Energy Economics 152 (2025) 109001

Contents lists available at ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneeco

Minimum energy taxes for climate and clean air in the EU: Environmental and distributional impacts

Sofia Maier [a], Toon Vandyck [a,b,*], Mattia Ricci [a], Luis Rey [a,c], Marie Tamba [a], Fabian Wagner [d]

[a] European Commission, Joint Research Centre, Seville, Spain
[b] KU Leuven, Leuven, Belgium
[c] Basque Centre for Climate Change (BC3), Leioa, Spain
[d] International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

ARTICLE INFO

JEL codes:
C68
D62
D63
H23
Q52

Keywords:
General equilibrium
Microsimulation
Fairness
Energy taxation
Green transition

ABSTRACT

EU energy taxes could provide a powerful lever to enhance climate action, yet they are characterized by exemptions and are not aligned with climate and environmental goals. This paper assesses the environmental and distributional impacts a revised Energy Taxation Directive, broadening the tax base and increasing the minimum energy tax levels across energy sources, sectors, and EU countries. We combine an economy-wide general equilibrium model and a household-level microsimulation model to quantify the effects on emissions of greenhouse gases and air pollutants, tax revenue, poverty, inequality, and welfare. Three scenarios consider additive reforms as they gradually stack up energy, climate, and air pollution-based components in the design of minimum energy tax rates. These reforms raise effective energy taxation in the EU roughly by one quarter, by half, and by two-thirds, respectively. Removing exemptions and harmonizing tax rates based on energy content brings down CO_2 and $PM_{2.5}$ emissions in the EU by 2–3 %, with substantial heterogeneity across EU countries. Reform scenarios that add climate and air pollution-based tax components lead to stronger emission reductions and reveal environmental co-benefits, as CO_2-based tax rates lower air pollutant emissions, and tax rates reflecting air pollution damages lower CO_2 emissions. We furthermore quantify the social trade-off between emission reductions and inequality, and illustrate numerically that regressive impacts can be overcome through revenue recycling. The inequality-increasing price effect is partially offset by income-side impacts (before revenue recycling) but is strengthened by cross-country heterogeneity in energy use and taxation. Overall, our findings suggest that gearing the EU's energy tax structure towards environmental sustainability can help deliver a just transition when embedded in a broader policy package.

1. Introduction

Energy use is an important driver of environmental externalities, such as climate change and air pollution, yet the associated societal costs are typically not or only partially reflected in the corresponding energy price signals (Parry et al., 2014). Taxation, along with other instruments (Stiglitz, 2019), can help address environmental challenges, but current fiscal regimes contain fossil fuel subsidies, either explicitly or implicitly in the form of rebates, reductions, and exemptions.

Under the banner of the Green Deal, the European Union (EU) is charting out the energy transition on the road to climate neutrality by mid-century. As an intermediate milestone, policymakers have set the target to reduce net greenhouse gas (GHG) emissions by 55 % by 2030, compared to 1990 levels (EC, 2020a). In order to reach this target, the European Commission proposed a comprehensive set of policy measures in 2021, the so-called 'Fit for 55' package. This package overhauls the existing climate and energy legislation of the EU and contains several price- and non-price-based policy initiatives to further decrease GHG emissions, including a revision of the Energy Taxation Directive (ETD; see Section 2), which dictates minimum energy taxation levels across EU countries. The current Directive, issued in 2003, is not aligned with advances in climate goals and energy technologies, prompting the EC to propose options for reform. A comprehensive evaluation of potential ETD reforms – including the removal of tax exemptions – is essential, as it carries important political economy implications and explores the economic trade-off between emission reductions and income inequality.

* Corresponding author at: European Commission, Joint Research Centre, Seville, Spain.
E-mail address: toon.vandyck@kuleuven.be (T. Vandyck).

https://doi.org/10.1016/j.eneco.2025.109001
Received 31 January 2024; Received in revised form 13 October 2025; Accepted 16 October 2025
Available online 17 October 2025
0140-9883/© 2025 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

Here, we assess the environmental and distributional impacts of ETD reform scenarios, leveraging economy-wide modelling and household-level data for all 27 EU countries. In doing so, our analysis sheds new light on the distributional impacts of exemptions in existing environmental tax design, an area overlooked in the literature (Shang, 2023). While most studies rely on highly stylised tax scenarios, our assessment reflects the complexity of the EU's energy taxation landscape by taking stock of out-of-scope provisions, exemptions, and rebates in the Energy Taxation Directive, acknowledging the heterogeneous, real-world implementation of the Directive across EU Member States.

We furthermore contribute to three related strands of literature. First, there is a large and growing body of literature on the distributional impacts of environmental taxes,[1] including carbon pricing. The role of equity was acknowledged early on in the 'double dividend' debate (Proost and Van Regemorter, 1995), and related research has since expanded to cover a broad range of applications (see reviews by Drupp et al., 2025, Köppl and Schratzenstaller, 2023, and Pizer and Sexton, 2019). Our assessment adds a unique application that features a detailed household-level analysis for 27 countries and provides a decomposition of distributional impact channels, addressing the need to go beyond blanket assessments (Shang, 2023). As earlier work (Rausch et al., 2011; Goulder et al., 2019) illustrates that income-side effects represent a potentially important channel in shaping distributional outcomes, we combine microsimulation with computable general equilibrium (CGE) modelling, which enables us to assess changes in energy taxes that apply to both households and firms, and the corresponding impact on emissions, consumption prices (including pass-through of producer costs, accounting for firm-side emission abatement), and factor incomes. As such, our analysis leverages household-level details across 27 countries while complementing research that builds only on microsimulation, which assumes exogenous pre-tax incomes (see van der Ploeg et al., 2025, for a recent application to carbon taxes in Germany).

Second, the academic and political debate on carbon price floors is gaining traction in particular countries as well as internationally (Böhringer and Fischer, 2023; Parry et al., 2021; Flachsland et al., 2020; Newbery et al., 2019). We contribute to this stream of literature with an assessment of household-level distributional impacts, as the ETD reform proposal implicitly represents a price floor across countries based on energy content, carbon intensity, or damages from air pollution (depending on the scenario, see Section 3.5.2).

Third, this paper contributes to the literature on instrument choice to tackle environmental externalities. While much work exists on energy taxes and carbon pricing, approaches to internalize damages from air pollution into prices (and associated distributional impacts) have been scarcely researched (Kiuila and Markandya, 2019; Mardones and Mena, 2020), although there are many real-world examples of price-based policies to control air pollution. For instance, air pollution-related taxes have been introduced in France, Sweden, and Chile; Korea differentiates diesel taxation motivated by air pollution concerns; and the US has implemented cap-and-trade policies for sulphur dioxide (SO_2) and nitrogen oxide (NO_x) emissions. In this paper, we assess the impact of introducing an air pollution-related component in the minimum energy taxes on the emissions of air pollutants, on the positive side-effects for climate change mitigation (CO_2 emissions), and on distributional outcomes. We also quantify the synergies and trade-offs of CO_2-based energy taxation with the emissions of air pollutants, contributing to the literature on co-benefits of climate action (Vandyck et al., 2018). We thus provide a broader (two-way) interpretation of environmental co-benefits that covers the effects of taxing air pollutants on CO_2 emissions and, vice versa, of taxing CO_2 on air pollutant emissions.

The results of our analysis indicate that broadening the energy tax base and increasing (energy content-based) tax rates contributes to the Green Deal objectives of climate neutrality and zero air pollution by reducing CO_2 and air pollutant ($PM_{2.5}$, SO_2, NO_x, VOC) emissions, respectively. Introducing a climate-based component in the minimum tax rates generally benefits air quality and vice versa, reflecting air pollution damages in the tax rates tends to lower greenhouse gas emissions. These results suggest overall environmental co-benefits, despite trade-offs at the more granular sector-fuel level (e.g. CO_2 tax raising air pollutant emissions from biomass use).

The modelling simulations furthermore quantify the distributional implications of these reforms. From our micro-simulations based on household survey data, we identify an inequality-increasing effect of the expected change in consumer prices and a counter-balancing inequality-reducing effect from the expected decline in gross labour and capital income, in line with recent studies (Goulder et al., 2019; Rausch et al., 2011; Böhringer et al., 2021a; Böhringer et al., 2021b). Jointly, expenditure- and income-side effects lead to only slightly regressive effects across income groups within countries, relatively large impact heterogeneity within income groups, and a slight increase in poverty rates. Impacts are not only heterogeneous within countries, but also between EU Member States. When we account for differences across countries (including stronger reliance on fossil fuels and lower existing tax rates in countries with comparatively low income levels), a more pronounced regressive impact pattern across EU households emerges. However, the inequality- and poverty-increasing effects of the reform are largely reversed once we account for a within-country revenue recycling through an equal-per-capita lump sum cash transfer. Hence, our results suggest that the additional tax revenues from the increase in minimum tax rates would be enough to broadly reconcile climate and fairness goals in all EU Member States.

The rest of the paper is organized as follows. Further background on the EU ETD is provided in Section 2. In Section 3, we describe the data, models, and empirical strategy behind the analysis, as well as the policy scenarios. In Section 4, we summarize the main results in terms of CO_2 and $PM_{2.5}$ emissions, energy prices, sectoral wages, tax revenue, and the impact on poverty, inequality, and welfare. Finally, in Section 5 we provide concluding remarks and discuss the policy implications of our results.

2. The EU Energy Taxation Directive

The Energy Taxation Directive (ETD) sets minimum levels of excise taxes on energy products across the EU to improve the functioning of the internal market and to avoid a race-to-the-bottom in terms of energy taxation. While EU Member States can decide on the tax rates applied in each country, the ETD sets minimum rates for energy products (Council Directive 2003/96/EC) including oil for use as heating fuel or motor fuel, gas, solid fossil fuels (including lignite, coal and coke), and electricity. Minimum tax levels are expressed per volume, for instance 359 EUR per 1000 l of unleaded petrol (Annex I of Council Directive 2003/96/EC). As such, they do not factor in the energy content (Joule per litre) or the associated environmental harm due to climate change or air pollution.

