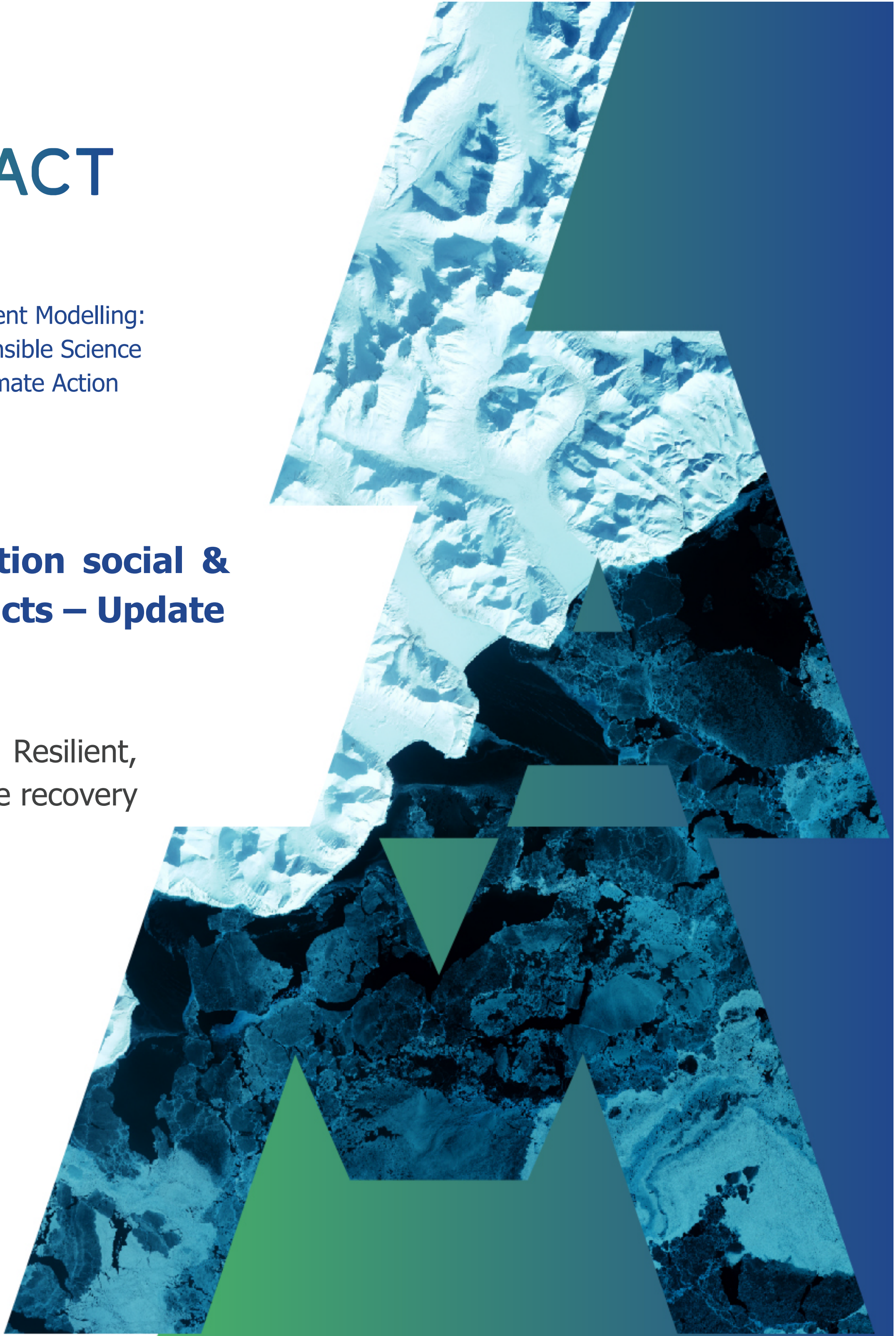
IAM COMPACT

Expanding Integrated Assessment Modelling: Comprehensive and Comprehensible Science for Sustainable, Co-Created Climate Action



D5.3 – Climate action social & distributional impacts – Update

WP5 – Expanding – Resilient, inclusive, and sustainable recovery and development

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EC Summary Requirements

1. Changes with respect to the DoA

No changes with respect to the work described in the DoA.

2. Dissemination and uptake

The results of this deliverable will be disseminated through IAM COMPACT's website, and uploaded onto Zenodo, while parts have been (or will be) shared with the wider scientific community through publication in peer-reviewed journals, and with the policy community and civil society via targeted policy briefs.

3. Short summary of results (<250 words)

This document updates Deliverable D5.2, by presenting two new distributional analyses on inequality impacts of climate policies developed within IAM COMPACT. Each analysis applies a different methodology, building on earlier work while expanding the geographical scope and methodological complexity to better assess the inequality impacts of climate policies. The first analysis explores how different implementations of the EU's climate policy portfolio affect various consumer groups across and within Member States. It finds that a general EU-wide carbon price, while cost-efficient, has regressive impacts, disproportionately burdening low-income households. In contrast, policies based on national plans (NECPs) are less regressive. Although income is the dominant factor influencing outcomes, gender, urban-rural location, and household structure also play a role. The second analysis evaluates global decarbonisation scenarios for passenger transport through to 2050, focusing on differentiated carbon taxes across income groups. It shows that uniform cost policies are regressive, burdening lower-income consumers, especially in air travel. In contrast, a global per capita emissions cap by 2050 sets heterogenous carbon prices, shielding low-income households, while the higher costs borne by wealthier individuals lead to a faster adoption of clean transport technologies, which may translate into faster decline of clean technology costs, thereby benefitting all consumers in a mitigation context. The model enhancements and inter-model connections presented in these analyses reflect major methodological progress developed in the project, offering a robust, integrated framework for evaluating the system-wide and distributional and impacts of climate policy.

4. Evidence of accomplishment

This report.

Section 2 is a paper in progress: "*Towards a just transition: the distributional effects of EU environmental policies*". Eva Alonso-Epelde, Xaquín Garcia-Muros, Clàudia Rodés-Bachs, Jon Sampedro and Dirk-Jan Van de Ven.

Section 3 is also a paper in progress, while preliminary analysis has been presented at EGU 2024: Van de Ven, D.J. and Sampedro, J., 2024, April. Passenger transport decarbonisation under different equity considerations. In EGU General Assembly Conference Abstracts (p. 19615).

MEDUSA is open source and available at: https://bc3lc.github.io/medusa/. The documentation paper has been recently accepted for publication in the Journal for Open Source Software (JOSS).

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Preface

IAM COMPACT supports the assessment of global climate goals, progress, and feasibility space, and the design of the next round of Nationally Determined Contributions (NDCs) and policy planning beyond 2030 for major emitters and non-high-income countries. It uses a diverse ensemble of models, tools, and insights from social and political sciences and operations research, integrating bodies of knowledge to co-create the research process and enhance transparency, robustness, and policy relevance. It explores the role of structural changes in major emitting sectors and of political, behaviour, and social aspects in mitigation, quantifies factors promoting or hindering climate neutrality, and accounts for extreme scenarios, to deliver a range of global and national pathways that are environmentally effective, viable, feasible, and desirable. In doing so, it fully accounts for COVID-19 impacts and recovery strategies and aligns climate action with broader sustainability goals, while developing technical capacity and promoting ownership in non-high-income countries.

NTUA – National Technical University of Athens	EL
Aalto – Aalto Korkeakoulusaatio SR	FI
AAU – Aalborg Universitet	DK
BC3 – Asociacion BC3 Basque Centre for Climate Change – Klima Aldaketa Ikergai	ES
Bruegel – Bruegel AISBL	BE
CARTIF – Fundacion CARTIF	ES
CICERO – Cicero Senter for Klimaforskning Stiftelse	NO
E3M – E3-Modelling AE	EL
KTH – Kungliga Tekniska Hoegskolan	SE
POLIMI – Politecnico di Milano	IT
UPRC – University of Piraeus Research Center	EL
UVa – Universidad De Valladolid	ES
WI – Wuppertal Institut fur Klima, Umwelt, Energie GGMBH	DE
IIMA – Indian Institute of Management	IN
THU – Tsinghua University	CN
USMF – University System of Maryland	US
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TUM – Technical University of Mombasa	KE
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Executive Summary

This deliverable is the update of a previous deliverable (D5.2[1]) that described the initial analysis of distributional impacts of climate change policies performed in IAM COMPACT. In D5.3, we present two distributional analyses, each based on a different methodology, building upon the studies and methods introduced in D5.2, while taking a step further in modelling complexity and geographical scope. The developed model capabilities and integration of diverse tools in these analyses illustrate the methodological advancements achieved throughout IAM COMPACT.

The first analysis examines how different approaches to implementing the current EU climate policy portfolio, including more prescriptive versus cost-effective scenarios, impact various consumer groups both across and within Member States. These scenarios were co-designed with a range of stakeholders in a dedicated workshop[2] to ensure their policy relevance. Results show that the most cost-efficient pathway to achieve the EU climate targets, i.e., the implementation of a general carbon price across the EU, will have some regressive distributional impacts. Other approaches, as in implementing country-level National Energy and Climate Plans (NECPs), would reduce the burden on low-income households and therefore reduce the regressive impacts. The analysis also highlights that, while income remains the primary factor influencing the distributional impacts of emission reduction policies, gender-related consumption patterns and whether individuals live in urban or rural areas also play a significant role. This analysis relies on an innovative methodological framework that integrates two distinct modelling tools to capture both system-wide transformations and distributional impacts. First, we employ GCAM-Europe, a well-established Integrated Assessment Model (IAM), to project scenario-specific changes in the energy mix and key (primarily energy-related) prices. These projected price changes are then input into MEDUSA, a tool for high-resolution distributional analysis. MEDUSA incorporates a wide range of household socioeconomic and demographic characteristics, such as income level, geographic location, family structure, and degree of feminisation, enabling a detailed assessment of how different population groups are affected by the transition.

The second analysis examines global decarbonisation pathways for passenger transport through to 2050, under varying equity and sustainability assumptions. It introduces a range of emissions taxation scenarios tailored to the passenger transport sector, including differentiated carbon taxes across global income groups. The findings reveal that uniform cost-distribution policies, where all users bear the same financial burden, are regressive, disproportionately affecting lower-income individuals, particularly in their access to air travel. Conversely, implementing a global per capita emissions cap by 2050 results in differentiated carbon prices. This approach protects lower-income households from some of the negative effects of carbon pricing, while higher-income individuals, facing greater costs, drive the accelerated adoption of clean transport technologies through technological learning. The analysis is based on an enhanced version of the Global Change Analysis Model (GCAM), named GCAM-GRAPHICS, which incorporates consumer heterogeneity in the transportation passenger sector. In this model version, passenger transport demand and mode choice are disaggregated by income decile, using estimated shares and the shadow value of time as key determinants.

Together, these two analyses demonstrate the significant methodological advancements made throughout the course of IAM COMPACT. The combination of the two complementary approaches has enhanced the ability to capture both macro-level system dynamics and micro-level distributional effects of alternative scenarios. This integrated framework represents a substantial improvement in assessing the equity and effectiveness of emission reduction policies, offering a more comprehensive understanding of their impacts across population groups.

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[1] DOI: 10.5281/zenodo.15756815
[2] https://iam-compact.eu/news-events/core-working-group-workshop-citizens-transition

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1 Introduction

Addressing the major challenges of the 21st century, such as climate change, requires system-wide policies that promote social justice alongside ambitious climate action. This can be achieved through integrated policies or through parallel climate and social measures. In both cases, efficiency and equity must be central to avoid deepening existing inequalities. Gender inequalities play a relevant role in just transition and are a key element of energy and climate justice (Feenstra & Özerol, 2021). Prior research identifies differential vulnerability of women to mitigation policies (Markkanen & Anger-Kraavi, 2019) and differences in support for climate mitigation policies. Policies that reduce economic inequality can also reduce gender inequalities, especially if female-headed households are over-represented in the low-income groups. Likewise, energy poverty is playing a relevant role in the energy and political debate, since climate policies can have a greater impact on those who are already vulnerable. Energy poverty, understood as the inability of a household to achieve a socially and materially necessary level of household energy services (Bouzarovski & Petrova, 2015), is at the centre of public debate (Baker et al., 2018, Dobbins et al., 2019), especially due to the recent energy crisis. Moreover, the cost associated with climate action may disproportionately affect households at risk of energy poverty in the short term.

As highlighted by several institutions, including the IPCC (IPCC, 2022) or the European Commission (Bednar-Friedl et al., 2024), one of the major research gaps in global scenario analysis is the limited understanding of the within-region distributional impacts of climate policies. Despite growing recognition of the importance of inequality and socioeconomic diversity, these dimensions remain significantly underrepresented in most models used to assess the system-wide implications of climate policy scenarios. This gap is particularly evident in Integrated Assessment Models (IAMs) (Low et al., 2025). Although IAMs have long been the dominant tools for global scenario analysis (van Beek et al., 2020), and have made notable progress in increasing the spatial and temporal granularity of their outputs, using a single "representative consumer" is still the most common approach (Emmerling & Tavoni, 2021). This simplifying assumption fails to capture the heterogeneity of consumer behaviour and limits the analysis of the socioeconomic and distributional consequences of the climate transition across different households and social groups. Moreover, this oversimplification hinders the ability to identify the most vulnerable population groups, which is essential for designing effective and targeted compensatory measures (Alonso-Epelde et al 2024).

Therefore, it is essential to develop methodologies and tools that reflect real-world social and economic diversity, enabling more nuanced analyses of how different climate pathways impact various segments of the population. IAM COMPACT advances in this direction by using state-of-the-art methodologies to generate more detailed evidence of the extent of transition impacts on different household typologies, combining large databases, microeconomic models (MS) and IAMs. MS and databases are an appropriate tool for assessing micro-economic effects and distributional impacts of policies and for showing the impact of climate protection measures on consumers; however, partial analysis often limits the overall perspective, particularly from a macro and multiregional standpoint. On the other hand, IAMs provide an economy and technology-wide analysis that is not captured with MS. Therefore, the main advantage of linking these approaches is that environmental protection can be analysed from different perspectives, in particular, equity and efficiency. A summary of the numerical models, data and methods used is presented Table 1.

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Table 1. Numerical models, data and methods to explore Climate action social & distributional impacts. Adapted from D5.2.

	Method-Data	Type	Distinguishing feature in IAM COMPACT
Micro Models and data	Microdata	Micro-economic data from household surveys	The household surveys provide information about households' final consumption of goods and services and information on socioeconomic characteristics.
	Microsimulation	Microsimulation models based on large data from household surveys	Distributional effects (horizontal and vertical) of climate mitigation policies and possible compensatory scenarios.
Macro Models and data	IAMs	Integrated Assessments Models	IAMs presents an exhaustive description of the productive process and the resource-use balance of the international economy.
Integrated Methods	IAMs-MS Methods	Multi-household, multi-regional, multi-sector, IAMs	Analyse the socioeconomic and distributional impacts of public policies that directly affect households, both economic, energy, environmental or fiscal at multiregional level.

