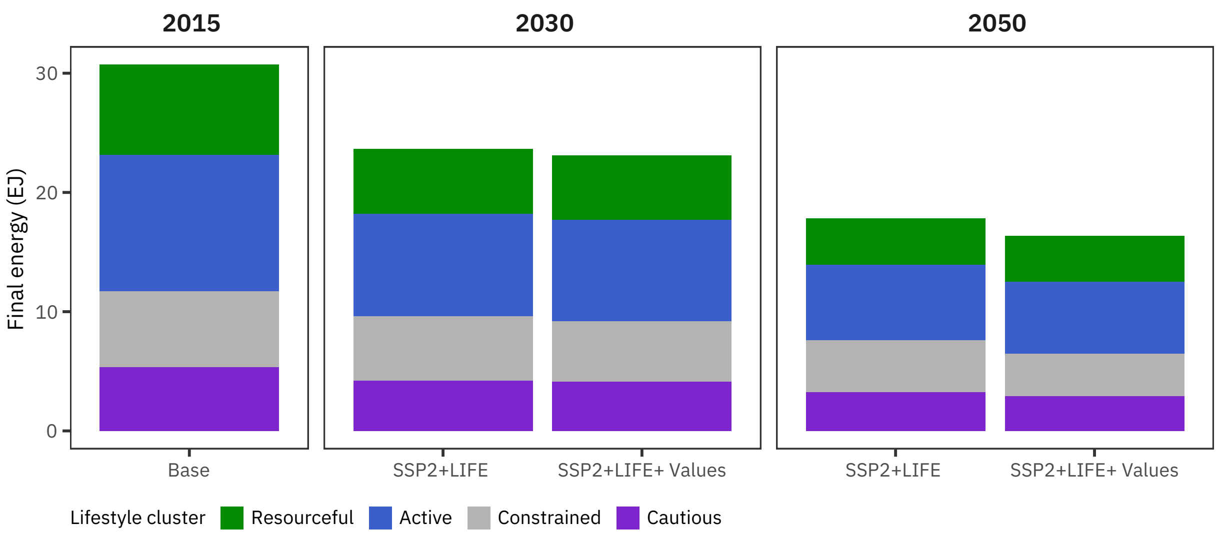


FIGURE 3.4: Global Final Energy Demand for Space Heating by Lifestyle Type. Energy demand changes due to a combination of Avoid and Improve type behaviours. 'Engaged' lifestyle types are 'Resourceful' or 'Active'; 'Disengaged' types are 'Constrained' or 'Cautious'. SSP2 (Base) is a middle-of-the-road reference scenario with no stringent climate policy. SSP2+LIFE includes the newly developed LIFE Model for simulating low-carbon lifestyle change. SSP2+LIFE+Values additionally simulates a universal shift to low-carbon values (but without additional climate policy assumptions).



For example, 'Improve' behaviours (e.g., efficiency investments) and 'Avoid' behaviours (e.g. thermostat adjustments) are influenced in different ways. 'Disengaged' lifestyle types who are 'Constrained' by lower incomes or capabilities or who are 'Cautious' in having lower motivations to act on climate change, are more highly responsive to energy- and cost-saving 'Avoid' behaviours (Figure 3.3).

Lifestyle change is highly variable across different population segments and 'disengaged' groups risk being marginalised in the absence of strong social learning on climate action. For example, 'Engaged' lifestyle types experience faster and higher reductions in final energy demand from the combination of Avoid and Improve behaviours compared to 'Disengaged' types in our modelling analysis. In Europe, final energy demand in the 'Engaged' types reduces by an average of 65% compared to 57% in the 'Disengaged types' (see Figure 3.4 for comparable global data from the SSP2 reference scenario with coupled lifestyle modelling: 'SSP2+LIFE'). This small but important gap between 'Engaged' and 'Disengaged' lifestyle types is completely closed under the assumptions of a universal shift to low-carbon values (Figure 3.4, 'SSP2+LIFE+Values').

An important element of just transitions is therefore to ensure lifestyle groups with lower inherent propensities towards low-carbon lifestyles are not left behind. Not only could 'Disengaged' households with higher carbon lifestyles delay progress towards net-zero, they could also face higher carbon prices or stricter regulations as climate policy becomes more stringent over time. As some 'Disengaged' households also have lower incomes this has important equity implications for how the mitigation burden is distributed (discussed more fully for households by income decile in Section 5).

3.3 DECARBONISING ROAD TRANSPORT: POLICY, BEHAVIOR, AND TECHNOLOGICAL ADVANCES

MOTIVATION

Attempts to significantly reduce transport emissions and energy use through past policies have mostly been unsuccessful, or at least have not achieved the rapid decarbonisation needed for the transport sector. This is due to a lack of understanding of the factors driving travel demand (as noted by Schäfer et al., 2009 and Mattioli and Adeel, 2021), consumer behaviour and the distributional impacts of such policies (as noted by Schwanen, 2021). Researchers and policymakers need a much more sophisticated understanding of the likely development of travel demand, consumer' response to ongoing innovations and policies, and new transport fuels and vehicle technologies.

METHODS

The case studies selected here use a range of modelling tools and data at different spatial and temporal resolutions. For example, through the creative application of big data analytics, we develop new insights into the behavioural factors that affect travel (e.g. individual heterogeneity in travel behaviour, the impact of COVID restrictions on travel by socio-economic class). The case studies use the best available data and experiment with different theoretical frameworks from the travel literature.

KEY FINDINGS

The COVID-19 pandemic caused a significant reduction in human mobility worldwide. Gärdenäs & Magnusson (2021) investigated the changes in mobility due to the COVID-19 outbreak in Sweden and how the socio-economic factors of subpopulations affected their mobility changes. They found that **socially disadvantaged clusters had the lowest reduction in mobility range, while the wealthiest had the largest. Most people reduced the trips between their home region and the neighbouring regions except for the rich group** (Figure 3.5). For longer-distance trips, all groups of individuals reduced their mobility significantly, especially those from the working class and countryside. It is noteworthy that minority groups have had more limited mobility compared to others, both before and during the pandemic. The findings indicate that tradi-

FIGURE 3.5: Mobility range changes by the five socio-economic groups. Graphic reproduces figure 5.8 from Gärdenäs & Magnusson (2021)

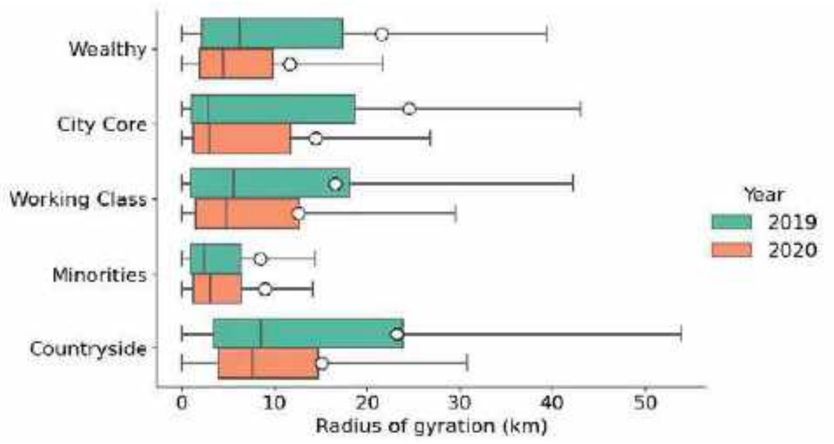
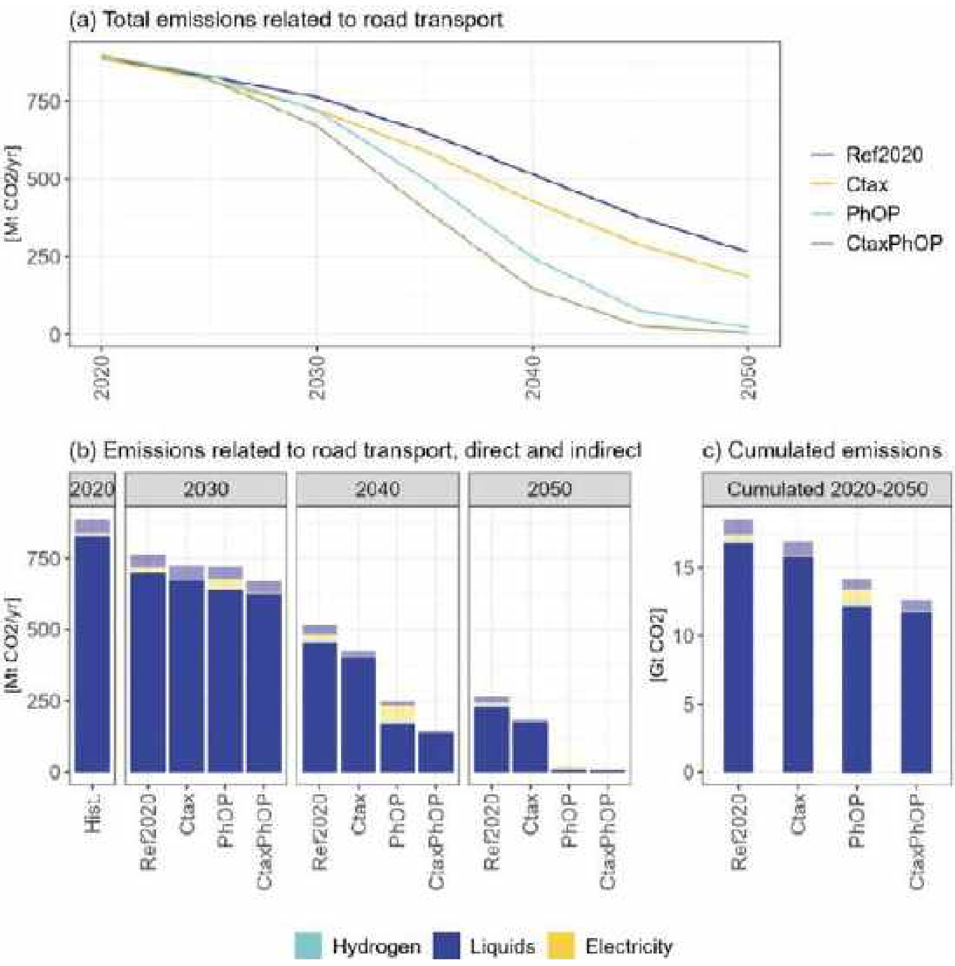


FIGURE 3.6: Total emissions (direct and indirect) associated with road transport in the different scenarios (a); direct and indirect emissions from road transport for different scenarios by fuel type (b); cumulated direct and indirect emissions from road transport by fuel, for the time period 2020–2050 (c). In both bar charts: indirect emissions have a faded fill, while direct emissions a solid fill. Ref2020 (Reference with policies that were implemented in 2020), Ctax (Carbon tax), PhOP (Phase Out Policy), CtaxPhOP (Carbon tax with Phase Out Policy). Source: Rottoli et al. (submitted)



tional demand modeling for transport and mobility may not sufficiently account for socio-economic disparities and minority statuses, which could lead to inaccurate assessments and ineffective policy measures. Therefore, policymakers should integrate socio-economic variables and minority considerations into demand modeling to better inform equitable transport and health interventions.

Shared autonomous BEVs can reduce the carbon footprint if it results in a higher driving intensity of each vehicle. Car sharing and ride sharing could increase resource efficiency and reduce the environmental load of the system by replacing ten individually owned cars per shared car. At the same time, shared cars will likely be used more intensively during their lifetimes than individually owned cars. New mobility services and innovations like car clubs, peer-to-peer car sharing, ride sharing, shared ride hailing, electric vehicles, and e-bikes can reduce GHG emission from passenger transport. Early adoption by consumers is motivated by a combination of functional, symbolic and societal considerations, as well as social influence and other effects. Results for **the UK and Canada emphasises the importance not just of mobility innovation attributes and their value to users, but also the socially structured context in which mobility innovations are used.**

Higher efficiency in electricity use substantially reduces total primary energy demand, particularly in high-demand scenarios. Studies corroborate that low-demand growth also decreases energy needs, while maintaining a significant reliance on renewables (Luderer et al., 2022; Rottoli et al., 2021). Further evidence from the PRIMES-TREMOVE transport model suggests that by 2050, 62% of passenger cars in the EU could be electrified, necessitating an investment of 44.3 to 80.3 billion euros in infrastructure from 2031–2050. Notably, **a well-developed fast-charging network is pivotal to this transition, with the energy output per charging point identified as a crucial variable.**

Research by Rottoli et al. (submitted) (see Figure 3.6) presents a compelling case for EU policymakers to employ a two-pronged strategy for reducing transport emissions: implementing both a carbon tax and a phase-out policy for internal combustion engines. The study finds that while existing 2020 policies could cut emissions by 70% by 2050, adding a carbon tax could push that to 80%. However, the real game-changer is the phase-out policy, which could bring emissions close to zero by 2050. Furthermore, these policies have complementary benefits; a carbon tax significantly reduces “indirect” emissions like those from electricity production, while a phase-out policy slashes “direct” emissions from vehicles. As the EU moves toward electric vehicles, there will be a surge in electricity demand, necessitating preparations for a sustainable increase in supply. Therefore, **a multi-faceted approach involving both strategies can offer the most effective route to decarbonize Europe’s road transport, underlining the value of strengthening both vehicle emission standards and carbon pricing by expanding emissions trading across all sectors.**

The study by Siskos et al. (2023) quantifies two contrasting transport scenarios for the EU: one with notable contribution from e-fuels, and a second scenario without e-fuels but with maximum use of alternative options. Without technology advances in e-fuels, biokerosene will meet 57% of the aviation sector’s energy demand in 2050. In this scenario, biofuels cover most of the energy needs of road freight by 2050. Hydrogen fuel cell trucks also emerge to complement the use of biofuels. However, other studies see a larger role for electric trucks, pointing to considerable uncertainty about technology choice in the road freight sector. In the “E-fuels contribution” scenario, e-fuels contribute about one-third, and biokerosene contributes about one-quarter of the aviation sector’s final energy demand in 2050. Given the pessimistic outlook on E-trucks in the scenario, E-fuels can make significant inroads in heavy goods vehicles shortly after 2030, where they are mainly used in diesel and natural gas trucks operating over long-distances. **The research suggests that e-fuels, biokerosene, and hydrogen could each play significant roles in helping the heavy-goods and aviation sector to meet 2050 energy demand and decarbonization targets.** The extent to which this will be the case depends, among others, on the penetration of E-trucks for road freight.

3.4 DECARBONISING THE INTERNATIONAL AVIATION AND SHIPPING SECTORS

MOTIVATION

International aviation and shipping present significant challenges when it comes to decarbonisation. The reasons why international transport is difficult to decarbonize are: existing technologies are largely based on fossil fuels, these fossil fuels have a high energy density (impacting range and efficiency), vehicles have long lifecycles, and international transport involves complex logistics and regulations. Transitioning to alternative fuels or technologies, such as electric, hydrogen, and advanced biofuels requires significant investments in research, development, and infrastructure upgrades. Moreover, most of these technologies are still in relatively early stages of development.