Furthermore, the current legislation is outdated and contains various loopholes in the form of rate reductions, exemptions and rebates (Parry and Vollebergh, 2016). In particular, the legislation includes out-of-scope provisions covering biomass, mineralogical and metallurgical processes; mandates exemptions for inputs to electricity generation, aviation and maritime transport; and allows applying rate reductions or exemptions for energy used in public and commercial transport, energy-intensive sectors, and agriculture. Unchanged since its adoption in 2003, the current ETD has therefore resulted in a patchwork of tax rates across the EU, moving further away from harmonization each year due to the lack of inflation-indexing in minimum tax rates. Importantly, the Directive is not aligned with the EU's climate ambitions, such that a

[1] Following Eurostat's definition, we can interpret environmental taxes as the collection of energy, transport, and pollution & resource taxes. In economic terms, taxing energy use on the basis of the associated CO_2 emissions is equivalent to a carbon tax (on energy use).

revision can facilitate an efficient transition to a low-carbon economy (Rocchi et al., 2014) by ensuring the right price signals that guide investment choices of households and industries to carbon-neutral options.

For these reasons, the European Commission proposed a revision of the ETD in July 2021, as part of the Fit for 55 package of the EU Green Deal. More recently, the European Scientific Advisory Board on Climate Change (ESABCC, 2024) emphasised the importance of reforming the ETD for emission reductions as one of its key recommendations, and the President of the European Commission instructed the Commissioner for Climate, Net Zero and Clean Growth to "conclude negotiations on the revision of the Energy Taxation Directive" when taking office for a second term on the first of December 2024.

Several reform options were tabled in 2021 to realign the ETD with EU environmental goals. This paper assesses the socio-economic and environmental impacts of three different approaches to reforming the ETD. These reforms extend the tax base by eliminating exemptions, such as for intra-EU aviation, intra-EU maritime and inland shipping. They further broaden the tax base by covering the use of energy products for mineralogical as well as metallurgical processes (other than dual-use), and the use of solid biomass. The reforms furthermore limit industrial and household tax reliefs, and the possibility of differentiation between commercial and non-commercial use of gas oil. In terms of tax rates, the reform proposals put forward harmonized rates reflecting *energy* content, and incrementally add components related *climate* change (at 45 EUR per tonne of CO_2 in 2035) and *air* pollution (health impacts of fine particulate matter emissions, $PM_{2.5}$). Combined, the expansion of the tax base and the increase in the rates raise effective energy taxation in the EU roughly by one quarter (25.1 %), half (53.4 %), and two-thirds (65.6 %), respectively, in the three reform proposals that we study in this paper (*Energy*, *Climate*, and *Air* scenarios; see Section 3.5).

3. Methodological framework

Energy taxation affects both producer (firms) and consumer (households) sides of the economy, as energy serves as an input into production processes and is also consumed directly by households. We therefore develop a comprehensive macro-micro modelling framework to quantify the environmental and distributional impacts of the proposed ETD reform. An economy-wide model (macro) captures both firms and households (and corresponding emissions, factor returns, and prices of goods and services), while a micro-simulation model provides a disaggregated representation of households that enables an assessment of distributional consequences.

This framework improves and combines different models. First, we have refined the representation of excises on energy products (coal, oil, gas, biofuels, solid biomass, and electricity) in the JRC-GEM-E3 model, capturing the details of the current ETD and its implementation in the EU Member States. Furthermore, we have extended the JRC-GEM-E3 model to cover air pollutant emissions on the basis of emission coefficients per energy use from the GAINS model (Amann et al., 2011). Additionally, we use the Indirect Tax Tool extension of the EU tax-benefit micro-simulation model EUROMOD, which leverages micro-datasets that contain information on individual and household socio-economic characteristics, incomes, and expenditures. Finally, we have developed a link between the JRC-GEM-E3 and EUROMOD models, which allows us to study the distributional impacts on the household level, further extending previous work (Vandyck et al., 2021) with sector-specific labour income impacts and EU-wide coverage. Jointly, these refinements, extensions, and model connections represent an assessment framework that enables a comprehensive analysis of environmental and socio-economic impacts, tailored to the context of energy taxation in the EU.

3.1. Economy-wide modelling

At the macro level, we use a general equilibrium model to evaluate the economic and environmental impacts of the proposed ETD reform. Using a CGE model enables the assessment of both expenditure- and income-side channels of distributional impacts of policies. In particular, we use the JRC-GEM-E3 model, a multi-sector, multi-country, energy-economy model with global coverage and EU Member State detail. With a detailed sectoral disaggregation of energy activities (from extraction to production to distribution sectors) as well as endogenous mechanisms to adjust energy use and mitigate carbon emissions, the JRC-GEM-E3 has been extensively used for the economic analysis of climate and energy policy impacts. For examples of recent climate policy applications of this model, we refer to Weitzel et al. (2019, 2022) and Tamba et al. (2022). The model represents the behaviour of firms, disaggregated into 31 sectors of activity, households, governments, and the responses of supply chains and international trade flows to changes relative prices induced by policy action. Further details are provided in Capros et al. (2013) and in Appendix A.1.

For this exercise, the model has been refined in terms of the representation of current energy excises in the EU, capturing exemptions, rebates, and out-of-scope provisions (e.g., dual use, electrolytic processes). Firms consume energy products as inputs into the production function. For households, we distinguish between energy carriers for heating and appliances, and energy use for private transportation. To improve the representation of energy excises, we introduce new model parameters for firms and households that represent the excise tax per volume of energy consumption (tonne of oil equivalent in the model). This enables the implementation of the current-policy baseline and the reform scenarios described below, with tax rates differentiated by country, year, sector (also distinguishing between heating and motor fuels for households) and energy product.

To study the impact of the various proposals on air pollutant emissions, the JRC-GEM-E3 model was further developed to cover emissions of NO_x, $PM_{2.5}$, and SO_2 for all sectors, energy carriers, and countries in the EU. Air pollutant emissions were provided by the GAINS model[2] (IIASA), and corresponding emission control policies are in line with the baseline of the Second Clean Air Outlook (EC, 2021b) for the year 2030. After mapping the sectors of both models, these emissions were converted into emission factors by dividing with the corresponding drivers: energy use or economic activity. Emissions that could not be clearly linked to either energy use or sectoral activity were kept fixed across scenarios. Emission factors for 2030 were then applied to the year 2035, which could lead to slight overestimation of emission reductions in 2035 if emission factors are decreasing faster in regions were the ETD scenarios are particularly impactful. While the JRC-GEM-E3 model combines economy-wide coverage with sector- and fuel-specific detail, a few caveats should be considered when interpreting the results on air pollutant emissions. First, emissions related to the use of solid biomass for energy in industry are not accounted for. Second, the model does not capture the split between diesel and petrol, hence may underestimate the benefits of the air pollution component in the minimum rates in terms NO_x emission reductions.

3.2. Household-level microsimulation

To assess the distributional consequences of the expected changes in consumer prices, sector-specific wages, and capital income, we use EUROMOD, the EU-wide tax-benefit micro-simulation model (see Sutherland and Figari, 2013 and Maier et al., 2022, for more

[2] https://iiasa.ac.at/web/home/research/researchPrograms/air/GAINS.html

information).[3] EUROMOD combines country-specific coded policy rules with household-level microdata based on the European Union Statistics on Income and Living Conditions database (EU-SILC) to simulate tax liabilities and cash benefit entitlements. Therefore, EUROMOD simulations take into account (interactions between) tax-benefit instruments to generate the disposable household income after direct taxes and cash benefits. By working with disposable income based on EU-SILC, our results are directly comparable with the official statistics on poverty and inequality published by Eurostat.

EUROMOD Indirect Tax Tool (ITT) extends the scope of the EUROMOD core simulations, allowing for the joint analysis of direct and indirect taxation. To simulate indirect tax liabilities from household consumption, EUROMOD-ITT combines the underlying EU-SILC data with household expenditure information for more than 200 commodity categories from the 2010 harmonized Eurostat Household Budget Surveys (EU-HBS), the latest available release at the time this model was developed.[4] To combine expenditure and income microdata, a semi-parametric matching procedure developed by Akoğuz et al. (2020) is used with HBS and EU-SILC as source and recipient datasets, respectively. Further details on this procedure are provided in Appendix A.2.[5] When running the analysis for policy years which are successive to the year the underlying dataset refers to, appropriate uprating factors are used to update incomes and consumption expenditures in nominal terms. These uprating factors are aggregate indices (e.g. mean wages by sector, or CPI) that are used to transform 2010 incomes into 2019 levels. Starting from the household disposable income simulated by EUROMOD, we consider the indirect taxation rules in place in each country to simulate households' adjusted disposable income after direct taxes, cash benefits and indirect taxation. For recent applications of this model, see Amores et al. (2023, 2025).

3.3. Top-down macro-micro link

Following the general approach of Vandyck and Van Regemorter (2014) and Vandyck et al. (2021), we link the general equilibrium and micro-simulation models in a "top-down" fashion, feeding the outcomes of the CGE model into the micro-simulation analysis. The link is unidirectional, as no information is passed on from the micro to the macro level. The macro outcomes that are fed into the micro model for each of the 27 EU countries are: i) consumer price changes for 14 aggregate product categories (see Table A1 in Appendix A), ii) gross wages changes for six sectors, iii) gross capital income changes, and iv) government revenues (which are used to design compensatory measures). Jointly, this set of information that links both models comprises approximately 600 variables.

Consumption categories from input-output data and EUROMOD-ITT use different classifications (GTAP versus COICOP). To map them, we use the matrices developed by Cai and Vandyck (2020). Moreover, baseline scenarios of the two models are aligned. To this end, the consumption of each household in the EUROMOD-ITT is adjusted proportionally in order to ensure that the aggregate shares of consumption expenditure by group of goods and services (e.g. "Education" or "Food") match those of the JRC-GEM-E3 model.

To measure the welfare impact of *consumer price changes*, we estimate the expected change in expenditures driven by the change in consumer prices, if households would keep their consumption basket unchanged. This effect can be interpreted as the additional income that a household would need in order to keep its consumption basket unchanged under the new prices, in line with the welfare concept of compensating variation.[6] This welfare effect driven by consumer prices is what we call the "price effect" in the remainder of the paper.

