NAVIGATE

Next generation of advanced integrated assessment modelling to support climate policy making

The EU’s 2040 target

Insights from the NAVIGATE project

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The NAVIGATE consortium

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Executive summary

The EU's 2040 target is an important milestone on the path to net zero greenhouse gas (GHG) emissions. The 2040 target needs to be identified such that it builds on the decarbonization trends under way to reach the 2030 targets and that it allows to reach net zero emissions by 2050. At the same time, EU policy makers need to make sure this transition is a "fair" one, keeping the societal and economic implications in view. This briefing note contains relevant insights from the NAVIGATE project informing a range of these aspects for a sound identification of the EU 2040 target.

Industry

To achieve the 1.5°C target, industrial emissions in Europe need to be reduced by 55% until 2040 (average across models) with a broad range of up to 80% in the strongest case, but only 25% in the weakest case. Seven Integrates Assessment Models (IAMs) were used to evaluate efficient global mitigation strategies with a focus on the industry sector. The emission reductions in all regions and sectors are endogenously determined, consistent with a uniform carbon price level, and do not necessarily meet emission targets discussed in the EU. The optimistic potentials result from a broad set of mitigation options including material demand reductions, recycling, electrification, biomass use as well as capture and storage of fuel and process CO_2 emissions. While many process innovations are based on mature technologies, additional R&D efforts are required to make key options such as high temperature heat by electricity and industry CCS ready for deployment.

Key risks to achieve the emission reductions are posed by the supply of low carbon energy (particularly, renewable electricity) and the flexibility of the demand for industrial products. These risks must be seen in the broader context of the transformational changes in all sectors, particularly the simultaneous decarbonization of electricity production and the expansion of electricity use. Moreover, the ramp-up of new production facilities can pose substantial risks. A broader analysis of global burden sharing shows that rigidities to reduce emissions in Europe and other developed economies tighten trade-offs with developing and emerging economies and increase the risk of failure to reach long-term climate targets.

Buildings

Sectoral policies to avoid, shift, and improve energy service demands can reduce direct CO_2 emissions in the European building sector by 59% (average across models) in 2040 compared to 2015 even in the absence of general climate policies like carbon pricing to drive the reduction of carbon intensive fuels. Sectoral policies include measures for floorspace reduction and conservative temperature setpoints (Avoid), electrification and fuel shifts (Shift), and technology improvements and energy efficiency (Improve). The investigated Avoid-Shift-Improve policies are highly complementary and entail the largest reduction potential when combined together.

The combination of sectoral policies and stringent climate policies is needed to achieve net-zero targets for the European building sector, corresponding to a reduction of direct CO_2 emissions of up to of 89% by 2040 compared to 2015. A variety of measures, including tighter building codes, subsidies and incentives, fuel mandates, and information campaigns can support the implementation of sectoral policies.

Road transport

Analyses show that direct electrification has the potential for a substantial decarbonization of road-based private passenger transportation, reaching 65% of the stock by 2040. Indirect electrification via H2 or synthetic fuels is in principle also viable, but would be slower and inefficient due to the higher cost and energy demand. In parallel, phase-out policies can substantially accelerate and deepen the transition in the road transport segment, while a carbon tax alone has a smaller impact on consumer choices and emissions. However, carbon tax and phase-out policies are complementary, as phase-out policies alone accelerate the demand-side transition but are unable to incentivize the decarbonization of energy supply.

Methane emissions

Achieving the Global Methane Pledge (GMP), aimed at reaching 30% reduction of methane emissions in 2030 compared to 2020, would require a maximum, concerted global effort. In Europe in particular, technical (end-of-pipe) reduction measures will likely not be enough to reach the GMP. Lower emitting activities, particularly lower animal-based meat and dairy demand, will likely be needed to reach the target. CH_4 mitigation is increasingly more difficult over time, as the relative share of agriculture emissions increases. In 2040, EU methane emissions in the most optimal mitigation case (green growth assumptions, 1.5-degree target and human diet change) are projected to be more than halved (-52%) compared to 2020. If diet change is excluded, this is found to be 41%. In both scenarios, this would require maximum GHG pricing for all methane (and other non-CO_2) emissions. The EU27 would roughly require 0.3 - 0.7 Gt CO_2 Carbon Dioxide Removal (CDR) to compensate for remaining non-CO_2 emissions in stringent mitigation scenarios, depending on the level of methane mitigation, highlighting its important role.

Targeted transfers of carbon revenues

Without transfers, carbon pricing would disproportionally affect EU low-income households, around 2-3 times more than households with high income. This effect is due to significant differences in the tax burden across countries.

Negative social impacts to low-income households can be alleviated with appropriate use of ETS revenues. Well-designed strategies are required to achieve progressive outcomes of ambitious climate policies by considering appropriate compensation schemes, either by increasing household income through lump-sum payments ("climate dividend") or reducing other (direct or indirect) taxes, or through the social security system. In this way, climate policy becomes an inequality-reducing and growth-supporting policy package and public support can be enhanced as well.

Recycling of carbon revenues

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.

Despite limited GDP losses, the transition is expected to create new jobs in the EU, especially if carbon revenues are used to reduce labour costs. The analysis shows that there is an EU-wide again of 700 thousand jobs in 2030 which further increases to 1.3-1.4 million jobs in 2040 and 2050.

By 2050, Europe's direct energy jobs are likely to increase substantially – from around 1.3 million to over two million. 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. On the other hand, around 300 thousand jobs are lost notably in the coal and oil sectors while in the NDC scenario this loss amounts to only 100 thousand jobs.

Climate impacts and net benefits of mitigating climate change

Climate impacts are already felt today and are expected to increase. In general, **negative impacts tend to correlate, with warmer regions becoming climate hotspots.**

Increasing climate mitigation ambition, and action, can greatly reduce climate impacts. Therefore, in contributing to the global implementation of the Paris Agreement, the EU 2040 target can provide significant net-benefits, avoiding climate impacts regionally and globally.

1. Introduction

The EU's 2040 target is an important milestone on the path to net zero greenhouse gas (GHG) emissions. It is mid-way between the 2030 target of reducing the EU's GHG emissions by 55% from 1990 levels and the goal to reach net zero GHG emissions by 2050. It will be the reference point for tightening the targets in the EU regulatory framework towards 2040, including ETS-1, ETS-2, ESR, renewable energy and energy efficiency targets, and targets for land-use and agricultural emissions and carbon dioxide removal (CDR). It is therefore central for accelerating the rapid replacement of emissions-intensive with emissions-neutral activities during the 2030-2040 period. It will also form the basis for the submission of the EU's NDCs for the years 2035 and 2040 under the Paris Agreement.

An informed identification of the EU 2040 target requires much more than just identifying a headline GHG emission reduction number for 2040. The 2040 target needs to be chosen such that it builds on and accelerates the decarbonization trends in the various sectors that are currently set in motion with a view to the 2030 targets. **It also needs to be chosen such that it allows to complete the final act of replacing or compensating the residual emissions in hard to abate sectors like heavy industry, aviation and shipping, and agriculture in the remaining 10 years after 2040.** This will require by 2040 a fully decarbonized electricity sector, a high and increasing level of electrification in the energy end use sectors, a strongly reduced and further reducing emissions intensity in the agricultural sector, and an established and scalable capacity for permanent CDR. Hence the EU 2040 target should be formulated based on a detailed analysis of sectoral emissions reductions trends and targets and the required interplay between sectors to instigate the most effective and rapid way of reducing overall GHG emissions. This includes not only an analysis of CO_2 emission reduction potentials by sector including AFOLU sector, but also reductions of other GHG emissions, particularly methane (CH_4) and nitrous oxide (N_2O).

At the same time, the identification of the EU 2040 target needs to keep in view the societal and economic implications of a rapid replacement of emissions intensive with zero emissions activities and the associated changes to labour markets, household incomes, and consumer behaviour during the 2030-2040 period. It is likely during this period that the deep changes to the way we use energy and land will be most acutely felt by EU citizens. Hence there needs to be a fair transition in order to successfully implement the EU Green Deal and follow through with a rapid drop in emissions between 2030 and 2040 leaving no one behind.