In a previous deliverable (D5.2) we showed two different examples on distributional analysis with two different methodologies, approaches and focus regions, which represented a good example of the previously mentioned methodologies and the type of analysis that can be performed with them. The first analysis explored the distributional consequences of a key policy at EU level, the Energy Taxation Directive, using a microeconomic model which includes a large database on European households. The second analysis offered an overview of the distributional impacts on vulnerable households of different climate and policy paths in Greece. For doing so, GEM-E3-FIT was expanded to represent ten household income classes in EU Member States, to consistently capture the potential distributional impacts of ambitious energy and climate policies for Greece until 2050. These two analyses offered a good overview of the type of distributional analysis that is and will be performed in the environment of the IAM COMPACT project. In addition, D5.2 included a description of MEDUSA, an R package initially developed for the Spanish economy that enables distributional analyses either independently or in conjunction with other models, such as IAMs. Its extensive database allows for highly disaggregated results, considering numerous socio-economic and demographic characteristics of households, such as income level, place of residence, type of family or the degree of feminisation of the household.

Since the submission of that D5.2, we have significantly advanced in some methodologies that allow for more comprehensive and complete distributional analyses. First, MEDUSA has been expanded to cover all EU Member States, allowing for the assessment of household-level policy impacts across the entire EU. In parallel, we have developed an automated soft-link between the GCAM/GCAM-Europe IAMs and MEDUSA, enabling the quantification of within-region distributional impacts for each IAM scenario. Finally, we have enhanced a version of the GCAM model (*GCAM_GRAPHICS*), which incorporates consumer heterogeneity in the three main end-use sectors (residential, food, and transport), and we adapted it to address key IAM COMPACT research questions.

This deliverable presents two new analyses, building on the aforementioned methodological advancements, to provide deeper insights into how climate policies impact different population segments. Section 2 examines how implementing different strategies to meet the current EU climate policy portfolio affects different consumer groups within each Member State. Section 3 analyses the implications of alternative decarbonisation scenarios for passenger transport, with a focus on different equity considerations.

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2 Towards a just transition: the distributional effects of EU environmental policies

2.1 Motivation

Implementing alternative strategies to address climate change will have system-wide effects on production systems and consumption patterns, influencing all segments of society. In order to address the current climate crisis, the European Union launched the comprehensive Fit-for-55 policy package[3], that sets the objective to reduce greenhouse gas emissions by 55% below 1990 levels by 2030 (European Commission, 2021). This ambitious initiative represents a critical step in EU's climate action, aiming to put the bloc on a clear path toward achieving net-zero emissions by 2050. The package combines EU-wide regulations with country-specific strategies, targeting multiple sectors that include energy, transport, buildings, and industrial systems with tailored policy instruments. However, the rollout of Fit-for-55 has sparked a range of policy debates. Key concerns include the feasibility and economic costs of meeting such ambitious targets within a tight timeframe, how the effort should be fairly distributed among member states with varying capabilities, and how different sectors will share the burden. These discussions also encompass the potential co-benefits of the transition, such as improved air quality, energy security, and job creation in green industries.

Nevertheless, few existing models are well-suited to assess comprehensive policy packages like the EU's Fit-for-55 (FF55). Global models often lack the geographic and sectoral detail needed to capture national and regional differences, while national models typically miss cross-border interactions and wider economic dynamics (Brutschin et al., 2021; De Cian et al., 2020). Moreover, many modelling tools struggle to incorporate the complexity of overlapping, real-world policy mixes. Particularly, IAMs generally focus on identifying "least-cost" pathways to emission reduction targets (van de Ven et al., 2023). This usually involves applying a uniform carbon price across all sectors and countries, with little attention to non-emission outcomes such as equity or social impacts. As a result, these models often produce scenarios that diverge significantly from political realities, such as over-reliance on negative emissions technologies (NETs) or unrealistic policy assumptions (Gambhir et al., 2019).

In addition, IAMs often fail to adequately represent the diversity of household behaviour and consumption, which critically limits their ability to assess inequality impacts and the broader social and distributional consequences of climate transitions (Low et al., 2025; Peng et al., 2021; Rubiano Rivadeneira & Carton, 2022). To ensure a just transition, it is crucial to design policies that are both efficient and equitable, avoiding the exacerbation of existing inequalities related to income, gender, or other factors, while also identifying vulnerable groups to implement targeted compensatory measures that leave no one behind in the shift to a low-carbon future (Alonso-Epelde et al., 2024; Budolfson et al., 2021; Emmerling et al., 2024). This highlights the urgent need to develop new methodologies and tools that better reflect the complexity of real-world social and economic diversity, enabling more nuanced analyses of how different climate pathways affect various segments of the population (Koasidis et al., 2023).

To address this gap, we integrate an enhanced version of the Global Change Analysis Model (GCAM-Europe), which enables detailed bottom-up modelling of EU policies, with MEDUSA, a tool designed for high-resolution distributional analysis. This combined approach allows us to examine how different strategies for implementing the current EU climate policy portfolio impact various consumer groups within and across Member States. These strategies were co-designed with diverse stakeholders during a dedicated workshop[1] in order to ensure that the produced results were relevant and of direct interest for key agents of the transition.

[3] https://www.consilium.europa.eu/en/policies/fit-for-55/

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2.2 Study design

2.2.1 Methodology

The methodological framework in this analysis combines multiple modelling tools to capture both system-wide changes and distributional outcomes. First, we use GCAM-Europe (see Section 2.2.1.1), a well-established IAM, to project scenario-specific changes in the energy mix and key prices, including energy, food, and water. These projected price changes are then fed into MEDUSA, a specialised tool for high-resolution distributional analysis (see Section 2.2.1.2). MEDUSA accounts for a wide range of household socioeconomic and demographic characteristics, such as income level, location, family structure, and degree of feminisation, allowing the assessment of how different population groups are affected by the transition.

2.2.1.1 GCAM-Europe

GCAM-Europe is an expansion of the Global Change Analysis Model (GCAM), a well-reputed IAM widely used in global scenario analysis (Calvin et al., 2019). The model is designed to analyse alternative "what-if" type scenarios within a single computational platform. GCAM-Europe includes technology-rich representations of the economy, energy sector, land use, and water linked to a climate model that can be used to explore climate change mitigation policies, including carbon taxes, carbon trading, regulations and accelerated deployment of energy technology. Regional population and labour productivity growth assumptions drive the energy, land-use and water systems employing numerous technology options to produce, transform, and provide energy services, as well as to produce agricultural and forest products and to determine land use and land cover. A full description of the GCAM model can be found in the online documentation4.

GCAM-Europe's geographical disaggregation is highly-detailed for the European continent. While core GCAM divides the European continent in five different regions, namely EU-12, EU-15, Europe Eastern, Europe-non-EU, and European Free Trade Association (EFTA), in GCAM-Europe all European countries are disaggregated into individual model regions (Figure 1). Having this level of detail enables us to explore the country-level effects of European policy packages or transformational strategies, as well as the potential international effects (e.g., carbon leakage).

[4] https://github.com/JGCRI/gcam-doc

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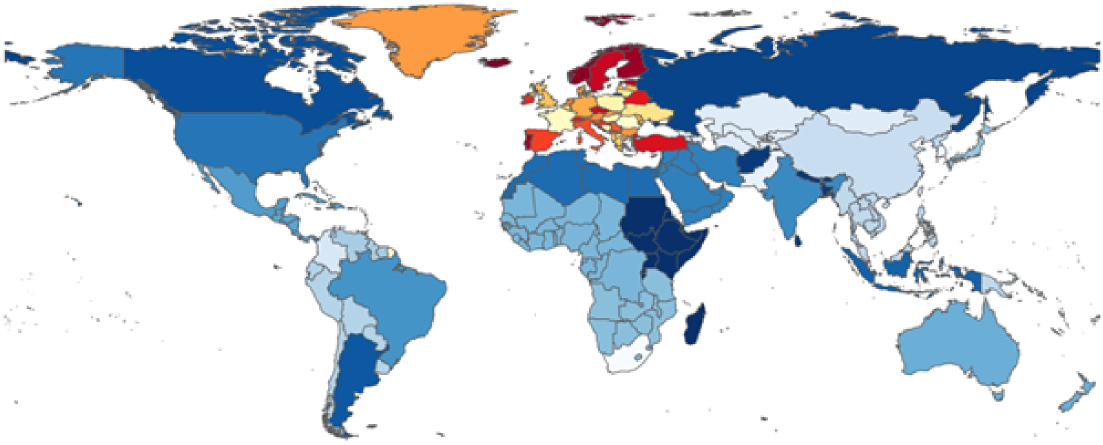
Figure 1: Regional disaggregation in GCAM-Europe. *Yellow-to-red colours represent the regional groups that are explicitly disaggregated for this model. White-to-blue regions represent model regional groups that were part of the original model.*



The model has been developed in a sister Horizon Europe project, DIAMOND[5], and, beyond the regional disaggregation, it includes additional features compared to the core version. First, GCAM-Europe replaces the default (international) data sources for all newly defined European countries with Europe-specific data, such as energy statistics from Eurostat, whenever available. If certain countries lack coverage in these European datasets, alternative sources must be used—most commonly reverting to the default GCAM data, such as IEA energy statistics. In terms of sectoral and technological coverage, the model has been expanded across multiple dimensions (see Figure 2), with a particular emphasis on building energy demand. This includes the introduction of new demand categories such as hot water, cooking, and various household appliances, as well as the integration of emerging technologies like heat pumps. These enhancements leverage the richer and more detailed data available for European countries, enabling more accurate and granular modelling of energy consumption patterns and technology adoption within the building sector.

[5] https://climate-diamond.eu/

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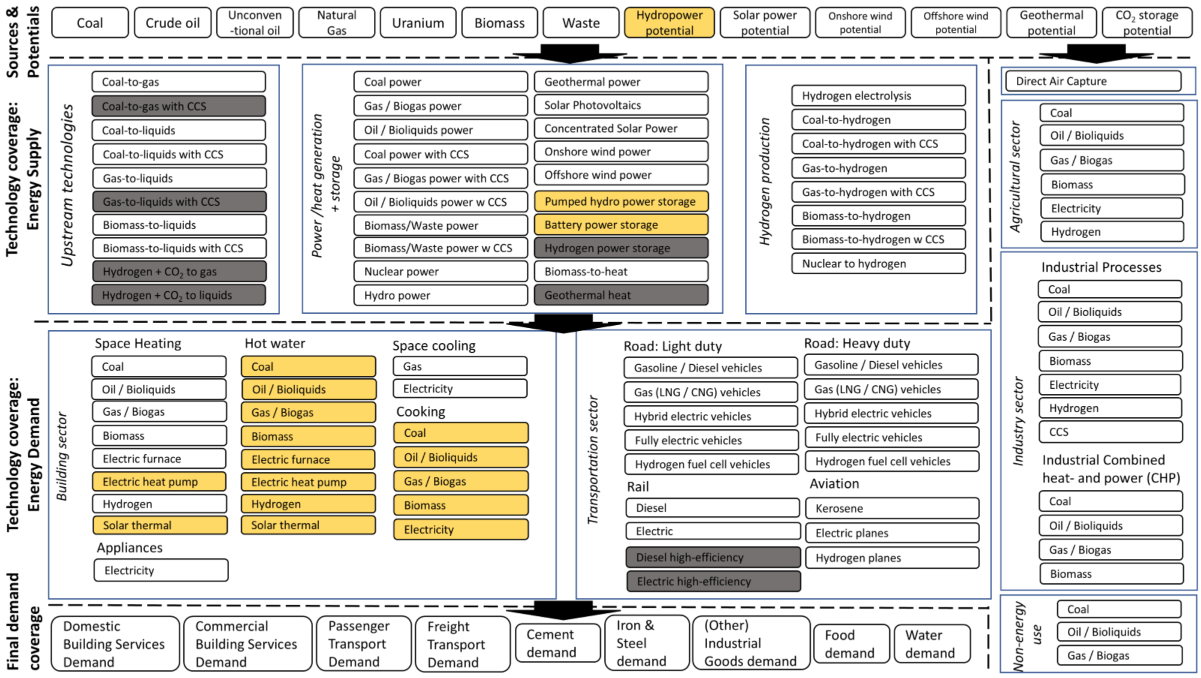
Figure 2: Summary of the resource, technology, and end-use demand representation in GCAM-Europe. *White boxes indicate features already part of the original model. Grey boxes indicate features not part of the core nor the updated model. Dark yellow boxes indicate the features that will be explicitly developed for GCAM-Europe in the DIAMOND project, and which are not in the core version of the model*



The electricity grid in GCAM-Europe is modelled as an interconnected system structured around grid regions Figure 3, load segments, and inter-segment storage. This framework allows for a more realistic representation of electricity flows and flexibility within and between regions. The load segmentation is based on the ENTSO-E "National Trends" scenario (ENTSOE, 2024). This approach captures temporal variation in electricity demand and supply more accurately, while enabling the analysis of storage technologies and their role in balancing the grid across different segments and regions. Each grid region and cluster operates its own electricity market, with prices typically lowest during off-peak demand periods and highest during peak times. Price variations between clusters can incentivise investment in electricity storage, while differences between grid regions may promote cross-regional electricity trade.