To account for the welfare impact of *factor price changes* (i.e. gross labour and capital income), we use the uprating factors and the tax-benefit rules coded in EUROMOD-ITT. This allows us to explicitly consider the interplay of taxes and benefits, i.e. to simulate the change in household disposable income given the expected changes in gross labour and capital income, accounting for the interaction of direct taxes (e.g. personal income tax) and cash benefits (e.g. child benefits, social assistance, etc.). This additional welfare effect through changes in household disposable income can be interpreted as the additional monetary resources a household would need to keep its savings (or debt) unchanged with respect to the baseline. This welfare effect driven by income changes is labelled as the "income effect" in the results section. We provide further background on the welfare concept in Appendix A.3. A well-known issue with survey data is the underrepresentation of capital incomes compared with national accounts. A full harmonization of capital incomes between microlevel data and national accounts lies beyond the scope of this paper. However, work on distributional national accounts (Piketty et al., 2018) provides a promising avenue to reconcile data sources in future exercises. Our approach is consistent with the common assumption of a residual 'capitalist' household (see Rausch et al., 2011; Böhringer et al., 2022) that owns the remaining capital, for which returns are not covered by the microdata (and thus do not feature in the distributional results). Furthermore, as in earlier work (e.g. Rausch et al., 2011), we do not distinguish capital incomes from different sources. The implicit assumption is that the distribution of ownership in energy- or emission-intensive industries matches the distribution of capital ownership in general. Recent work (Semieniuk et al., 2022) tracks the ownership of potential stranded assets, including across ultimate owners but without providing insight on ownership along the income distribution.

The final channel of distributional impacts concerns the recycling of the simulated government revenues to compensate households. We simulate a uniform lump-sum transfer per individual, which recycles all the extra revenues raised through increased taxation from the household sector through equal-amount cash transfer to all individuals of the population within the same country, including children and adults out of the labour force. For the distributional analysis, we do not redistribute the additional revenues obtained from firms to households. This is a conservative assumption that reflects real-world situations where government budgets are constrained and need to satisfy other demands, e.g. to support other areas of the transition such as financing investment in low-carbon technologies to enable industrial decarbonisation.

Our modelling extends previous methodological approaches (Vandyck et al., 2021) along several lines, beyond the expansion of the country coverage. First, we extend the income channel by considering heterogeneous impacts across sectors. In particular, while Vandyck et al. (2021) consider only one wage change rate for all workers, in this study

[3] The model and data are publicly available, and with open-source software. All related-information can be found in EUROMOD's website: https://euromod-web.jrc.ec.europa.eu/

[4] EU-SILC files correspond also to 2010, as they are the best match for EU-HBS 2010. There are only two exceptions to this general rule: for Denmark and Croatia we used SILC 2012, given data availability restrictions for these countries for 2010. EUROSTAT harmonized 2010 HBS datasets for Austria and the Netherlands were not available and the data of Luxembourg did not contain information on income. For Austria and Luxembourg, we use national HBS data. In particular, for Luxembourg the 2013 national HBS was used as this was the first year where the income information was adequate for the imputation method. For the Netherlands, EUROSTAT 2015 HBS dataset was employed instead.

[5] For a comprehensive description of the Indirect Tax Tool, including the construction of the underlying micro dataset, the simulation of consumption taxes as well as the validation of the model, we refer to Akoğuz et al. (2020) and Decoster et al. (2010).

[6] As discussed by Vandyck et al. (2021), this could be interpreted as derived from Leontief preferences. This concept matches the definition of Compensating Variation as a money metric of the welfare change exerted by changes in consumer prices (King, 1983).

the macro model estimates the expected change in gross wages across broad sectors of activity, and we translate these changes into the micro model. Considering this additional dimension is a relevant extension in the context of this paper, as the impacts of energy tax reforms are heterogeneous across (workers in different) sectors and these workers are located at different points of the income distribution between and within countries. After mapping the different sector classifications used by the two models, we end-up with six sectors (see Appendix A): i) Agriculture, including agricultural and fishing activities; ii) Industry, including mining, manufacturing, and utilities; iii) Construction; iv) Transport; v) Other services, including wholesale and retail, communication, financial services, banking; and vi) Public services, including public administration, health and education.[7] Second, we decompose the distributional effects to shed light on the contribution of price and income channels. Third, we present synthetic indicators to measure income inequality (Gini coefficient) and impacts on the bottom-part of the distribution (at-risk-of-poverty rates, AROP). These synthetic figures provide a more comprehensive view and facilitate broader comparison of the magnitude of these effects in the multi-country, multi-scenario setting of the paper.

3.4. Data

The empirical base underpinning the analysis consists of four main types of data. First, at the aggregate, economy-wide level, the Global Trade Analysis Project (GTAP) dataset provides a central input for the *base year* calibration of the CGE model. The GTAP data covers input-output and trade linkages between sectors and countries, and depicts the economic structure of countries and the production structure of firms in line with national accounts. The CGE model parameters are calibrated to replicate the benchmark as represented by the GTAP10 version (Aguiar et al., 2019) with base year 2014. A second type of numerical input relates to energy-economy projections for the current-policy *baseline* trajectory up to 2035 in the CGE model. Projections of GDP, population, labour supply, and unemployment rates follow the 2021 Ageing Report (EC, 2020b). Energy production and use, and the corresponding CO_2 emissions, follow projections of the PRIMES energy system model, which are based on the same set of GDP and population projections to enhance consistency. Air pollutant emissions in the baseline are derived by combining PRIMES model energy use with emission factors from the GAINS model. Third, at the household level, Household Budget Survey (HBS) data harmonized across EU countries captures the heterogeneity in spending patterns across households. Gathering data on households' annual consumption for all goods and services (disaggregated along the COICOP classification), this dataset provides the backbone for assessing the distributional impacts through the expenditure-side channel. A fourth data source for the analysis is the EU Statistics on Income and Living Conditions (EU SILC), providing household-level details on the sources of income. While this dataset covers a broad range of indicators, of key interest for this paper are the household-level income shares of labour income, capital income, and transfers (including social benefits such as pensions and unemployment benefits). HBS and SILC data are merged (for the year 2010) to enable a joint assessment of expenditure- and income-side impacts, as discussed above and in Appendix A.2. Additionally, auxiliary data (bridging matrices from Cai and Vandyck, 2020) is used to match consumption categories at macro and micro levels.

3.5. Scenarios

The aim of the analysis is to compare the impacts of the proposed reform options of the EU Energy Taxation Directive against the backdrop of current energy taxation in the EU. Therefore, one crucial element of the analysis is to capture accurately the details of existing energy and proposed excises across EU countries, sectors, and energy carriers. We assess three scenarios that differ in terms of the tax base and rates by comparing them to the current-policy Reference (or baseline). The following subsections describe in detail the estimation of effective tax rates in the Reference and the policy scenarios. Table 1 lists the EU-wide minimum tax rates across energy products and scenarios.

3.5.1. Reference: Current ETD legislation

The ETD defines the scope of energy taxation, the conditions for exemptions and reductions, and sets minimum levels of taxation. Member States retain competence to implement rates above these minimum levels or apply optional exemptions and reductions according to their own national needs within the provisions set out in the ETD. These harmonized rules result in significant heterogeneity in both nominal and effective energy tax rates across uses and countries (OECD, 2022). The same nominal rates can imply different effective rates through the existence of exemptions, reductions, and rebates.

In order to reflect this heterogeneity in the current-policy baseline, our analysis is based on a comprehensive data collection exercise, gathering inputs directly from Member States' Finance ministries which

Table 1
Tax rates across energy products in the Reference and reform scenarios, expressed in EUR per GJ (2035, non-indexed).

	Reference	Energy	Climate		Air	
			Increment	*Total*	*Increment*	*Total*
Motor fuels						
Petrol	10.74	10.75	3.15	13.90	0.23	14.13
Gasoil	9.08	10.75	3.15	13.90	0.55	14.45
Kerosene (aviation)	0.00	10.75	3.15	13.90	0.05	13.95
LPG	2.66	10.75	2.70	13.45	0.19	13.64
Bioethanol E100	0.00	5.38	0.00	5.38	0.35	5.73
Biodiesel B100	0.00	5.38	0.00	5.38	0.83	6.21
Heating fuels and fuels for agriculture, stationary motors, maritime and inland shipping (including fishery)						
Gas oil	0.58	0.9	3.15	4.05	0.37	4.42
Heavy fuel oil	0.37	0.9	3.60	4.50	0.37	4.87
Coal and coke, business	0.15	0.9	4.05	4.95	7.41	12.36
Coal and coke, non-business	0.30	0.9	4.05	4.95	7.41	12.36
Kerosene business and non-business	0.00	0.9	3.15	4.05	0.37	4.42
LPG business and non-business	0.00	0.9	3.15	4.05	0.37	4.42
LPG (other)*	0.87	0.9	3.15	4.05	0.37	4.42
Natural gas business	0.15	0.9	2.70	3.60	0.32	3.92
Natural gas non business and other*	0.30	0.9	2.70	3.60	0.32	3.92
Biomass (wood and pellets)	0.00	0.45	0.00	0.45	7.40	7.85
Other						
Electricity	0.00	0.15	0.00	0.15	0.00	0.15

* other: agriculture and stationary motors.

[7] Within sectors, we employ a uniform change rate, as the macro model does not have further information (e.g. skills nor occupation) to consider more disaggregated effects and identify more precisely who would experience the strongest/weakest wage changes.

systematically collected information on rates applied by product and use, as well as potential reductions, reductions or rebates applied. This data collection was complemented by other databases (Taxes in Europe database,[8] Eurostat[9]) and subject to a peer-review process by JRC and OECD experts. This data collection exercise confirmed the heterogeneity of effective tax rates across Member States due to the current ETD provisions. For instance, in household use, five countries fully exempt electricity and gas from excise taxes, while three others exempt only electricity and three more only exempt gas. Other Member States provide partial relief or rebates for some vulnerable consumer groups or vulnerable regions.