METHODS

To explore possible futures of international transport in terms of energy carriers and GHG emissions, we perform a multi-model comparison of these two sectors. The six global models used in this study are COFFEE, IMACLIM-R, IMAGE, PROMETHEUS, TIAM-UCL and WITCH. These models have been improved recently in their representation of international transport during the NAVIGATE project. Rather than thinking of sectoral emission reductions as the final objective, our analysis sees international transport as just a part of a global decarbonisation challenge under specific carbon budgets. We conducted two studies focusing on shipping and aviation separately. For international shipping, we developed three scenarios, with the reference (NDC) assuming the implementation of Nationally Determined Contributions (NDCs) and then the 2°C and 1.5°C scenarios (Figure 3.7 – left panel). For the aviation sector, we developed three different scenarios: NDC and two scenarios compatible with the 1.5°C target. The 1.5°C scenarios are characterised by different levels of pre-calculated demand are applied for the aviation sector by scenarios (Figure 3.8 – left panel): The scenarios are named NDC, 1.5°C (a scenario with demand reduction from NDC due to higher costs including fuel and carbon price (1.5°C) and a low demand scenario including non-cost driven consumer behaviour in addition to cost driven reduction in demand (1.5°C_LD).

FIGURE 3.7: Left panel: International shipping activity level between 2020 and 2050 across models and scenarios indexed to 2020 (dotted lines: ensemble mean and coloured cones: models spread; scenarios: red NDC, orange 2°C and green 1.5°). Right panels: change in annual CO_2 emissions from international shipping in 2050 from 2020 levels (ensemble average, standard variation and maximum and minimum across model results). The reduction by 50%, 63% and 88% of shipping emissions in 2050 are represented by the blue, grey and black dash-dotted lines in the right panel to show level of reduction as presented in IMO 2018 goals, the Sustainable Development Scenario and the IEA Net-Zero-Emissions scenario.

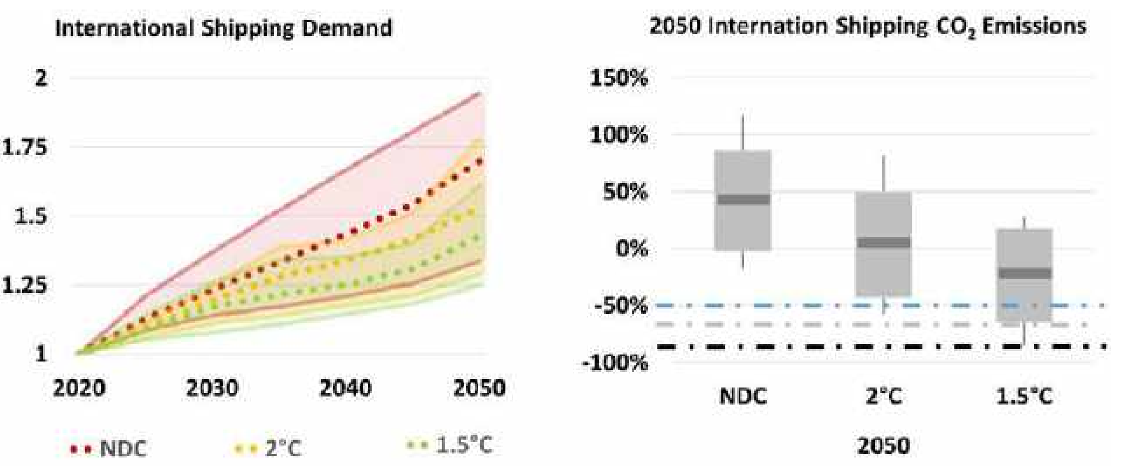
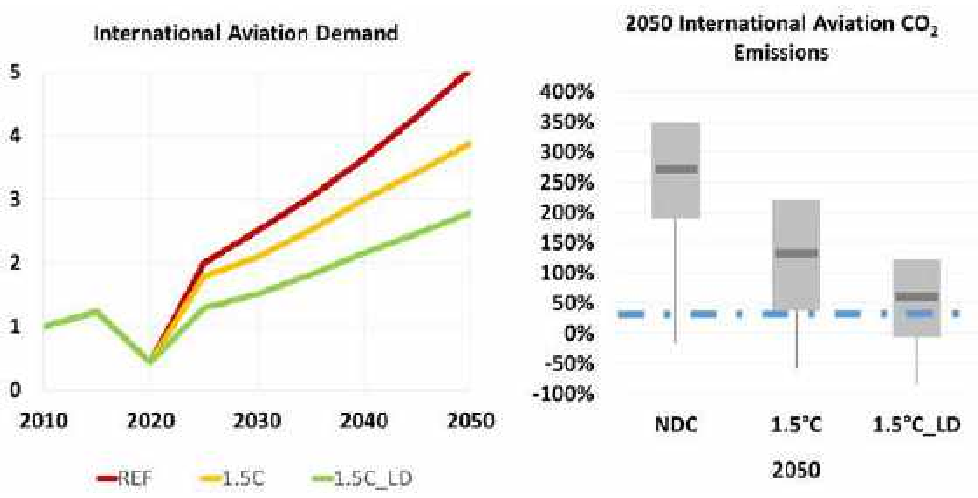


FIGURE 3.8: Left panel: International aviation activity level between 2010 and 2050 across scenarios. Right panels: Variation of the annual CO_2 emissions from international aviation in 2050 compared to 2010 across scenarios. Blue dot-dashed line level of CORSIA emissions reduction. (Note: we choose 2010 as reference for aviation as 2020 was an unusual year due to the COVID pandemic)



KEY FINDINGS

Deep mitigation scenarios of the global energy system in 6 IAMs show that international shipping emissions must stabilize or decrease before 2050 to be compatible with a global warming below 2°C by the end of the century. Under the NDC scenario, international shipping emissions rise in the long-term due to increase in shipping activity. Most models show international shipping emissions to fall significantly in the 2°C and 1.5°C scenarios compared to the NDC case (Figure 3.7 – right panel). This is driven by efficiency improvement and fuel switching. In 2050, for the 2°C scenario emissions average between the six models are at the same level as 2020. From the results, the International Maritime Organisation (IMO) 2018 target (-50%) is larger than the most reductions seen in shipping for a 2°C and still strong for a 1.5°C compatible world. The larger reductions seen in scenarios published by the International Energy Agency (IEA) 2019 and 2021 (“Sustainable Developments Scenario” and “Net Zero Scenario” respectively) are rarely achieved by the IAMs in this analysis of Paris-compatible pathways.

International aviation seems harder to decarbonise as most of the models in all the scenarios present increasing emissions after 2050 even under a 1.5°C compatible carbon budget (Figure 3.8 – right panel). The rise in emissions is driven by the large increase in the demand (in 2050 the demand is 2.8, 4 and 5 times higher than in 2010 for NDC, 1.5C and 1.5C_LD respectively) and the limited efficiency gains and fuel switch available. **In the two sectors, with decreasing energy efficiency potentials, emissions suppression must be achieved with the deployment of low-carbon fuels.** These alternative fuels reach different levels of penetration. Up to 88% and 55% (maximum in one model) for international shipping and aviation final energy in 2050 respectively.

For international shipping, drop-in biofuels and alcohols seem the most promising short-term candidates, while ammonia and synthetic energy carriers become essential towards 2050 and beyond. In any case, shipping is reducing its use of fossil fuel faster and deeper than aviation.

The aviation sector has limited alternative fuels to fulfil its demand growth. When biomass is available in the model specific representations, the share of biokerosene increases rapidly, but if electrofuel is the preferred option due to limitation in biomass availability the decarbonisation occurs later. Even at the end of the century, if available in models, electric or hydrogen aircrafts show limited diffusion in the aviation system.

No single fuel has an unlimited potential and relying on a single option might limit the emission reduction of international transport as models that represent only a few low-carbon fuels tend to keep a larger share of fossil energy supported by higher reliance on CDR (particularly for the aviation sector).

3.5 DECARBONISING THE BUILDING SECTOR

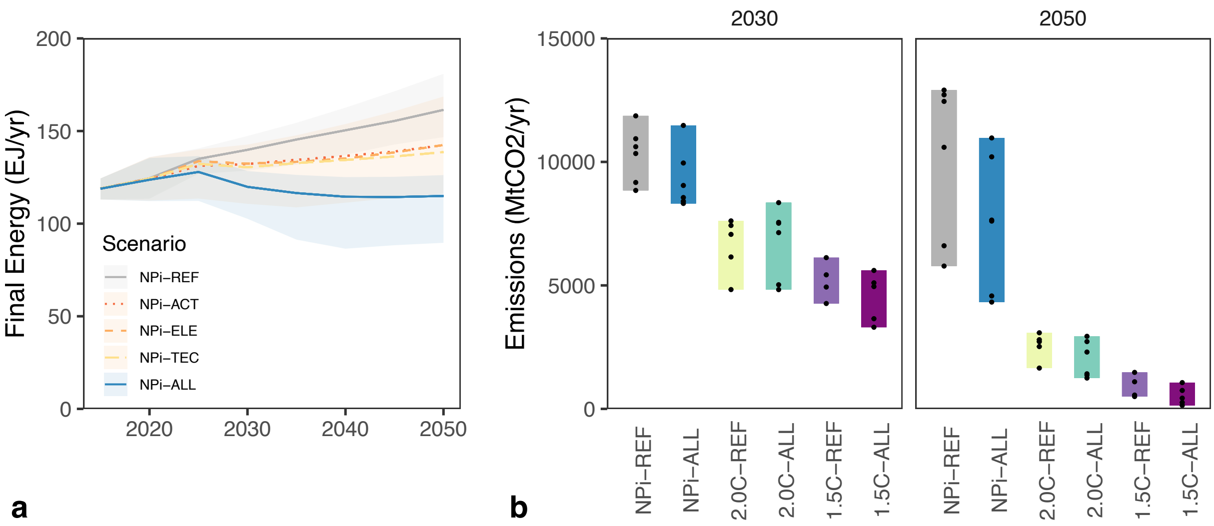
MOTIVATION

Buildings accounted for 21% of GHG emissions in 2019 (Cabeza et al., 2022). Urgent action is required to reduce energy demand and GHG emissions in the global building sector to meet climate mitigation goals (IEA, 2019; Ürge-Vorsatz et al., 2020). A global GHG emissions reduction potential for buildings was estimated at 61% by 2050 relative to baseline scenarios by aggregating results from bottom-up studies (Cabeza et al., 2022). Global and European decarbonization scenarios for buildings are, however, limited and mostly focusing on technological improvements, while behavioural and structural changes are commonly overlooked (Daioglou et al., 2022; Edelenbosch et al., 2021; Levesque et al., 2019; Mastrucci et al., 2021). A high degree of complexity and heterogeneity in both building characteristics and actors characterizes the building sector (Mastrucci et al., 2021), not properly considered in current modelling. IAMs used to assess global climate change mitigation scenarios have mostly been limited in representing end-use sectors and demand-side interventions (Creutzig et al., 2018). The assessment of global and European mitigation strategies for buildings required model improvements to capture key heterogeneities and dynamics, and represent a broader set of sectoral interventions.

METHODS

The NAVIGATE project brought methodological advancements to improve the representation of buildings in a set of established IAMs (Imaclim-R, IMAGE, MESSAGEix, PROMETHEUS, REMIND, and WITCH), focusing on both residential and commercial (service) sectors, at the global and European level. With these improvements, it is possible to explore a comprehensive set of mitigation scenarios towards net-zero emissions, considering both key sectoral interventions and broader climate policies. The investigated sectoral interventions, contrasted to a reference (REF) scenario assuming a continuation of current policies and trends, include: activity reduction and shift (ACT); electrification and fuel shifts (ELE); technological improvements and energy efficiency (TEC); and the combination of all above interventions (ALL). We assess the combined effect of these sectoral policies with a set of climate policy scenarios, including: continuation of current

FIGURE 3.9: (a) Global buildings final energy demand projections without stringent climate policies (NPi) for different sectoral intervention policy scenarios: reference (REF); activity reduction and shift (ACT); electrification and fuel shifts (ELE); technological improvements and energy efficiency (TEC); and a combination of all sectoral interventions (ALL). Lines indicate averages across models, shaded areas indicate ranges across models. (b) Global buildings total CO_2 emission, including direct and indirect emissions, in 2030 and 2050 combining different climate policy scenarios (stringent climate policies according to 2.0C and 1.5C climate targets) and sectoral interventions. Bars indicate result ranges across models, points indicate single model results.



national policies (NPi); and stringent climate policies according to the 2.0C (2.0C) and 1.5C targets (1.5C).[5]

KEY FINDINGS

Sectoral interventions can substantially reduce energy demand and CO_2 emissions. The global final energy demand of buildings (Figure 3.9, panel a) increases by 35% until 2050 (average across models) in the reference scenario (NPi-REF), mostly driven by growing population and higher affluence in the Global South. In Europe, final energy decreases already in the reference scenario (NPi-REF) due to continuing energy efficiency improvements. Sectoral interventions have an average energy demand reduction potential of 10% to 15% each, and in combination of up to 30% compared to the reference NPi-REF in 2050 (averages across models), which would stabilize energy demand over time. Global total (direct and indirect) CO_2 emissions from buildings increase by 5% until 2050 (average across models) in the reference scenario (NPi-REF). With all sectoral policies implemented (NPi-ALL), total CO_2 emissions are on average reduced by 25% compared to the reference scenario (NPi-REF) in 2050 (Figure 3.9, panel b). In Europe, average reduction potentials for final energy are similar to the global results, while total CO_2 emissions can be reduced up to 35% (average across models).

Combining demand-side policies with more stringent climate policies leads to the highest CO_2 emission reduction potentials. Stringent climate policies without additional sectoral interventions drive significant total CO_2 emission reductions (on average up to 75% in the 2.0C-REF scenario and 90% in the 1.5C-REF scenario compared to NPi-REF in 2050), due to the decarbonization of electricity and district heating (Figure 3.9, panel b), but entail only moderate final energy demand reductions (on average between 10% and 15% compared to the NPi-REF scenario in 2050). Adding sectoral policies to the stringent climate policy scenarios drives additional CO_2 emission reductions, reaching 80% in the 2.0C-ALL scenario and 95% in the 1.5C-ALL scenario in 2050 (average across models), and final energy demand reductions up to 35% (1.5-ALL scenario). Even in the 2.0C-ALL and 1.5C-ALL scenarios, the continuing use of fossil fuels in some regions, especially for heating, results in residual direct emissions. In Europe, average decarbonization potentials are similar to the global results (80% in the 2.0C-ALL scenario and 95% in the 1.5C-ALL scenario in 2050), while energy demand reduction potentials are higher (up to 45% in the 1.5C-ALL scenario in 2050).

These results show that combining a broad set of sectoral intervention and stringent climate policies is required to decarbonize the global and European building sector, contributing to achieve ambitious climate targets. The investigated sectoral measures on activity reduction and shift, electrification and fuel shifts, and technological improvements are highly complementary and, when combined together, can achieve the largest reduction potential. The implementation of these sectoral interventions can be supported by different policy instruments. While several policies are commonly implemented for energy efficiency improvements, including building codes, subsidy programs, achieving higher rates of deep renovation and electrification in existing buildings would require addressing financial, structural, and other barriers. Shifts in activity levels can also entail a significant mitigation potential, as shown by this study.

5 NPi (national policies implemented): scenarios considering only current policies but no additional plans; 2.0C (Likely 2.0°C): scenarios with peak and end-of-century budgets equal to 1150 $GtCO_2$; 1.5C (1.5°C with low overshoot): scenarios with peak budget of 650 $GtCO_2$ and end-of-century budget of 400 $GtCO_2$.

4

ADVANCING DEEP MITIGATION IN PRODUCTION SECTORS AND BY STRUCTURAL AND TECHNOLOGICAL CHANGE

Technological and structural changes in production sectors represent essential policy areas that allow reduction of emissions without directly targeting households and consumers. Furthermore, this approach reduces the trade-offs between emission reduction objectives and socio-economic development aims. Transformational changes in the production sectors, prompted by technological and sectoral advancements, primarily target the energy, industry and agriculture sectors. These sectors are central to the provision of basic materials and services, yet they are also responsible for a significant proportion of the overall direct emissions. The Paris Agreement anticipates emission reductions in developing and emerging economies, which face a considerable socio-economic catch-up process, including rapid infrastructure development and a constantly evolving private consumption landscape.