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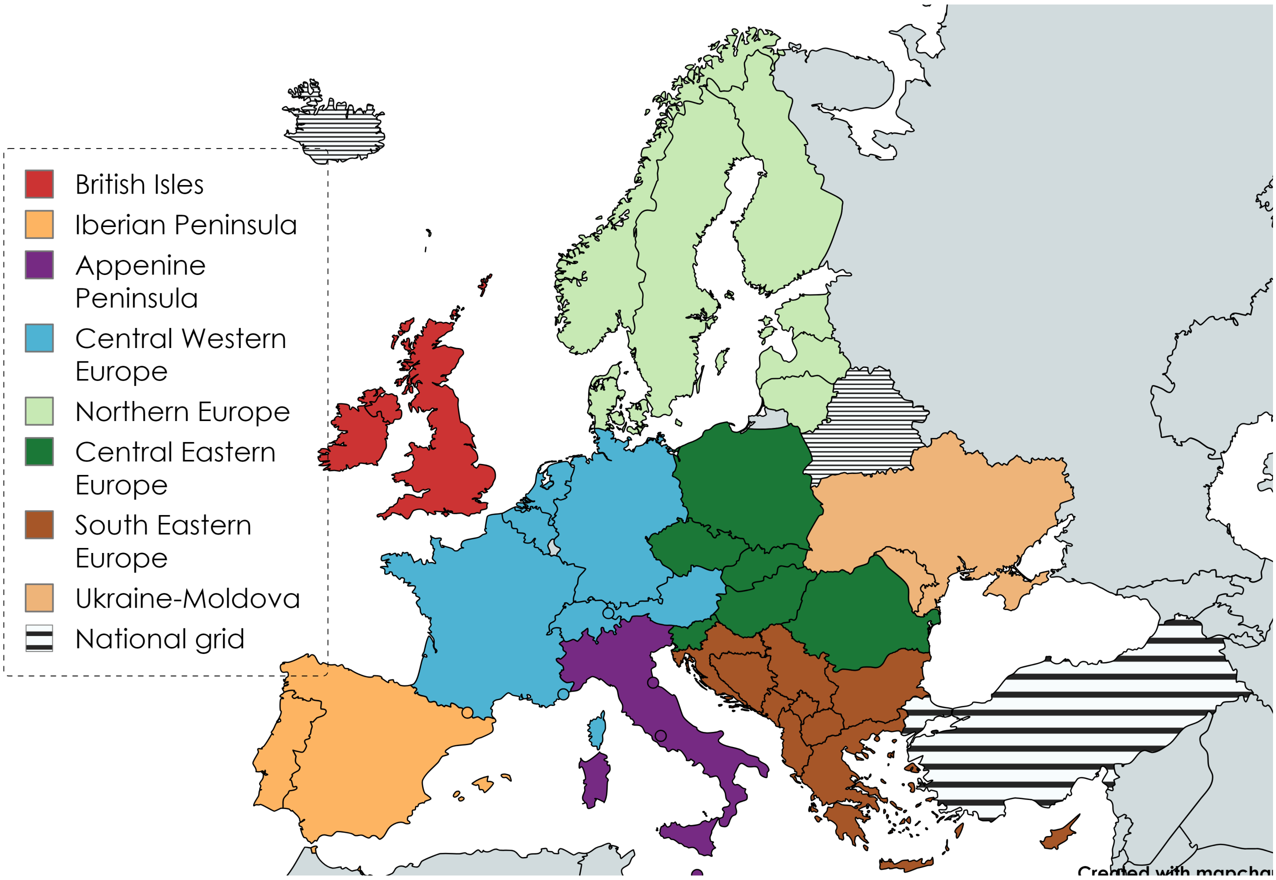
Figure 3: Electricity grid regions GCAM-Europe



GCAM-Europe incorporates a trade structure that reflects the European Economic Area (EEA) and the internal free-trade market among EU member states, Norway, and Iceland. In the standard GCAM framework, trade in commodities such as energy, food, and certain industrial goods (e.g., steel and ammonia) is governed by Armington coefficients (Armington, 1969), which determine the substitutability between domestic and imported goods both within and across regions. In the GCAM-Europe update, EEA countries are treated as a unified trading bloc in the global market, while an additional layer of trade, also modelled using Armington coefficients, captures trade flows within the EEA. Trade costs between the EEA and non-EEA regions remain consistent with the global GCAM assumptions, but intra-EEA trade is assigned lower costs to reflect reduced trade barriers. This enhanced structure not only improves the realism of trade dynamics within Europe but also facilitates the future integration of common trade policies such as the Carbon Border Adjustment Mechanism (CBAM).

2.2.1.2 MEDUSA

MEDUSA is an R package that allows the development of distributional analyses in isolation or in connection with other models such as IAMs. It features a comprehensive database that enables highly disaggregated assessments across the entire EU, considering a wide range of household socio-economic and demographic characteristics, including income level, place of residence, family type, and the degree of feminisation within households.

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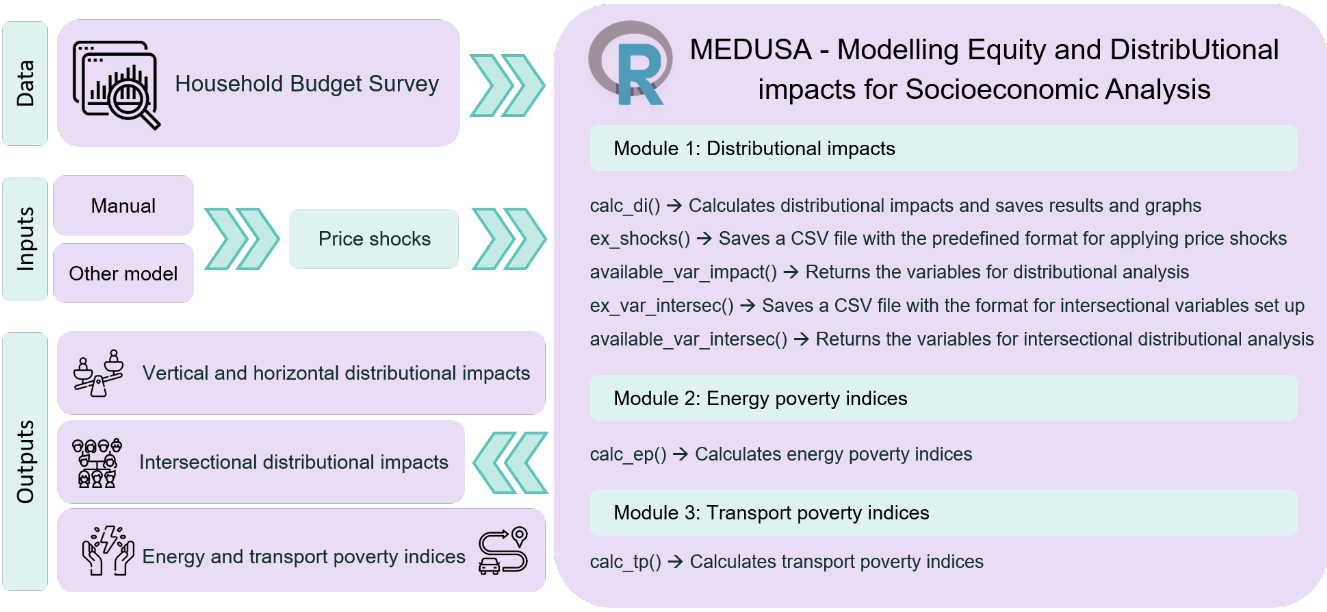
Figure 4: Overview of MEDUSA



The distributional analysis in MEDUSA is based on the overnight effect microsimulation model. The model is built up with the microdata from the Household Budget Survey6, a common statistic in all EU countries which is increasingly standardised, and which has relevant potential due to the large amount of socioeconomic information that it collects. The HBS provides information on household final consumption expenditure for goods and services and information on some socioeconomic and demographic characteristics of each household. The HBS provides information at two levels: one for households and their expenditures and the other for household members. More details on the underlying microsimulation model, as well as the structure of the R package can be found in D5.2, and online documentation7. The package is also extensively described in a documentation paper, which is currently being reviewed at the *Journal of Open Source Software*8.

2.2.2 Scenarios

In this study, we simulate three alternative policy scenarios, along with a benchmark baseline, each representing a distinct pathway toward achieving the EU's current emission reduction targets and broader climate goals. These scenarios are summarised in Table 2. For the purpose of isolating the relative price impact of climate policy, all scenarios (including EU_NOPOLICY) consider existing Member State specific energy taxes (electricity, gas, and transport fuels) up to 2024 and assume them to stay constant until 2030.

[6] https://ec.europa.eu/eurostat/web/household-budget-surveys
[7] https://bc3lc.github.io/medusa/
[8] https://github.com/openjournals/joss-reviews/issues/7697

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Table 2: Summary of the simulated scenarios

Scenario	Description
EU_NOPOLICY	In this baseline scenario, we assume the absence of any climate policy. While several cross-sectoral policies and objectives are currently in place at both the EU level and within individual Member States, this theoretical scenario serves as a benchmark. It enables comparison with alternative pathways to assess the impact of various climate policy interventions.
EU_NECP	The scenario reflects the most detailed representation of the existing FF55 policy portfolio, including EU-wide targets for the EU ETS (1 and 2) and vehicle emission standards, as well as country-specific coal phase-out strategies, and renewable energy (% of final energy use, see Table A1 in Appendix) and energy efficiency (maximum to final energy use, see Table A2 in Appendix) targets as defined in country-specific National Energy and Climate Plans (NECPs).
EU_FF55	This scenario is similar to the EU_NECP scenario, but instead of applying NECP-specific targets, an EU-wide targets for 2030 in line with FF55 are applied for renewables (42.5% of final energy) and energy efficiency (11.7% reduction in final energy w.r.t. 2020), allowing the model to optimally allocate efforts for these targets over the different member states.
EU_FF55_FREE	In this scenario, the EU achieves the same level of carbon dioxide (CO2) emissions mitigation as in the EU_FF55 scenario. However, in this case, EU emissions reductions are accomplished through emissions constraints without considering the current climate policies, allowing the models to select the cost-optimal pathway for reducing emissions.

In summary, this set of scenarios presents alternative narratives that combine "least-cost" approaches with more prescriptive mitigation pathways. While all scenarios achieve the same overall level of CO_2 emissions at the EU level, the distribution of mitigation efforts across countries and sectors varies depending on the specific scenario. These scenario-specific emission pathways are summarised in Figure 5.

In terms of implementation, population and GDP projections are aligned with the EU Ageing Report 2024 (European Commission, 2024), ensuring consistency with official demographic and economic outlooks. The EU-wide policies include the EU Emissions Trading Scheme (ETS), which imposes a carbon cap on the power and industrial sectors; the upcoming ETS2, which introduces a carbon price of €45 (in 2020 prices) by 2030 for buildings and road transport; and a vehicle emission standard assumed to tighten progressively, targeting near-zero emissions by 2035, aligned with the legislation to ban the sale of new ICE vehicles. The country-specific policies, which reflect national commitments under the National Energy and Climate Plans (NECPs), include the Energy Efficiency Directive, which aims to reduce final energy consumption to 764 Mtoe EU-wide by 2030; and the Renewable Energy Directive, targeting a 42.5% renewable share in final energy use by the same year. National plans for coal phase-out in electricity generation are also incorporated.

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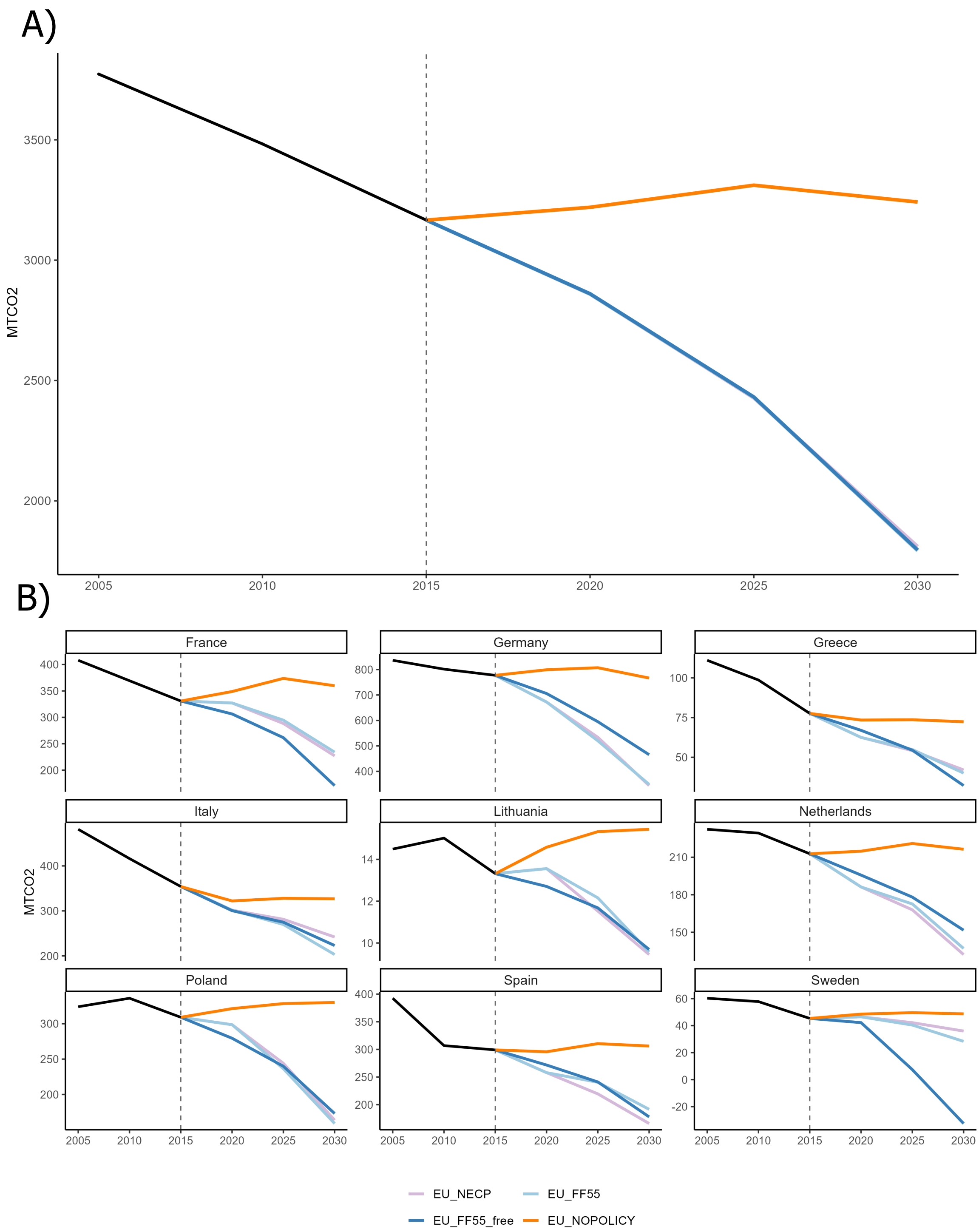

Figure 5: CO2 emissions by period, region, and scenario (MTCO2). Panel A shows the emissions at EU level, while Panel B) shows emissions for a representative subset of EU Member States

2.3 Results

2.3.1 Energy Mix

The implementation of environmental policies will directly impact the energy system by accelerating the transition

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toward cleaner and more sustainable energy sources. Specifically, these policies are expected to reduce the reliance on fossil fuels and significantly increase the share of non-emitting technologies, namely wind, solar, hydro, or nuclear power, in the overall energy mix.

Total EU-wide primary energy consumption largely varies across scenarios. While in the baseline scenario (EU_NOPOLICY) primary energy is projected to reach around 54 EJ, this value is expected to decrease to 50 EJ in the EU_FF55_free scenarios. Moreover, in those scenarios where an explicit energy efficiency target is implemented, namely EU_FF55 and EU_NECP, total energy consumption in 2030 would decrease to 42 EJ, aligned with the existing directive (European Commission, 2023).

In terms of energy mix, the policy scenarios show a shift from fossil fuels to clean energy sources, which largely varies across scenarios. In the cost-optimal scenario (EU_FF55_free) the reduction in coal and gas is smaller than in the more prescriptive EU_FF55 and EU_NECP scenario, which have more aggressive policies towards the phase out of these fuels. Likewise, in the EU_FF55_free scenario, there is a rapid increase in biomass deployment (up to 16.5 EJ in 2030) due to its cost-efficiency, while other scenarios show a much less pronounced increase (10-11 EJ). The exogenously implemented renewable energy target also entails a relatively higher penetration of non-biomass renewable energy sources, namely solar and wind, in the EU_FF55 and EU_NECP scenario. These results are summarised in Figure 6. In addition, similar results for EU Member States are presented in Figure 7.