In addition, the exercise required detailed calculations of the share of industrial energy use falling outside the scope of the ETD according to Article 2, using energy balances published by Eurostat and the JRC-IDEES database.[10] For instance, out-of-scope provisions apply to dual use and electrolytic and mineralogical processes. Capturing correctly the tax base required four steps. First, we adjust for the auto-production of electricity and heat by disaggregating EUROSTAT energy balances by industry according to the installed capacities reported by S&P Global Platts "World Electric Power Plant Database" (S&P Global Platts, 2019). Second, we account for the consumption of energy for non-energy uses (e.g. feedstocks) by disaggregating EUROSTAT energy balances on the basis of the "memo items" available from the IEA's Extended World Energy Balances (International Energy Agency, 2020). Third, we calculate the total amount of energy used by each industrial sector by subtracting the feedbacks from coke ovens, blast furnaces, and power plants from the total amount of energy inputs, as only the inputs from external sources are considered to be taxable and the feedbacks of energy carriers that are produced internally are considered exempt from additional taxation. Fourth, we classify total energy use by industry into in/out-of-scope categories according to the shares resulting from assigning the processes included in the detailed energy balances of the JRC-IDEES database (Mantzos et al., 2017) for the year 2015 to the categories considered in the ETD (and assume they remain constant over 2015–2018). Out-of-scope categories include chemical reduction, electrolysis, metallurgical processes, mineralogical processes, other dual uses, wood and wood products, peat, electricity, and uses other than motor or heating fuels. We also account for specific rates on heat generation in combined heat and power (CHP) generation.

We implement the resulting effective tax rates in the JRC-GEM-E3 baseline using a detailed mapping of ETD energy carriers and uses to energy suppliers and consumers in the CGE model, building on above-mentioned calculations and detailed energy balances. One caveat of the modelling framework in this analysis is that diesel and petrol are not represented separately in the JRC-GEM-E3 model, so effective tax rates on oil products are modelled in an aggregated way. Effective energy tax rates and other implemented climate policies feed into an input-output balancing procedure (Wojtowicz et al., 2019), which allows demographic and economic assumptions to be combined with exogenous projections of energy use and greenhouse gas emissions in a consistent multi-regional input-output format, compatible with the GTAP database underpinning the JRC-GEM-E3 model. The projections are aligned to the PRIMES model Reference, including policies before implementation of newly proposed measures in the Fit for 55 package. Since minimum tax rates, as well as the excises applied in several countries, are set in nominal terms (unlike Value Added Taxes in percent), we represent current policies by setting tax rates at their current nominal levels. As a result, real effective energy excises decline over time with inflation as (minimum) tax levels are not automatically indexed to inflation in the current legislation.

3.5.2. Reform scenarios: Energy, climate, air

The first scenario studies the impact of a broadening of the scope while reforming the tax rates to reflect the energy content of different energy carriers.[11] The second and third scenarios incrementally add a CO_2-based and an air pollution-based component to the tax rates, aiming to contribute to the Green Deal objectives of climate neutrality and zero air pollution. We label these scenarios *Energy*, *Climate*, and *Air*, respectively, which match scenarios 2a, 3a and 3c in the European Commission's proposal (EC, 2021a).

The policy scenarios are additive as the rates are based on energy-content, energy- *plus* carbon-content, or energy- *plus* carbon-content *plus* a component related to damages from air pollution. All three scenarios involve a 10-year transition period starting in 2023 for selected products and sectors (in particular gas and aviation). The ETD covers end use of energy, such that energy transformation (e.g. the electricity generation sector) is out-of-scope.

In the first scenario, *Energy*, the ETD minimum rates are revised to be based on energy content (e.g. expressed in Joule), rather than energy volumes consumed (in litres of kilogrammes). This eliminates the disadvantage implicit in volume-based taxes for fuels with comparably lower energy content, such as biofuels. The European Commission proposed a set of new minimum rates in EUR per Gigajoule, harmonized across fuels used for a same use (heating or motor). In this scenario, the tax base is also expanded to remove exemptions: a number of out-of-scope industrial processes are brought back into scope, namely: (i) products used for metallurgical processes in the iron and steel and the non-ferrous metal industries, (ii) those used for mineralogical processes and (iii) the share of energy input to produce heat in combined heat and power generation. For all land transport, the minimum rates apply. Furthermore, the tax base is extended to cover biofuels and intra-EU aviation and navigation. While traditionally energy taxes have served a revenue-raising purpose, the energy content-based taxation can be motivated also in the context of the EU targets on energy efficiency, and to some extent can be justified by the literature on internalities (Allcott et al., 2014).

The *Energy* scenario we implement here does not include the "ranking obligation" that was mentioned in the policy proposal (EC, 2021a): "Member States must ensure that the environmental performance and use of each product is reflected in their national tax rate by respecting the ranking between the different rates." For some countries, this rule would imply necessary changes in the tax rates. However, it is a priori unclear how countries would implement such ranking, as it could be achieved by either raising or lowering existing tax rates.

In the second scenario *Climate*, the same elements of the *Energy* scenario are included, and in addition, the minimum tax rates are increased to include a component reflecting the carbon content of the fuel. In this scenario, fuels with a higher carbon content[12] are taxed at higher rate for the same amount of energy use in GJ, representing the corresponding contribution to global warming (CO_2 only). This 'climate component' in the energy tax rates is thus equivalent to a carbon tax on

[8] https://ec.europa.eu/taxation_customs/tedb/#/home

[9] https://ec.europa.eu/eurostat/web/environment/information-data/environmental-taxes-subsidies

[10] See Annex 10: Quantification of the industrial energy consumption within the scope of Article 2 of the Energy Taxation Directive, SWD 641 final.

[11] For the same volume (litre) or mass (kg), energy products have varying energy content (e.g. Joule per litre) and greenhouse gas and air pollutant emissions. For instance, a uniform tax *per litre* of petrol and gasoil would imply unequal taxation between petrol and gasoil on an energy content or emissions basis.

[12] The emission factors used for the conversion for motor fuels are 0.07 tCO_2/GJ for petrol, gasoil, and kerosene, and 0.06 tCO_2/GJ for LPG and natural gas. For heating fuels (plus fuels for agriculture, stationary motors, maritime and inland shipping, including fishery), fuel emission factors are 0.09 tCO_2/GJ for coal and cokes, 0.08 tCO_2/GJ for heavy fuel oil, 0.07 tCO_2/GJ for gasoil, kerosene, and LPG, 0.06 tCO_2/GJ for natural gas, and zero for bio-energy and electricity.

energy use. Implicitly, this proposal thus introduces a carbon price floor of 45€/tCO_2 in 2035 across the EU for the sectors covered, with the goal of aligning energy taxation with climate change mitigation targets. Intra-EU aviation is excluded as it is covered by the EU ETS system, while maritime transport is included since it was not covered by the EU ETS at the time of the proposal.

Finally, in a third scenario (*Air*), an air pollution component is added to the rates of the *Climate* scenario in order to reflect the associated damages from air pollution. This component is based on an EU-wide valuation of mortality associated to air pollution from fine particulate matter ($PM_{2.5}$) and NO_x emissions. The calculation, described in detail by the European Commission (2021), takes a conservative approach and disregards technology characteristics (e.g. end-of-pipe abatement), impact heterogeneity across space, and damages from air pollution from other channels (morbidity, crop yields, eutrophication, etc.) and pollutants (SO_2, ground-level ozone). The valuation of mortality is based on years of life lost, with an assumed EU-wide valuation of 79′500 EUR_{2005} per life year lost. Combining this estimate with emission coefficients from the EMEP/EEA guidebook[13] gives the resulting tax rates per energy use as shown in Table 1 (see Appendix A.4 for further details). While literature acknowledges that a pure Pigouvian tax on air pollution is technologically infeasible (Jacobsen et al., 2023), the proposed air pollution component can complement other forms of regulation to mitigate air pollution.

3.5.3. Resulting tax rates

Fig. 1 presents an overview of the scenarios across EU energy use. The figure illustrates *effective* energy tax rates – accounting for exemptions, rebates, and out-of-scope provisions – for the projected baseline tax base (in 2035) (panel a) and disaggregated by energy product (panel b), country (panel c), and sector (panel d).

Panel a of the figure illustrates the heterogeneity in energy excises that are currently applied, across all fuels, sectors and countries. Note that the figure only shows energy excise taxes and does not include other levies such as carbon taxes and various charges that may apply on electricity. Overall, the figure shows that particularly the *Energy* and *Climate* scenarios raise tax rates for a substantial amount of energy use, while the *Air* scenario has a more limited, yet concentrated impact on tax rates.

Cutting across the fuel dimension, panel b of the figure illustrates that the proposed reform options have little or no impact on excises on electricity. Intentionally, excises on electricity are not raised to enable an electrification of end-use while the Emission Trading System decarbonizes electricity generation. Tax rate increases for gas, coal, and oil aim to level the playing field and shift final energy use towards electricity. Final energy use of coal is relatively limited in magnitude, but corresponding rate increases are large, particularly in the *Climate* and *Air* scenario.

A comparison across countries (panel c) confirms the difference in starting points, with e.g. lower excises and larger changes in the scenarios for Poland compared to France. This heterogeneity will drive part of the distributional impacts that we assess later in the paper.

While the analysis accounts for tax rate changes on both the household and firm sides, it is worthwhile to pay particular attention to the rate changes that apply to household energy use, as these will have a direct impact on socio-economic outcomes. In terms of household heating, rates are generally low (compared to transport), as many Member States make use of exemptions present in the current ETD. The *Energy* scenario leads to a general harmonization of minimum rates across fuels and Member States. The majority of countries is currently taxing energy for household heating less than the proposed new minima based on energy content. The inclusion of carbon content penalises the most carbon intensive fuels, with oil heating and heating from solids experiencing a larger increase in minimum rates than natural gas. Countries where households heavily rely on solid fuels for space heating (e.g. Poland, Czech Republic, Bulgaria), or on fuel oil (e.g. Belgium, Cyprus, Greece), or both (Ireland) will be more strongly affected by the ETD reform. Similarly, the inclusion of the air pollution component leads to more than a doubling of minimum rates for solids used for household heating, affecting households in countries most reliant on such fuels. In general, the pattern of tax rates (changes) in the services sector is similar to the one for residential energy use of households.