The NAVIGATE project funded by the EU Horizon 2020 research programme is ideally suited to inform a range of these underlying aspects for a sound identification of the EU 2040 target. The project's main research goal is to develop the **N**ext generation of **A**d**V**anced **I**nte**G**rated **A**ssessment modelling to support clima**TE** policy making (NAVIGATE). It is bringing together some of the leading Integrated assessment modelling teams from Europe with recognized domain experts on transport, industry, buildings, agriculture, lifestyles, industrial metabolism, macro- and welfare economics, climate impacts, and sustainable development. 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 offer valuable information to support the design and evaluation of emission reduction pathways, associated timetables, milestones and targets and related climate policy needs. The NAVIGATE project is advancing IAMs capability in two directions. First, it is improving the representation of transformative structural and technological change in the economy and different sectors such as industry and land-use, and is analysing changes in lifestyle and consumption and their implications. Secondly, it is investigating the distributional implications of climate policies, the impacts of climate change and the benefits of mitigation and adaptation strategies in terms of avoided damages and reduced inequality. Another main goal is to improve transparency, legitimacy and usability of IAM results for users such as policy makers, businesses, civil society organizations, as well as experts from related disciplines interested in using IAM results for climate policy analysis. The project is now in the final year of a four-year research programme and is currently exploring new insights that the advanced modelling frameworks can offer international climate policy processes and EU climate policy discussions with regard to the implementation of the Green Deal.

In the following, we present relevant insights from the NAVIGATE project for a sound, science-based identification of the EU 2040 target. The briefing note begins with a detailed look into individual sectors: industry, buildings, transport, and an investigation of methane emission reduction potentials in the EU. This is followed by a collection of insights on the economic implications of the net zero transition in the EU with regard to a fair transition including the distributional impacts of carbon pricing, and the scope for redistributive measures and revenue recycling to ensure a fair transition. It also includes insights on the benefits of mitigation and residual climate impacts for the EU and beyond.[1]

[1] Many of the results are still preliminary and require some further analysis before being submitted to peer-reviewed journals. Publications of final results and a final synthesis report are scheduled for the fourth quarter of 2023.

2. Sector decarbonisation strategies and methane emissions reductions

2.1. Decarbonisation of the industry sector

The industrial CO_2 emissions continuously decreased since 1990 with two remarkable steps after the end of the centrally planned economies in Eastern European countries and the impacts of the global financial crisis 2007. Industrial CO_2 emissions over the decade 2010-2020 only saw a moderate decline.

The industry sector covers a highly diverse and heterogeneous set of input-output relationships that are tightly integrated with the energy sector and the overall economy. The demands for input factors such as energy carriers but also residual emissions compete with other sectors. The CO_2 emissions from the industry sector have been frequently portrayed as hard-to-abate, which would require emissions reductions or removals in the other sectors to achieve a total quantity target in a cost-efficient manner (Buck et al., 2023; Daioglou et al., 2014; Luderer et al., 2018, Lee and Calvin 2023).

We use seven global IAMs to derive global scenarios for CO_2 emissions. All IAMs feature improved industry sector representations and up-dated assumptions on demands for industrial products and commodities, incl. recycling and circularity. The IAMs are run with global carbon budgets to keep global mean temperature below 1.5°C and well-below 2°C compared with pre-industrial levels. The policy is a comprehensive carbon pricing system that covers emissions from all countries, sectors and sources and charges every ton of CO_2 at a unique price. The industry sector is divided into the sub-sectors chemicals, iron & steel, non-metallic minerals (dominated by cement) and the aggregate other sector that also includes manufacturing and construction. Each model solves the allocation of emissions to the European industry sector endogenously.

Assuming that National Policies are frozen at the level they are implemented (NPi) the industrial CO_2 emissions decrease from 2020 to 2040 by 13% (average across models). Figure 1 panel a) shows a large variation. Models at the lower end of the emission range assume wide spread electrification in the industry sector even without additional climate policies (POLES). Compared with the publications of the International Energy Agency (IEA) our model average lies between the World Energy Outlook and the Energy Technology Perspectives. A deeper look into the sub-sectors shows that on average all the emissions are expected to decrease 8-21% (Figure 1 panel b). Also, at this level the ranges across models are substantial, which indicates that emissions might decrease due to techno-economic baseline assumptions and overall market developments, but could also increase. E.g. the REMIND model projects strongly increasing CO_2 emissions in the iron & steel and the non-metallic minerals sector due to a cheap coal supply that becomes available due to rapid expansion of renewable energy in the electricity sector.

To achieve the well below-2°C scenario globally, the 2040 emission reduction in the European industry sector compared with 2020 would need to be 34% and if the target is set to keep global warming below 1.5°C it would need to be 55%. The sub-sector reductions vary by a larger extent in the wb-2°C case (27-47%) as in the 1.5°C case (54-60%). Again, there are large variations across models. The NAVIGATE partners investigated the results and the uncertainties in-depth and identified major risks and opportunities for the necessary transformation. For the assessment of mitigation potentials, it is crucial to consider the full range and relate these ranges to differences in models. The most important conclusions are as follows:

1. Broad deployment of all mitigation options are success factors for deep and rapid emission reductions in all industry sub-sectors.
2. Reductions of demand for energy intensive products are feasible, but require changes in regulations of, for example, the building sector. Not all demand reductions can be triggered by pure pricing signals.

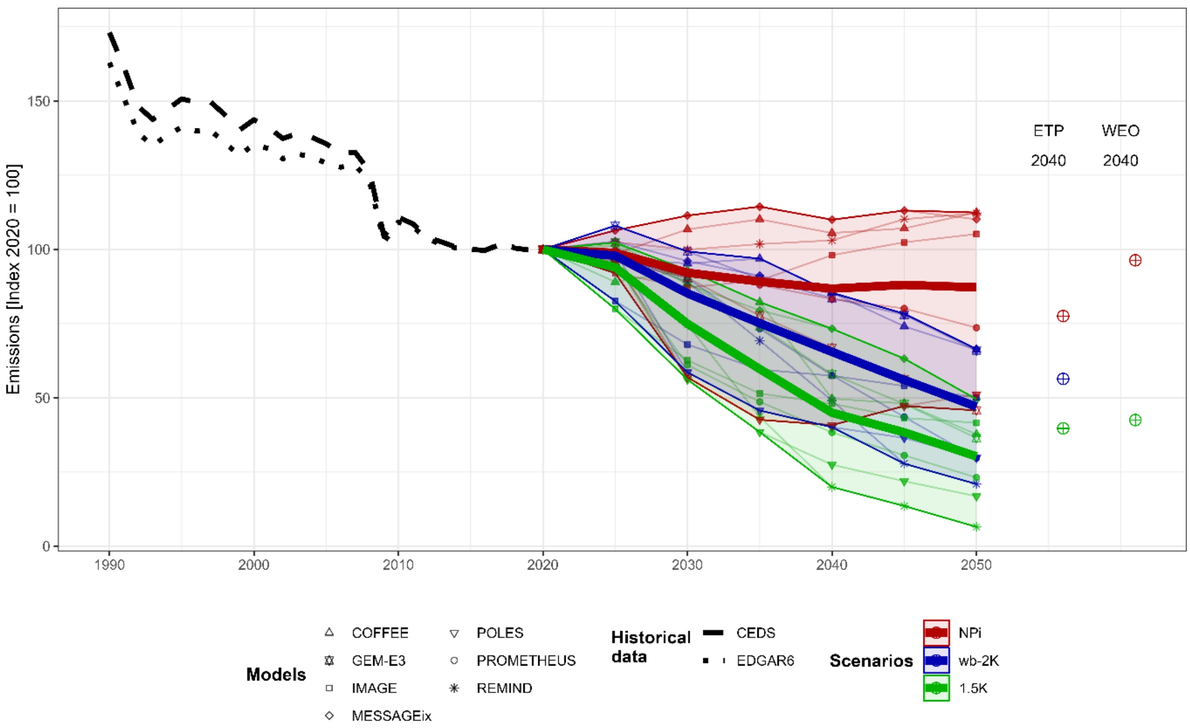
3. Residual fossil fuel use is mostly relevant in the chemicals sector as chemical feedstock demands are difficult to substitute by 2040. Biomass can serve as an alternative feedstock, whereas synfuels derived from hydrogen and capture carbon are playing a minor role.
4. In the iron & steel sector the combination of increased recycling and electric arc furnaces are crucial. Scrap steel production is a factor four more energy efficient than primary iron production. However, increasing the share of steel recycling requires improved regulations to avoid impurities such as cooper and improved end-of-life collection systems. Fossil CCS and hydrogen-based iron production are also deployed and can serve as a fallback option. The technology readiness levels (TRL) in the steel sector are relatively high and commercialization of key technologies can be expected by 2030. The use of biomass plays a minor role at best.
5. The non-metallic minerals sector is dominated by cement production. Also, here: demand reductions are crucial, that can be partially achieved by changes in the clinker ratio and innovations of cement processing (such as CO_2 injection to improve hardening). For the heat source a switch to the proven practice of biomass use or the use of electricity and also hydrogen can bring down CO_2 emissions. The use of CCS is crucial to reduce the process emissions from the calcination process. This can be added to any primary energy carrier that supplies the process heat. Cement kilns with electricity-based process require additional R&D effort, but would minimize the overall amount of CO_2 to be treated, if electricity is not combustion based, and it requires only small additional effort to capture the process related CO_2.
6. In the other industry sectors the electrification of process heat is crucial to reduce the residual fossil fuel use. Also, biomass and hydrogen can be used as alternatives for heat production, whereas the relatively smaller scales of production facilities reduce the feasibility of CCS. The increased electrification of process heat also requires efficiency improvements in existing facilities, to overcome temporarily high electricity prices.
7. CCS in the industry sector can reach up to 300 Mt CO_2/yr by 2040. This is the extreme case when the demand side is unresponsive and the decarbonization of industrial energy supply and the electrification of industrial use is too inflexible. Besides this extreme case the application of CCS in the chemical and the cement sector is key to reduce the industrial CO_2 emissions to very low levels. Carbon removals in the industry sector are possible, but are not found to play a notable role by 2040.