4.1 THE INTERACTION OF STRUCTURAL CHANGE WITH CLIMATE CHANGE MITIGATION PATHWAYS

MOTIVATION

The restructuring of the economy, involving the redistribution of activity and employment among different sectors, is intricately tied to economic progress and the use of resources such as energy and land. This phenomenon represents a supplementary influence in either advancing or impeding greenhouse gas emission progression, as diverse sectors and industries exhibit varying carbon and energy intensities. This process will shape future development in the energy sector and corresponding emission profiles to some extent, thereby affecting the opportunities and barriers related to climate change mitigation. In contrast, carbon neutral climate policies will introduce additional driving forces and transitional dynamics to the structural changes within the economy, extending beyond the energy sector. These policies will determine how economic sectors interact as we strive towards carbon neutrality.

METHODS

Throughout the NAVIGATE project, we have enhanced the conceptual and empirical underpinnings of structural changes in IAMs and IAM-based scenarios. We have principally refined the representation of structural transformations. Leimbach et al. (2023) have employed an econometric technique to devise a set of structural change scenarios for the Shared Socioeconomic Pathways (SSPs). This work aims to address a previously missing component in the SSP framework and the socioeconomic assumptions of IAMs – the development of the sectoral structure of economies. Also, the implementation of stringent climate policies for deep mitigation drives specific structural transformations and economic reconfigurations in the energy sector and other areas. We have created complementary modelling tools to assess these impacts on different scales. Koch et al. (2023) have developed a multi-sectoral growth model capable of assessing the effects of climate policies on the redistribution of economic undertakings within the macro sectors of agriculture, manufacturing, and services. Our enhancements to existing global multi-sectoral macroeconomic IAMs have also augmented the representation of structural change effects through expanded sectoral and regional resolution. These models have the capacity to assess not just the structural transformations at the macroeconomic level (Lefèvre et al., 2022) but also the intricate sectoral and labour market adaptations prompted by climate policy within the energy sector as well as other areas of the economy.

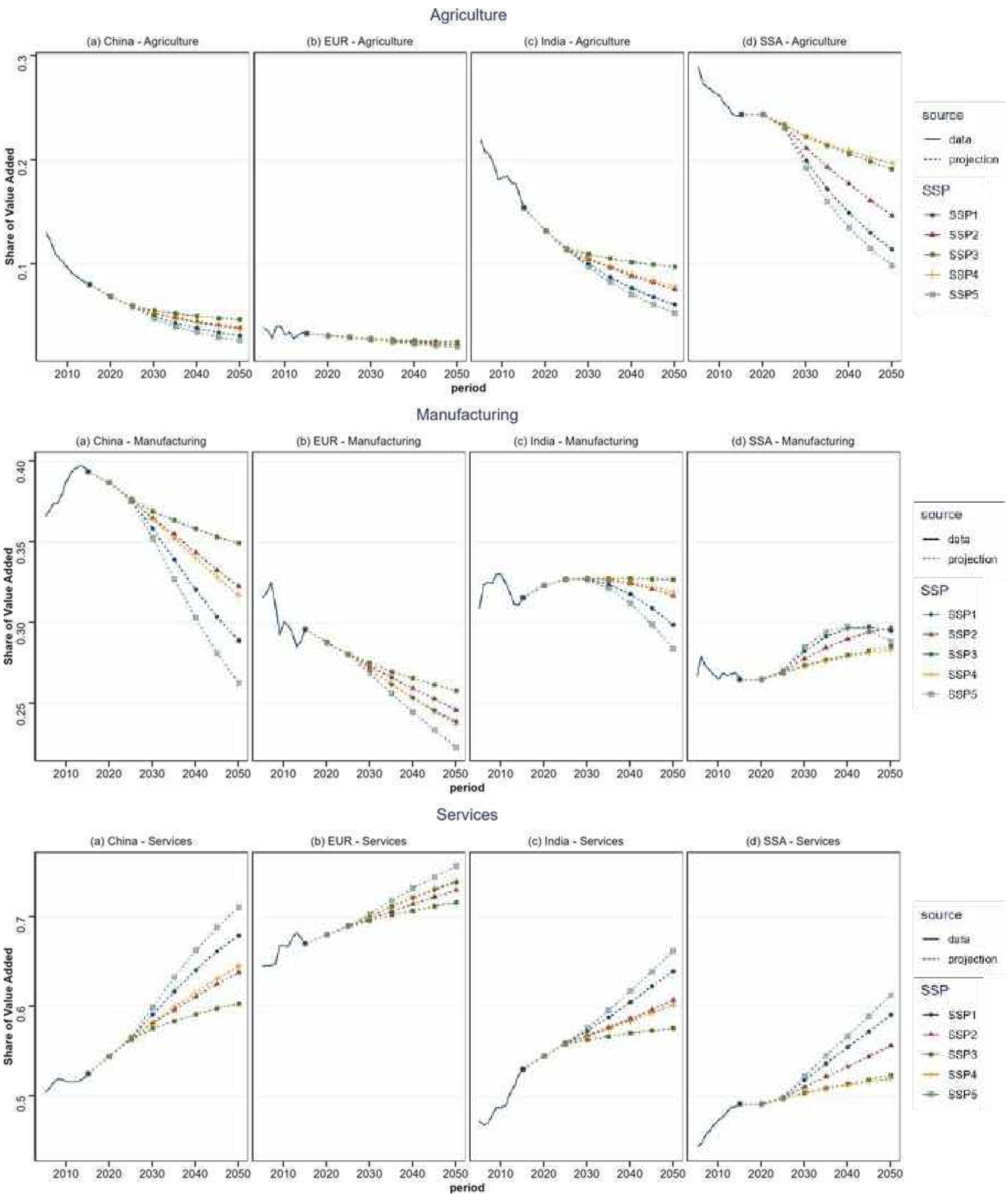
KEY FINDINGS

The extent and speed of future structural change vary among shared SSPs. Figure 4.1 illustrates that scenarios for developing countries in all SSPs mimic previous patterns of structural change observed in developed countries (e.g. a hump-shape for manufacturing sector share). However, the extent and speed of these structural modifications vary considerably among different SSPs and nations, resulting in divergences in total energy consumption and GHG emission trajectories.

The potential impact of climate policy on structural changes is anticipated to be minimal at the macro-

economic level. The modelling experiments indicate that the climate policy-induced reallocation of economic activities among the agriculture, manufacturing, and services sectors is projected to be minimal when compared to the structural transformations foreseen in baseline scenarios. The variations in baseline scenarios, especially for developing and middle-income countries, are expected to be significant (e.g. pathway beyond the manufacturing peak in China and India in Figure 4.1). The reduction of emissions resulting from macroeconomic structural changes is also minimal when compared to that achieved through technological advancements and efficiency enhancements. These results hold for climate policies that focus on techno-

FIGURE 4.1: Sectoral shares on total value-added across SSPs (historical data are shown until 2015)

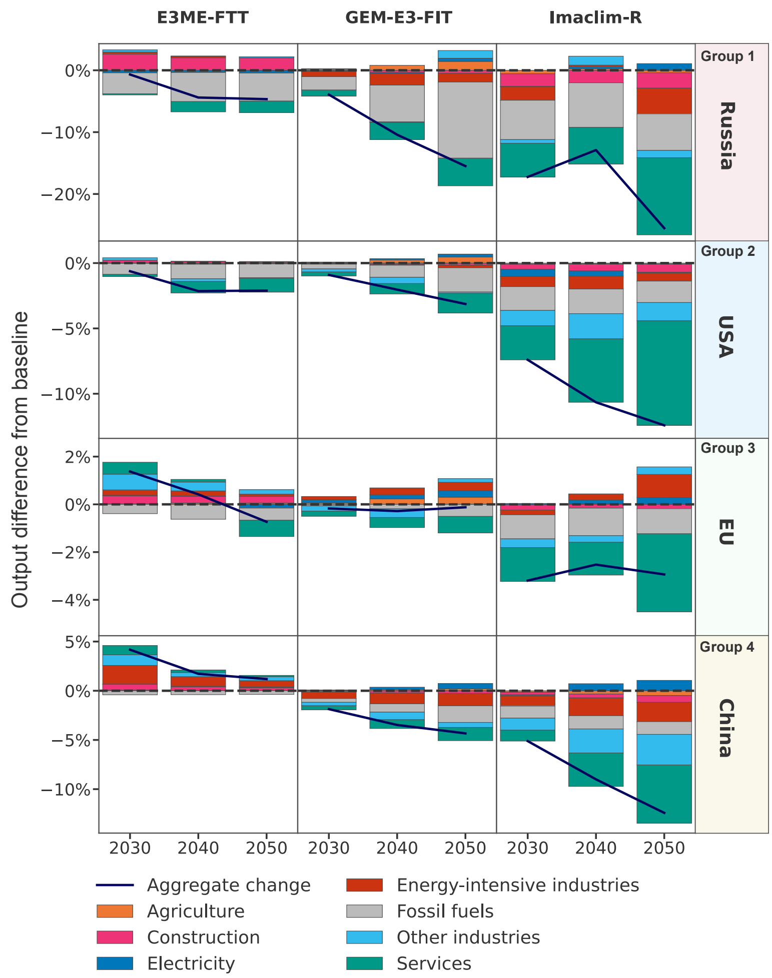


logical innovations and market-driven measures, like carbon pricing, and do not account for significant transformations in consumption and production patterns.

Climate policy will result in significant structural changes in individual sectors, notably in the energy sector. As depicted in Figure 4.2, fossil fuel industries face the most significant economic risks while the transition to net-zero paves the way for job creation and economic value in low-carbon energy and agricultural sectors. Although the overall economic impacts on the industry and construction sectors may be limited, we anticipate internal structural changes. The effects on the services sector will ultimately depend on the wider macroeconomic consequences of the net-zero transition, which can vary considerably between countries. These findings highlight the distributional impacts of mitigation strategies within countries, economic sectors, and their respective workforce.

The macroeconomic impacts of achieving global net-zero emissions would vary across nations. Modelling results (see Figure 4.2) demonstrate that fossil fuel-exporting nations would undergo the most substantial macroeconomic impacts, whereas high-income fossil fuel-importing countries (for instance, the majority of EU member states) would face the least impact in a global net-zero transition. Net GDP impacts may range from small losses to slight gains, specifically depending on the level of crowding-out of low-carbon investments. The greatest economic uncertainties lie in the middle-income countries that are both carbon-intensive and dependent on fossil fuel imports, such as India and China. The magnitude of economic impacts relies on the ability of these nations to efficiently eliminate high-carbon technologies and practices (e.g. coal-based industries), finance low-carbon infrastructure and equipment, and enhance their comparative advantages in low-carbon technologies.

FIGURE 4.2: Contributions of a range of sectors to the relative aggregate output difference from baseline in a net-zero scenario for E3ME-FTT, GEM-E3-FIT, and Imaclim-R models.



4.2 TRANSFORMATIVE POLICIES ON THE PRODUCTION SIDE CAN PAVE THE WAY TO 1.5°C

MOTIVATION

The decarbonization of the global economy required to meet Paris Agreement goals, presents significant challenges due to increasing economic activity, population and the absence of ambitious climate policies globally. Early and rapid emissions reductions as mandated by the Paris Agreement and national targets require using advanced mitigation measures. In this study, we analyse to what extent production- and energy supply-side policies leveraging advanced emission reduction options can pave the way towards Paris-compatible pathways with low overshoot without relying on large-scale consumption and demand-side transformations.

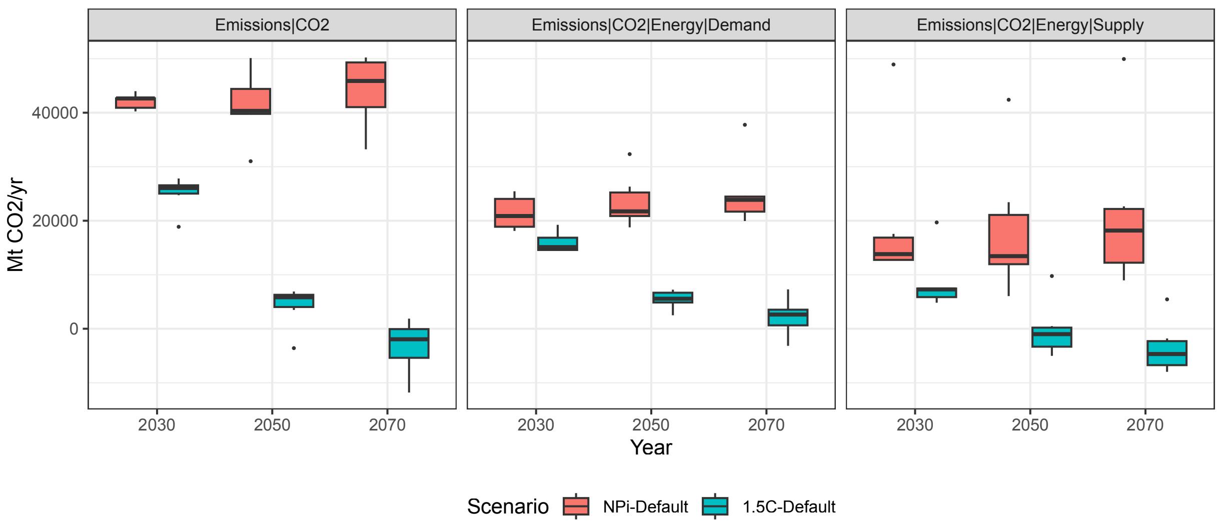
METHODS

For the analysis we use a comparison of six IAMs that have been considerably improved within the NAVIGATE project to better represent structural change, technology innovation, industry transformation (integrating several novel mitigation technologies and processes), land-based mitigation and socio-economic developments. The scenarios explore different combinations of climate policy (well-below 2°C or 1.5°C with low overshoot), two different supply paradigms (enhanced electrification (Elec), or a continuation of combustion systems (Comb)) and technology limitations (limited nuclear (LimNuc), limit on CCS (LimCCS), or a limited biomass but high variable renewable energy scenario (HighVRE)). In the mitigation scenarios, all models impose uniform carbon pricing across regions and sectors to meet the carbon budget of 1150 GtCO_2 (for 2°C scenarios) and 650 GtCO_2 (for 1.5°C scenarios) from 2020 to the time of net zero CO_2 emissions. We compare these with a Reference scenario based on currently existing policies (NPi).

KEY FINDINGS

Paris-compatible pathways lead to a rapid reduction in global CO_2 emissions by 45% (2030) and 88% (2050) on average in the 1.5°C scenario relative to NPi by 2030 reaching net-zero around 2060 (Figure 4.3). In the second half of the 21st century, all models show net-negative emissions driven by the uptake of CDR technologies to compensate for residual emissions. Supply-side emissions reach net zero in the 2040–2050 decade in the 1.5°C scenarios driven by the rapid and profound transformation of energy supply through massive uptake of renewable energy. Mitigation scenarios significantly reduce demand-side emissions to around 5 GtCO_2 by 2050 and 2.5 GtCO_2 by 2070, but some bottlenecks exist in specific sub-sectors, like aviation, navigation and heavy industry, that prevent demand-side emissions from reaching net-zero.