For household motor fuels, the rates are significantly higher than for heating in the baseline, as no exemptions are possible. The rates for gasoline (petrol) are higher than for gasoil in all Member States. Only four countries are significantly affected by new minimum rates on petrol for household use in the *Energy* scenario (Bulgaria, Cyprus, Hungary, and Poland). Accounting for energy, carbon, and air pollution content (*Air* scenario), baseline rates remain higher than new minima in nine Member States. In contrast, for diesel (gasoil) where rates are lower in the baseline, the new minimum rates impact 21 of 27 Member States in the *Energy* scenario alone (particularly Bulgaria, Hungary, Poland, Luxembourg, and Romania), thereby removing the existing favouring of diesel over petrol in excise taxes. Accounting for carbon and air pollution content increases minimum rates compared to the baseline in all Member States. For those countries with very high shares of diesel in the motor fuel mix (more than 60 % for Spain, Portugal, Latvia, Lithuania, and Slovenia), the increase in minimum rates for gasoil will result in higher motor fuel cost. The changes in rates for commercial transport across baseline and scenarios are similar as those of motor fuels for households. However, the fuel mix in commercial transport is more homogeneous in the EU, with over 90 % of diesel (gasoil) in fuel for trucks and light-duty vehicles in most Member States, resulting in increases in transport services costs across the economy.

Other sectors of the economy where the ETD reform proposals introduce notable changes are industry and air transport (kerosene), where the proposed legislation closes various loopholes that characterise the current ETD legislation (panel d).

4. Results

This section presents the main results in three blocks. Section 4.1 focuses on *between-country* impact heterogeneity with a presentation of the key environmental and economics outcomes at the country level: changes in emissions, wages, household energy prices, tax revenue, and welfare across the three scenarios and 27 Member States. These results form the basis for the distributional analysis that follows. We assess *within-country* impact heterogeneity in Section 4.2, including the household-level impacts on poverty and inequality within countries, and a deeper dive into vertical (across income groups) and horizontal (within income groups) equity. Finally, we combine between- and within-country heterogeneity in the EU-wide household-level distributional results in Section 4.3.

Throughout Section 4, the results are presented as changes from the current-policy baseline (Reference) in 2035, as the proposed phase-in of the new rates will have been completed by that year. In the Reference, CO_2 emissions in the EU decline by approximately 37 % over the 2015–2035 period, with stronger reductions in sectors covered by the Emission Trading System (ETS) (−42 % and − 31 % in ETS and non-ETS, respectively).

4.1. Country-level results: Environmental and economic impacts

The main country-level effects on emissions, wages, energy prices, and tax revenues are shown in Fig. 2 (panels a, b, c and d, respectively). The results indicate declines in emissions, with magnitudes varying across scenarios, pollutants, and countries (Panel a of Fig. 2). Broadening the tax base by eliminating exemptions and aligning the tax rates based on energy content (*Energy* scenario) brings down CO_2 emissions

[13] https://www.eea.europa.eu/publications/emep-eea-guidebook-2019

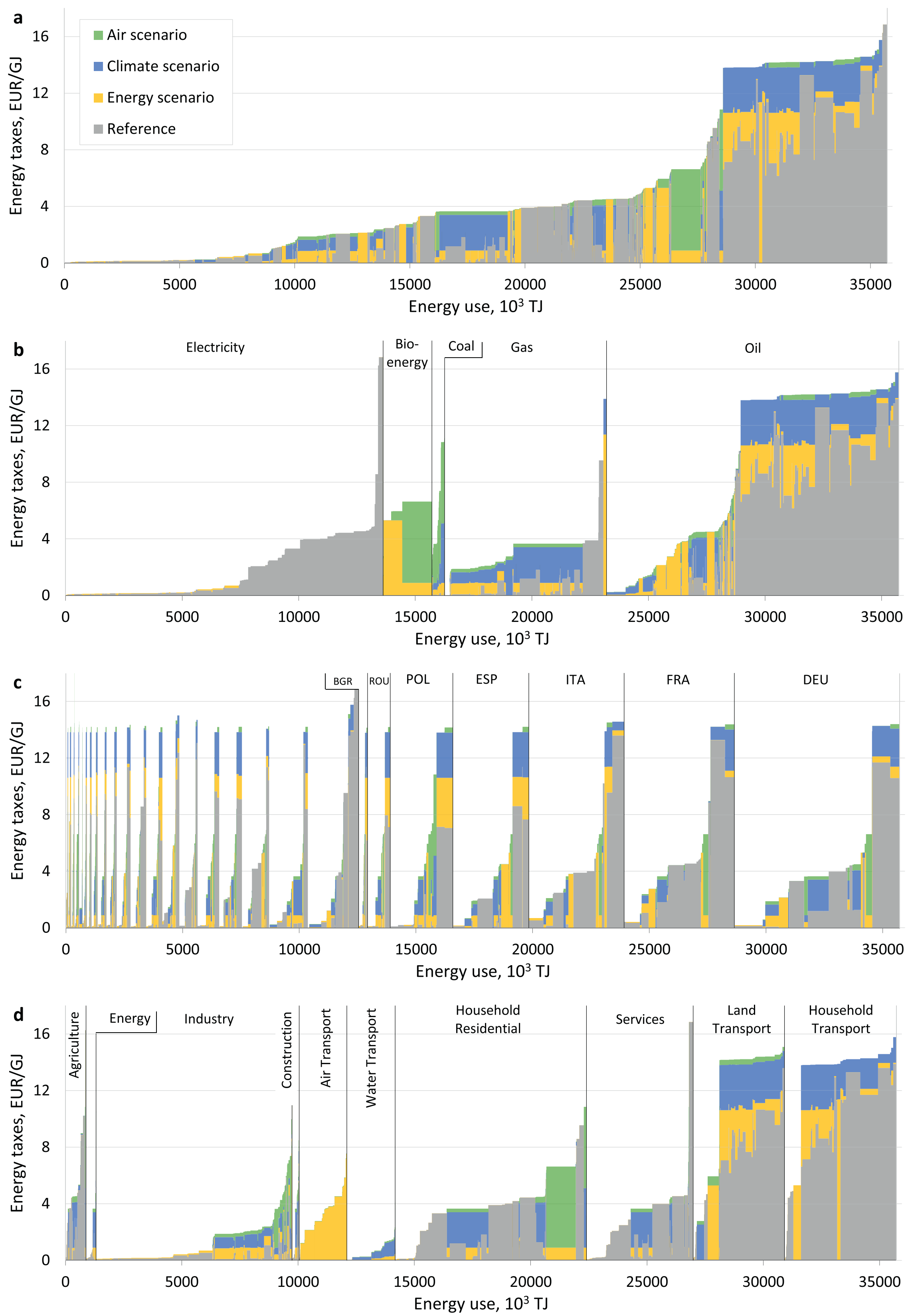

Fig. 1. Effective energy tax rates across scenarios. Different panels show rates across energy use a) without clustering, and b) clustered by energy product, c) by country, and d) by sector. For sector mapping, see Appendix A.

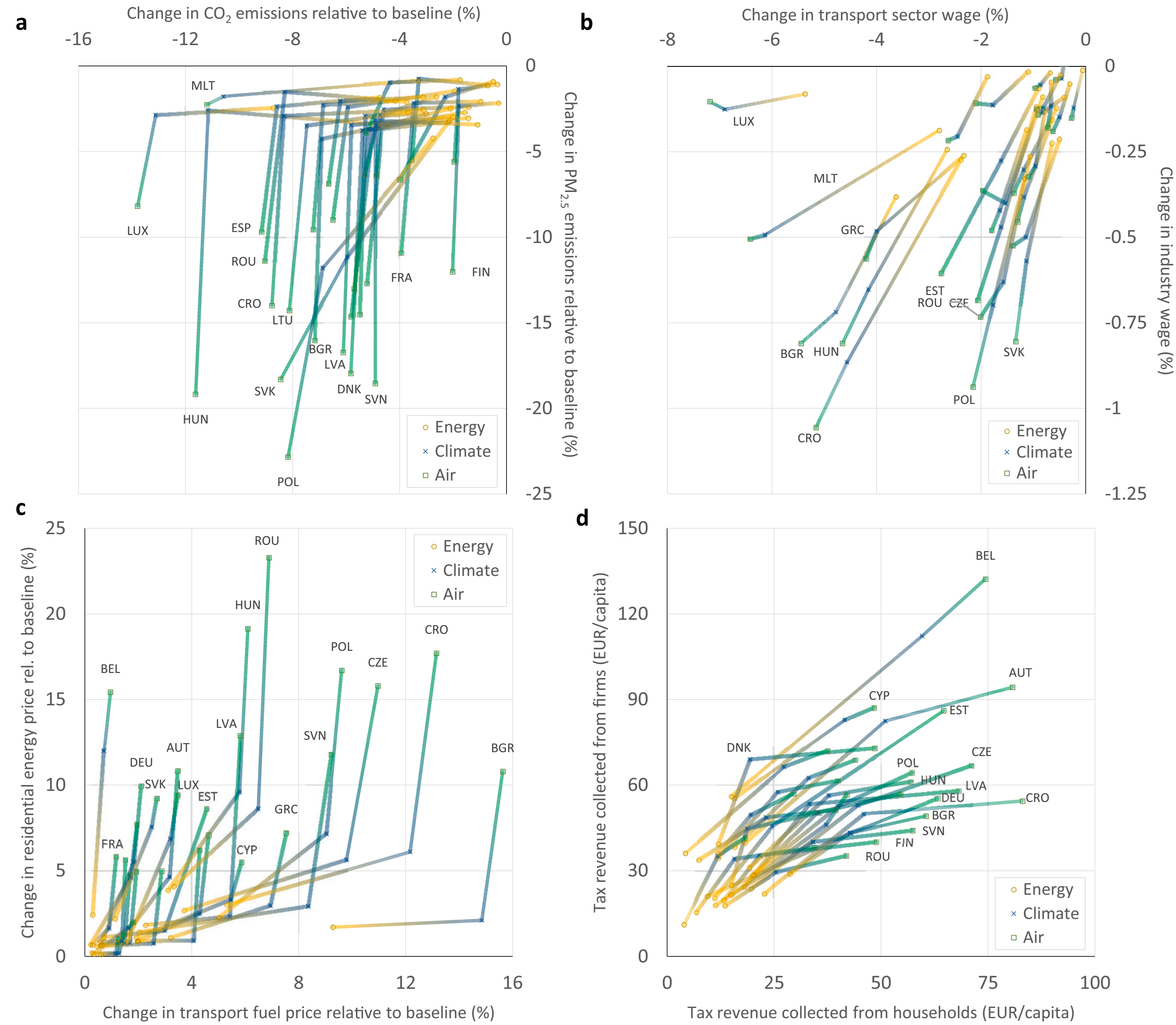

Fig. 2. Impact of ETD reforms on emissions, wages, prices, and tax revenue compared to the baseline in 2035.