The modeling results also point to potential barriers for the transformational changes in the industry sector. The first risk relates to the demand side that might be less responsive to policy interventions and, consequently, more energy, feedstock and process emissions would be realized. The same applies to the realization of increased recycling rates. Since changes in regulations and practices take time early adjustments need to be prioritized. Second, the energy sector needs to decarbonize the supply of electricity and at the same time it needs to fulfil increasing demands from the industry and also the transport, residential and services sector. During the period of this twin challenge the supply of other electricity based energy carriers (hydrogen and synfuels) is relatively limited and therefore their prices are also relatively high. Therefore, the deep and rapid decarbonization of the industry sector crucially depends on growth of low-carbon electricity supply. Third, models with relatively high CO_2 emissions feature pessimistic assumptions about the key mitigation options (such as demand reductions, CCS, electrification potentials, decarbonization of energy supply, ...) and/or rigidities to ramp-up the deployment of such mitigation options. Finally, the credible signal of increasing CO_2 prices is fundamental for redirecting investments into low-carbon technologies. Models that assume investments to be based on current carbon prices misallocate capital by deriving investments that turn into stranded assets. Thus, the major risks for the decarbonization are related to the transition and the transformation speed of the energy sector and its interaction with the energy and the demand sectors.

If the European industry sector, along with other OECD countries, faces slow transformation speed and limited mitigation potentials, the industry sector emissions would turn out to "hard-to-abate". In that case the ambitious 1.5°C target would turn out to be very stringent leading to very high CO_2 prices (up to 330 US$ per ton of CO_2 in 2030), which increases total mitigation costs and therefore increases the trade-off between economic costs and the long-term climate target. Also, the European industry sector would demand a relatively high share of the global carbon budget, which requires stronger emission reduction in other countries or sectors or more carbon removals are required. Therefore, the speed of emission reduction in developed countries, such as the European industry sector, is a crucial precondition to find fair agreements with developing and emerging economies based on the entitlement of equal per-capita emissions as the long-term target. It is worth to recall that the policy assumption of a unique carbon price across countries and sectors leads to relatively high-income losses in developing countries that either call for huge financial transfers or regional differentiation of carbon prices between countries (Bauer et al., 2020).

Finally, it should be noted that the accounting of CO_2 emissions from the chemical sector is modelled differently than it is represented in emission statistics. In most models the use of fossil fuels as chemical feedstock leads to oxidization of all embodied carbon that then enters the atmosphere. In emission statistics only part of the carbon is oxidized and the remainder is stored in long-lived products. Thus, the emissions in the models are biased upwards.

(a)



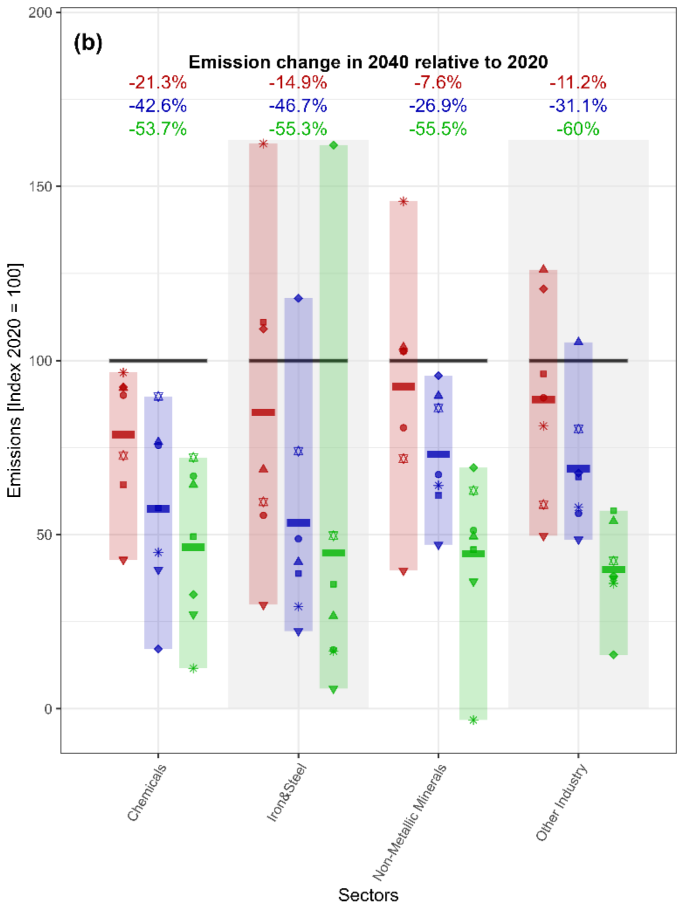


Figure 1 Emissions and reductions in the European industry sector. Panel (a) shows the total industry sector emissions over time until 2050. The colored patches show the ranges covered by the seven IAM models for the different scenarios. The IEA results are shown for the year 2040. Panel (b) show the emission reductions per sub-sector in 2040 relative to 2020. All results indexed to the models' original 2020 emissions (incl. IEA scenarios).

2.2. Mitigation strategies for the European building sector

Accounting for 36% of the energy-related greenhouse gas (GHG) emissions in the European Union (EU) (European Climate Foundation, 2022), buildings play a pivotal role in climate change mitigation. To achieve the ambitious EU climate targets (European Parliament and the Council, 2021), the building sector will need to reduce its GHG emissions by 60% by 2030 and fully decarbonize by 2050 (European Climate Foundation, 2022; European Commission, 2020). Demand-side policies (Creutzig et al., 2022) can make the climate transition faster and easier by rapid and deep adoption of mitigation strategies to avoid, shift or improve energy demand (Avoid-Shift-Improve framework).

The NAVIGATE project brought methodological advancements for an improved representation of the building sector in IAMs, commonly used to develop global and European climate change mitigation scenarios. Here, we present the results from a multi-model study, exploring the CO_2 emission reduction potential for the building sector to support policy decisions towards carbon neutrality and intermediate targets to be set for 2040 (European Parliament and the Council, 2021).

We assess the effect of implementing a broad set of sectoral demand-side policies for buildings:

- activity reduction and shifts (Avoid), including reduction in floorspace, shift to multi-family houses, change in heating and cooling setpoint temperatures.
- electrification and fuel shifts (Shift), including shift to electricity, on-site renewable sources, and phase-out of non-clean fuels.

- technology improvements and energy efficiency (Improve), including improved insulation and heating and cooling systems in new construction and renovation, increased renovation rate.
- and a combination of all interventions above (All).

We combine the sectoral policies above with two cross-sectoral policy scenarios: a continuation of current national policies with no stringent climate policies (Current national policies); and stringent climate policies consistent with the 1.5°C target (Stringent climate policies), and compare results to a Reference case with continuation of current sectoral policies. The scenarios have been implemented in five IAMs including detailed representation of the building sector: Imaclim-R (CIRED/SMASH, 2016), IMAGE (Daioglou et al., 2022), MESSAGEix (Mastrucci et al., 2021), PROMETHEUS (E3-Modelling, 2018), and REMIND (Baumstark et al., 2021).