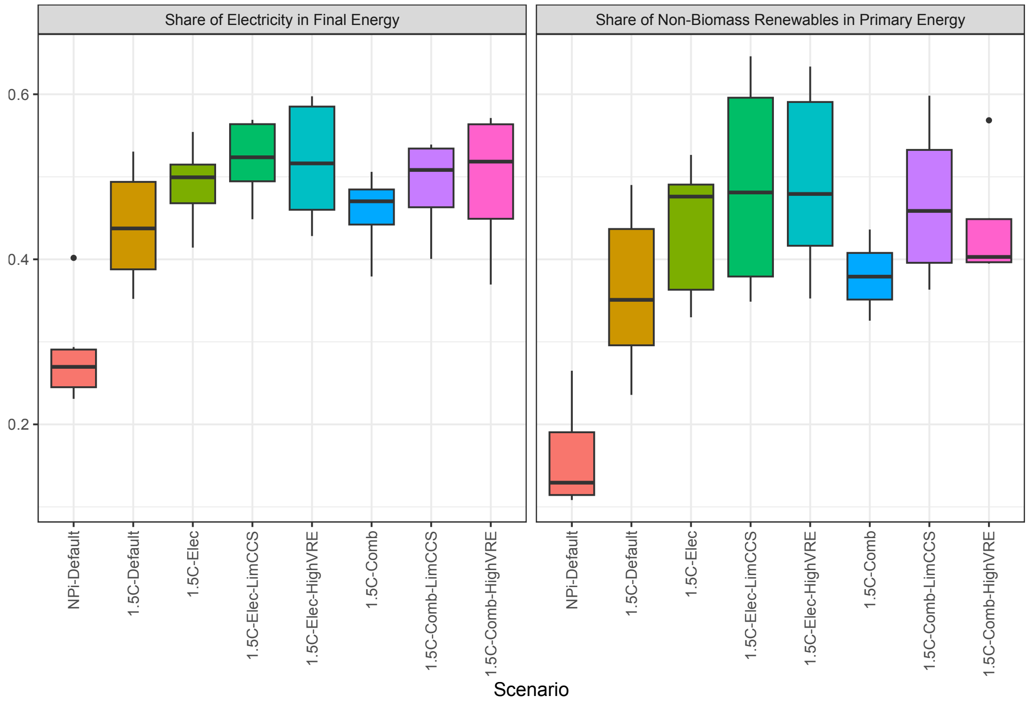
FIGURE 4.3: Global CO_2 emissions across two climate mitigation scenarios.



Energy system transformation is based on renewable energy expansion (Figure 4.4**), accelerated electrification of end-uses, uptake of clean fuels, and (to a lower extent) on efficiency improvements.** High policy ambition in the 1.5°C scenario leads to accelerated uptake of renewable electricity with a profound expansion of solar PV and wind reaching shares higher than 80% by 2050, while renewable energy accounts for 56% in 2050 ([45%–70%] across models) and 70% in 2100 (range [52%–90%]) of global primary energy consumption.[6] Most of this growth is driven by the uptake of non-biomass renewables, especially solar and wind power, with their share increasing to about 50% (range [42%–59%]) by 2050 in the strong electrification scenarios. The lowest renewable energy shares are projected in models that project high potential for CCS uptake. The strong electrification of end-uses based on zero-carbon electricity supply is a major pillar of decarbonization across regions. The share of electricity in final energy is projected to increase from 20% in 2020 to 46% in the 1.5°C scenario (range [39%–52%]). An even higher use of electricity is projected in the electrification scenarios with electricity share in final energy increasing to more than 50%–60% after 2050 (Figure 4.4). Further electrification in the 1.5°C scenarios is not constrained by a lack of potential for renewable energy expansion, but is mostly demand-side constrained as the change from Default to Elec scenario is much larger than the change from Elec to highVRE. The large expansion of renewable energy (especially solar and wind) coupled with a strong electrification of end-uses is a robust strategy to reach Paris goals, while clean fuels (biofuels, hydrogen, e-fuels) will also play a role to achieve net-zero.

CCS can be a major option to reduce industrial emissions and reach net negative CO_2 emissions, but the scale of its deployment depends on the degree of electrification of energy end use sectors. In 1.5°C scenarios, CCS increases on average to more than 5 $GtCO_2$ in 2050 and 10 $GtCO_2$ in 2100. Some models depend highly on CCS to achieve decarbonisation. In case the electrification of demand sectors cannot be improved, a policy push that pursues a combustion enhancing narrative requires higher uptake of CCS with models projecting a deployment higher than 15 $GtCO_2$ and close to 20 $GtCO_2$ after 2050, raising issues of technical and economic feasibility for such a rapid technology upscale. However, deep decarbonisation is feasible even when assuming limitations in CCS to less than 4 $GtCO_2$ annually (LimCCS scenarios), but this pushes other mitigation options to their limits and increases mitigation costs.

FIGURE 4.4: Energy transition indicators in the 1.5°C scenarios.



6 Based on the direct-equivalent accounting method for the reporting of primary energy from non-combustible energy sources

4.3 DECARBONISATION IN THE INDUSTRY SECTOR

MOTIVATION

The global industry sector today emits nearly a quarter of all CO_2 emissions. Over the past three decades this share increased from 19% mostly driven by rapid economic development and urbanisation as well as a strategy of heavy industry, infrastructure investments and export orientation (see section 4.1). So far, integrated transition scenarios to achieve the Paris climate targets arrived at the conclusion that industry sector CO_2 emissions are hard-to-abate because residual fossil fuel use in heavy industry and process emissions are tightly linked with economic development and difficult and in some cases even impossible to avoid.

This perspective has been challenged by technology and sector specific studies that suggest a broad spectrum of technologies that are already available or at sufficiently mature technology readiness levels. Many of these novel processes use electricity or hydrogen as the ultimate energy base, but also highlight the importance of demand reductions and recycling as well as Carbon Capture and Storage and Utilization (CCUS). These analyses are, however, based on partial modelling frameworks that do not capture the full scope of the overall transition dynamics. Particularly the dynamics of energy supply side prices and the demand side have to be considered. The electricity market comes under pressure from the supply side as fossil electricity generation is phased out and the demand side as end-use sectors electrify. Therefore, electricity prices will experience upwards pressure. The same becomes true for other low carbon energy carriers such as hydrogen and bioenergy.

METHODS

For the analysis in NAVIGATE the industry sector modelling of seven IAMs has been improved and the assumptions on the energy sector have been updated to reflect recent advances in renewable energy and other clean energy technologies. The models represent the various sectors in an integrated framework. In particular, the supply and demand of energy are fully represented, which allows the investigation of potential limitations such as bioenergy supply constraints for which various demand sectors compete. Moreover, rigidities that constrain the ramp-up of new technologies such as renewable electricity generation are represented.

KEY FINDINGS

Much more rapid emission reductions are required in the industry sector to achieve the 1.5°C target, compared to the well-below 2°C target. The results (Figure 4.5) show a remarkable step-change between the well-below 2°C and the 1.5°C scenario. In 2050 the well-below 2°C target allows for emissions of 4.9 $GtCO_2$/yr (3.0–6.5) and the industry sector emission share only increases moderately compared with the NPi scenario. The results substantially change for the 1.5°C target as industrial residual net emissions in 2050 are 2.8 $GtCO_2$/yr (1.0–4.7). On average this means that the industry sector emissions are partly off-set by Carbon Dioxide Removals outside of the industry sector. This is not the case for all models, particularly those that can mitigate industry emissions to a large extent by 2050. Thus, the rapid emission reductions required to achieve the 1.5°C run the risk of hitting decarbonisation bottlenecks in the industry sector.

The decarbonisation bottlenecks are mostly due to limits to and rigidities of emissions reductions in the heavy industry sectors of Developed and Industrialised Countries (DIC: OECD, Reforming economies and China). These limitations can become constraining factors in the 1.5°C scenarios (1.5K), while the well-below 2°C target (wb-2K) does not approach these limits. If the limits are reached, it is mostly the DIC group of countries that are too slow to decarbonise. The DIC group will demand a higher share of residual emissions and thus drive up the CO_2 price. Thus, decarbonization bottlenecks impede not only the feasibility of ambitious climate targets but also imply issues regarding a fair and equitable distribution of residual emissions.

A broad set of industry sector mitigation options is required. Material demand reductions reduce the overall energy demand. In the steel sector, recycling can additionally increase electrification, while in the cement sector CCS helps to abate process emissions from lime rock calcination. In the industry sector a substantial share of residual fossil fuel use is maintained (20–35 EJ/yr in 2050). Biomass feedstocks and biofuels and -gases can substitute a significant share of fossil fuels but already reach limitations to achieve the well-below 2°C target, while e-fuels play a more limited role. Hydrogen can play a substantial role in the steel and the chemical sector. In heavy industry sectors CCS helps to overcome bottlenecks to reduce residual fossil fuel and process emissions, if material demand reductions can not be effectively mobilized.

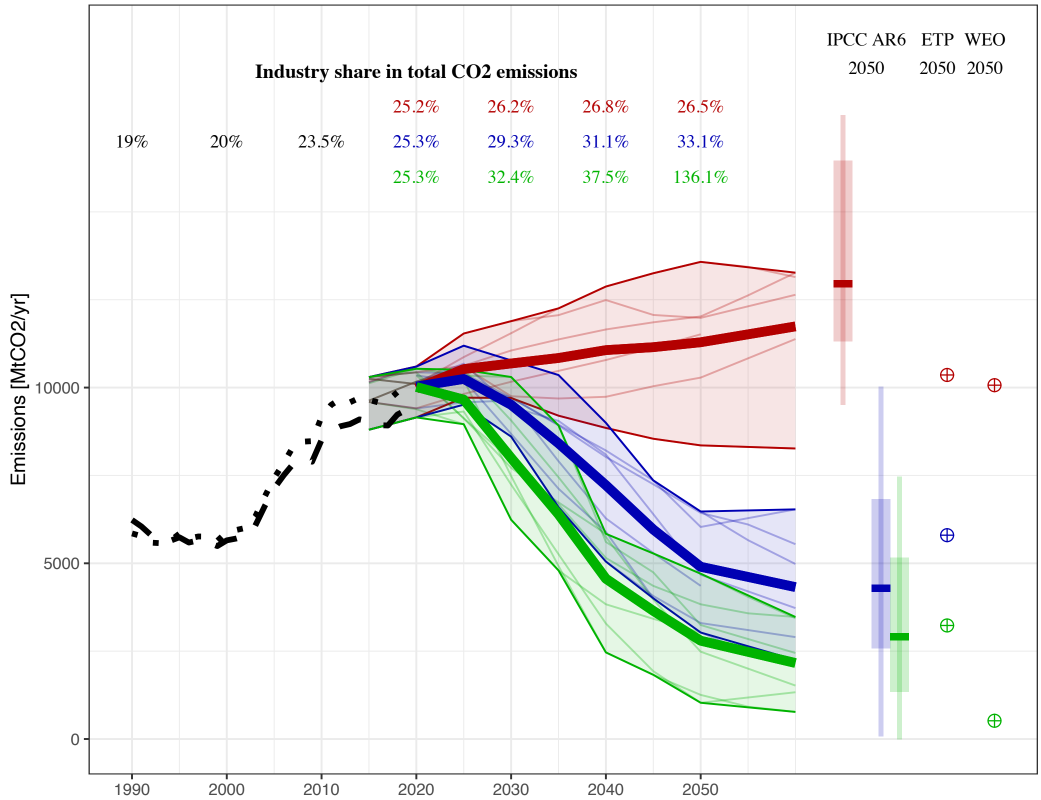
Non-Heavy industry is already electricity intensive and will continue this trend under current policies. It can substitute a large share of fossil fuel use for low- to medium temperature heat by heat-pumps. **The rapid electrification of a broader set of industry processes needs to be combined with an efficiency strategy of existing processes.**

The technology readiness of required technologies is already at relatively mature levels and expected CO_2 prices reach levels that make the deployment of these technologies competitive. Key decarbonisation facilitators are all processes that help to electrify industry processes and supply of other low-carbon energy carriers (incl. bioenergy and electricity derived energy carriers).

The direct CO_2 emissions from the European industry sector decreased during 1990–2010. The most significant emission drops occurred after the collapse of heavy industry in the former Centrally Planned Economies and after the 2008 financial crisis. Since 2010 industry emissions stagnate. **For a 1.5°C compatible pathway, the most optimistic models (REMIND, POLES) in terms of industry sector decarbonization potential project European CO_2 emissions to decrease by 73 to 82% by 2040 and 83 to 95% by 2050 compared to 2020.** Energy efficiency improvements and fuel substitution allow, e.g., to reduce the residual use of coal by 90% until 2050 (REMIND).

Demand reduction and increased recycling, particularly of scarp metal, allow to deepen the decarbonization of the industry sector. Increasing the recycling rates has positive synergies with energy efficiency as steel recycling is three times more efficient and relies on electricity that is easier to decarbonize than combustible energy carriers. The use of electricity is also increased in other industries, particularly to run heat pumps for low temperature heat, but also high temperature processes such smelting. The European electric-

FIGURE 4.5: Direct industry sector CO_2 emissions The IPCC scenarios shown here are consistent with NPi (P1b) and stabilization targets (C1–3). Further we filtered scenarios with 2020 emissions outside the 8–11GtCO_2/yr range. The whiskers show the full range, the 10–90% range and the average.



ity markets are projected to be tight for the coming decade because of ramp-up of carbon-free electricity needs to keep up with fossil fuel phase-out and increasing electricity demands from all sectors. In such situation biofuels are likely to outperform e-fuels to supply hydrocarbons. The tight electricity markets also call to strongly increase efficiency in all processes, including existing well-established processes. Subsidies on electricity prices for incumbent industries and technologies will likely cause misallocations and prevent the rapid decarbonization of industry processes that currently rely on fossil fuels.

The deployment of CCS is an important option for emission intensive industries (iron&steel, cement and chemicals). In combination with bioenergy use this can help to reduce their CO_2 emissions substantially and even turn them net-negative. The REMIND model ramps-up carbon capture in the European industry sector to around 200 $MtCO_2$/yr by 2040. Carbon capture from biomass reaches 70 $MtCO_2$ by 2050, whereas capture of CO_2 released from the calcination process in the cement industry reaches 60 $MtCO_2$. Further emissions from the cement industry can be reduced by using electricity used as a heat source for the calcination process. Captured carbon is mostly stored in geological formation and is not used as an input for e-fuel production, which would lead to its eventual release into the atmosphere nullifying the emissions avoidance (cement) or atmospheric carbon removal (biomass).

4.4 REDUCING LIVESTOCK EMISSIONS: MICROBIAL PROTEIN AS SUBSTITUTE FOR RUMINANT MEAT

MOTIVATION

The global food system is at the root of a third of greenhouse gas emissions, with ruminant meat production being the single largest source (Herrero et al. 2016; Crippa et al. 2021). That is because more and more forests that store a lot of carbon are cleared for cattle grazing or growing its feed. Today, about 80% of global agricultural land including cropland and pasture is used for feeding livestock (Steinfeld and Gerber, 2010; Weindl et al., 2017). Furthermore, livestock production causes considerable amounts of methane (CH_4) and nitrous oxide (N_2O) emissions.

Part of the solution to this problem could be existing biotechnology: Nutritious protein-rich biomass with meat-like texture produced via fungal fermentation in bioreactors, known as microbial protein. Microbial protein is commercially available today in grocery stores, for example in the UK or in Switzerland. Life Cycle Assessment (LCA) studies have estimated substantial environmental benefits of microbial protein, produced in bioreactors using sugar as feedstock, compared to ruminant meat (Hashempour-Baltork et al. 2020; Rubio et al. 2020). However, especially the land-use effects of large-scale substitution of animal-farmed products are likely to be non-linear and cannot be scaled up based on static LCA footprints of current production systems.