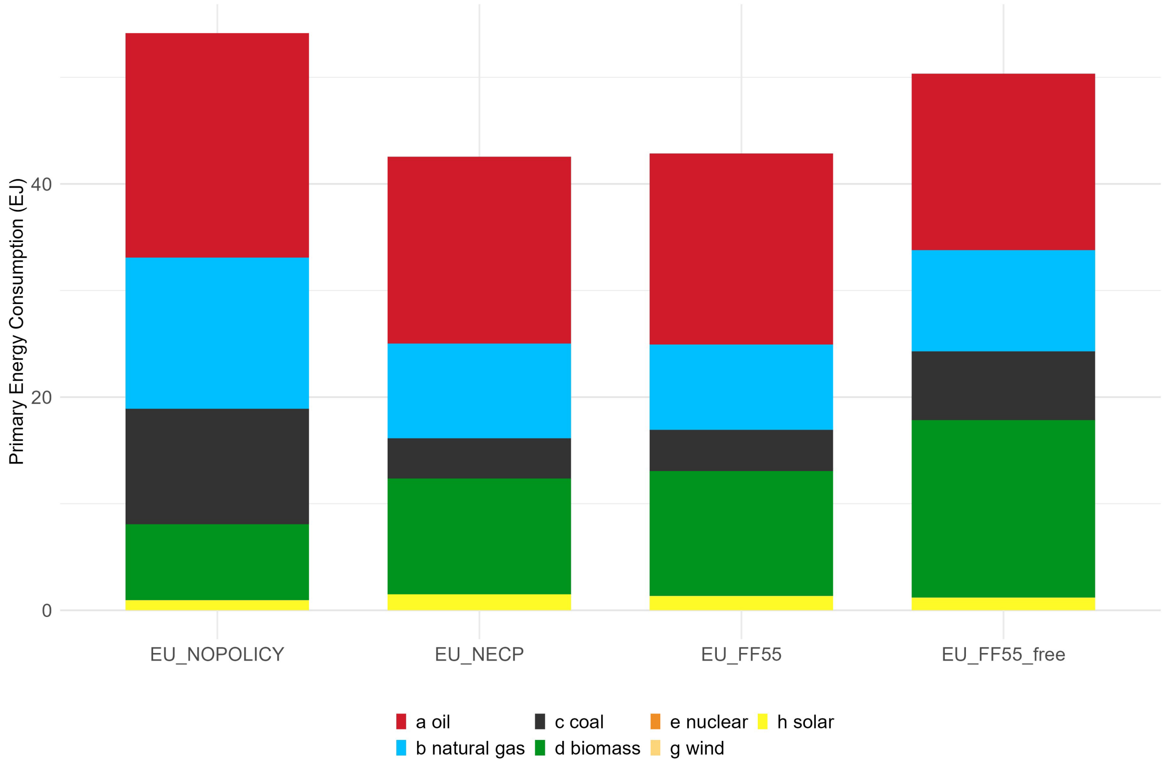

Figure 6: EU-wide primary energy consumption in 2030, by scenario and fuel (EJ)

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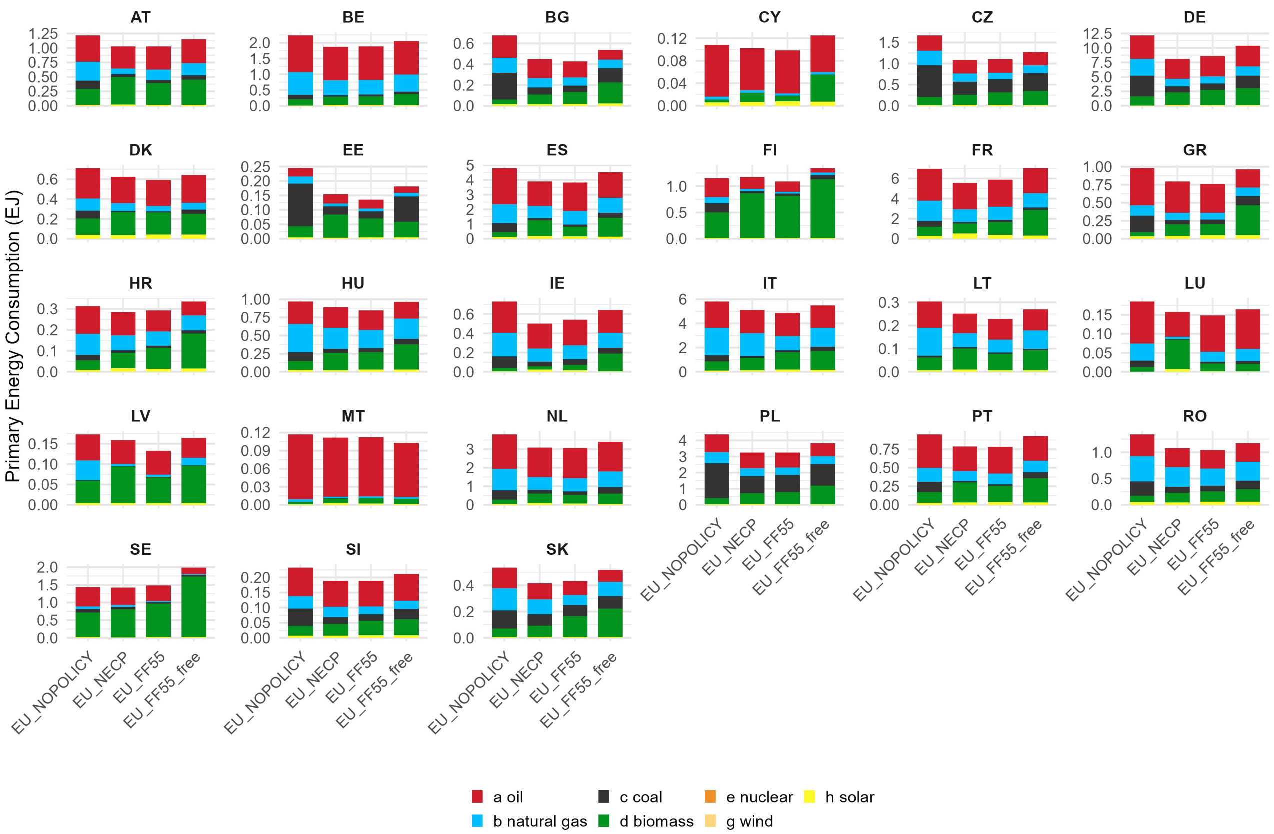

Figure 7: Primary energy consumption in 2030, by scenario, fuel, and Member State (EJ)

2.3.2 Price changes

The abovementioned changes in the energy mix will, in turn, affect energy prices and, indirectly, the prices of other end-use sectors (e.g., food) across different EU Member States. These price changes vary significantly across scenarios. In the less prescriptive scenarios, such as EU_FF55_FREE, mitigation efforts are distributed based on a "least-cost" approach across countries and sectors, and the projected price increases are relatively moderate. In contrast, scenarios where mitigation is exogenously directed toward specific sectors in line with actual policy goals (e.g., EU_FF55) and also towards specific countries (e.g., EU_NECP), tend to result in higher price increases. The following Figure 8 illustrates the changes in prices for three key categories, namely electricity, gas, and transport fuels, across alternative policy scenarios, relative to the baseline scenario (i.e., EU_NOPOLICY). These sectors were selected for visualisation due to their significant share in average household expenditures. Additionally, we focus on a representative subset of regions that reflect the diversity of the EU bloc, capturing variation in both geographic location and economic size.

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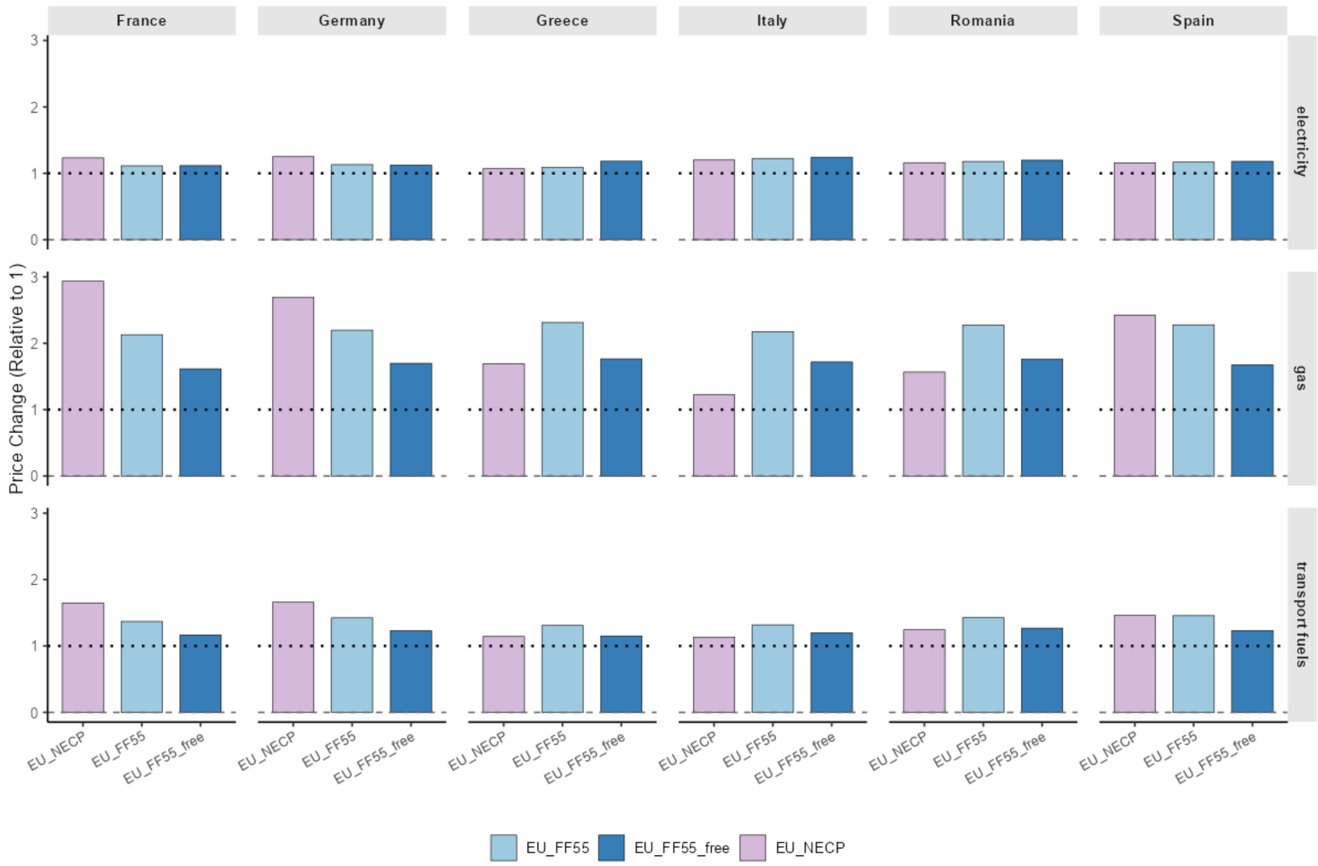

Figure 8: Price changes across scenarios by region and sector in 2030. Indexed changes, compared to the EU_NOPOLICY baseline.

2.3.3 Socioeconomic impacts

This section presents the distributional and social impacts associated with the price changes in the alternative emission reduction scenarios (as shown in Figure 8). We explore the socioeconomic effects by Member State, as well as distributional and inequality impacts at both the EU and national levels. Importantly, the results only look at the direct welfare impact[9] from price changes, assuming consumption patterns in 2015, and do not consider the potential alleviating impacts of redistributing tax revenues and price-induced consumer responses, including technology switches. While most of the results are focused on EU-wide, all the country-level results can be downloaded from an open source Zenodo repository[10].

2.3.3.1 Households Welfare Impacts by Member State.

Figure 9 depicts the average welfare impacts by Member states. The figure shows that, on average, the scenario with the lowest welfare impacts at the EU level is the EU_FF55_free scenario, followed by EU_FF55 and EU_NECP, although the aggregated impact of the latter two scenarios is very similar. These results, on average at the EU level, align with expectations, as the "cost-optimal" EU_FF55_free is the most cost-efficient scenario, given that the model assumes the entire EU reduces emissions through the lowest possible carbon price. In contrast, the

[9] For our analysis, we consider welfare as the capacity of the households to consume. Hence, the welfare impact of each household has been calculated based on the total household expenditure, since it is considered a better proxy for the permanent income of families as it undergoes a lower fluctuation than income both in the medium and long term. Therefore, the analysis is closely linked to the economic capacity of households, rather than to other factors that may affect overall well-being.

[10] https://zenodo.org/records/15622172

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other scenarios (EU_FF55 and EU_NECP) include current policies proposed by the European Commission and various Member States, which not only aim to reduce emissions at minimum cost, but also incorporate additional policy parameters into the equation, such as the heterogeneous nature of mitigation capacities in different sectors and Member States, support for specific key technologies, and other policy goals such as public health, industrial competitiveness, and energy security.

If we explore the differences between Member States, Figure 9 shows that under the EU_FF55_free scenario, welfare losses range from 13% in Poland to below 2% in Sweden. Likewise, despite some differences, under the EU_FF55 scenario the most affected countries remain similar to those in EU_FF55_free, with Poland being the most affected and Finland the least affected, followed by Sweden. However, under the EU_NECP scenario, the most affected Member State becomes Luxembourg, followed by Ireland, while the least affected is now Bulgaria. Moreover, the EU_NECP scenario shows the greatest differences when compared to EU_FF55_free, highlighting once again that the policy packages implemented by different Member States are not solely aimed at minimising the cost-efficient reduction of emissions across the EU.

As can be seen in the EU_FF55_free, the largest welfare losses are mainly concentrated in Central and Eastern European Member States. In addition to Poland, the Czech Republic, Slovakia, and Hungary experience the highest welfare losses. Central and Eastern EU Member States (CE-MS) are characterised by a high share of energy consumption and energy expenditure. Therefore, these are the most affected countries by the introduction of high carbon prices. Moreover, carbon pricing would significantly increase consumer prices due to relatively low initial price levels, for example, due to lower current energy taxes on products consumed by households. In contrast, a carbon tax would have a smaller effect on households in Sweden, Finland, and Denmark.

As mentioned before, despite the differences, the EU_FF55 scenario follows a similar trend when compared to EU_FF55_free. However, under the EU_NECP scenario, the differences compared to the other scenarios are more pronounced. For example, in Member States such as Bulgaria, Romania, Hungary the welfare impacts are much smaller under the EU_NECP scenario, whereas other countries such as Luxemburg, Ireland or Netherlands suffer a greater impact under this scenario, due to the relative differences in national climate policy stringency compared to what would be attributed when policy targets are achieved at the EU-wide level. Although it depends on each Member State, under the EU_NECP scenario we observe that most of the smaller impacts are in CE-MS, with the exception of some countries such as Poland and the Czech Republic, which continue to experience significant welfare impacts.

In the EU_FF55_free scenario, the carbon price ensures the most cost-efficient emission reductions at the EU level, without considering the differing costs faced by individual Member States. However, the EU_NECP establishes specific targets for each Member State based on their Nationally Determined Contributions (NDCs). Hence, our results show that under the EU_NECP scenario, it is possible to achieve the same level of emission reduction at the EU level, but with lower welfare implications for some Central and Eastern Member States (CE-MS). Although EU_FF55_free, or even EU_FF55, are likely more cost-efficient in reducing emissions, the EU_NECP results highlight clear trade-offs between cost-efficiency and the distributional impacts of climate policy between Member States.