The results under current national policies (Figure 2, top panels) show that Avoid and Improve policies could reduce direct CO_2 emissions[2] of European buildings in 2040 by respectively 30% and 38% (average across models), compared to 2015, going significantly beyond the 22% reductions in the Reference scenario. Combining all sectoral policies (All) provides the largest reduction of 59% of direct CO_2 emissions by 2040 (average across models). Similar trends can be observed for 2050, with the largest reduction in direct CO_2 emissions reaching 69% (average across models) when implementing all sectoral policies.

Combining sectoral policies with stringent climate policies (Figure 2, bottom panels) results in more drastic CO_2 emission reductions, due to simultaneous decrease in energy demand and decarbonization of electricity and heat supply systems. The combination of all sectoral policies (All) and stringent climate policies drives average reductions in direct CO_2 emissions of 74% in 2040 and 90% in 2050 compared to 2015. The residual CO_2 emissions are mostly due to residual fossil fuel use, mostly in space and water heating and cooking, requiring additional efforts for full decarbonization.

The 2050 net-zero GHG target of the EU under stringent climate policies could only be met by one of the selected models. The reduction of direct emissions in the building sector for this model ranges between 66% (Avoid) and 89% (All) for 2040, and between 93% (Avoid) and 99% (All) for 2050 compared to 2015 for the stringent climate policies scenarios. Results from the other models confirm that similar level of reductions are easier to achieve with a combination of all sectoral policies and stringent climate policies.

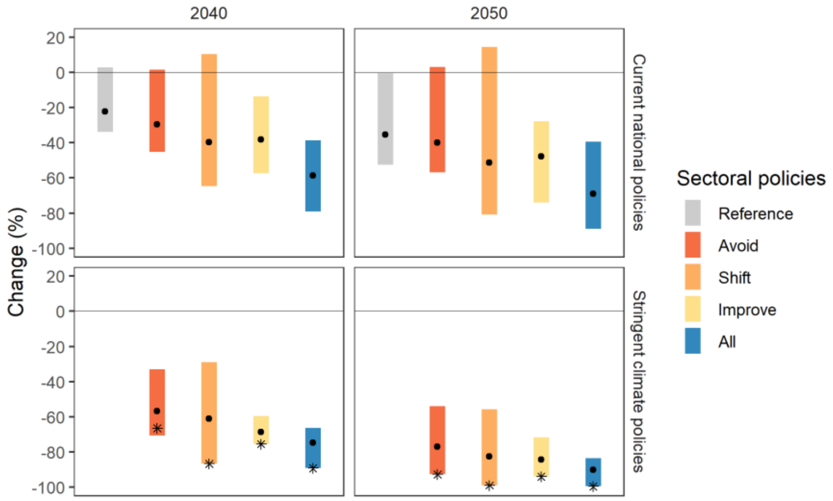


Figure 2 Change in direct CO_2 emissions in 2040 and 2050 compared to 2015 for the European residential and commercial sector under different scenarios including a set of sectoral policies and climate change mitigation policies. Coloured bars indicate the ranges covered by available model results, dots indicate the average, stars indicate the scenarios reaching net-zero GHG emission targets for the European Union.

[2] Emissions from electricity, hydrogen or biofuels are not included.

The results of this study show that a combination of a broad set of sectoral and cross-sectoral policies is needed for the building sector to reach the ambitious climate targets set by the EU. The investigated Avoid-Shift-Improve policies are highly complementary and entail the largest reduction potential when combined together. Different policy instruments can support the implementation of the investigated sectoral policies. Tighter building codes, regulations and subsidy programs are commonly implemented for energy efficiency improvements. Speeding up the rates of deep renovation and electrification is key for existing buildings, but requires addressing both financial, structural, and other barriers. While not yet well investigated, we show that reduction in activity levels in buildings have significant mitigation potential. This would entail changes in lifestyles and behaviours, potentially posing implementation challenges due to a series of barriers, such as individual preferences. These could be addressed by nudges, information policies and other consumer policies, but also touch the dimension of land use and urban planning.

2.3. Decarbonization of road transport

The decarbonization of road transport is a central challenge for the transition to net zero emissions. The topic is especially relevant in Europe, where an ambitious phase-out of emitting vehicles is under discussion as road decarbonization is prominently addressed in the EU's Fit for 55 package. There is, however, considerable debate on suitable instruments for reaching emissions neutral road transportation. A range of alternative technologies could prove to be suitable for achieving the sector's decarbonization, namely battery electric vehicles, fuel-cell electric vehicles and e-fuels. In parallel, the relative roles of carbon pricing and other sector-specific policies is being discussed by policymakers. Carbon pricing is generally regarded as the most effective instrument to drive the power sector decarbonization, and the transition to a carbon-free power sector is necessary to ensure an effective decarbonization of road transport. However, concerning road transport it is not clear if carbon taxation per se could be an effective tool to drive a deep transition given the sector-specific characteristics that slow down the uptake of the decarbonization options.

To contribute to this debate, we offer a timely analysis of road transport decarbonization pathways in Europe until 2050. We first focus on the potential of electrification for light duty vehicles (LDVs) analysing a range of possible decarbonization pathways, comparing the potential of direct (namely, electrification via battery vehicles (BEVs)) and indirect (namely, fuel-cell EV and e-fuels) electrification. We then broaden the analysis to the whole road sector, analysing the decarbonization potential of alternative policy packages, namely carbon taxation and internal combustion engine phase-out policies for light and heavy-duty road, both separately and combined.

For this analysis, we use the Integrated Assessment Model REMIND[3] model soft-linked with the transport-specific EDGE-T[4] model (Baumstark et al., 2021; Rottoli, Dirnaichner, Kyle, et al., 2021). Together, the models projects detailed transport trajectories within a macro-economic framework that features the competition for scarce resources with the other energy intensive demand sectors, ensuring full consistency between energy supply quantities and prices, and demand side choices in the transport sector. REMIND determines the absolute demand for transport as a result of the welfare optimization process, while EDGE-T splits in detail the demand composition also considering non-monetary aspects of mobility consumption.

We find that direct electrification has the potential for a substantial decarbonization of road-based private passenger transportation, allowing BEVs in the LDVs fleet to achieve around 65% of the stock

[3] The REMIND model is an open source IAM developed and maintained at the Potsdam Institute for Climate Impact Research (PIK). REMIND is a multiregional model featuring a detailed representation of the energy sector, able to analyse a broad range of technical and socio-political transformations in the time range 2005-2100.

[4] EDGE-T is a transport bottom-up detailed model featuring competition across different powertrain options, vehicle types and transport modes for both passenger and freight sectors.

by 2040. In the same year, the tailpipe emission in the direct electrification scenario are around 30% of the corresponding value in the conservative benchmark (Rottoli, Dirnaichner, Pietzcker, et al., 2021). Indirect electrification via H_2 or synthetic fuels is in principle also viable, but would be slower due to lower maturity of the required technologies and their higher cost. On top of the difference in potential market share associated with the electrification alternatives, the pathways differ significantly concerning the required primary energy demand, in terms of absolute value, composition and emissions implications. Indirect electrification proves to be significantly more energy intensive, as additional steps and energy losses are necessary to provide the energy for a passenger-km. Lastly, a timely deployment of the recharging or the H_2 refuelling infrastructure is a prerequisite for the adoption of zero-emission vehicles: consumers perceive a lag in the infrastructure build up as a very strong deterrent to the uptake of alternative vehicles as it poses additional non-monetary cost barriers. The monetary and non-monetary cost mark-ups result in a delayed or hindered transition away from internal combustion engine vehicles (ICEs) and towards zero emission vehicles (ZEVs), and call for strong and dedicated phase-out policies disincentivizing ICE sales. The crucial importance of the combined effect of monetary and non-monetary costs is also reflected in the policy package required to achieve deep road transport decarbonization. The introduction of a carbon tax together with phase out policies for ICEs proves to be complementary for achieving stringent mitigation targets: only relying on phase-out policies would lead to relevant indirect emissions from electricity generation for the transition period 2030-2045, while only relying on a carbon price would mean a slow reduction of direct emissions due to slow electrification. Only the combination of both approaches leads to a fast transition to ZEVs fuelled by low-carbon electricity (Rottoli et al., under review).