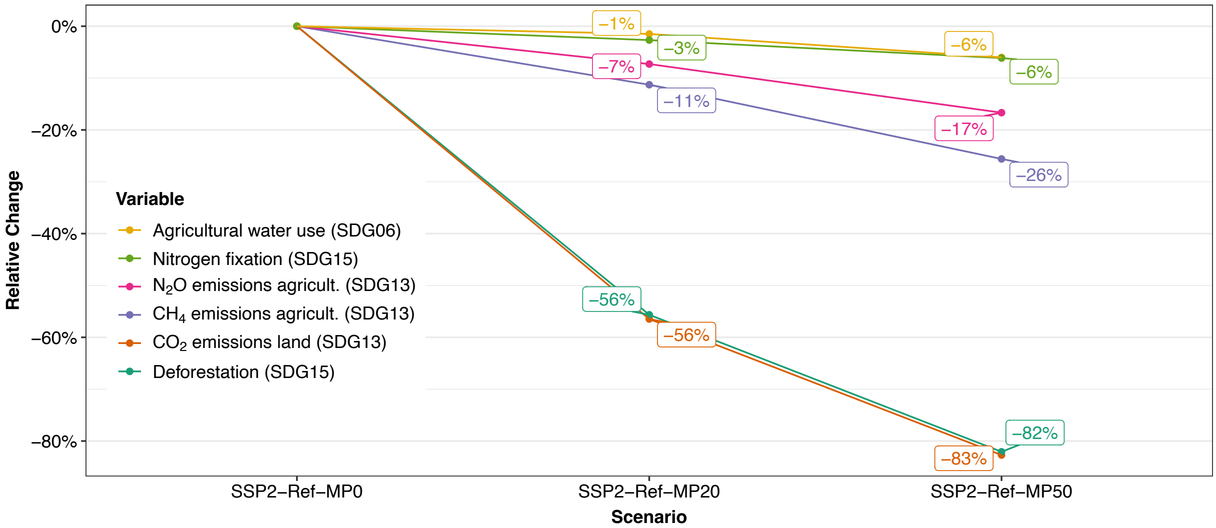
METHODS

NAVIGATE researchers included microbial protein in a dynamic global land-use modelling framework (MAgPIE) to analyse the environmental effects of substituting ruminant meat in the context of the whole food system (Humpenöder et al., 2022). The forward-looking scenarios run until 2050 and account for future population growth, food demand, dietary patterns as well as dynamics in land use and agriculture. The scenarios substitute 0% (MP0), 20% (MP20) or 50% (MP50) of per-capita ruminant meat consumption with microbial protein, and did not include dedicated climate policies such as regulating and pricing of CO_2 and other GHG emissions beyond existing national climate policies (NPIs).

KEY FINDINGS

The substitution of 20 percent of per-capita ruminant meat consumption with microbial protein globally by 2050 (MP20) would cut annual global deforestation and related CO_2 emissions from land-use change roughly in half as it would offset projected future increases of global pasture area compared to a MP0

FIGURE 4.6: Relative difference of global environmental indicators in 2050 as function of scenarios with increasing ruminant meat substitution, compared to the reference scenario without microbial protein. MP0, MP20 and MP50 refer to the substitution of 0%, 20% and 50% of per-capita ruminant meat consumption with microbial protein globally by 2050, respectively.



scenario (see Figure 4.6). The reduced numbers of cattle do not only reduce the feed demand but also reduce methane emissions from the enteric fermentation and nitrous oxide emissions from fertilizing feed or from manure management. Our projections show that for the same protein supply the production of microbial protein requires much less agricultural land and causes fewer GHG emissions from land-use change and agriculture compared to ruminant meat.

4.5 THE IMPORTANT ROLE OF NON-CO_2 GREENHOUSE GAS MITIGATION

MOTIVATION

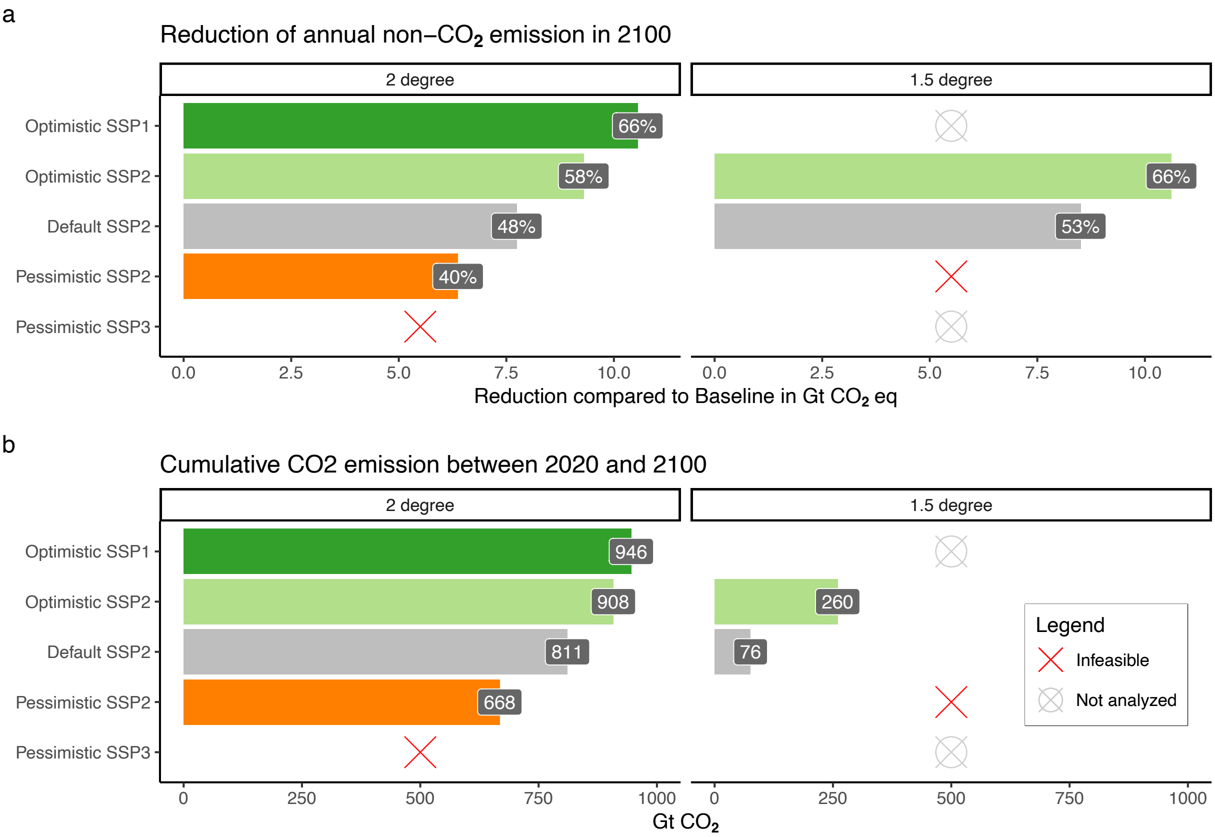
Achieving the stringent global climate target of the Paris agreement, limiting global temperature change to well-below 2°C or even 1.5°C, requires unprecedented emission reductions of CO_2, as well as non-CO_2 greenhouse gases, such as methane, nitrous oxide and fluorinated gases. Most attention in climate policy research has been paid to CO_2, due to its large share in overall emissions, but non-CO_2 emissions also play an important role, as they cannot be fully brought to zero and removal technologies are far from technological maturity. It is expected that by the end of the century, non-CO_2 emissions will predominantly arise from the agricultural sector, where substantial methane and nitrous oxide emissions from livestock, and fertilizer application are unavoidable. However, the exact level of remaining non-CO_2 emissions is highly uncertain.

METHODS

IAMs almost universally make use of non-CO_2 marginal abatement cost curves (MACCs), to represent non-CO_2 mitigation in climate policy scenarios. However, the underlying data is often more than 10 years old (Gernaat et al., 2015; Harmsen et al., 2020; Harmsen et al., 2023)) and generally provides one middle-of-the-road-estimate of mitigation potentials and costs, despite inherently high uncertainties, and potentially massive implications for the feasibility of global climate policy and the need for CO_2 mitigation.

To provide an estimate of the total uncertainty in non-CO_2 mitigation, recently developed non-CO_2 MACCs (Harmsen et al., 2019) were updated and complemented with a set of “optimistic” and “pessimistic” MACCs, with high and low mitigation potentials, respectively. The MACCs have been built-up

FIGURE 4.7: Non-CO_2 greenhouse gas reduction (a) shows reduced Gt CO_2 equivalents (based on AR4 100-yr GWP) relative to baseline (SSP2) with % reductions in bars. Carbon budgets (b) represent the net global CO_2 emissions over the 2020–2100 period. 2 Degree scenarios: left panels, 1.5-degree scenarios: right panels



from quantitative components (representing reduction efficiency, technical applicability, implementation barriers, technological progress, correction for overlap between measures and costs), all with specific uncertainty ranges, based on the most recent literature. The MACCs have been used to assess how different possible levels of non-CO_2 mitigation could affect the feasibility of global climate policy, in terms of 1) achievable climate targets 2) climate policy costs and 3) remaining global carbon budgets, i.e., the need for CO_2 mitigation (see Figure 4.7 for an overview of the results).

KEY FINDINGS

Under pessimistic non-CO_2 mitigation assumptions, limiting temperature change to 1.5 degrees is not possible (see Figure 4.7). Moreover, in an extreme case with very high emissions (SSP3), pessimistic non-CO_2 mitigation assumptions might even keep the 2-degree target out of reach as CO_2 emission reductions also need to compensate for the level of non-CO_2 reductions. In a 2°C scenario, the difference between the optimistic and pessimistic non-CO_2 mitigation assumptions leads to a difference of 240 $GtCO_2$ in the CO_2 budget, about 20% (50%) of the median remaining carbon budget for 2°C (1.5°C) estimated by the IPCC in its 6th Assessment Report. This makes non-CO_2 a very substantial factor in 1.5–2°C mitigation pathways.

Climate policy costs highly depend on the available non-CO_2 mitigation potential, illustrated by 32% and 42% higher mitigation costs under pessimistic assumptions about the non-CO_2 emission reduction potential in a 2°C and 1.5°C case, respectively.

Partly, the variation in non-CO_2 mitigation potential signifies different courses of human efforts to influence this potential (mostly those influencing emitting activities; see Section 4.4 for an example), but it also indicates uncertainty about technical limitations. More case studies of non-CO_2 mitigation measures could help reduce the uncertainty and lead to more effective climate policy strategies.

5

TOWARDS A JUST AND EFFICIENT TRANSITION

Climate change mitigation and climate policies have far-reaching effects on society, including economic impacts, considerations of inequality, and shifts in employment. Empirical evidence indicates that different climate policy instruments often disproportionately impact poorer households. For example, a carbon price of 25 EUR per tonne of CO_2 could pose a 3% expenditure burden on the poorest decile, whereas wealthier households experience only a 1.5% burden. To tackle this regressiveness, redistributive measures such as uniform per-person payments can be effective, especially in the immediate future. Nevertheless, a long-term perspective indicates that mitigating the impacts of climate change can considerably enhance equitable results.

Since decarbonisation efforts can have significant macroeconomic and distributional impacts, different models assess the impact of carbon tax revenue use. The shift to zero-carbon technologies may boost long-term benefits, despite short-term costs. Reducing labour taxes and social security contributions could have positive macroeconomic effects. Nonetheless, providing lump-sum transfers to households with the intent of reducing inequality may not fully realize productivity opportunities.

In recent years, the international equity aspect has gained significant attention alongside the distributional implications within jurisdictions. The Paris Agreement underscores the importance of collabouration in limiting global warming while accounting for equity. The challenge at hand is to balance sovereignty, equity, and efficiency. It is possible to achieve distributional objectives without straining national economies or sovereignty by implementing moderate deviations from uniform carbon pricing, which are guided by international financial transfers. Large disparities in carbon pricing may result in sustainability concerns and technological disparities between regions, which emphasises the importance of meticulous policy planning.

In terms of equity implications of climate policies, it is crucial to comprehend the employment shifts caused by climate action for designing fair transition policies. Integrated assessment models suggest that notwithstanding limited GDP losses, the climate transition is predicted to create new jobs, particularly if carbon revenues are applied to decrease labour expenses. Renewable energy sectors are expected to exhibit significant job growth, while coal and oil sectors may encounter a decline in employment.

This chapter explores the various socioeconomic impacts associated with climate change mitigation and policies. It highlights the importance of addressing inequality, economic repercussions, and employment effects in designing and executing climate policies. A comprehensive approach enables policymakers to tackle climate change while promoting economic and social equity.

5.1 DISTRIBUTIONAL IMPACTS OF CLIMATE CHANGE AND CLIMATE CHANGE MITIGATION MEASURES

MOTIVATION

The impact of climate and energy policies, as well as the effect of climate change on inequality and poverty have gained considerable attention in recent years from scientific and policy communities, as well as from the public, exemplified by the Yellow Vest protests. Although empirical evidence on the degree to which distinct climate policies or damages from climate change disproportionately affect poorer households has grown, scientific assessments of future implications remain limited.

METHODS

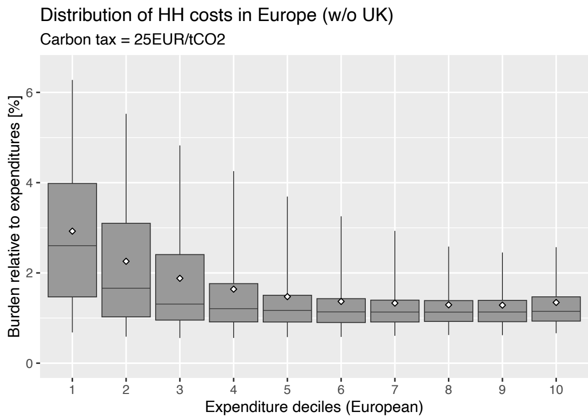
In the NAVIGATE project, we addressed this gap by introducing distributional effects and heterogeneity across income deciles (i.e. 10 income brackets ranging from the poorest to the most affluent 10% of the population) in eight IAMs. Significant advancements have been made in developing various types of IAMs, including Computable general equilibrium (CGE) models (GEM-E3, AIM), process-based integrated assessment models (ReMIND, WITCH, IMACLIM), cost-benefit IAMs (NICE, RICE50+), and neo-Keynesian macro econometric models (E3ME). These models have been designed to assess within-country inequalities and to capture the diverse impacts of energy, food, and carbon prices on household consumption patterns. We analysed household surveys from a large group of EU and non-EU countries to assess how climate policies are expected to affect different households. Several publications have subsequently documented the individual model outcomes for the distributional incidence (i.e. the effect on the income distribution) of climate policies. To enable a comparable analysis with the extensive set of models employed, we conducted a multi-model comparison that encompasses eight models and focuses on ten large countries. The focus is on investigating the distributional implications of various mitigation scenarios (Current policies and 1.5°C scenarios) and redistribution schemes. We have also considered recent evidence of the uneven distributional impact of climate change, acknowledging that its economic effects vary across different income levels within and between countries. Using methods from the existing literature on climate and economic growth, we examine the economic consequences of temperature increases for each income decile within a country. This analysis incorporated various climate and redistribution policies and compared the results across different scenarios and countries to determine their impact on the Gini index – a measure of income inequality ranging from 0 to 100 points, with 0 indicating a perfectly equal distribution of income. As of 2021, the Gini coefficient of the population in the EU was approximately 52 points.