by 2.1 % at the EU level compared to the reference in the year 2035 (when the transition has ended), with reductions ranging between 0 and 5 % for the majority of countries. This magnitude suggests that additional measures of the Fit for 55 package are needed to deliver on the ambition for climate change mitigation. The *Climate* scenario further raises EU-wide CO_2 emission reduction from about 2.1 % in the *Energy* scenario to 5.2 %, with stronger relative reduction from households (more than 8 % reduction compared to baseline) than from firms (−4 % vs. baseline). These reductions in emissions from households mostly stem from reduced oil and gas use, as final use of coal is limited in volume.

The numerical results furthermore point to climate co-benefits of air pollution-based taxes, raising CO_2 emission reductions from 5.2 % in the *Climate* scenario to 5.7 % in the *Air* scenario (Panel a of Fig. 2). These co-benefits are relatively strong in countries with coal use by households (e. g. Poland) and industry (e.g. Slovakia), but are generally more modest than in global studies that include large coal-based electricity generation sectors (Parry et al., 2015).[14]

The results also illustrate air quality co-benefits of climate-based taxation, with reductions of $PM_{2.5}$ emissions increasing from 2.5 % in the *Energy* scenario to 3.7 % in the *Climate* scenario, relative to the baseline (Panel a of Fig. 2). The *Air* scenario leads to more substantial reductions in $PM_{2.5}$ emissions: 13 % at the EU level, exceeding a reduction of 5 % in most countries, reaching approximately 20 % in several countries (Hungary, Poland, Slovakia, Slovenia) and exceeding 20 % for households on the EU average. These findings suggest that accounting for air pollution externalities in energy prices can bring significant clean air benefits by limiting the use of fossil fuels and

[14] Note that the additive scenario design may affect the magnitude of our estimates, as energy efficiency enhancements already occur in the Energy and Climate scenarios, and since investments in energy efficiency are characterized by increasing marginal costs.

biomass.

However, a deeper dive also illustrates trade-offs between climate and clean air. Although the effect is limited in size, the addition of a CO_2-based component in the energy taxation raises $PM_{2.5}$ emissions from residential energy use in some countries (Romania, Germany, Hungary) by inducing a shift from gas- to biomass-based heating. The results indicate stronger co-benefits for other air pollutants, such as SO_2 and VOC, and particularly for NO_x given the increase in excises on oil in transport (Figure SI-2 in Appendix B). Likewise, we find minor trade-offs with climate change mitigation of introducing an air pollution-based tax component in a few countries. With biomass taxation, the effect on climate change mitigation could go either way, in principle. In most instances, energy efficiency and electrification prevail such that overall effect on CO_2 mitigation is positive for all countries. Negative spillovers arise in a handful of countries: CO_2 emissions increase following the introduction of the air pollution-related tax rate component due to a biomass-to-gas shift in the residential energy mix, but the magnitude of the increase is limited (e.g. household CO_2 reduction falls from 17.9 % in the *Climate* scenario to 17.6 % in the *Air* scenario for Romania). These results highlight the importance of integrated policy responses to tackle climate change and air pollution jointly.

Emission reductions differ substantially across countries – both in magnitude and in relative contribution of sectors – reflecting differences in the energy mix and in current tax rates. We provide some examples here, as they illustrate the impact heterogeneity across countries which feeds into the distributional assessment in Section 4.3. In the *Energy* scenario, CO_2 emission reductions in Luxembourg reach 8.7 % (vs. 2.1 % at the EU level) due to taxation on oil use in transport, with about half the emission reduction coming from air transport, and the other half from land transport (including household private transport). For Central Eastern European countries such as Poland, Bulgaria (transport), and Romania (transport; gas in residential energy), the CO_2 emission reductions from household energy are more pronounced than overall EU averages (−2.9 %), exceeding 7 % in 2035 compared to the baseline. Countries with substantial use of biomass (Bulgaria) and coal (Poland) in residential energy see reductions in household $PM_{2.5}$ emissions that go beyond the 0–5 % range in the *Energy* scenario. For some countries, like France and Ireland, percentage CO_2 reductions are stronger for firms than for households, because the latter already face relatively high excises on fossil fuels for heating and transport under the current taxation systems represented in the baseline. These countries do see small reductions in fine particulate matter emissions in the *Energy* scenario due to the taxes introduced on biomass for residential heating and biofuels in transport. In the *Climate* scenario, the results indicate a CO_2 emission reduction of around 20 % for households in Bulgaria (transport), Hungary, Romania (transport and gas in residential energy) and Poland. In the latter, increased taxation on coal use for residential heating and in industry leads to relatively strong co-benefits for air quality, with a 12 % reduction of $PM_{2.5}$ emissions in the *Climate* scenario. Finally, in the *Air* scenario, CO_2 emission reductions range between 2.0 % (Netherlands) and 13.8 % (Luxembourg), with a wider range for $PM_{2.5}$ emission reductions between 2.3 % (Malta) and 22.8 % (Poland), illustrating the strong heterogeneity across EU Member States.

Three additional sets of outcomes are worthwhile highlighting at this stage, as they form the key inputs into the assessment of distributional impacts. First, changes in wages (Panel b of Fig. 2) influence income-side effects. Factor price changes are generally limited, but most pronounced in the transport sector, where fuel inputs represent an important component in overall production costs.[15] Industry wage reductions are more modest and generally do not exceed 1 % compared to the baseline level.

Second, changes in household energy prices (panel c of Fig. 2) drive expenditure-side effects. Energy prices for residential energy and private household transport (panel c of Fig. 2) stay within a + 5 % range for most countries under *Energy* scenario, but go well beyond in the more ambitious scenarios. The *Climate* scenario shifts this range to the order of +10 %, generally affecting more the transport fuel prices as the carbon intensity of energy mix for residential heating (electricity, gas, biomass) is typically lower than oil in transport. Countries with currently relatively low energy taxes for households (including Romania, Hungary, and Croatia) experience stronger price increases.[16]

Third, changes in tax revenues (panel d of Fig. 2) determine how much funds are available for revenue recycling. Considering all EU countries, additional tax revenue from households and firms tends to be below 25 and 40 EUR per capita, respectively, in the year 2035 for the *Energy* scenario, shifting upwards towards 50 and 80 EUR per capita in the *Climate* scenario and asymmetrically increasing to 80 and 90 EUR per capita for households and firms, respectively, in the *Air* scenario. Compared to the changes in emissions, the tax revenue results indicate larger contributions to the aggregate outcome from the firm side, which has a relatively large tax base (energy use) but generally smaller rate increases (e.g. gas use in industry). In summary, the proposed energy tax reforms bring substantial fiscal revenue from both household and firm side, with relative magnitudes differing across countries.[17]

The decrease in wages and the increase in energy prices illustrated in panels b and c of Fig. 2 imply negative welfare effects that are moderate in magnitude. Without accounting for the potential use of additional tax revenues and for the environmental benefits, the results indicate average EU27 welfare losses of 0.35 %, 0.75 % and 1.1 % of baseline household disposable income in the *Energy*, *Climate* and *Air* scenarios. Country-level welfare impacts vary substantially around the EU27 average. In the *Energy* scenario, the welfare loss ranges from 0.04 % in the Netherlands to 1.25 % in Bulgaria (Figure SI-6). This min-max range, led by the same two countries at opposite ends, shifts to 0.16 %–2 % and 0.2 %–2.7 % in the *Climate* and *Air* scenarios, respectively. Generally, the strongest effects take place in Central Eastern European countries.

The extent to which these welfare impacts are driven by changes in the sources of income (factor returns) versus the uses of income (consumption prices) again differs across scenarios and countries (see the additional results in Figures SI-6 to SI-8 and Table SI-3 in Appendix B). On the EU level, the (consumption) price effect represents just over half (52 %) of the total welfare impact (before revenue recycling) in the *Energy* scenario, which illustrates the importance of capturing the firm side (and associated endogenous factor returns) when assessing reforms of energy taxes that are also paid by producers. In the *Climate* and *Air* scenarios, the share of the total welfare impact explained by the price

[15] In line with the above-mentioned results, impacts on wages are relatively strong in the transport sectors in Central and Eastern European countries, Luxembourg (land and air transport), Malta (water transport), and Greece (air and water transport).

[16] For countries with a significant share of bioenergy in the projected residential energy mix, such as Bulgaria, the price changes in panel c of Figure 2 move along the horizontal axis (transport fuel price) from the *Energy* to the *Climate* scenario, as the *Climate* scenario does not raise the tax rates for bioenergy. From the *Climate* to the *Air* scenario, prices then move along the vertical axis as the *Air* scenario increases minimum tax rates for bioenergy. Other countries follow a different pattern. Belgium, for instance, moves mainly along the vertical axis, as current excises are high for household transport and low for residential energy use, and since residential heating relies on oil more than in most other EU countries.