2.4. EU efforts to achieve the Global Methane Pledge

At the COP 26 in Glasgow in 2021, the European Commission and the United States launched the Global Methane Pledge (GMP) (European Commission & United States of America, 2021). This pledge states that contributing nations should achieve a 30% reduction in global methane emissions in 2030 compared to the 2020 level. 150 nations have joined the GMP, emitting around 55% of global methane emissions (Crippa et al., 2021). Notably, China and Russia, the largest emitters, have not joined. However, the GMP is framed as a global goal, implying that participating countries must go beyond a 30% reduction. Mitigation actions as pledged in the nationally determined contributions (NDCs) could achieve the global GMP goal, but only if implemented to their fullest possible extent and mainly dedicated to methane mitigation (Malley et al., 2023). This also indicates a large overlap between the GMP and NDCs as well as net-zero emission goals. It is highly likely that countries achieving deep methane reductions will use that to achieve their NDC goals as well. However, this does not mean that the GMP does not contribute to successful climate policy. Agreements like these make climate policy more concrete, allow for increasing ambition in the future, and enhance chances of policy implementation.

The analysis in this policy brief assesses the implications of uncertainty in non-CO_2 greenhouse gas (GHG) mitigation on the feasibility of the Global Methane Pledge. The analysis relies on the NAVIGATE project study (Harmsen et al., 2023) aimed at understanding uncertainty in non-CO_2 greenhouse gas mitigation and its implications for the feasibility of global climate policy. In this study, we have developed pessimistic, default, and optimistic marginal abatement cost (MAC) curves for non-CO_2 mitigation potentials. These curves represent the lower, middle, and upper bounds of the uncertainty range in relative emission reduction and cover all major emitting sectors, including agriculture, industry, waste, and fossil fuel production. The MAC curves have been used in a scenario study, performed with the IMAGE integrated assessment framework. IMAGE is a model describing possible future changes in the human and earth system and their interaction (Stehfest et al., 2014; Van Vuuren et al., 2021). The scenarios are based on the SSP2 (middle-of-the-road) and SSP1 (sustainability-focused) pathways, including variations in:

- 2100 radiative forcing target (baseline, 2.6 W/m², 1.9 W/m², corresponding with a 2-degree and 1.5-degree target, respectively)
- Non-CO_2 mitigation potentials (pessimistic, default, optimistic),
- Diet change (with, without)

In the Diet scenarios, we implemented a global shift towards a low meat human diet, i.e., a shift towards the so-called Willett or EAT-Lancet diet that has been developed as part of health recommendations (Fuss et al., 2018). [5]

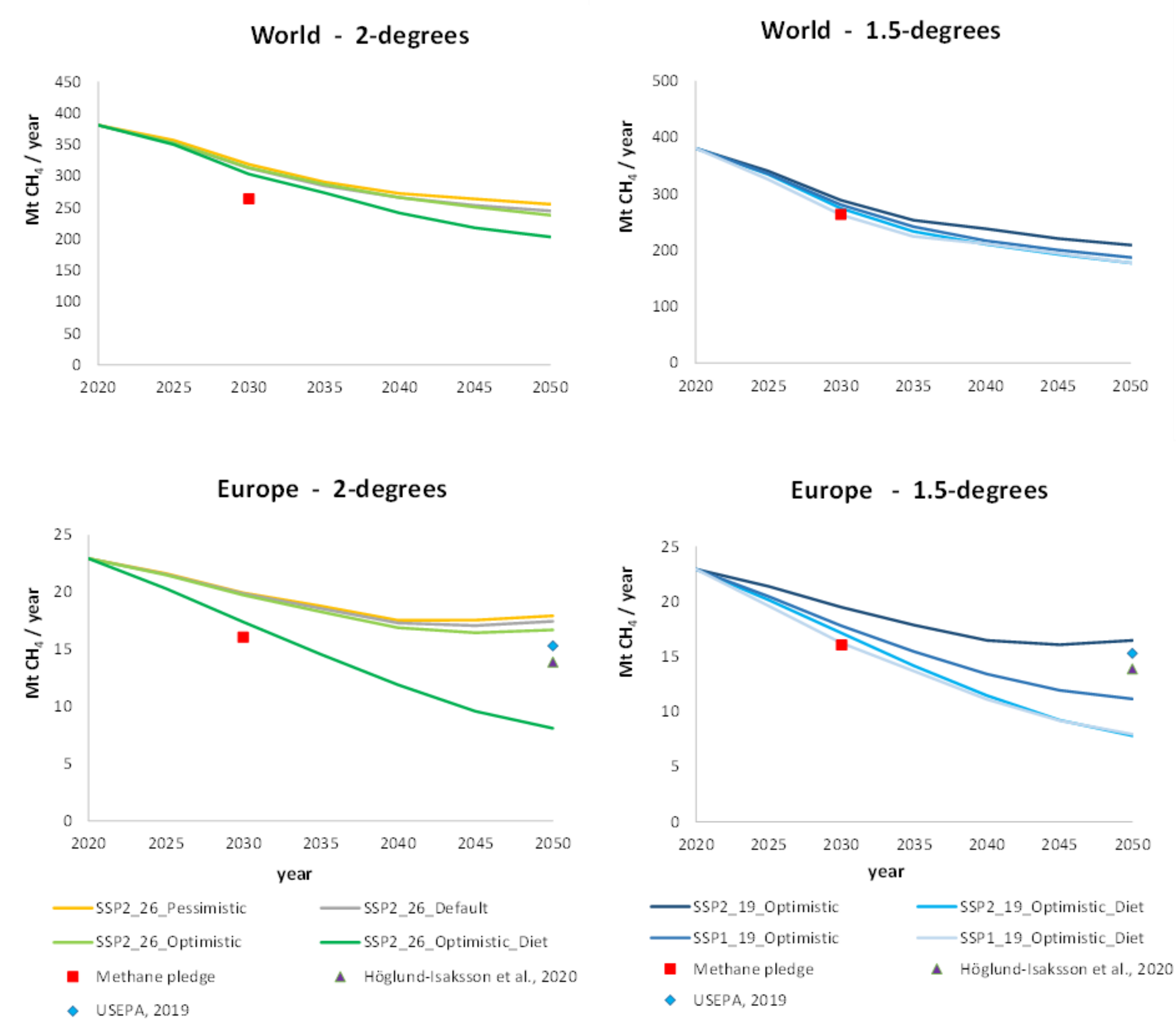


Figure 3 Total CH4 emissions. 2-degree scenarios (left) and 1.5-degree scenarios (right) compared to the methane pledge. Top: global results, Bottom: Europe (all European countries, combination of the IMAGE regions West- and Central Europe). In 2019, anthropogenic CH4 emissions in EU27 + UK GHG are estimated to amount to 17.1 Mt/year representing 10.5 % of the emissions in CO_2 eq. [12]). The GMP minimum emission reduction of 30% in 2030 is indicated by the red square. Höglund-Isaksson et al., 2020 and USEPA, 2019 are MAC-based studies used as a benchmark for Europe.[6]

Figure 3 shows the global methane emission pathways of the developed mitigation scenarios compared to the GMP. Both globally (top panels) and for Europe (bottom panels), the GMP is not reached in both of the 2-degree scenarios (left panels), even under optimistic methane mitigation assumptions combined with more plant-based human diets. Based on these results, the GMP can be

[5] In these scenarios, we also limit annual crop-based bio-energy use to a more sustainable level of 60 EJ. Furthermore, carbon-price-driven afforestation is excluded to avoid competition with food supply and biodiversity, and only afforestation on abandoned crop lands and grasslands is permitted.

[6] Data has been scaled to IMAGE regions. These studies only assess reductions in emission intensities, not in activities. Therefore, they are comparable and relatively in line with the SSP2 scenarios excluding diet changes, showing slightly more end-of-pipe reduction potential for Europe in 2050.

considered an ambitious goal, given the short time horizon. Achieving it would require a maximum, concerted global effort. Only under ideal circumstances, in *SSP1_19_Optimistic_Diet* with SSP1 (green growth) assumptions, a 1.5-degree target, diet change and full global participation, is the GMP just reached both globally and in Europe. In Europe in particular, technical (end-of-pipe) reduction measures will likely not be enough to reach a 30% reduction of methane emissions in 2030. Lower emitting activities, particularly lower animal-based meat and dairy demand, will likely be needed to reach the target, indicated by the substantially lower emissions in both the SSP1-based and Diet scenarios. CH_4 mitigation is increasingly more difficult over time, as the relative share of agriculture in EU27 + UK CH_4 emissions increases (51% between 2010 and 2019, compared to 44% in the 2000-2009 period) and will further increase under stringent climate policy (Petrescu et al., 2023). Höglund-Isaksson et al. (2020) project a global relative reduction potential of 54% below the baseline emissions in 2050. However, the abatement potential for agricultural sources is estimated at 21% below the baseline in 2050 (Höglund-Isaksson et al., 2020).