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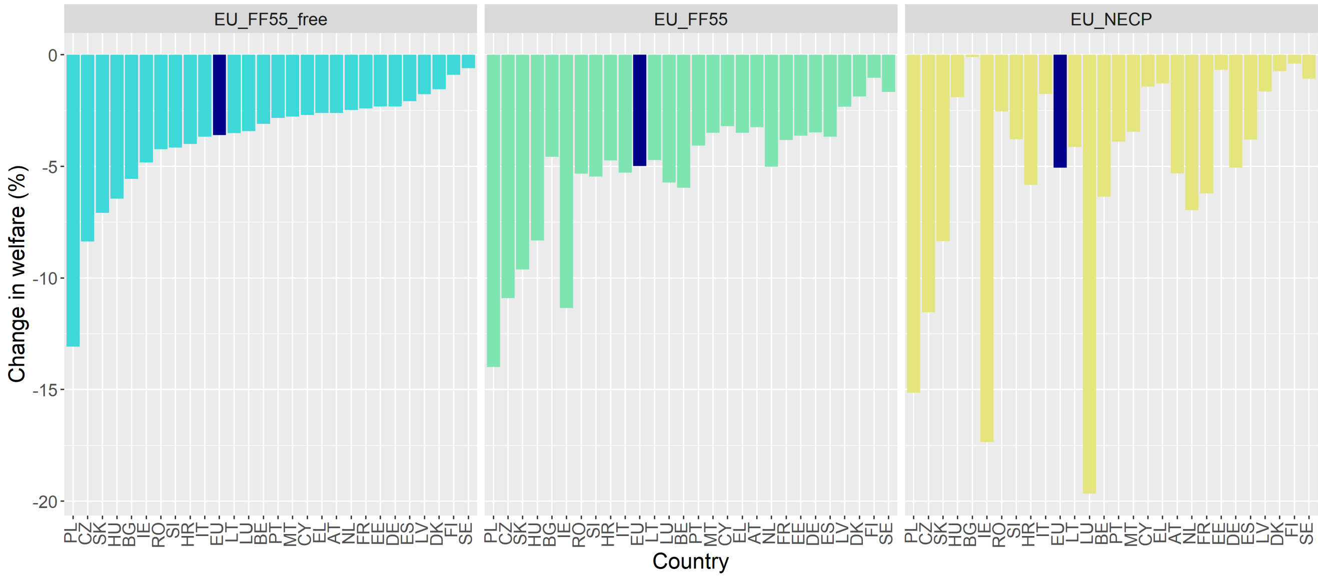

Figure 9: Welfare impacts by Member State (ordered by the welfare impact) and scenario (%) by MEDUSA

2.3.3.2 Vertical analysis

2.3.3.2.1 Distributional impacts at EU level

Figure 10 shows the distributional welfare impact of the policy scenarios by EU expenditure deciles[11], i.e., we distribute the 200.000 households included in MEDUSA as if the EU was a single economy, allowing us to explore the distributional effects of the different emission reduction scenarios. In terms of the distributional impacts, Figure 10 reveals that welfare will be asymmetric across the income distribution but similar across scenarios. Thus, in policy scenarios households belonging to the middle low deciles (from D1 to D4, i.e., households with lower income) would be more affected by the decarbonisation cost in the EU, whereas households in higher income brackets are less affected by the policy scenarios. Therefore, in line with many concerns, and in the absence of redistributive policies, the cost of the emission reduction in the EU would have regressive impacts at the EU level.

[11] Expenditure is used since it is considered a better approximation of permanent household income (Goodman, & Oldfield, 2004). Equivalent expenditure deciles are calculated from household expenditure relativised by the modified OECD equivalence scale. The modified OECD scale values the reference person in the household at 1, all other persons aged 14 and over at 0.5, and all other persons under 14 at 0.3.

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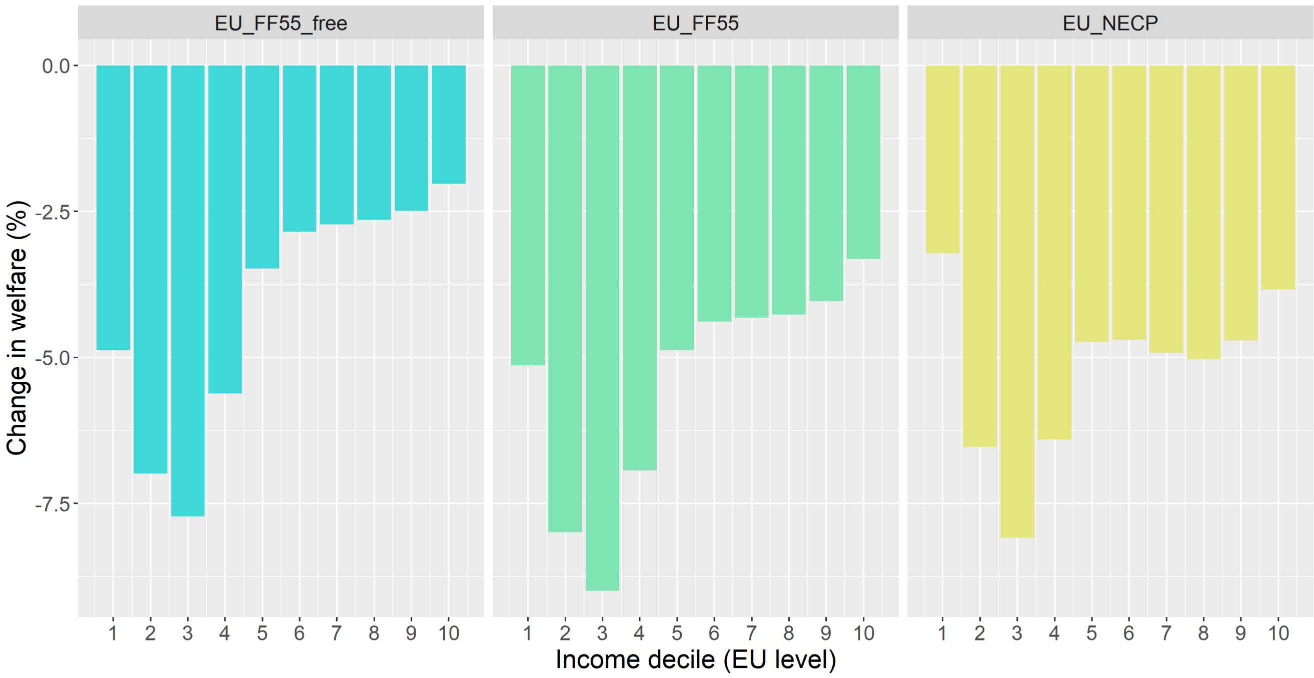

Figure 10: Welfare impacts by income groups at EU level (%) by MEDUSA. D1 is lowest income households in the EU whereas 10 is the wealthiest

These distributional results are directly related to the income distribution at the EU level, as well as the varied impacts among Member States. As seen in the average welfare analysis by country (see Section 2.3.3.1), the Central and Eastern Member States (CE-MS) would experience larger welfare impacts, given their current larger dependency on fossil fuels. Simultaneously, these regions are associated with lower income groups in the EU income distribution. This explains the regressive impacts at the EU level on the different scenarios, as the households most affected by the reform are in countries with lower average incomes that need to increase their current taxation more substantially.

Although the regressive tendency is similar in the different scenarios, the results indicate that welfare impacts are lower under the EU_FF55_free scenario, compared to the EU_FF55 or the EU_NECP scenario. This outcome is clearly related to the previous analysis (see Section 2.3.3.1), which already shows that the EU_FF55_free scenario is the most cost-efficient policy. However, the trend across EU income groups differs slightly between scenarios, with the EU_NECP scenario showing the lowest welfare impacts for the bottom income groups in the EU, and highest welfare impacts for the above-median income groups. As we already highlighted before, under the EU_NECP scenario, lower costs for some CE-MS also mean that lower-income groups in the EU (i.e., the first income deciles) are less affected by decarbonisation. The lower welfare impacts in EU_NECP is specially more pronounced among very low-income groups (D1). This suggests that the EU_NECP scenario is less regressive than the FF55 scenarios at EU level. These results highlight how the design and implementation of emission reduction policies can significantly influence welfare outcomes at the EU level and shape their distributional implications, while also highlighting the required shape and focus of potential social policies (such as the SCF) to compensate regressive implications from climate policy.

2.3.3.2.2 Distributional impacts at average national level

Although the previous analysis offers relevant insights and results about the distributional impact of the cost of the decarbonisation at the European level, it does not allow us to analyse how these policies can affect national inequality in the different Member States. Therefore, Figure 11 presents the distributional welfare impact of the decarbonisation scenarios by national expenditure deciles of each country.

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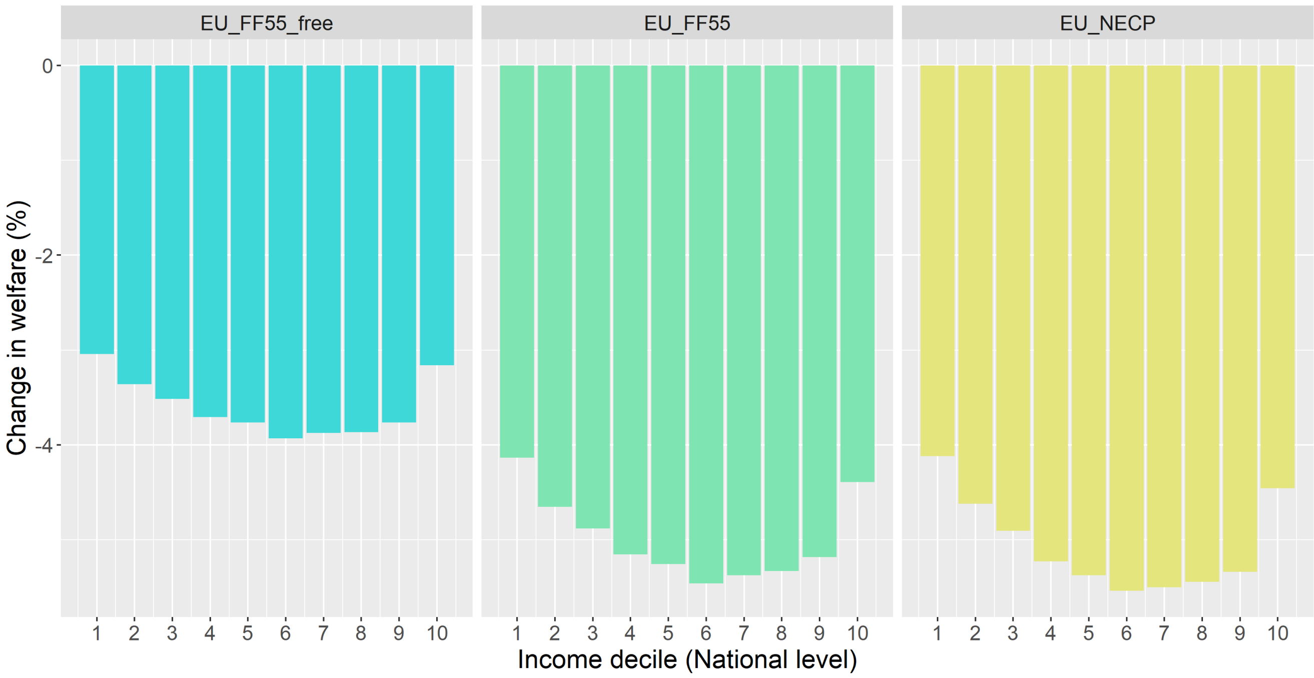

Figure 11: Welfare impacts by national income groups and scenario by MEDUSA. D1 is lowest income households in each Member States whereas 10 is the wealthiest.

At the national level, the impact is less regressive, with welfare losses being higher for the middle- and high-income brackets across all scenarios. This contrasts with the EU-wide results (Figure 10) discussed earlier, which show that the emission reduction scenarios could increase inequality at the EU level. As we also showed in the analysis on the previous deliverable D5.2, the distributional impacts can be explained by the consumption pattern of the energy products of European households (see Figure 12). Although, as we have seen in the price analysis, not only energy products are affected by the emission reduction scenarios, they are the commodities most affected. Therefore, at the national level, we can see that energy expenditure constitutes a significantly larger share of total spending for lower-income households compared to higher-income ones. It is also important to note the differences between energy products: transport fuels constitute the largest share of expenditure for middle-income households (as private car ownership is less common among lower-income households), whereas electricity accounts for a larger share among the poorest.[12]

While this is the average picture across the income distribution, there are important differences in the structure of energy consumption both between and within MSs. Average energy expenditure as a share of household income among MSs ranges from around 4% in Malta to nearly 14% in Poland, with significant differences in the shares of different fuels among the MSs. Within MSs, we find that in lower-income MSs, transport fuel expenditure tends to increase more in proportion with income compared to the EU-wide pattern of transport expenditure, while the EU-wide pattern is more typical of higher-income MSs. Electricity, however, makes up the largest share of expenditure of lower-income households across the vast majority of EU MSs. This is mainly because in lower-income households, a larger proportion of income is allocated to covering the basic needs. Electricity is a fundamental necessity for daily living and low-income households allocate a higher percentage of their income to essential utilities. Furthermore, low-income households reside in less-energy efficient housing, which lead to

[12] Our results are directly connected to the current consumption patterns of households, but not to their use of essential utilities or minimum living standards. Therefore, our analysis does not examine the different behaviours of households or the extent to which they may use or overuse certain energy commodities.

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higher electricity consumption due to inefficient insulation and outdated appliances.[13]

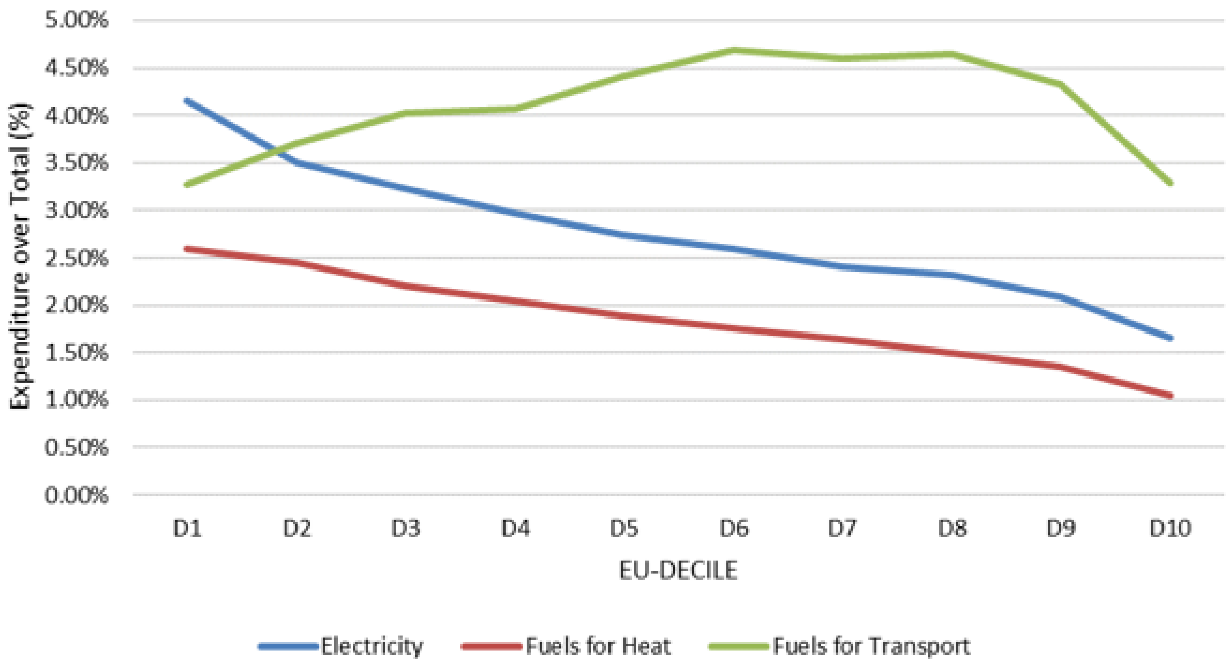

Figure 12: Energy expenditure pattern in by EU-Deciles in 2015 (%)

Considering these consumption patterns and examining the price impacts of the different scenarios, we can see that higher prices for fossil fuels used in transport are a key factor explaining why upper-middle-income groups in many Member States are more affected by emission reductions in the EU, regardless of the policy design. Therefore, although in many Member States, and across different scenarios, electricity and heating prices are significantly impacted, thus disproportionately affecting the poorest households, this effect is clearly offset by the larger impact of transport fuel prices, which causes the policies to have a greater effect on middle-income households (Figure 11).