KEY FINDINGS

Climate policies are often found to be regressive, meaning that less wealthy households carry a greater proportion of the costs. In an empirical and simulation study for Europe, it was found that a carbon price of 25 EUR per tonne of CO_2 would result in a burden of approximately 3% of total expenditures on the poorest 10% of households, whereas richer households would bear only 1.5%, as Figure 5.1 (Feindt et al., 2021).

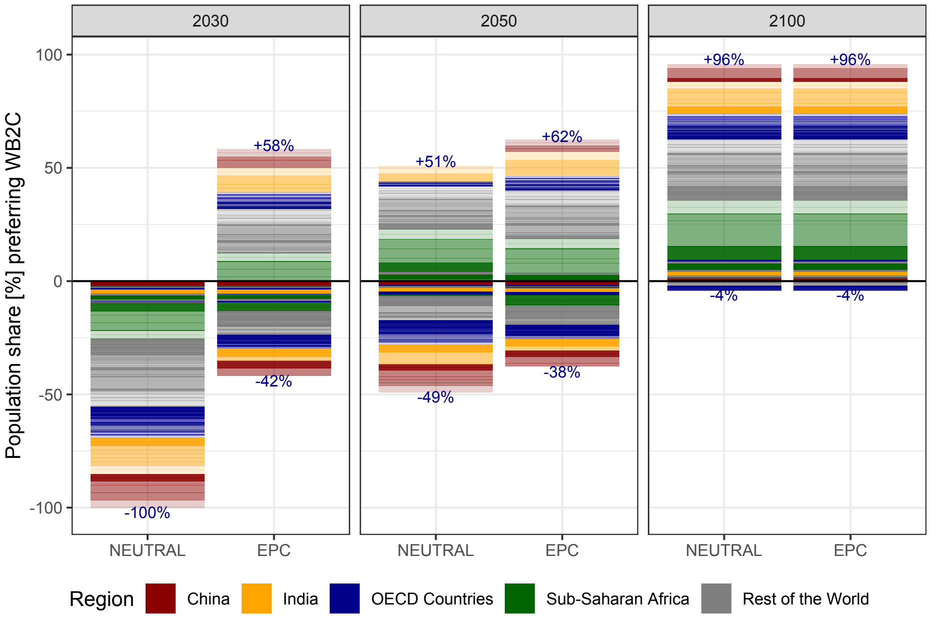
Although climate policies based on pricing without complementary measures typically are regressive, in most cases the effect is offset by recycling revenue through equal per capita transfers within countries. Looking towards the medium and long-term, actively avoiding regressive climate impacts is likely to greatly enhance the distributive result of a well-below 2°C climate scenario compared to the reference scenario. While short-term redistribution is crucial for achieving a just transition, in the long term, avoided impacts will more than offset policy costs, including those affecting lower-income households. Figure 5.2 illustrates that by 2030, climate policy costs outweigh benefits for everyone without redistributive policies; however, an equal per capita climate dividend can improve outcomes for 58% of the world population under a climate policy consistent with well-below 2°C. By the end of the century, a warmer world is predicted to benefit only 4% of the global population (Emmerling, Andreoni, and Tavoni, 2024).

FIGURE 5.1: Impact of a carbon price of 25 EUR per tonne of CO_2 across households in Europe ordered by deciles of total expenditures from left (1=poorest decile) to right (10= richest 10% of the population. Graphic reproduces figure 1 from Feindt et al. (2021).



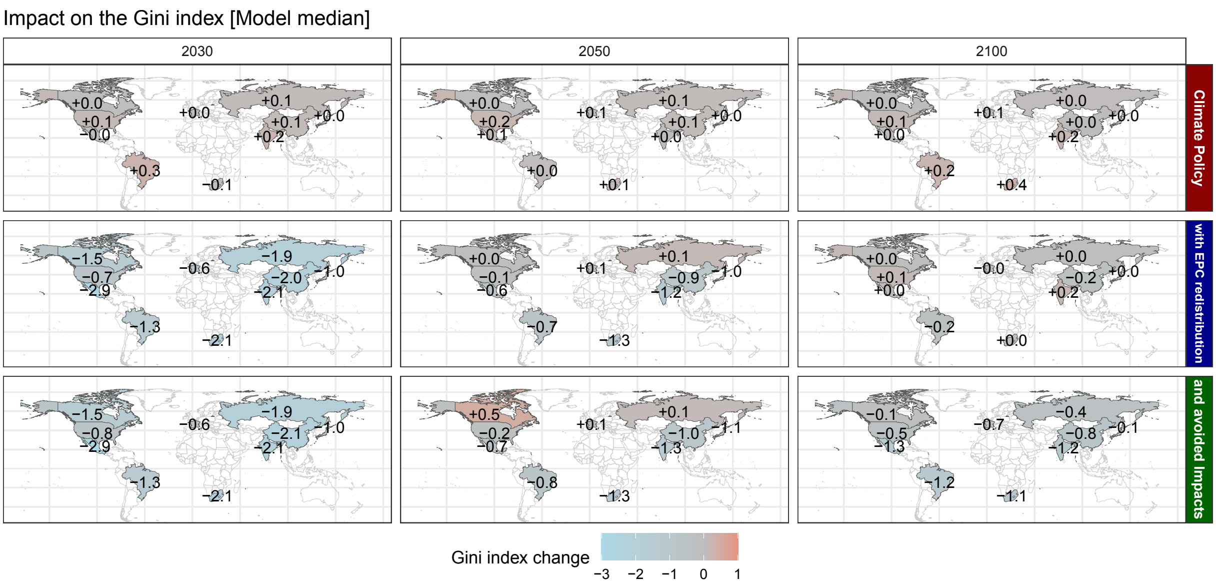
Climate change disproportionately affects the poorer segments of the population within countries, even when a country's capacity to adapt to climate change is considered, while the richest suffer the lowest damages. If no further measures to mitigate climate change are taken beyond existing regulations, we estimate that the resulting climate impacts could cause the Gini index to rise by up to six points, particularly in Sub-Saharan African countries, resulting in substantial worsening of income inequality. It is estimated that around three-quarters of the total variation in climate change impacts are caused by differences between countries, while one-quarter comes from within-country inequality. Our calculations suggest that the economic impact of climate change is regressive, with damages having an income elasticity of 0.72. This means that a household twice as wealthy (100% richer) is predicted to experience only around 72% larger damages (Gilli et al., 2023). Climate impacts are particularly regressive in hotter and poorer countries. Therefore, incorporating the distributional impact supplies an additional rationale to avoid excessive global warming.

FIGURE 5.2: Share of the population that is better off under well-below 2°C compared to the Reference scenario with climate impacts. The deciles are shown in different shades, differentiating the bottom 20%, middle 60%, and top 20% of the income distribution (darker bars indicating richer deciles) with inequality-neutral redistribution (NEUTRAL) and equal per-capita carbon dividend (EPC). Source: Emmerling, Andreoni & Tavoni (2024).



While climate policies without redistributive policies and without considering avoided climate damages are found to affect poorer households disproportionally, both redistributive policies and the avoided increase in inequality from climate damages revert this finding. Climate policies combined with redistributive policies benefit the poor and reduce inequality. This finding was derived from a first-of-its-kind multi-model comparison study of distributional implications of climate policies, redistribution schemes, and impacts with eight IAMs. Figure 5.3 shows over time and across regions the estimated impact on the

FIGURE 5.3: Impact of climate targets (650 $GtCO_2$ target) of mitigation costs (first row), then adding equal-per capita "carbon dividend" redistribution (second row), and finally also avoided climate impacts (third row). Source: Emmerling et al. (2023).



Gini index of inequality. First, the climate policy unanimously leads to an increase of inequality over the whole horizon, on average between 0.1 and 0.2 points of the Gini index. When the carbon revenues are redistributed as a "climate dividend" equally among citizens, (second row), the climate policy effect is reversed, i.e. inequality is actually lower than in a no-policy case due to the redistribution– a reduction of about 2.7 points by 2030. This positive effect on inequality is however reduced over time as carbon revenues diminish with reduced emissions. When we also include impacts from climate change (third row), this increases the positive effect on inequality further. In the long run, a robust decrease of the Gini index is found across almost all countries, indicating that the mitigation scenario becomes progressive leading to a reduction of inequality within countries overall (Emmerling et al., 2023).

5.2 IMPACTS OF CARBON REVENUE RECYCLING ON EQUITY AND EFFICIENCY

MOTIVATION

Decarbonisation is expected to cause large macroeconomic, structural change and distributional impacts across countries, sectors and households. Well-designed strategies are required to achieve progressive outcomes of climate policies by considering appropriate compensation schemes using revenues collected from a carbon tax, either by increasing household income through lump-sum payments ("climate dividend"), reducing pre-existing, distortionary taxes, or through transfers towards the social security system.

METHODS

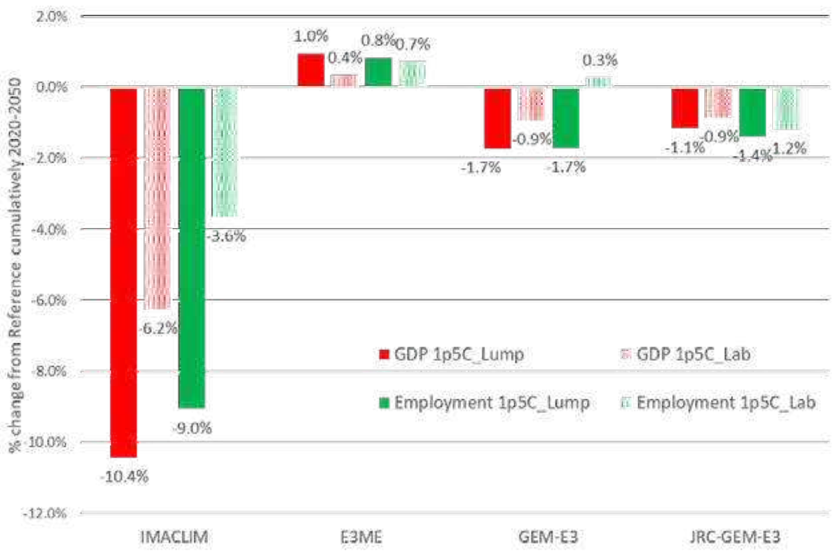
We explore the macro-economic impacts of decarbonisation using carbon revenues in alternative ways, using four well-established multi-sectoral macro-economic models (IMACLIM, GEM-E3-FIT, E3ME-FTT, JRC-GEM-E3). These models have distinct features and integrate different theoretical assumptions on how the economy operates (Lefèvre et al., 2022; Mercure et al., 2019). E3ME-FTT is a demand-driven, nonequilibrium model that assumes that both labour and capital are not fully utilized, whereas GEM-E3-FIT, Imaclim-R and JRC-GEM-E3 are supply-driven, CGE models that assume that any additional decarbonisation-related investment crowds-out investment in other productive sectors, increasing the price of capital and thus having negative economic impacts. These models were used to develop scenarios with increasing climate policy ambition: the NPi scenario assumes the continuation of currently implemented policies, while Paris temperature goals are met in the 2°C and 1.5°C target scenarios through universal carbon pricing. We explore the macro-economic impacts of different ways of recycling carbon revenues, focusing on two main options suggested by the World Bank (2016): 1) reducing labour taxes and social security contributions (2C_Lab and 1p5C_Lab scenarios), 2) providing lump-sum transfers to households based on an equal-per-capita basis (2C_Lump and 1p5C_Lump scenarios).

KEY FINDINGS

The uptake of zero-carbon technologies, electrification and energy efficiency brings about a shift from high operating expenditures to technology- and capital-intensive processes. Fossil fuels are substituted by low-carbon alternatives, which may cost more in the short-term. This can increase overall production costs reducing economic output especially in CGE models assuming crowding-out of investment (Figure 5.4). As expected, **more stringent climate policy in a 1.5C scenario increases GDP losses relative to the 2C scenario in all CGE models**. The lack of crowding-out effects in the E3ME macro-econometric model creates positive economic effects triggered by the assumed investment stimulus and endogenous learning (Lefèvre et al., 2022; Mercure et al., 2019).

Using carbon tax revenues to reduce labour taxes and social security contributions has positive macroeconomic impacts in the CGE models with GDP losses reduced by 30%-70% across models and scenarios. This comes from two channels: reduced labour costs would lower the production cost for firms and distortions are gradually removed so the allocation of resources is more efficient, while additional labour demand would increase household income and consumption. Transferring carbon revenues directly to households on an equal per capita basis can reduce inequality (as shown in Fragkos et al. (2021)) and al-

FIGURE 5.4: Global GDP and employment impacts of 1.5°C compatible scenarios across models. A discount rate of 3% is used.



leviate negative macro-economic impacts, in particular if their consumption pattern depends on goods and services with a large domestic content. However, this misses opportunities for enhanced productivity and for the creation of new jobs especially in resource-constrained CGE models. Overall, lump-sum transfers to households can improve income equity despite the lower GDP than in the labour tax reduction scenario, illustrating the potential trade-offs of different carbon revenue recycling schemes in terms of efficiency and equity. In contrast, lump-sum transfers have stronger positive GDP impacts than reducing labour taxes in E3ME as they further increase private demand in the non-equilibrium demand-led modelling framework.

The effective and sustainable recycling of carbon revenues can act as an enabler for acceleration of EU's emissions reduction efforts in 2030–2040, with increasing carbon revenues (higher carbon price and wider reach of carbon markets) providing opportunities to enhance growth and reduce adverse-side distributional impacts of carbon pricing, while enhancing the social acceptance of decarbonisation.

The impacts on aggregate employment are driven by two contradictory trends (Figure 5.4): declining economic activity tends to reduce employment (in CGE models); but the economy could move toward a more labour-intensive structure as renewable technologies have higher labour intensity on average compared to fossil fuels (Fragkos et al., 2021). The trade-off between jobs lost in some sectors (e.g. in fossil fuel supply) and jobs creation in others (e.g. renewable electricity, biofuels) would lead to lower impacts on employment than on GDP. The LAB scenarios have more positive employment effects in all CGE models as they directly reduce labour cost thus increasing labour demand; this effect is pronounced in GEM-E3 showing that this policy can even lead to net creation of jobs globally by 2050. Meanwhile, in E3ME-FTT, the additional demand created through lump sum transfers has a stronger job creation effect than reducing labour taxes because of the demand-driven nature of the model.

In the Labour tax recycling scenarios, the services sector production registers the largest increases compared to Lump sum transfer scenarios in the CGE models accounting for about [49%-60%] of total GDP gains, while industries account for [28%-30%] across scenarios. This relative positive effect on services is explained by (i) its large contribution on total economic activity (ii) the fact that it is more labour intensive than industries on average, with a higher labour cost share on total costs (iii) and is less carbon intensive than industries. Regional differences are also observed depending on the initial carbon intensities of the economies, labour costs and the initial share of industry in GDP.

Carbon revenues, if carefully and strategically considered, can represent a large financial resource for governments to support public policy goals, including growth, societal cohesion, and decarbonization. Emission trading systems can support governments to achieve ambitious climate goals. The generated carbon revenues can be used for various purposes, each having benefits and costs. We demonstrate the socio-economic benefits of using carbon revenues to reduce distortive labour taxes, while lump-sum transfers to households can reduce inequality.

5.3 EMPLOYMENT EFFECTS OF THE NET-ZERO TRANSITION IN THE EU

MOTIVATION

Understanding the potential shifts and losses in sectoral employment due to climate action, in particular in energy-intensive sectors, is critical for the design of compensation and adjustment policies, in order to ensure an equitable and socially acceptable transition.