The diet (and SSP1-based) scenarios show that mitigation potentials are projected to be much higher when meat/dairy demand is lowered. In addition, for Europe, there are relatively low livestock mitigation potentials in the MACs, as emission factors are already relatively low compared to the rest of the world. However, in all scenarios (i.e., also under pessimistic assumptions), mid-century methane reductions are found to be larger than 30% globally, thus allowing for future increases in the ambition level of the GMP.

In 2040, methane emissions in the most optimal mitigation case (SSP1 assumptions, 1.5-degree target, including diet change) are projected to be more than halved (-52%) compared to 2020. If diet change is excluded, this is found to be 41%. In both scenarios, this would require maximum GHG pricing for all methane emissions.

In the most optimal scenario, residual yearly methane emissions in Europe in 2050 amount to 8 Mt (or 6.6 Mt in EU27), i.e., a 65% reduction compared to 2020. In order to reach and maintain net-zero emissions in 2050, the EU27 would roughly require a minimum of 0.3 Gt CO_2 Carbon Dioxide Removal (CDR) to compensate for the minimum level of remaining non-CO_2 emissions[7]. In the most pessimistic methane mitigation case this would be 0.7 Gt CDR, highlighting the advantage of maximizing methane mitigation.

[7] Assuming the AR6 100-year global warming potential and a two-thirds contribution of methane to total non-CO_2 induced warming.

3. Economic and fairness implications of the transition to net zero

Carbon pricing is a powerful instrument to bring about the necessary changes for the low-carbon transition, as it provides an important incentive to invest in low- and zero-carbon technologies and infrastructure and encourages compliance with emission reduction targets. An increasing number of jurisdictions have adopted emissions trading schemes (ETS) to enforce carbon pricing. The European Union ETS is the world's biggest and oldest carbon market. It is generating significant revenues (around USD 43 billion in 2022 (International Carbon Action Partnership, 2023)) which will further increase with further rises in the price of permits and the extension of carbon pricing to additional sectors (transport & buildings; ETS-2). Many governments channel these resources back into further climate action, subsidizing emerging technologies, or supporting lower-income households and protecting the society from high energy prices and their fluctuations.

Against this backdrop, it is important to study the socio-economic and distributional implications of carbon pricing and other climate policies to ensure a fair transition towards net zero GHG emissions. The increased ambition of climate policies in the EU will result in large-scale economic restructuring with potential regressive societal and distributional impacts. Studies have shown that high carbon pricing disproportionately affects disadvantaged population groups, which face high energy expenditures as a share of their income combined with difficulties in accessing low-cost funding. The imposition of additional taxes on energy products would increase the risk of energy poverty and other challenges facing low-income households. Ambitious climate policies also affect employment and labour income in European countries, showing a limited reduction in low-skilled labour demand combined with an increase in high-skilled jobs required for the low-carbon transition (Fragkos et al., 2021). This raises negative distributional impacts through the labour market leading to higher inequality levels.

To counteract these adverse distributional impacts, the EU is introducing a series of measures including the earmarking of carbon price revenues for a Social Climate Fund. There is an ongoing debate about the most effective and equitable way of using these revenues, with large implications for the EU's 2040 target. NAVIGATE has conducted several studies on the distributional and growth impacts of carbon revenue recycling whose key insights are summarized in the following subsections.

3.1. Targeted transfers to mitigate the distributional impacts of carbon pricing

The insights presented in this section are based on a study with the GEM-E3-FIT model which was further expanded to represent ten income classes in EU Member States to consistently capture the potential distributional impacts of European energy and climate policies towards the net-zero transition.

Without recycling the carbon price revenue, the distributional impact at the member state level is often neutral or even progressive. The tax burden is approximately proportional to household expenditure. However, at the EU level, the distributional impact is regressive. The carbon price disproportionately affects households with lower income. This effect is due to significant differences in the tax burden across countries. For example, households in Poland, Romania, or Bulgaria emit, on average and relative to their income, 2-3 times more than households in Germany, France, or Spain and constitute the largest share of the lowest EU deciles. Based on an Input-Output model, we implemented a 25EUR/tCO_2 across all sectors, and the analysis considers both direct and indirect carbon emissions, imported and locally produced. Figure 4 illustrates the initial distributional impact at the EU level for four scenarios: without redistribution (purple), with national equal-per-capita transfers (red), with EU equal-per-capita transfers (green), and targeted transfers (blue). Households are grouped into deciles based on total expenditures, with the poorest 10% of EU households in decile 1.

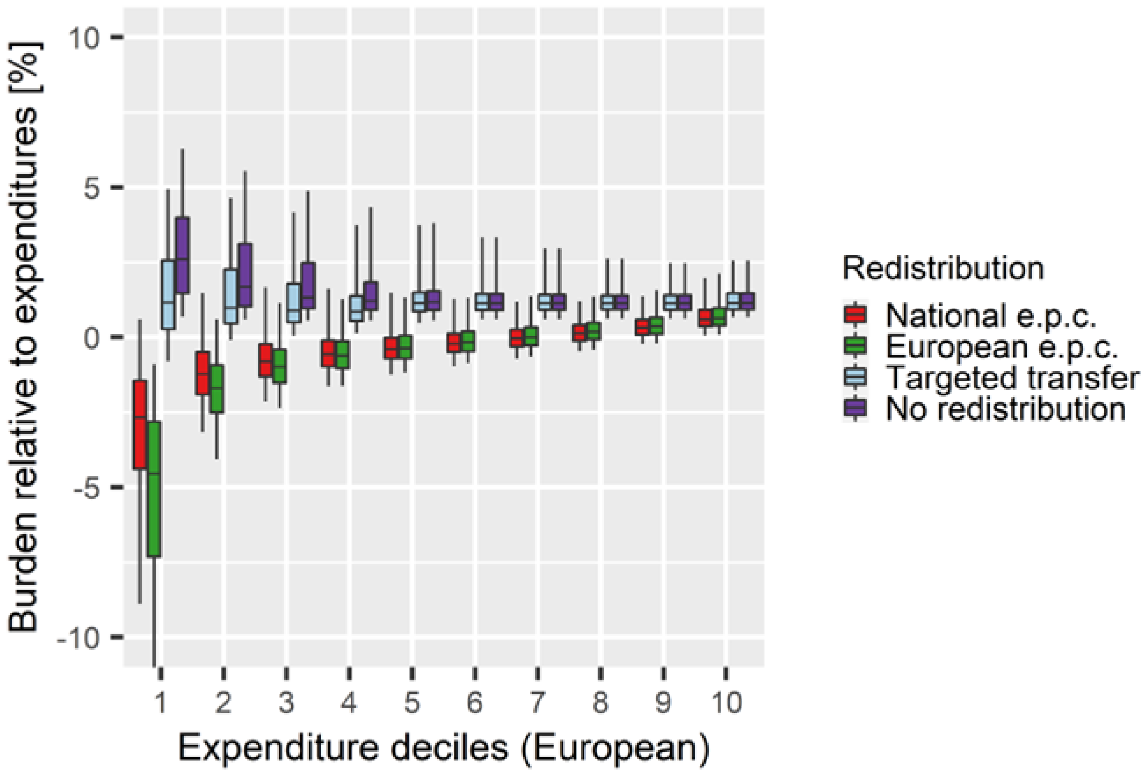


Figure 4 European carbon-tax incidence under different redistribution mechanisms. 1. A national equal-per-capita redistribution of a national carbon tax revenue (red); 2. a European equal-per-capita redistribution of a European carbon tax revenue (green); 3. an equal-per-household redistribution for deciles 1 to 4 only that equalizes the median incidence in decile 1 to that of decile 5 (blue). 4. incidence of the tax without refunding where the revenue raised has not been returned to the economy and all deciles are negatively affected (purple). Similarly, the Targeted program (blue) also leaves tax revenue that is not refunded. Outliers are excluded.