Moreover, the effect on different Member States also plays a key role in shaping the average national income impacts. As we have seen, in most scenarios, Central and Eastern Member States (CE-MS) are more affected by carbon pricing, as they are more dependent on fossil fuels than Western Member States. Therefore, the greater impact on transport prices, combined with the fact that CE-MS are more affected overall, means that in these countries, middle- and higher-income groups are more impacted by the policies. This is because transport fuel expenditure tends to increase more with income in these Member States.

[13] One of the main limitations is that we are not exploring the impacts of hidden energy poverty; that is, we are analysing vulnerability among those who are able to consume, and whose consumption represents a large proportion of their income, but not among households that cannot afford essential energy services.

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2.3.3.3 Horizontal Distributional analysis

Emission reduction policies can have distributional impacts not only across income groups but also based on other socioeconomic characteristics, which may be essential for understanding the socioeconomic implications of the energy transition in the EU. The different socioeconomic characteristics included in MEDUSA allows us to develop horizontal and granular analyses, exploring impacts according to different household socioeconomic characteristics.

In this section, therefore, we analyse how different socioeconomic groups could be affected by the implementation of large-scale decarbonisation efforts in the EU. More specifically, we focus on two socioeconomic characteristics that are central to the policy debate and essential for understanding the distributional implications and ensuring that the policies are publicly acceptable: (i)households by gender, and (ii) households along the rural–urban dimension.

2.3.3.3.1 The gender dimension of the achievement of large emission reductions in the EU

As we mentioned in the previous deliverable D5.2, despite the calls from international community to integrate gender dimension into all policies and analyses, the gender dimension of energy and climate policies has not often been addressed in depth within European policy frameworks (Alonso-Epelde et al., 2024). Therefore, in this section, we provide new evidence from our microsimulation to assess the role that gender can play in various large-scale emission reduction options in the EU. Figure 13 shows the welfare impacts of the different scenarios by the gender of the reference person of the households (i.e. the breadwinner of the households) at EU level.

Figure 13: Gender impacts of the emission reduction scenarios (%) by MEDUSA

We can clearly see how the gender of the reference person plays a relevant role in the welfare impacts that we can expect from the different scenarios. Hence, in all scenarios the larger cost of the products due to the emission reduction involve larger welfare losses on male-headed households. This impact is, once again, explained by the higher cost of fossil fuels for transport. Car use and ownership have a clear gender bias, with male-headed households being the ones that own and use cars the most. One factor that can explain this gender bias is the observation that households where women are the reference persons often belong to low-income groups with distinct socioeconomic characteristics. On EU average, fuel expenditure as a share of household expenditure by the gender of the reference person is around 4.4% for male-headed households and only 3.5% for female-headed

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households. However, this difference is even larger among low-income groups, in the first quintile, female-headed households dedicate only 2.5% of their total expenditure to transport fuel, whereas male-headed households dedicate 4%.

The results across different scenarios follow a similar pattern to those previously explored at the income level. The EU_FF55_free scenario shows the lowest welfare impacts for both female- and male-headed households, once again indicating that the free scenario is the most cost-efficient policy option. Moreover, since many of the price impacts remain similar between EU_FF55 and EU_NECP, the average welfare impact by gender is also similar in both scenarios.

Finally, to explore deeply the role that gender can play in the socioeconomic impacts of the different emission reduction scenarios, we have included an intersectional approach in our analysis, considering both gender and the economic classes of different households. Individuals experience oppression or privilege based on their belonging to multiple social characteristics(Cho et al., 2013; Djoudi et al., 2016; Kaijser & and Kronsell, 2014). Therefore, in any gender analysis, it is relevant to include the intersectionality approach as an analytical tool to examine how the articulation of different interconnected socioeconomic categories (e.g., class, gender, race, etc.) can be crucial in understanding the performance and impacts of a policy. Therefore, Figure 14 shows the distributional impact based on the gender of the household reference person by income quintile.

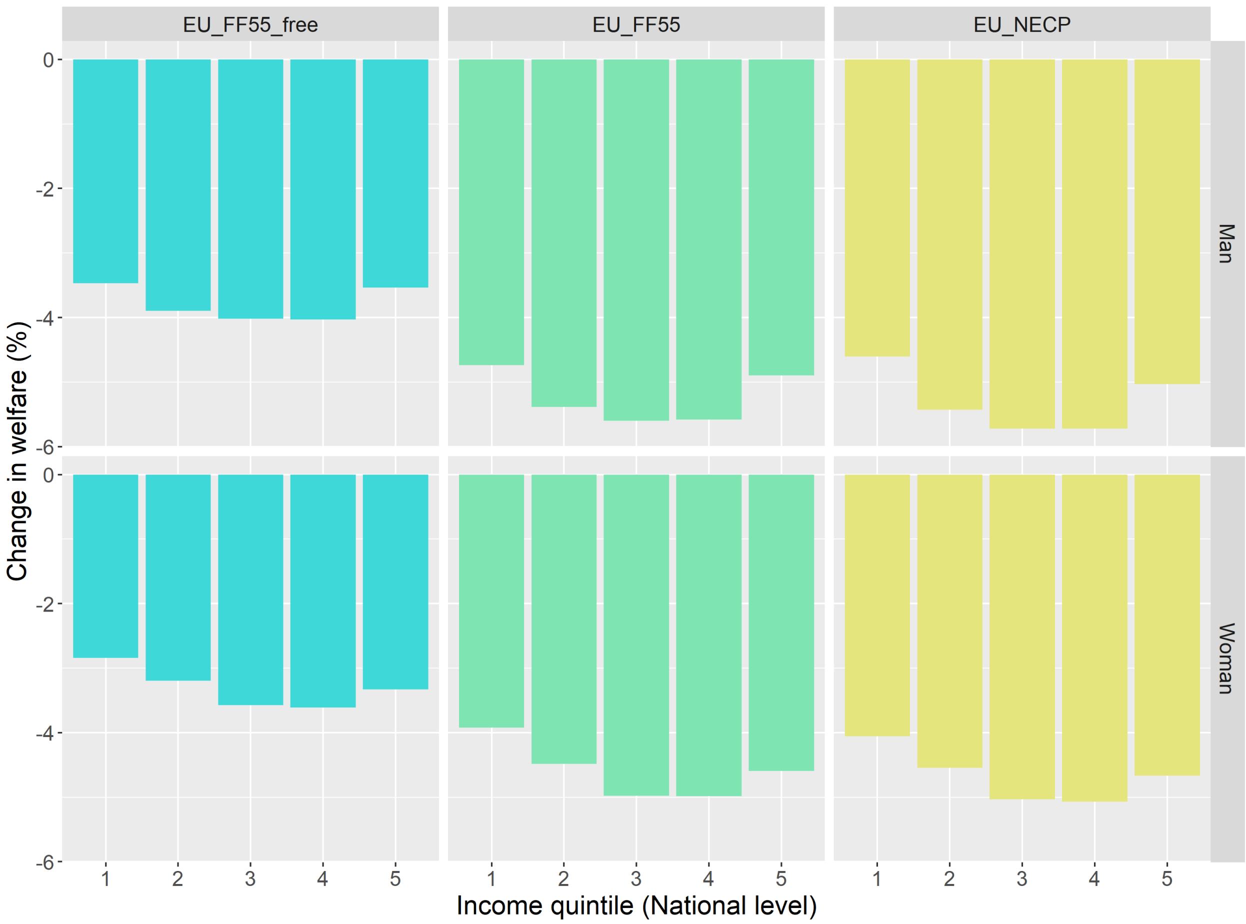

Figure 14: Welfare impacts by gender and income group (%) by MEDUSA

It can be observed that the distributional impacts follow a similar path in terms of progressivity or regressivity of the scenarios, as explained in the analysis of the national income distribution (see previous section). This demonstrates that, although gender may play a relevant role in explaining the distributional implications of the emission reduction, the income profile of the households still predominantly influences the welfare impacts resulting from the different applications of the policy. However, there are some noteworthy differences to mention.

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We can observe how the differences in welfare impacts between women and men, regarding the reference person of the households, remain similar for all income groups. This fact reflects that the distinct consumption patterns between women and men not only depend on the economic capacity of the households, but there are also other socioeconomic factors that explain why women have a more environmentally friendly consumption, such as greater use of public transport.

2.3.3.3.2 Rurality impacts of the achievement of large emission reductions in the EU

Another dimension that is key during the energy transition is the zone of residence and the rurality dimension of the households, as we have also seen in some analysis in the previous version of the deliverable (D5.2). Therefore, in this section we focus on the rural dimension of the households based on the population density of the zones of residence: sparsely populated areas; intermediate areas; and densely populated areas[14].

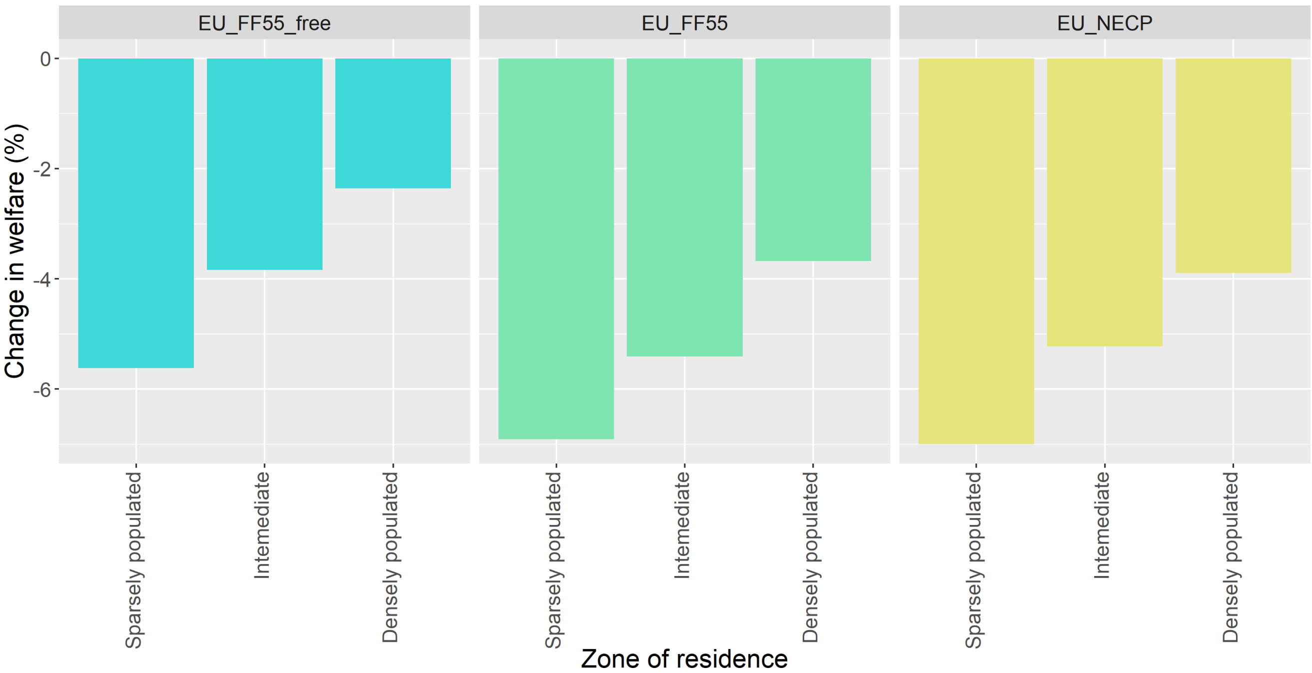

Figure 15: Welfare impacts by density of population and income group (%) by MEDUSA

Figure 15 shows that rural households (those residing in sparsely populated areas) are the most affected by price increases under the emission reduction scenarios. These households dedicate a larger proportion of their income to mobility and are therefore more negatively impacted. Residents in rural areas or areas with low population density tend to rely more on private vehicles due to the lack of alternative public transportation options and their greater mobility needs (Flues & Thomas, 2015; Tomás et al., 2020, 2023).

As in the gender analysis, to explore more deeply the role that rurality can play in the socioeconomic impacts of different emission reduction scenarios, we have adopted an intersectional approach in our analysis, considering both population density and the economic class of households. On average, as shown in Figure 15 and further illustrated in Figure 16, welfare impacts are higher in rural areas, particularly under scenarios that are less cost-efficient than EU_FF55_free. However, when disaggregated by income group, the results vary depending on the area in which households reside. For example, households living in urban (densely populated) areas exhibit a

[14] For rurality, densely populated is defined as those households in populations with at least 500 inhabitants/km^2; Intermediate is defined as those households in populations with between 100 and 499 inhabitants/km^2); and Sparsely is defined as those households in populations with less than 100 inhabitants/km^2.

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similar income-based distribution to that shown in Figure 11, with middle-income groups being the most affected by the emission reduction scenarios. In contrast, as population density decreases, the policy scenarios become more progressive, with higher-income households being the most affected. This impact is more pronounced among rural households and in the EU_NECP scenario, where the difference in impacts between low- and high-income groups is greater. This reflects the fact that in rural areas, income inequality is higher, and access to and use of private vehicles is more strongly associated with higher-income groups. However, it should be noted that the results shown in Figure 16 reflect the EU average, and the impacts may vary when the analysis is downscaled to the Member State level.