METHODS

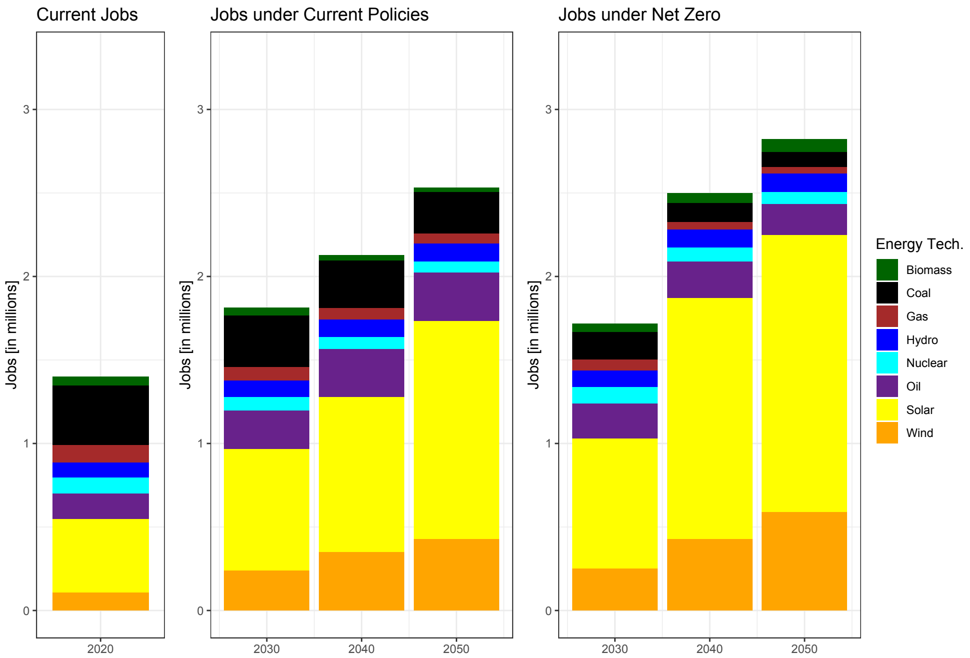
We employ different IAMs that include employment effects across sectors and in the energy system, and study the effect of the 1.5°C target on employment in the EU economy.

KEY FINDINGS

By 2050, Europe's direct energy jobs are likely to increase substantially – from around 1.3 million to over two million (Figure 5.5). In the Net zero scenario, this increase is even higher reaching about 2.5 to 3 million jobs by mid-century. Of the total jobs in 2050 under the Net Zero scenario, 80% would be in the renewables sector. Solar PV with the highest jobs' intensity accounts for about three quarters of the increase, Wind for around 15%. On the other hand, around 300,000 jobs are lost notably in the coal and oil sectors while in the NDC scenario this loss amounts to only 100,000 jobs. Across countries, in terms of share of the workforce, the losses notably in the coal and oil sector are highest in Poland, the Czech Republic, and Norway.

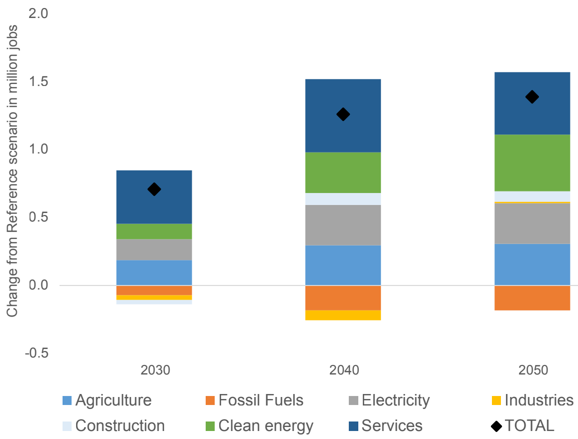
In addition to the direct energy jobs, we also explored the employment impacts in sectors indirectly influenced by the transition through supply chains and overall macroeconomic effects induced by changes in prices, consumption patterns and resource allocation. Despite limited GDP losses, the transition is expected

FIGURE 5.5: Energy sector jobs (in million jobs) in the EU in the Net Zero and Reference scenarios by technology.



to create new jobs in the EU, especially if carbon revenues are used to reduce labour costs. The analysis based on GEM-E3 results shows that there is an EU-wide gain of 700,000 jobs in 2030 which further increases to 1.3–1.4 million jobs in 2040 and 2050 (see Figure 5.6). Services, the largest employing sector of the economy, increase demand for labour because of the reduced labour costs, despite the limited drop in domestic production. Job losses are registered only in fossil fuel production sectors and in industrial manufacturing. In contrast, jobs are created in sectors related to the low-carbon transition (and their supply chains), including electricity supply, clean energy manufacturing (e.g. wind turbines, EV equipment, hydrogen), construction needed for the build-up of low-carbon technologies and infrastructure and buildings' renovation, and agriculture needed to produce advanced biofuels.

FIGURE 5.6: Changes in EU sectoral employment in 1.5°C scenario in GEM-E3



5.4 SOLVING THE SOVEREIGNTY-EQUITY-EFFICIENCY TRILEMMA OF INTERNATIONAL CLIMATE POLICIES

MOTIVATION

The Paris Agreement calls for a cooperative response with the aim of limiting global warming to well-below 2°C above pre-industrial levels while reaffirming the principles of equity and common, but differentiated responsibilities and capabilities. Although the goal is clear, the approach required to achieve it is not. A major concern is the heterogeneity of per-capita incomes and the carbon intensity of GDP, which imply that relatively high GDP losses are incurred on countries with either low income levels (developing countries) or high carbon intensities (fossil fuel rich countries in the Middle East and Reforming Economies) or both (South and South East Asia).

Thus, cap-and-trade policies using uniform carbon prices across regions produce cost-effective reductions of global carbon emissions, but tend to impose relatively high mitigation costs on developing and emerging economies. Huge international financial transfers are required to complement cap-and-trade to achieve equal sharing of effort, defined as an equal distribution of mitigation costs as a share of income, and therefore the cap-and-trade policy is often perceived as infringing on national sovereignty.

METHODS

We use the integrated assessment model REMIND–MAgPIE to analyse alternative policies: financial transfers in uniform carbon pricing systems, differentiated carbon pricing in the absence of financial transfers, or a hybrid combining financial transfers and differentiated carbon prices. We developed an algorithm to differentiate carbon prices and limit international transfers that allowed us to apply a massive sensitivity analysis and derive a trade-off curve that gradually varied the mix between carbon price differentiation and international transfers. This methodological approach of a trade-off curve provided new insights on the degree to which efficiency and the amount of transfers (sovereignty) can be traded-off against each other while maintaining an equitable outcome, implying that the trade-off can be strongly relaxed by a policy mix.

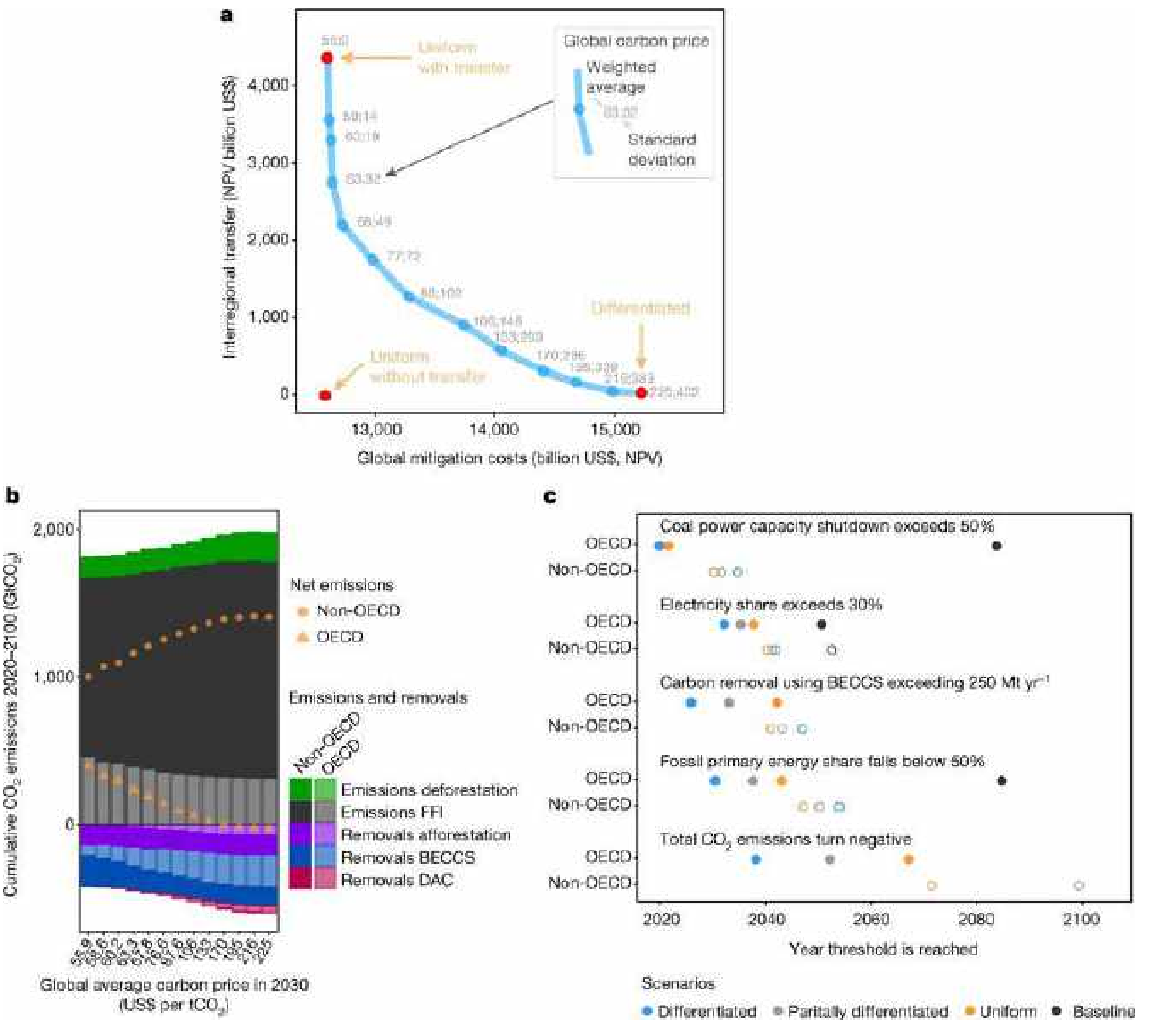
KEY FINDINGS

International financial transfers guided by moderate deviations from uniform carbon pricing could achieve the distributional objectives without straining either the economies or fiscal sovereignty of nations.

Under uniform carbon prices, a present value of international financial transfers of 4.4 trillion US dollars over the next 80 years to 2100 would be required to equalize effort. By contrast, achieving equal effort without financial transfers requires carbon prices in advanced countries to exceed those in developing countries by a factor of more than 100, leading to efficiency losses of 2.6 trillion US dollars.

Hybrid solutions reveal a strongly nonlinear trade-off between cost efficiency and sovereignty: moderate deviations from uniform carbon prices strongly reduce financial transfers at relatively small efficiency losses and moderate financial transfers substantially reduce inefficiencies by narrowing the carbon price spread (Figure 5.7, Panel a).

FIGURE 5.7: Sovereignty versus cost-efficiency trade-off and consequences of differentiated carbon prices. Graphic reproduces figure 3 from Bauer et al. (2020).
a) The trade-off curve, including the three corner solutions (marked with red circles). The numbers indicated the 2030 global average carbon price and the standard deviation using the regional CO_2 emissions as weights. The costs and transfers are NPVs for the period 2020-2100.
b) The cumulative net carbon emissions in OECD and non-OECD countries differentiated by emissions sources and carbon removals. FFI, fossil fuel and industry; DAC, direct air capture; BECCS, bioenergy with carbon capture and sequestration.
c) Different timing of mitigation measures in OECD and non-OECD regions. 'Partially differentiated' is the case with an average carbon price of US$63.3 per tCO_2. In some scenarios, the threshold is not reached before 2100 and, therefore, no marker is shown.



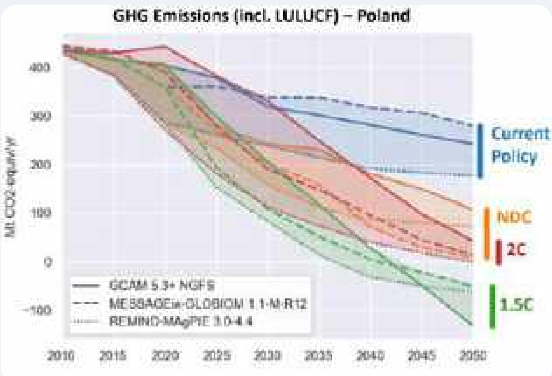
Large carbon price spreads can undermine other sustainability goals. If the differences in climate policy stringency remain large because international transfers are constrained by sovereignty concerns, market distortions can lead to adverse outcomes for sustainability objectives such as increased bioenergy trade from low to high carbon price countries. Also, the need for Carbon Dioxide Removal increases to offset additional emissions from regions with low carbon prices, such as fossil fuel rich countries (Figure 5.7, Panel b). Moreover, if the degree of carbon price differentiation reaches very large levels, the low-price countries, particularly large developing countries, would take up new technologies with delays. This can increase the risk that the technology divide across regions increases (Figure 5.7, Panel c).

Quantifying the advantages and risks of carbon price differentiation provides insight into climate and sector-specific policy mixes. Our analysis implies that moderate carbon price differentials can address the issue of limiting financial transfers and also avoid serious sustainability issues while equalizing relative income losses across regions.

SCALING DOWN GLOBAL TRANSFORMATION SCENARIOS TO THE COUNTRY LEVEL

Applying insights from global IAMs to individual countries has remained difficult because most of these models focus on large regional aggregates. Modelling teams are addressing this issue by increasing spatial heterogeneity. However, running these models for all countries in the world is still beyond computational capacity. To address this issue, new downscaling tools have been developed in the NAVIGATE project and applied to the development of climate transition scenarios for the Network for Greening the Financial System (NGFS) (www.ngfs.net/ngfs-scenarios-portal).

FIGURE 5.8: Downscaled GHG emission scenarios (including LULUCF) for Poland for four different climate policy cases: Continuation of current policies, implementation of nationally determined contributions (NDCs) until 2030 and continuation of NDC policies thereafter, and limiting global mean temperature increase to well below 2°C (2C) and 1.5°C (1.5C).



The downscaling tool (Sferra et al.,2021) provides results based on two types of information: regionally aggregated data from IAMs and observed historical data at the country level. In the short term, the downscaled results should be consistent with the observed data at the country level. In the long term, the energy variables converge to the regional IAM results and may differ from the historical data. The downscaling methodology is therefore based on two pathways: 1) “Short-term projections” based on extrapolation of historic trends; 2) “Long-term IAM benchmarks” based on regionally aggregated IAM results. Both pathways are harmonised so that the sum of country-level results within a region matches the regional IAM results, with large countries making the largest adjustments required to match the regional data. A linear interpolation is then made to converge from the “short-term” pathway to the “long-term” pathway between the base year (e.g. 2010) and a future “convergence time”.

Figure 5.8 shows the application of the downscaling approach to the NGFS climate transition scenarios for the example of Poland. Three global IAMs calculated a set of NGFS scenarios and the downscaling approach was used to translate these scenarios into corresponding emission pathways for individual countries. In this way, users of the NGFS scenarios can obtain country-specific information on the implications of the global transition scenarios for individual countries.