Ignoring such distributional effects may result in limited social acceptance of the energy transition in particular when strengthened towards 2040, less effective climate policies and even increased inequalities due to the lack of measures to mitigate negative impacts on vulnerable population groups.

3.2. Efficiency vs. equity considerations and trade-offs for the recycling of carbon revenues

Well-designed strategies are required to achieve progressive outcomes of ambitious climate policies by considering appropriate compensation schemes, either by increasing household income through lump-sum payments or reducing other (direct or indirect) taxes, or through the social security system. The World Bank and Carbon Pricing Leadership coalition (2016) have identified five main options to use carbon revenues, including the reduction of other taxes, lump-sum transfers to households, reduction of public debt and deficit, or funding green investment required for decarbonisation. All these options have benefits and trade-offs and thus the way these are used can impact the economic effectiveness and competitiveness, influence environmental outcomes, reduce inequality, and improve the political acceptability of carbon taxes.

In this section, we explore the macro-economic impacts of using carbon revenues in alternative ways, using four well-established multi-sectoral macro-economic models (IMACLIM, GEM-E3-FIT, E3ME, 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, non-equilibrium 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, Computable General Equilibrium (CGE) models that assume capital is fully utilised in the baseline scenario. In the context of NAVIGATE, these models were used under a common scenario protocol to develop scenarios with increasing climate policy ambition: the Reference scenario assumes the continuation of currently implemented policies, while the 1.5C target scenario assumes that the Paris goal of keeping global warming below 1.5C is met through the imposition of a universal carbon price to meet the 650 Gt carbon budget over 2020-2100 and avoid overshoot. We explored the macro-economic impacts of different ways of recycling carbon revenues, focusing on the main options suggested by the World Bank & Carbon Pricing Leadership coalition (2016): 1) reducing labour taxes and social security contributions, 2) providing revenues lump-sum transfers to households based on an equal-per-capita basis.

The transition towards a Paris-compatible pathway entails the restructuring of economic production and consumption across sectors and agents. Fossil fuels that are mostly imported in the EU are substituted by low-carbon ones, which may cost more in the short-term but have higher domestic value added as they are produced domestically. The macroeconomic impacts of the EU's low-carbon transition highly depend on i) the availability of capital for green investments, ii) whether key trading partners take similar action, iii) the flexibility of the economy, socio-technical, labour, and energy systems in the short to medium run, and iv) the carbon intensity of the EU economy. Our findings indicate that if all regions jointly take strong climate action towards the 1.5C goal, the macroeconomic implications for the EU would be limited by 2040, with low GDP reduction for the three CGE models and a slight increase for E3ME. Carbon pricing increases production costs and requires a shift to more expensive energy carriers, which increases the costs for European firms and households. At the same time phasing out fossil fuels results in important savings from avoided imports, leading to potential gains in competitiveness as the EU economy is less carbon intensive than most of its international competitors. Figure 5 shows that using carbon revenues to reduce the labour taxes and social security contributions has positive macro-economic impacts as it increases the EU's GDP in 2040 relative to the scenarios with distribution-neutral recycling in all models. The positive impact comes from two channels: reduced employers' social security contributions would lower the production cost for firms and hence increase their competitiveness, while the additional labour demand would increase household income and consumption. Transferring carbon revenues directly to households on an equal per capita basis can reduce inequality, which is quite beneficial if their consumption pattern is towards goods and services with a large domestic content. However, GDP impacts are slightly negative due to missed opportunities for enhanced productivity and for the creation of new employment opportunities. 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.

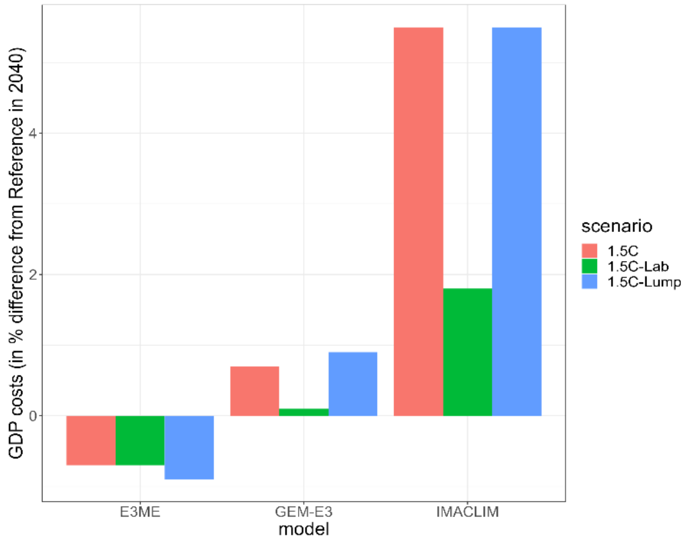


Figure 5 EU GDP impacts of the 1.5C scenarios relative to Reference in 2040

Despite limited GDP losses, the transition is expected 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 again of 700 thousand jobs in 2030 which further increases to 1.3-1.4 million jobs in 2040 and 2050 (see Figure 6). Services, the largest employing sector of the economy, increase demand for labour because of the reduced labour costs, despite the 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 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.

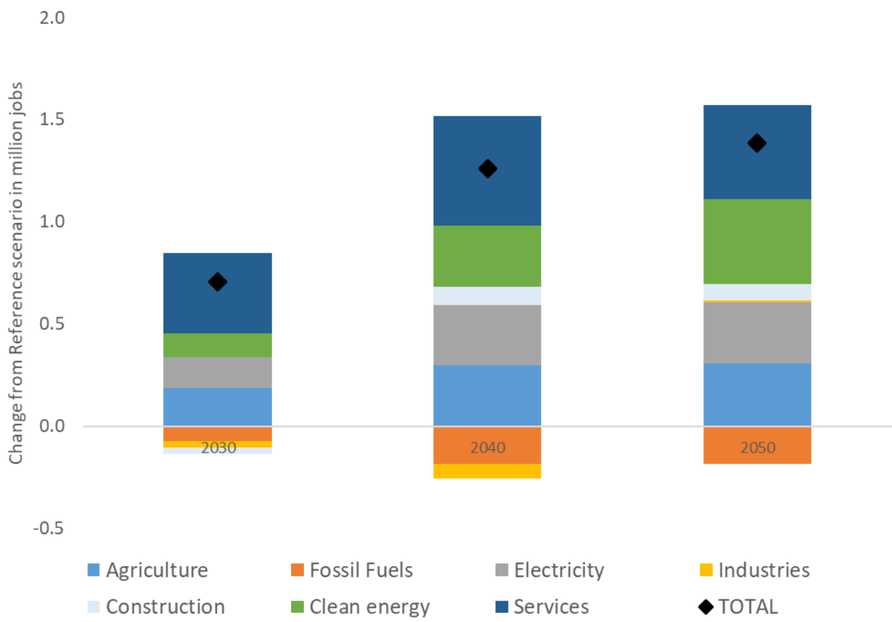


Figure 6 Changes in EU sectoral employment in 1.5C-Lab scenario from Reference in GEM-E3

We also estimate direct jobs in the energy sector in a Net Zero scenario for the European Union by technology and job type, using the WITCH model (see Figure 7). We find that by 2050, Europe's direct energy jobs are likely to increase substantially – from around 1.3 million to over two million. 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 thousand jobs are lost notably in the coal and oil sectors while in the NDC scenario this loss amounts to only 100 thousand jobs. Across countries, in terms of share of the work force, the losses notably in the coal and oil sector are highest in Poland, the Czech Republic, and Norway.