[17] Low tax rates for energy use in commercial buildings explain the relatively large tax revenue collected from firms in Belgium, where the service sector represents a significant share of the economy. Another example with high additional tax revenue from the firm side relative to the household side is Denmark, where household residential energy consumption is largely electricity-based and gas and oil face high excise taxes under current regulation. Tax revenue from the firm side in Denmark largely comes from the transport (air and land transport in *Energy* scenario; also water transport in the *Climate* scenario), industry and agriculture (*Climate* scenario) sectors.

effect rises to 59 % and 62 %, respectively. These results are in line with findings presented above, e.g. tax revenue (Fig. 2 panel d) collected directly from households represents 33 %, 38 %, and 45 % of total tax revenue in the *Energy*, *Climate*, and *Air* scenarios, respectively. Looking beyond EU averages reveals strong heterogeneity across Member States. For the *Energy* scenario, for instance, the price effect explains two thirds or more of the total welfare effect in some countries (Poland, Latvia, Finland, the Netherlands), but below one third in others (Portugal, Germany, Denmark).

In the following section, we explore the distribution of these aggregate welfare effects across households.

4.2. Within-country distributional impacts: inequality, poverty, and welfare

In this section, we assess the socio-economic consequences of the proposed tax reforms by means of commonly used synthetic indicators for inequality (the Gini coefficient) and poverty (at-risk-of-poverty rate, AROP), and present welfare impacts across and within income deciles.

The Gini is based on household-level incomes (equivalised with OECD modified equivalence scales) and is shown on the horizontal axis of the four panels displayed by Fig. 3. The AROP rate indicates the share of people with equivalised incomes below 60 % of the median income in the baseline, and is shown on the vertical axis of Fig. 3. We distinguish between price (panel a) and income effects (panel b), and compare the total effect before (panel c) and after revenue-recycling transfers (panel d). Overall, consumption price increases from ETD reforms tend to raise poverty and inequality; wage declines raise poverty but lower inequality; and the total impact after lump-sum revenue recycling is to lower both poverty and inequality in the majority of countries. The following paragraphs unpack these findings further.

For most countries, the results of the micro-simulation analysis indicate an inequality-increasing price effect that is modest in the *Energy* and *Climate* scenarios, and somewhat stronger in the *Air* scenario (Fig. 3, panel a). Typically, expenditure shares for residential energy decline with income, while energy expenditure shares for private household transport show an inverse U-shaped pattern over the income distribution (see Figure SI-9 in Appendix B). As a result, countries with a substantial increase in residential energy prices (see panel c of Fig. 2, e.g. Croatia, Hungary, and Poland) experience a comparably strong increase in inequality. In two countries, Bulgaria and Romania, the price effect is inequality-decreasing as progressive transport fuel taxation (see, e.g.,

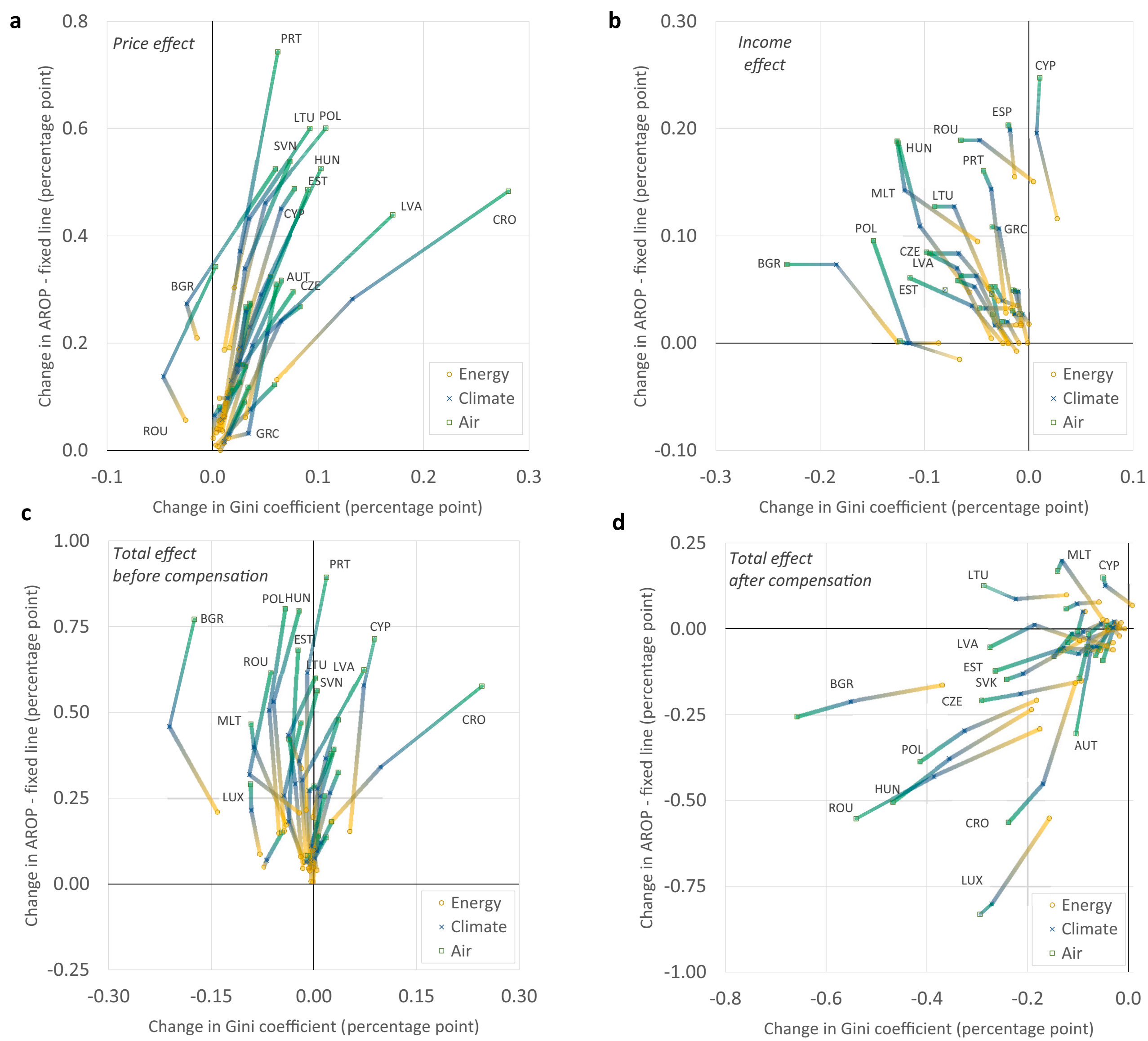

Fig. 3. Decomposition of impacts on inequality and poverty across countries and scenarios.

Amores et al., 2023) compensates the inequality-increasing effect of the rise in residential energy prices. In line with the results on emissions, prices, and tax revenue presented above, the *Air* scenario shifts the burden more towards households and residential energy, explaining the stronger effects on within-country inequality.

In contrast with the price effect, the results indicate an inequality-reducing income effect (panel b of Fig. 3). The decline in labour and capital income disproportionately affects the middle and top of the income distribution, as households at the bottom of the income distribution rely more on pensions, unemployment benefits and other government transfers. This inequality-reducing income effect tends to be larger in countries with stronger wage reductions (as shown in panel b of Fig. 2), but other factors also play a role. The proposed reforms have the largest inequality-reducing income effect in Bulgaria, for instance, as (1) increases in effective tax rates are relatively strong in the transport sector, (2) transport sector workers represent a comparably large share of the workforce, and (3) these workers tend to be more concentrated towards the higher end of the income distribution (see Figure SI-10 in Appendix B).[18]

Combined, the price and income channels lead to mixed inequality impacts across countries and scenarios before revenue recycling (panel c, Fig. 3). Generally, the changes in Gini coefficient are small, and outliers appear on both the positive and the negative side. Once we factor in within-country revenue recycling of additional tax revenue (obtained from households) through a (uniform per capita) lump-sum transfer (panel d of Fig. 3), the proposed energy tax reforms reduce within-country inequality, particularly in lower-income countries in the EU. Overall, these results illustrate that regressive effects arise in some countries, and that they can be offset by compensatory measures.

A more consistent pattern across countries emerges in terms of changes in poverty. Both price and income effects (panels a and b of Fig. 3) contribute to a modest increase in AROP rates compared to the baseline.[19] As in the case of inequality, lump-sum revenue recycling largely overturns these poverty impacts. In a few countries, however, the lump-sum transfer is insufficient to fully offset the poverty-increasing effects of higher prices and lower incomes, such that a minor increase in AROP rate remains after revenue recycling. Although the impact is small, recycling schemes that better target the poor than equal-per-capita transfers would be needed to decrease poverty in these instances.

The Gini coefficient and the AROP rate provide a useful first indication of the distributional impacts, but fail to reveal the impact heterogeneity (see, e.g. Jenkins, 2009) over the income distribution (vertical equity) and across households with similar income but different socio-economic and demographic characteristics (horizontal equity). We now turn to these vertical and horizontal equity impacts.

Vertical equity impacts are shown in panels a-d of Fig. 4, which present the (unweighted) average across country-level deciles of the price and income effects on welfare (panels a and b), and of the total welfare effect without and with lump-sum revenue recycling (panels c and d, respectively). The use of unweighted averages is motivated by the focus on within-country distributional effects in this section and implies that the average impacts for the bottom deciles in different countries receive equal weight regardless of the corresponding level of income and population size.

As before, the price effect of the ETD reform scenarios is regressive while the income effect is progressive. The price effect is relatively strong for the first decile. From the second decile onwards, total welfare impacts before transfer (panel c) show a somewhat progressive pattern that is roughly similar across scenarios. The main difference when moving from the *Energy* to the more ambitious (*Climate* and *Air*) scenarios comes from the order of magnitude. In line with what we discussed in the previous sections, we can see that a stronger price effect in the *Air* scenario results in a slightly flatter impact pattern over deciles two to ten. Once we account for the recycling of additional tax revenue via lump-sum per capita transfers, the impact pattern changes completely (see panel d, Fig. 4). The welfare losses of the bottom three deciles are more than offset, on average, resulting in net welfare gains with respect to the baseline (up to 1.3 % in the *Air* scenario). On the contrary, the welfare impacts after transfers remain negative for the top income deciles (up to −0.8 % in the *Air* scenario).