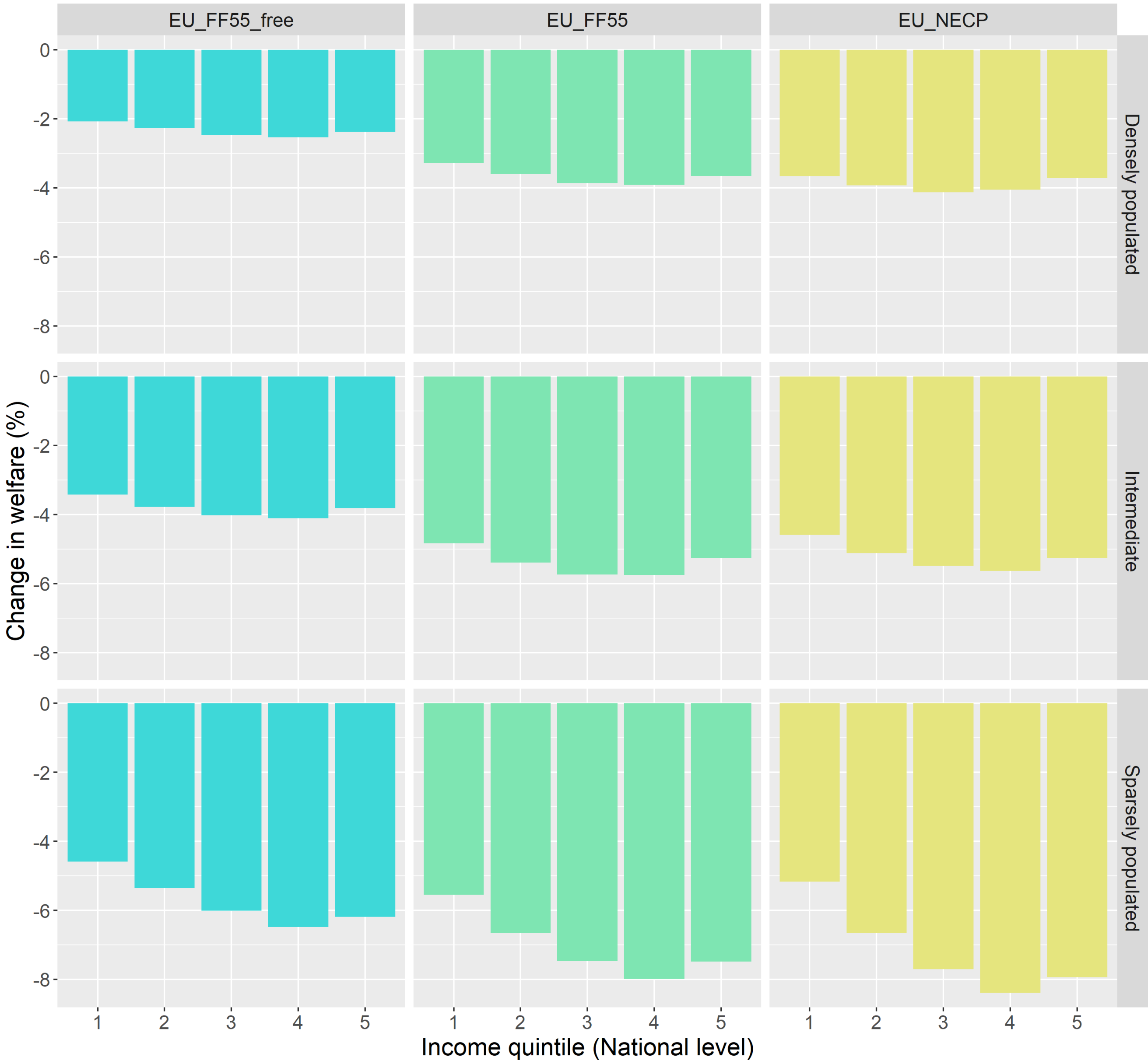

Figure 16: Welfare impacts by density of population and income group (%) by MEDUSA

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2.4 Policy implications

The European Union is facing a key moment to achieve the ambitious targets set out in the Fit for 55 package. Hence, in the coming year, it should implement crucial carbon and environmental policies that will have significant economic and societal impacts, such as the extension of the Emissions Trading System to the building and transport sectors (ETS II), the Social Climate Fund (SCF), or the new Energy Taxation Directive (new ETD). To ensure the success of these policies, it is essential to understand from the very beginning how different emission reduction scenarios and policies may affect inequality and thus implement compensation mechanisms that could mitigate these impacts and ensure a just transition.

This analysis demonstrates that the implementation of ambitious climate policies in the EU will directly impact the energy mix, driving a transition from fossil fuels to cleaner energy sources. This shift is expected to influence energy prices, which will, in turn, affect household energy expenditures and have broader implications for social inequality. In this context, several key insights and lessons can be drawn regarding the distributional effects of the energy transition. First, the **introduction of ambitious carbon policies in the EU will play a key role in increasing current inequalities between Member States**, although the national inequality impacts are not so clear. Second, we have seen that although introducing a general carbon price across the EU to achieve the Fit for 55 emission reduction targets (EU_FF55_free) may be the most cost-efficient option analysed, it may not be the most desirable when inequality and distributional implications are considered. This option would impose higher costs on Member States that are more dependent on fossil fuels, countries that also tend to have a larger share of lower-income households. As a result, the policy would have negative distributional implications at the EU level, affecting low-income households more severely, while having a smaller impact on those in wealthier Member States. This shows that, to achieve a just transition in the EU, compensation and support mechanisms will be needed to offset the possible regressive impacts, especially in lower-income Member States. However, our results also show the importance of the emission reduction design, and **with more country-focused approaches, such as those in the EU_NECP scenario, the regressive policy implication would be relatively less severe**. This is because they not only consider the overall and average cost of emission reductions at the EU level but also account for the varying capacities of different Member States to reduce emissions without imposing excessive costs on low-income households. Finally, our results suggest that although emission reductions may have a greater impact on inequality at the EU level, **the distributional effects at the national level may be less regressive and will depend on which commodities are most affected in each Member State**. Therefore, if emission reductions lead to higher costs for fossil fuels used in transport while keeping electricity prices relatively stable, the policies may be less regressive, affecting middle-income groups more than low-income ones. However, these impacts may vary across Member States. In terms of horizontal distributional impacts, our results underscore that, **while income remains the primary determinant of the distributional impacts of emission reduction policies, gender-related consumption patterns also play a significant role**. Women, tend to experience smaller welfare losses from higher fossil fuels prices for transport due to more environmentally friendly consumption behaviours. The analysis also finds that **rural households are more affected due to higher mobility needs and limited transport alternatives**.

To ensure fairness, policies and carbon revenues should be tailored by both income and population density, with targeted support for vulnerable rural populations and consideration of regional disparities. These results can therefore be relevant for informing further support mechanisms, such as those that will be implemented in the context of the Social Climate Fund.

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3 Passenger transport decarbonisation under different equity considerations

This chapter focuses on the distributional aspects of climate change mitigation in the passenger transportation sector. It applies a novel method to explore a variety of emission pricing schemes and look at the distributional impacts in terms of income and service access.

3.1 Introduction

Literature on the equity impacts of climate change mitigation tends to focus on the potential or empirically measured regressive impacts of climate change mitigation policies, or on achieving equity through revenue recycling of pollution taxes (Vona, 2023; Weitzel et al, 2023; Bohringer et al, 2019; García-Muros et al, 2022). On the other hand, literature on the topic of energy poverty tends to focus predominantly on basic energy needs for residential purposes (González-Eguino, 2015; Pachauri & Spreng, 2011), and often on current poverty-driven lack in energy services, in contrast to potential future energy poverty in the context of climate change mitigation (Sovacool et al, 2023; Bednar & Reames, 2020; Che et al, 2021). However, relatively less attention has been given to the impact of climate policy on transport service poverty in a climate policy context (Martiskainen et al, 2021), despite transport being the largest energy-consuming sector globally (IEA, 2023). One important reason is that transport demand is traditionally seen as a relatively luxury good, hence not seen as relevant for equity or poverty considerations as residential energy use (Sovacool, 2011; Fouquet, 2014).

Currently however, a large amount of energy and climate policies are directed towards passenger transportation, including both taxes for polluting cars and fuels, as well as subsidies for clean transport modes. At the same time, the upfront capital costs of clean private transport alternatives (e.g. electric cars, EVs) are significantly higher than that of conventional private transport technologies (e.g. internal combustion engine, ICE), despite the total costs per passenger-kilometre over the entire lifespan of the car being already similar around 2025. This creates a potential lock-in for poorer households into more polluting technologies that face continuously higher taxation rates (Martiskainen et al, 2021; Furszyfer Del Rio et al, 2023). At the same time, polluting transport modes like aviation have become more accessible to all households throughout the past decades, but the lack of investment in clean alternatives for aviation (and the lack of incentives to spur such investments, as aviation fuels are basically undertaxed anywhere in the world (Larsson et al, 2019)) causes that uniform carbon pricing will inevitably affect the access to aviation for poorer households (Büchs & Mattioli, 2022). Moreover, historical energy transitions have often been driven by wealthy consumers demanding higher quality goods and services, which consequently grew from niche to mainstream technologies (Fouquet, 2010). Particularly the transportation sector is one with traditionally high-income elasticities (Fouquet, 2014), implying a strong "niche-to-mainstream" effect. This effect has also been observed in the development of the EV market, which traditionally focused mainly on more exclusive high-end market segments, while this triggered the construction costs to go down quickly due to a rapid learning curve, and EVs are increasingly being sold to lower-end market segments (Jugé et al., 2025).

In this chapter, we simulate scenarios for global decarbonisation of passenger transport towards 2050 under different equity and sustainability considerations. We propose different emission taxation schemes specifically for the passenger transport sector, including heterogenous taxes between income groups worldwide, while also exploring potential impacts of such schemes on technological learning. We analyse the outcomes in terms of emissions, policy burden, and access to transport services for different income deciles.

3.2 Methodology

For the purpose of this chapter, a state-of-the-art version of GCAM was used with distinct income deciles in transportation demand, among other sectors, named GCAM-GRAPHICS (Sampedro et al., 2025). In this version, passenger transport demand is divided by income deciles for each of the 32 model regions, using estimated

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shares. The composition of transport modes by decile is estimated based on the shadow value of time. Future demand for transportation services is mainly driven by per capita income and the price of the services, which includes the shadow price of time spent in transport modes (calculated as the inverse of the transport speed multiplied by the average hourly wage).

Using this version of the model, one reference, and four policy scenarios were simulated, applying two different equity considerations, both with and without technological learning:

1. Reference: No climate policies applied, serves as a reference for comparing transportation costs and access in policy scenarios.
2. "Pay-to-pollute" principle: globally tradable permits for CO_2 from passenger transport (with and without technological learning)
3. "Equal-emissions" principle: isolated markets for each region-decile combination, converging towards equal per capita emissions in 2050 (with and without technological learning)

In all non-reference scenarios, total passenger transport emissions decrease from 5 Gt CO_2 in 2019 to ~1.5 Gt CO_2 in 2050. See Figure 17 for a graphical context of the scenarios.

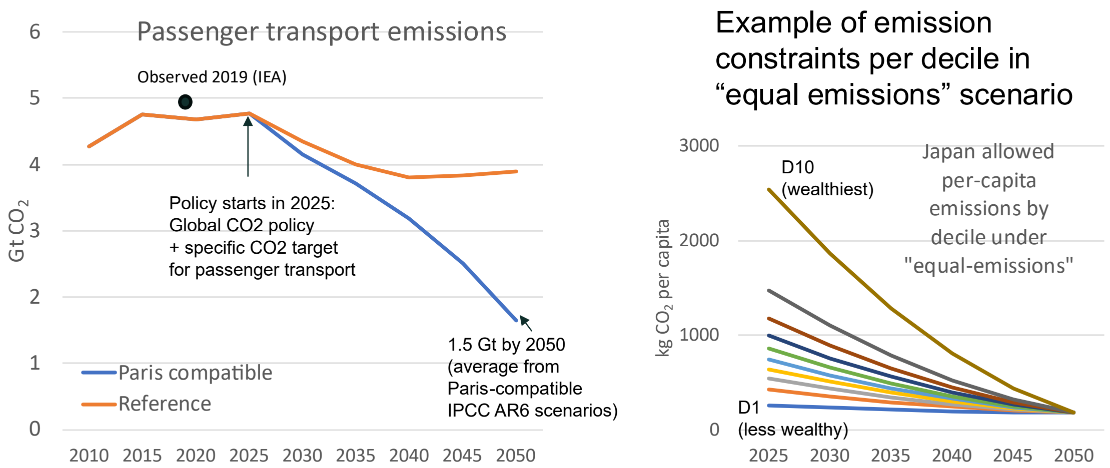

Figure 17: Scenario context. Total passenger transport emissions in reference and policy scenarios (left), and example of per capita emission allowance over time in "equal emissions" scenario.

To avoid policy scenarios diverging strongly towards biofuels, leading to significant uncontrolled land use change (LUC) emissions and biodiversity impacts, global bioenergy use is constrained to 118 EJ by 2050, in line with the average consumption in Paris-compatible IPCC AR6 scenarios (Byers et al., 2021). Also, the full supply chain emissions from biofuel production (including net land use change emissions as a result of land competition) are counted towards the applied emission constraints in each scenario and charged with the respective carbon price. In line with Rouhette et al (2024), we assume the average emission footprint of biofuels is around 37 $kgCO_2/GJ$, about half that of liquid fossil fuels.

In the technological learning scenarios of this study, baseline technology costs are assumed to be consistent with the technology uptake in the reference scenario. Deviations in global technology uptake under various policy scenarios contribute to learning-induced cost reductions. The analysis centers on electric and hydrogen technologies used in passenger road vehicles and airplanes, incorporating both scale effects and cross-technology learning. A uniform learning rate of 8% is assumed, meaning that costs decline by 8% with every global doubling of cumulative technology deployment. This rate of 8% was applied based on literature pointing out that the learning rate of battery storage is around 16% (Mauler et al., 2021), and the battery making up around 50% of the total cost of an EV. This means that implicitly, we assume no learning in other EV parts, since markets for

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other parts are assumed to be relatively mature. We also assume scale effects in learning (e.g. a bigger size EV contributes more than a smaller size EV), and cross-technology learning (e.g. EVs also contribute to hydrogen motors, which require batteries as well, and vice versa). Only a single iteration of learning is applied, as further uptake-driven cost reductions are not modelled—this simplification is justified by the limited influence of such feedback under fixed emission targets.

3.3 Results

This section first looks into the results in terms of technology take-up, which is used to make assumptions about technological learning taking place until 2050. Subsequently, the distributional impacts are explored with and without technological learning.

3.3.1 Technology take-up and learning

Figure 18 shows the global technology mix for light duty vehicles and aviation under the Reference, "Pay-to-pollute" and "Equal Emissions" scenario, and the technology costs we induce from this mix applying the technological learning assumptions explained above. The scenarios with "tech learning" will apply these lower technology costs in the policy scenarios.