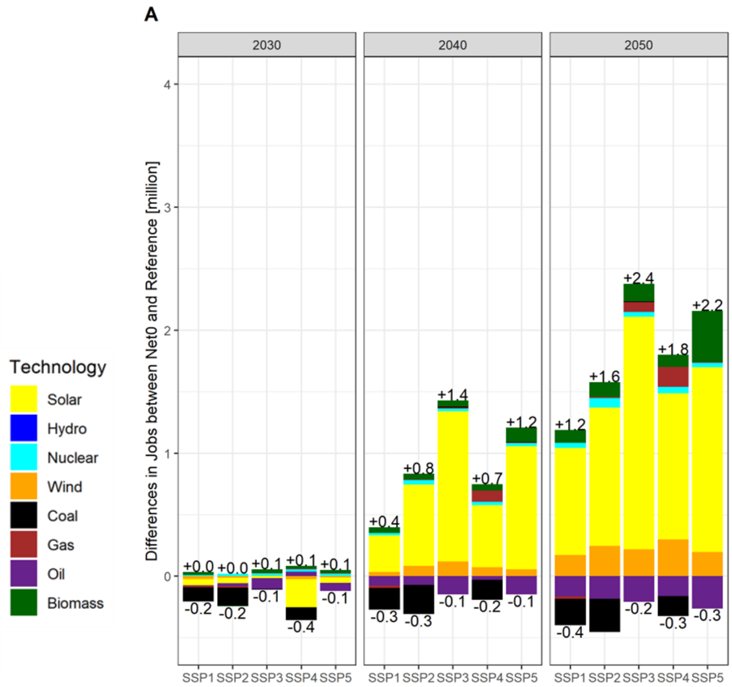


Figure 7 Job creations and losses (in million jobs) in the EU in the Net Zero scenario compared to the NDC by technology.

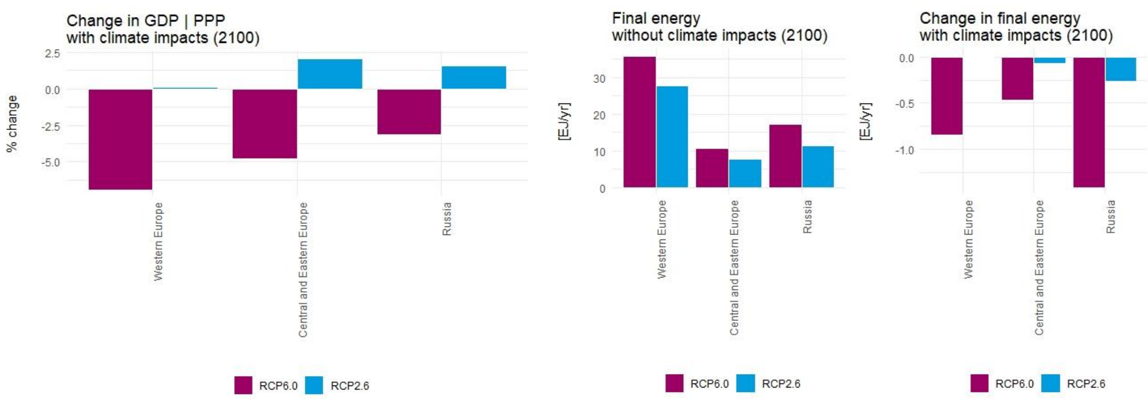
Emission trading systems can support governments to achieve ambitious emissions reduction goals and their net-zero targets by mid-century. The generated carbon revenues can be used for various purposes, such as the reduction of other distortive taxes, lump-sum transfers to households, or funding green investment. Each carbon price revenue option has benefits and costs and must be tailored to the specific circumstances and needs of a jurisdiction and aligned with existing policies. Our analysis demonstrates the socio-economic benefits of using carbon revenues to reduce distortive labour taxes and social security contributions, while lump-sum transfers to households have the potential to reduce inequality. Carbon revenues, if carefully and strategically considered, can represent a large financial resource for governments. Robust policymaking processes, including public and stakeholder consultation, can help to determine the most appropriate recycling option for the EU and its Member States, especially in the light of its new 2040 climate targets.

4. Avoided and residual climate impacts for Europe and the net benefit of climate change mitigation

While continued effort in increasing mitigation ambition is needed to ensure the limits of global mean temperature established in the Paris Agreement are held, climate impacts are already felt today and will continue to increase. The EU's net-zero target aims to contribute to the global implementation of the Paris Agreement, with significant net benefits for the world and Europe due to the avoided climate impacts. Hence when considering the 2040 target, it is important to not only look at potential costs and efforts to achieve it, but also at the signal it sends to other countries on route to net zero and the benefit it could have in terms of avoided impact if the world follows suit.

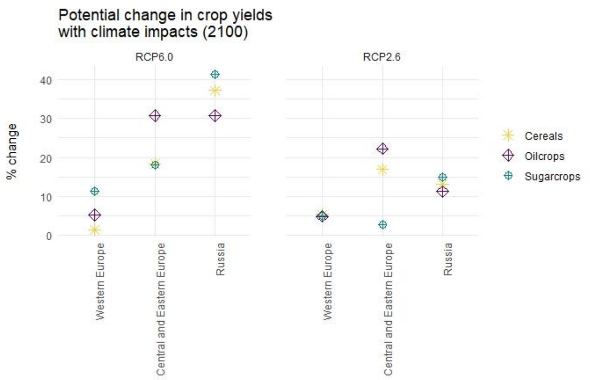
We used the IMAGE[8] model (Integrated Model to Assess the Global Environment) (Van Vuuren et al., 2021) to develop scenarios that combine multi-sectoral geographically-resolved estimates of the biophysical impacts of climate change with gridded socio-economic projections. The scenarios are based on a middle-of-the-road Shared Socio-Economic Pathway - SSP2 (Riahi et al., 2022). We compared baseline (RCP 6.0) and mitigation (RCP 2.6) scenarios, with and without climate impacts. Main results for Western Europe, Central and Eastern Europe, and Russia, are presented in Figure 8.
In both cases, negative impacts tend to correlate: temperate zones are generally less impacted, while warmer regions are climate impacts hotspots. Results from the baseline case show reductions in labour productivity and losses in GDP of over 7% in Western Europe, and 5% in Central and Eastern Europe. Negative impacts are also observed in renewable energy and water availability (increase in water stress and drought intensity). Although overall more negative impacts are observed, positive impacts exist, e.g., with regard to heating demand (lower heating demand due to higher temperatures) and potential crop yields (due to changes in temperature, precipitation patterns and CO_2 fertilization). It should be noted that the IMAGE model automatically assumes that crops are relocated to the best growing cells, so these results include some form of adaptation.

a) b)



8 More info about the IMAGE model can be found at www.pbl.nl/IMAGE.

c)



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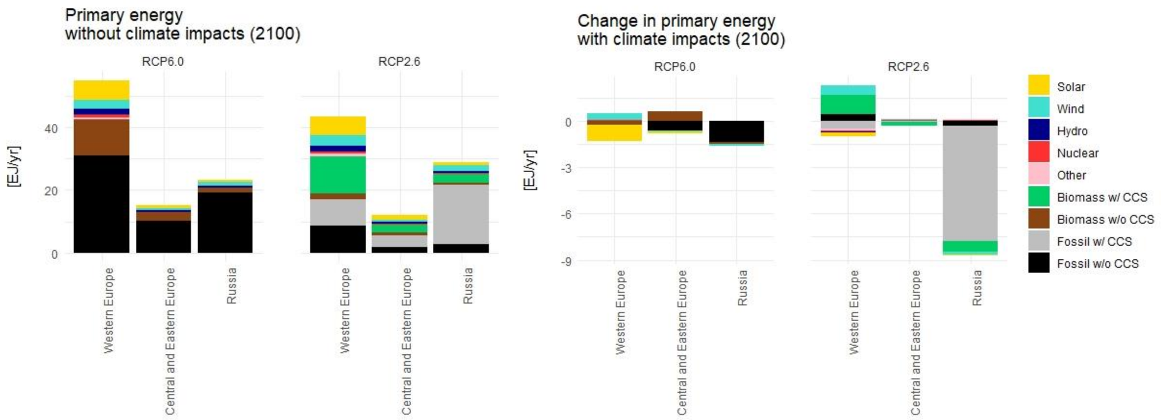

Figure 8 Climate impacts in the default RCP 6.0 (baseline) case and in the RCP 2.6 (mitigation) case, in 2100, using the IPSL climate pattern. Results show changes in GDP (a); final energy and changes in final energy (b); changes in crop yields for cereals, oil crops and sugar crops (c); and primary energy and changes in primary energy (d). From van Vuuren et al., 2023 (in preparation).

Climate impacts are more prominent in the baseline case, while the mitigation case shows that more ambitious climate action greatly reduces climate impacts. The results presented here paint only a partial picture. Improvements include extending the analysis of impacts on human health, extreme weather events, sea-level rise, and infrastructure. Furthermore, adaptation is only partly covered by this exercise, with feedbacks on the main drivers. Better representation of adaptation, with links to specific SSPs storylines, is expected in future work.

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