6

IMPROVING TRANSPARENCY OF INTEGRATED ASSESSMENT MODELS

In order to facilitate the wider use of IAMs and to promote the uptake of research results from their application, NAVIGATE has taken a number of steps to improve the transparency, interpretability and usability of IAMs and the scenarios they generate. This included

- highlighting the different capabilities and gaps in IAMs based on a review of the main criticisms raised against them,
- developing a three-step approach to promote the use of scenario ensembles, and
- improving model documentation.

6.1 TAKING STOCK OF THE DIVERSE CAPABILITIES AND GAPS IN INTEGRATED ASSESSMENT MODELS

The central role of IAMs in IPCC assessments and their influence on the international climate policy discourse has meant they have been subject to scrutiny and criticism. These criticisms include (1) lack of representation of actor heterogeneity, (2) inadequate modelling of technology diffusion and dynamics, (3) too simplified representation of capital markets, (4) inadequate representation of energy-economy feedbacks, (5) over-simplified modelling of policy instruments, and (6) insufficient grounding of scenario interpretation in political and social feasibility.

In all of these areas, the IAM modelling community has taken different approaches to address such criticisms and to ensure that IAMs continue to provide important insights through scenario modelling to help shape global climate action.

In modelling heterogeneity (1), a key consideration is the trade-off between added complexity and better representation of overall system behaviour. There are circumstances where heterogeneous behaviour plays an important role and work should continue to identify these areas and develop models further to better capture them. At the same time, elements that can be represented by a more aggregated formulation should not be unnecessarily complicated, but the underlying rationale and assumptions should be clearly communicated.

For technology diffusion (2), it is unlikely that the models will ever be able to fully endogenise the complex and numerous processes that determine technology dynamics. However, empirically derived explanatory factors add detail and robustness to the model formulations.

The modelling of capital markets (3) is complicated by the lack of consensus in the broader economic theory on how creation of finance should be understood. Progress in this area would also directly contribute to how finance should be modelled. Meanwhile, macroeconomic tools are being improved through the explicit inclusion of financing schemes, detailed budgeting of debt and interest rates. A key area of development is better representation of how financial institutions perceive the creditworthiness of borrowers, and how this affects the allocation of financial resources to them.

The representation of energy-economy feedbacks (4) in IAMs has been criticised, especially for the so-called “first best assumptions”. The community would benefit from including a broader range of economic visions, including those that emerge from alternative paradigms. This is particularly true as IAM scenarios often show a strong decoupling of emissions and economic growth, which has not been observed on a sustained basis at the global level.

The representation of policy instruments (5) in IAM scenarios does not directly reflect the model capabilities, but rather the way in which the models are used. Ongoing work in the modelling community, including within the NAVIGATE project, is extending representations to alternative policy formulations, beyond carbon pricing, including policy packages.

Communication (6) of assumptions and results can be improved with the continued efforts to increase transparency. Open-sourcing of the tools helps to broaden the user community, which can bring additional scrutiny to the tools. Similarly, reflecting more diverse interests and perspectives in the formulation of the scenario frameworks, beyond those emerging from the position of political power, can further enhance the credibility and legitimacy of the analysis.

The discussion presented here is published in Keppo et al. (2021).

6.2 USING LARGE ENSEMBLES OF CLIMATE CHANGE MITIGATION SCENARIOS FOR ROBUST INSIGHTS

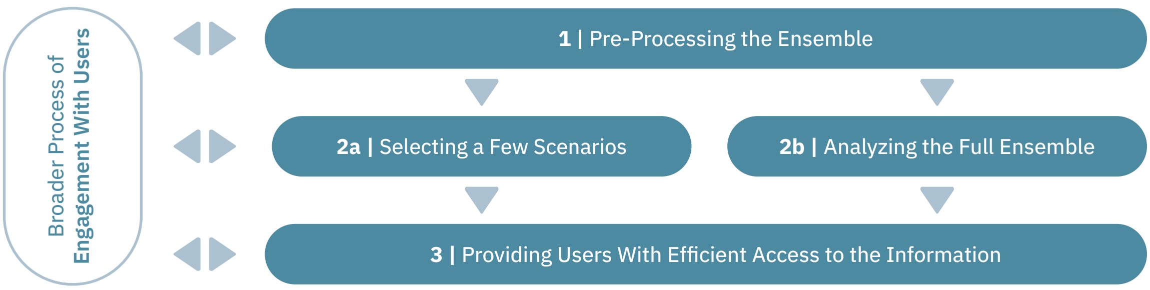
As they gain new users, climate change mitigation scenarios are playing an increasing role in the transition to net zero. A promising practice is the analysis of scenario ensembles. A mitigation scenario ensemble is a collection of a large number (from dozens to thousands) of emission and socio-economic scenarios calculated with different modelling frameworks that represent systems with comparable boundaries.

More extensive use of scenario ensembles has the potential to provide new and more robust insights to meet different end-user needs, particularly in the context of decision making under uncertainty. To fully exploit this potential, the uses, limitations and methodological issues of scenario ensembles have been reviewed and a three-step approach has been developed to promote their appropriate use: (1) pre-processing the ensemble, (2) either selecting a few scenarios or analysing the whole ensemble, and (3) providing users with efficient access to the information. Illustrative cases include the selection of a set of transition scenarios to perform stress tests to assess the stability of the financial system under contrasting climate policy alternatives, the assessment of the consistency of short-term targets with pathways compatible with the long-term climate goal, or the assessment of sources of uncertainty in, for example, solar photovoltaic development in mitigation pathways.

Selecting a subset of scenarios can help focus on the most relevant pathways, communicate to non-experts by simplifying the scenario space, or increase the tractability of information for further analysis. Quantitative techniques, guided by *desirability*, *plausibility* or *diversity* criteria, can improve the transparency and robustness of the selection process by making the selection criteria and process explicit. Alternatively, exploration of a full ensemble can also provide new insights by reflecting the full space explored by the scenarios. The analysis can highlight results that are robust to the uncertainties covered, or, on conversely, highlight the key factors influencing the results.

For each step of the methodology developed, key methodological issues, existing methods and applications to address them, as well as illustrative cases can be found in Guivarch et al. (2022).

FIGURE 6.1: Steps in using an ensemble of scenarios. Graphic reproduces figure 2 from Guivarch et al. (2022).



6.3 IMPROVING THE DOCUMENTATION OF INTEGRATED ASSESSMENT MODELS

Good model documentation is essential to provide transparency about the model scope, limitations, and assumptions of the model. It contributes substantially to building stakeholder confidence in model results. Model projections are only meaningful if the underlying assumptions are understood. Comprehensive model documentation is therefore a key requirement.

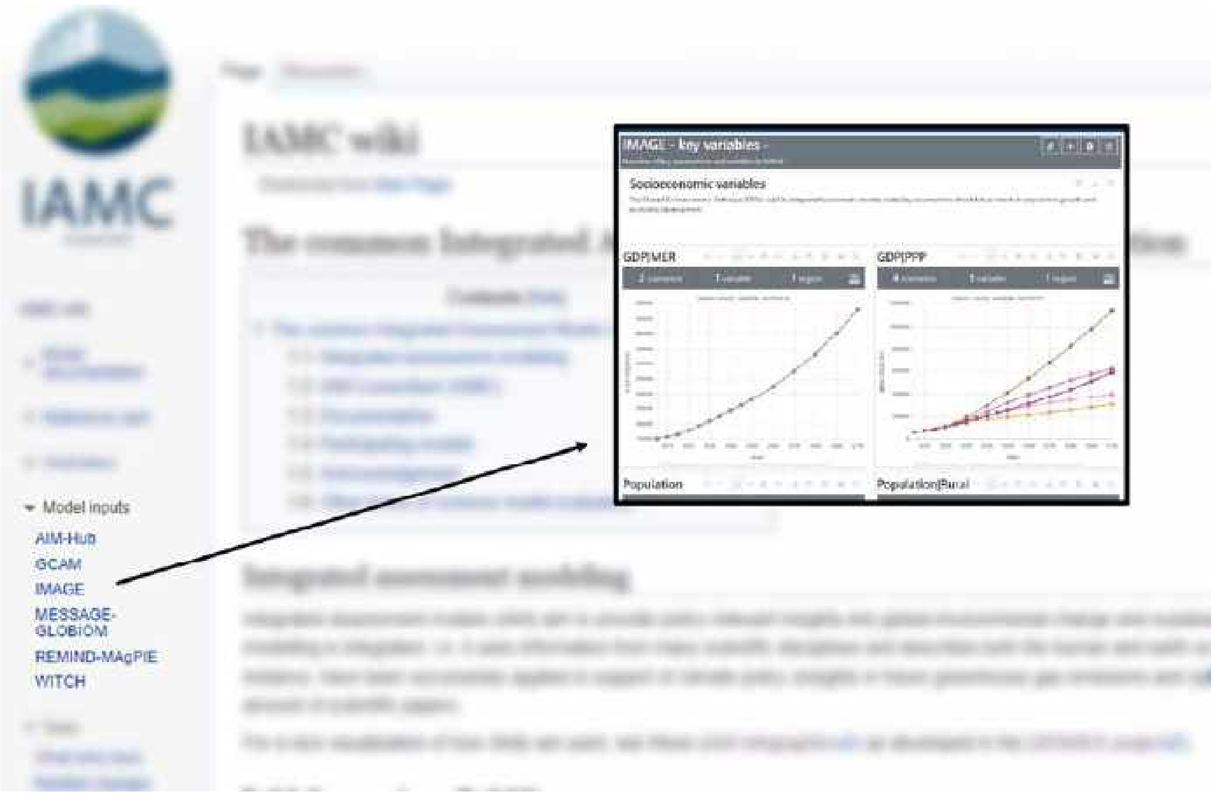
The common IAM documentation, also known as the IAMC wiki (www.iamcdocumentation.eu), serves as the primary platform for providing transparent and harmonised documentation of integrated assessment models. The centralised approach and harmonised structure allow for detailed model comparisons to understand model similarities and differences. The IAMC wiki is hosted by PBL and supported by the Integrated Assessment Modeling Consortium (IAMC) with the aim of „*setting new standards for transparency, documentation and public access to model methodologies, tools, and related data on the assumptions*".

The wiki has continued to grow in terms of model coverage. All IAMs participating in the NAVIGATE project (see) are now included, and the documentation platform has been made fully available to other teams, such as new models from IAMC member institutions and models contributing to the AR6 emissions scenario database.

Following a documentation workshop aimed at setting a new community standard for transparency, documentation for all national and global NAVIGATE IAMs has been updated on the IAMC wiki. At the same time, the IAMC wiki was enhanced with additional features to improve its usability.

The following features have been implemented to increase the usefulness of the common IAM documentation for researchers and non-academic users of IAM results alike.

FIGURE 6.2: Steps to use ensemble of scenarios.



A primer was developed with the aim of providing users with an introduction to IAMs and their application in scenario analysis, facilitating a deeper understanding of scenario analysis techniques using IAMs, and enhancing the ability to place scenario results in their appropriate context.

A diagnostic assessment and comparison of key model behaviours in response to climate policy was conducted (Harmsen et al., 2021), providing important insight into how key model behaviours differ between models and over time between different model versions. Several useful model comparison features and data export options have been added. Visitors can now download a complete overview of all reference card (= model overview page) data, which includes all key features of all models. It is now also possible to make a selection based on model type, scope and methods. The wiki also allows for a comparison of sections of the full (= more detail) model documentation across models.

The documentation system has been linked to the AR6 Scenario Explorer and Database (https://data.ene.iiasa.ac.at/ar6/), hosted by IIASA, which provides quantitative information on key input assumptions for the models. The IAMC wiki has been extended to include links to so-called workspaces that show the evolution of a set of key input variables over time for different scenarios (see Figure 6.2). Links are currently available for AIM-Hub, GCAM, IMAGE, MESSAGE-GLOBIOM, REMIND-MagPIE and WITCH, with the possibility to add more models. The data include variables describing economic growth, population growth, technology lifetimes and efficiencies, prices, capital costs, operating and maintenance costs, and discount rates for energy technologies and carbon capture and storage systems.

To ensure that the documentation for all models remains up to date and accurate beyond the NAVIGATE project, most major new IAM-based projects include goals for maintaining and improving the wiki. The documentation has been incorporated into the IAMC model documentation database to ensure that it is managed and maintained beyond the NAVIGATE project.

7
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A
ANNEX

A.1 CONSORTIUM PARTNERS

Potsdam Institute for Climate Impact Research, Germany (Project Coordinator)

International Institute for Applied System Analysis, Austria

Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici, Italy

Ministerie van Infrastructuur en Waterstaat, Netherlands

University College London, UK

E3-Modelling IKE, Greece

Centre national de la recherche scientifique CNRS, France

University of East Anglia, UK

Université de Genève, Switzerland

Chalmers Tekniska Hoegskola AB, Sweden

Mercator Research Institute on Global Commons and Climate Change, Germany

Climate Analytics GmbH, Germany

Norges Teknisk-Naturvitenskapelige Universitet, Norway

The University of Exeter, UK

Fundacja Warszawski Instytut Studiow Ekonomicznych I Europejskich, Poland

Fundacao Coordenacao de Projetos Pesquisas e Estudos Tecnologicos, Brazil

National Center for Climate Change Strategy and International Cooperation, China

University of Oxford, UK

A.2 MODELS USED

NAVIGATE brought together a diverse collection of internationally-recognised state-of-the-art tools and models to ensure successful implementation of the project. They combine

a| sophisticated integrated assessment modelling tools,
b| detailed state-of-the-art sector models,
c| other tools concerned with input-output modelling, socio-technical transition modelling, stochastic general equilibrium modelling, and country-level downscaling,

The range of IAMs and the breadth of other tools in NAVIGATE ensures that a broad spectrum of elements can be assessed in the field of transformative change and distributional impacts, but also allows for model comparisons in key areas of the project to evaluate uncertainty and robustness of results. More detailed information on which models and tools were used can be found on the NAVIGATE website:
www.navigate-h2020.eu/about-the-project/subpage-1

A.3 OPEN ACCESS PRODUCTS

The **IAM NAVIGATOR** is a toolbox including methods, modules and teaching material and IAM results generated during the project. It is available at www.navigate-h2020.eu/navigator and consists of three main pillars:

LEARN – In the learn section, interested individuals find capacity building material from the two summer schools, recordings of and slides presented during the webinars and detailed information on the models used.

USE – The use section contains a link to the database with final scenario results produced by the improved NAVIGATE models. The database is accessible for further use by the scientific community, for example in the context of future assessment reports by the Intergovernmental Panel on Climate Change (IPCC).

APPLY – The apply section contains a set of descriptions of the methodologies developed in the project to ensure they are easily transferable. It includes new model components, algorithmic approaches, examples of model code, and input datasets. Each methodology is accompanied by an instruction for implementation. The methodologies address among others improvements for modelling decarbonisation in the transportation and land use sector, and for modelling inequality.

A.4 JOURNAL PUBLICATIONS

NAVIGATE partners published around 100 publications presenting results generated during the project, many of them in high impact scientific journals.

Many of the publications present results on decarbonisation in different sectors, such as the buildings, transport, industry and land use sectors. Others analyse climate change mitigation policy instruments like carbon pricing and technologies like Carbon Dioxide Removal options. In other papers, NAVIGATE partners analyse the impacts of climate change and certain policies on inequality, employment, and sustainable development. Since the project just started when the COVID-19 pandemic hit the world, some partners also analysed the impacts of COVID-19 and green recovery options in the context of the project. Another thematic cluster of publications describes IAM improvements achieved in NAVIGATE.

For some key publications also slide decks are available, shortly summarising the methodologies and findings from publications.

All publications can be found on the NAVIGATE website: www.navigate-h2020.eu/products-and-publications

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