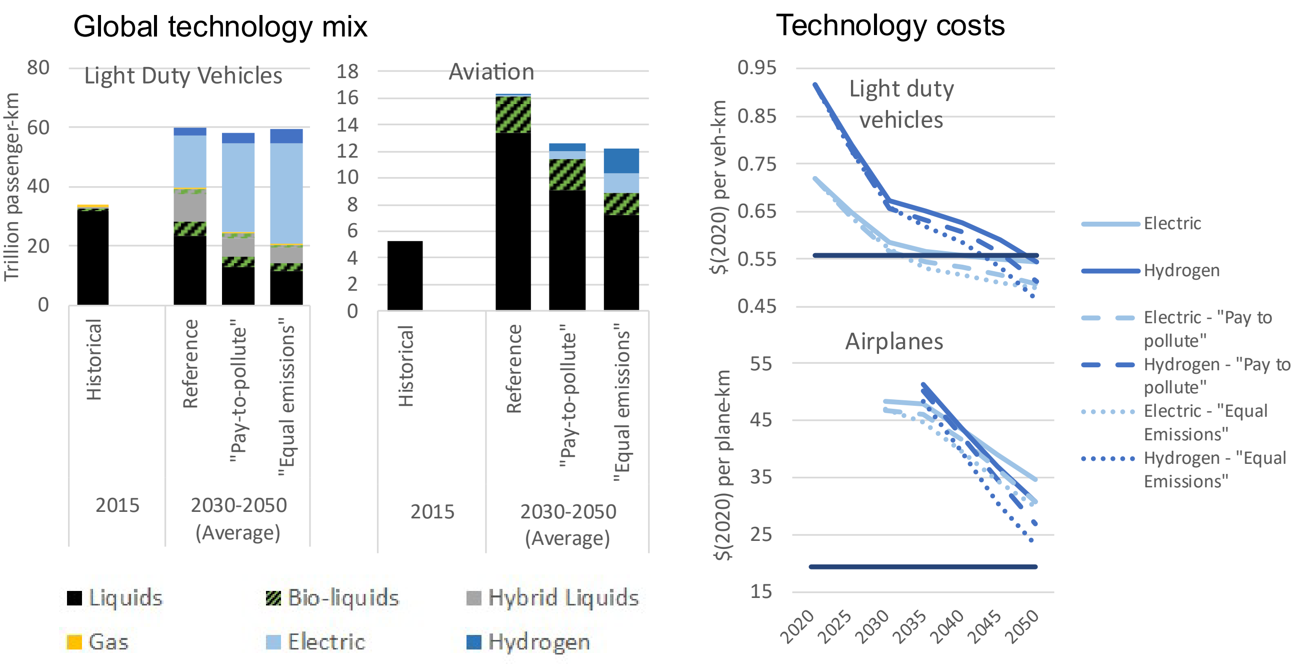

Figure 18: Global technology mix in reference and policy scenarios without learning (left). Technology costs evolution taking into account technological learning, applying a learning rate of 8% for each doubling in production (right).

In light duty vehicles (LDVs), electric and hybrid powertrains are expected to play a significant role towards 2050 also without climate policy, though its role is expected to increase significantly with climate policy, and slightly more so in the "equal emissions" scenario, driven by higher carbon prices towards wealthy consumers. Hydrogen powertrains become to play a role only beyond 2040, and also boosted by demand from wealthy consumers, its share can become non-negligible. Similar trends are obtained for other road vehicles like two-wheelers (slightly more rapid electrification than LDVs) and buses (slightly slower electrification than LDVs). Trains are almost entirely electrified from 2030 onwards, and demand is growing slightly with climate policy.

For airplanes, current-day technology is fully based on fossil liquids. In the absence of climate policy, demand for

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aviation is increasing a lot, and part for it is covered by biofuels. A common carbon price for all consumers ("Pay-to-pollute") is mostly diminishing the demand growth for aviation services, while towards 2050, a non-negligible share of electric and hydrogen powered airplanes come into the mix. Importantly, the share of electric and hydrogen powered aviation increases significantly in the "Equal Emissions" scenario, driven by high carbon prices for wealthy consumers, which are also the demanding the largest share of aviation services.

3.3.2 Distributional impacts of climate policy on passenger transport access and costs

Looking into the distributional impacts of the policy scenarios in terms of the carbon price burden and access to transport services (Figure 19), we can conclude that a "Pay-to-pollute" policy affects total transport service among all users, despite the already high inequality in transport service access in the reference. By charging a uniform carbon price to emissions from passenger transportation (of about $400 per ton of CO_2 on average by 2030-2050, required to achieve the global target of 1.5 Gt by 2050), access to total transport services is affected slightly and uniformly throughout all regions' income groups globally. However, in terms of transport service quality, the policy worsens equality, affecting access to aviation significantly more for lower income consumers. Instead, the "Equal Emissions" scenario implies heterogenous carbon prices between consumers (which is below the carbon price of "pay-to-pollute" for the less wealthy 5 billion people globally, including zero for the less wealthy 3 billion, and above the "pay-to-pollute" carbon price for the wealthier 3.5 billion), driven by higher demand from wealthy consumers. This leads to a more progressive impacts on total transport service access, sparing lower income consumers both in terms of access to transportation quantity and quality.

The induced technological learning these scenarios leads to further improves access to transport services under the same carbon budget for both wealthy and less wealthy consumers, while the net effect on total transport service access is positive for lower income consumers, driven by a zero carbon price and more economical access to mainly road transport relative to the reference scenario, driven by decarbonisation-related technological learning. The technology learning effect is significantly stronger in the "equal-emissions" scenario, alleviating also the impacts in terms of service access for the wealthier consumers. In fact, taking assumed technological learning into account, hardly any consumer is worse off in "equal-emissions" than "pay-to-pollute" over 2030-2050 in terms of access quantity and quality to transportation services.

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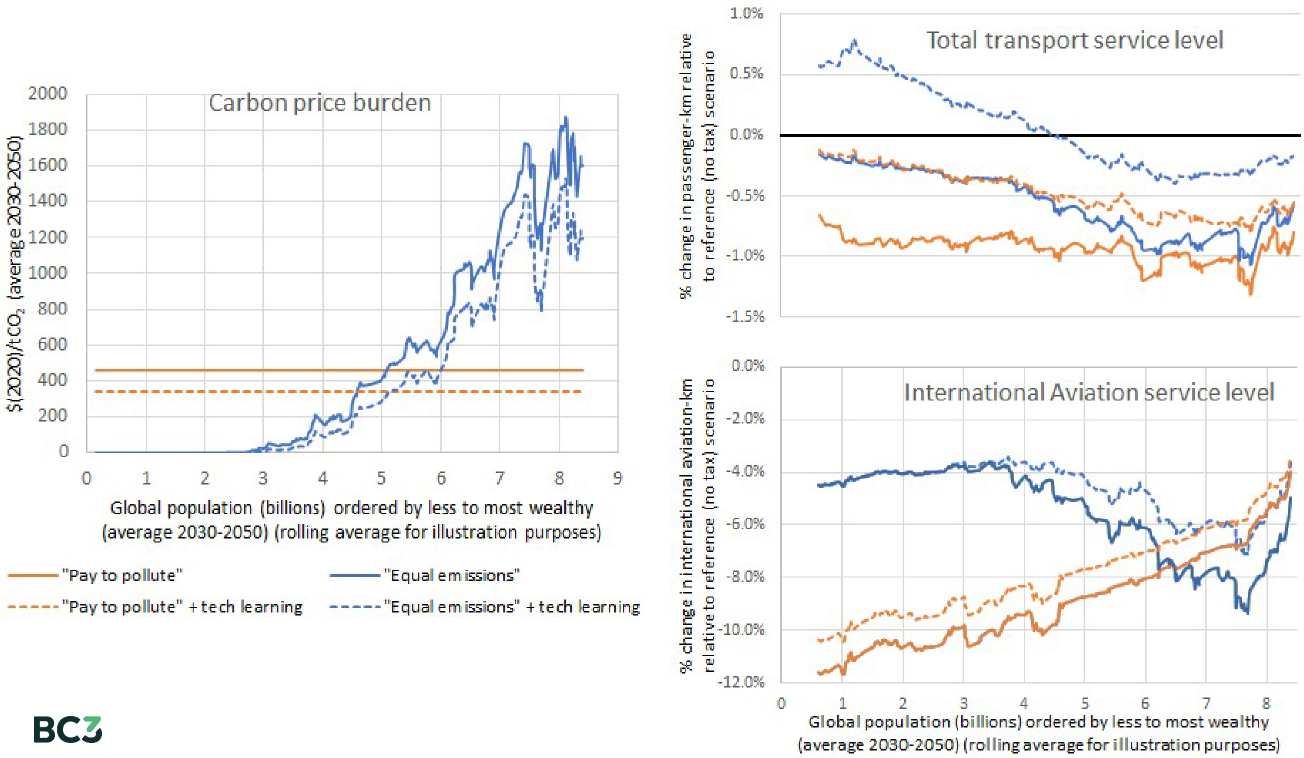

Figure 19: Results from 4 policy scenarios, ordered on the x-axis by wealth (starting with less wealthy population on the left). Carbon price burden for passenger transport CO2 in left-hand graph, access to transport services (total and international aviation) in right-hand graph.

3.4 Conclusion

This chapter has examined the distributional impacts of climate change mitigation in the passenger transport sector by simulating alternative emission pricing schemes under varying equity and technology learning assumptions. The analysis shows that policy design plays a critical role in determining not only the environmental effectiveness of mitigation strategies but also their social outcomes—particularly in terms of access to transport services and the equity of policy burdens.

Two primary policy approaches were evaluated: a uniform global carbon price on passenger transport emissions ("Pay-to-pollute") and a differentiated approach that aims for equal per capita emissions by 2050 ("Equal Emissions"). While both scenarios achieve similar aggregate reductions in transport emissions, they differ markedly in their distributional impacts. The "Pay-to-pollute" approach imposes an even burden across all income groups but worsens existing inequalities in access to high-quality transport services such as aviation. In contrast, the "Equal Emissions" scenario introduces progressive carbon pricing, shielding lower-income groups while targeting emissions reductions primarily among higher-income consumers with greater demand and higher-carbon transport preferences.

Importantly, incorporating assumptions about technological learning significantly improves the outcomes of both policy approaches—lowering costs and increasing access to clean transport technologies. However, the benefits of learning are particularly pronounced in the "Equal Emissions" scenario, which stimulates faster uptake of low-carbon technologies through higher demand among wealthier consumers. This not only accelerates cost reductions through scale and learning effects but also enhances access to decarbonised transport options for lower-income groups, even under strict carbon constraints.

Overall, the results suggest that considering equity in the design of climate policy for the transport sector reduces

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regressive impacts of mitigation, while also being beneficial when technological learning effects are taken into account. Practical examples for equitable climate policy would be the use of per capita transportation permits and a related permit market, more simple approaches like frequent flyer levies (Büchs and Mattioli, 2022), or the use of progressive carbon pricing schemes, either directly or through post-cycle tax returns (Frank, 2008). Desiging carbon pricing mechanisms that reflect differentiated responsibilities and capacities across income groups—while actively promoting technological innovation—can ensure that climate goals are met without sacrificing social equity or mobility access. As passenger transport continues to be a major contributor to global emissions, such integrative approaches are essential for aligning climate action with broader developmental and justice-oriented objectives.

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4 Data and Code availability

GCAM-Europe, used in Section 2, is fully accessible in an open-access GitHub repository: https://github.com/bc3LC-GCAMEurope

MEDUSA, the tool to develop the distributional analysis in Section 2 is fully accessible in an open-access GitHub repository: https://github.com/bc3LC/medusa. The repository also includes a documentation website: https://bc3lc.github.io/medusa/

All the country-level figures for results in Section 2 can be downloaded form a public Zenodo repository: https://zenodo.org/records/15622172

GCAM_GRAPHICS, the enhanced version of the GCAM model used in Section 3, is fully accessible in an open-access GitHub repository: https://github.com/jonsampedro/gcam-core

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Annex: Supplementary Information

Table A1: The share of Renewable Energy Sources (RES) in final energy use by EU member state and EU-wide, as assumed/applied in the EU_NECP and EU_FF55 scenarios respectively

	2015	2020	2025	2030
	Observed % RES in final energy		Target % RES in final energy	
Austria	33.5%	34.3%	43.8%	57.0%
Belgium	8.1%	11.5%	15.8%	21.7%
Bulgaria	18.3%	20.5%	26.6%	35.0%
Croatia	29.0%	29.9%	35.2%	42.5%
Cyprus	9.9%	16.4%	23.4%	33.0%
Czech Republic	15.1%	16.9%	22.4%	30.0%
Denmark	30.5%	39.4%	45.9%	55.0%
Estonia	29.0%	34.5%	47.3%	65.0%
Finland	39.2%	42.8%	50.9%	62.0%
France	14.8%	18.2%	27.9%	41.3%
Germany	14.9%	18.3%	27.8%	41.0%
Greece	15.7%	20.8%	30.1%	43.0%
Hungary	14.5%	13.4%	20.3%	30.0%
Ireland	9.1%	12.5%	25.3%	43.0%
Italy	17.5%	18.5%	21.7%	26.2%
Latvia	37.5%	41.5%	50.1%	62.0%
Lithuania	25.7%	26.8%	38.6%	55.0%
Luxembourg	5.0%	9.4%	20.9%	37.0%
Malta	5.1%	10.4%	16.5%	25.0%
Netherlands	5.7%	11.0%	22.7%	39.0%
Poland	11.9%	15.5%	21.5%	29.8%
Portugal	30.5%	32.3%	40.1%	51.0%
Romania	24.8%	24.1%	30.0%	38.3%
Slovakia	12.9%	17.2%	20.4%	25.0%
Slovenia	22.9%	23.5%	27.5%	33.0%
Spain	16.2%	19.2%	31.3%	48.0%
Sweden	52.2%	59.2%	62.4%	67.0%
EU-wide	17.8%	21.0%	30.0%	42.5%

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Table A2: Total consumption of final energy by EU member state and EU-wide, as assumed/applied in the EU_NECP and EU_FF55 scenarios respectively, in Million Tons of Oil Equivalent (Mtoe).

	2015	2020	2025	2030
	Observed Mtoe final energy use		Targeted Mtoe final energy use	
Austria	25.9	26.6	24.7	21.6
Belgium	34.5	33.4	32.1	29.9
Bulgaria	9.5	9.9	9.5	8.8
Croatia	6.6	6.8	6.4	5.9
Cyprus	1.7	1.7	1.7	1.8
Czech Republic	23.3	24.6	23.0	20.2
Denmark	14.1	13.8	13.8	13.7
Estonia	2.8	2.8	2.8	2.9
Finland	23.7	23.8	23.4	22.8
France	145.4	134.7	124.5	106.9
Germany	207.1	200.2	183.7	155.5
Greece	16.6	14.9	15.0	15.2
Hungary	17.0	18.4	18.1	17.7
Ireland	11.3	11.3	11.0	10.5
Italy	115.3	111.4	111.3	111.0
Latvia	3.8	4.0	3.9	3.7
Lithuania	4.9	5.5	5.4	5.2
Luxembourg	4.0	4.0	3.7	3.2
Malta	0.6	0.6	0.6	0.7
Netherlands	47.1	44.7	42.4	38.4
Poland	61.4	72.7	67.5	58.5
Portugal	16.0	15.4	15.0	14.4
Romania	21.8	24.6	23.8	22.5
Slovakia	9.6	10.1	9.5	8.5
Slovenia	4.7	4.6	4.5	4.3
Spain	80.2	77.5	75.4	71.7
Sweden	31.2	30.6	30.4	30.1
EU-wide	940.0	928.7	883.1	805.3

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