By averaging across deciles in all EU countries, these results provide a useful first glance of distributional impacts. At the same time, these figures conceal the heterogeneity (across countries) in impact patterns across deciles within countries. Figure SI-11 displays the range of the decile-average welfare effects across the EU-27 countries, illustrating that the average welfare impacts of the bottom decile range from slightly negative (welfare loss) to about +5 % (in the *Air* scenario in Romania). At the opposite end, the welfare impact experienced by the top decile ranges from approximately zero (e.g. in the Netherlands, *Energy* scenario) to −2.6 % (in Bulgaria, *Air* scenario).

In addition to impact heterogeneity across income groups, welfare effects can vary substantially within income groups, as households of similar income differ in expenditure patterns and income sources. These horizontal equity effects are important to consider, including for a better view on the acceptability concerns of energy price reform (Douenne, 2020; Cronin et al., 2019). The within-decile welfare impact dispersion can be clearly appreciated in the country-specific boxplots in Figures SI-12 to SI-14 in Appendix B and is particularly large at the lower end of the income distribution. While on average (and median) we see that in most countries the first and second deciles are better-off after the lump-sum transfer, this is not true for all households classified in this income group. The finding that households at the bottom end of the income distribution (including in the first decile) experience adverse welfare effects after the reform (also after the lump-sum transfer) suggests that more targeted measures might be needed to compensate vulnerable households that are particularly exposed to the energy price changes induced by the ETD reform scenarios.

The household-level microdata enables a further exploration of impact heterogeneity along other (non-income) socioeconomic characteristics of households and individuals. Figures SI-15 and SI-16 in Appendix B show the welfare effects in the *Energy* scenario by economic activity status (e.g. employed, unemployed, pensioners) and by age-gender groups, respectively. We plot the inter-quartile distribution of the total welfare effect for each of these groups before and after the lump-sum revenue recycling transfer. As our analysis accounts for income effects through wage changes, employed people tend to experience more negative welfare impacts than unemployed and pensioners (for which we assume that pensions and unemployment benefits are not indexed to prices or wages). The above-average adverse welfare effects experienced by children/students is due to a household composition effect: these groups tend to be over-represented both in households with employed adults as well as in the bottom deciles of the income distribution, where the price effect tends to be stronger. These composition and income effects also imply lower welfare losses for older people (over 65) and women, although we do not find a significant gender component in the results.

We can furthermore look at welfare impacts for households in energy poverty, where we use the 2 M indicator to identify people in energy

[18] Note that we assume here that social welfare benefits are not indexed to consumption prices or wages, which would influence distributional outcomes (see Vandyck et al., 2021). Furthermore, these results should be interpreted as short-term impacts, as the distributional assessment ignores household-level labour supply decisions, including adjustments at the external margin of the labour market and labour mobility across sectors, jobs, and countries. Empirical work has shown that these considerations can increase the regressivity of income effects from environmental policy (Vona, 2023).

[19] The only two exceptions are Austria and Poland in the Energy scenario, where the AROP rate slightly decreases after the income shock due to interactions with the tax-benefit system. For a small group of households that are close to the poverty threshold, the downward shift in labour income increases means-tested benefits and, correspondingly, household disposable income.

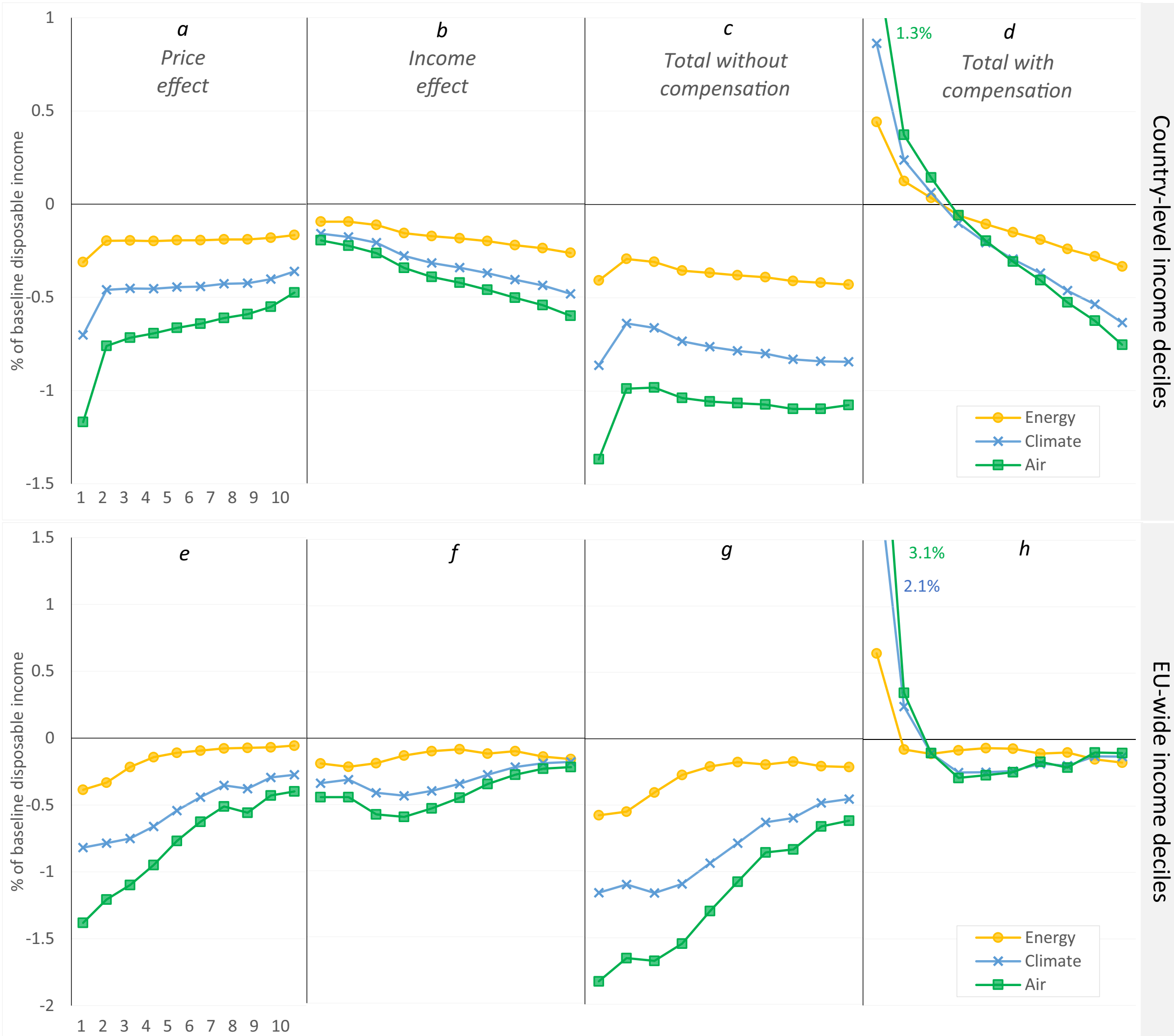

Fig. 4. Decomposition of impact on welfare by decile across scenarios. In panels a-d, welfare impact is averaged over country-level impacts per income decile. Panels e-h show average welfare effect per EU-wide income decile.

poverty if they live in a household with an income share of residential energy expenditures which is above twice the national median. For the majority of countries (across scenarios), the energy poor experience larger welfare losses than those not in energy poverty before accounting for the revenue recycling transfer (Figure SI-17 in Appendix B). This is mainly due to a stronger price effect, as the group of households in energy poverty is characterized by large residential energy expenditures relative to income. For the *Energy* and *Climate* scenarios, the results for about half of all EU countries indicate that the energy poor experience more negative impacts before transfer, but more positive welfare impacts from tax reform after the lump sum transfer, compared to those not in energy poverty. In the *Air* scenario, which results in stronger residential energy price increases (Fig. 2), households in energy poverty face stronger welfare losses than non-energy poor in all countries (except Luxembourg) before transfer, and in 17 countries after transfer of additional revenue.

4.3. EU-wide distributional effects

The results in the previous sections illustrate that impacts of proposed energy tax reforms differ across countries (Section 4.1) and across households within countries (Sections 4.2 and 1.1). In this section, we combine both dimensions by pooling all EU households and ranking them according to their baseline equivalised household disposable income, adjusted by purchasing power parity levels.[20] The resulting EU-wide income distribution offers a useful base to assess distributional impacts at the EU level. In this distribution, more than two thirds of the poorest 10 % and half of the second decile are individuals residing in Poland or Romania. In deciles 4 to 8, more than two thirds reside in Spain, Italy, Germany, or France. In the top income deciles (9th–10th), about 50 % are individuals in France or Germany, and the rest in other smaller Western or Northern European countries (see Appendix B, Figure SI-18).

Panels e-h of Fig. 4 are analogous to panels a-d of the same figure, but for EU-level income deciles instead of country-level deciles. Total welfare effects (panel g) before revenue recycling transfer for the poorest 20 % of the EU population indicate an average welfare loss of more than 0.5 %, 1 % and 1.5 % of baseline disposable income for the *Energy*, *Climate* and *Air* scenarios, respectively. Importantly, these welfare losses generally decline with income, which indicates that jointly accounting for within- and between-country heterogeneity leads to a regressive impact pattern. A comparison with the results that focus on within-country distributional impacts (panel c of Fig. 4) suggests that cross-country impact differences are an important source of regressivity for

[20] We use Eurostat's publicly available PPS series from 2019.

the ETD reform scenarios.

The price and income effects (panels e and f) reveal that the regressivity of the price effect is not compensated by a progressive income effect when considering the EU-wide income distribution. Stronger regressivity in the price effect when considering between-country differences confirms recent findings by Feindt et al. (2021) in the context of carbon pricing. This is driven by relatively more pronounced price changes in lower-income countries in the EU. More significant changes, however, occur in the income-side impact pattern (not included in Feindt et al., 2021). Unlike the results illustrating country-level impacts (panel b), the welfare losses via the income channel are now more concentrated towards the bottom end of the income distribution. As EU countries with relatively low income tend to have higher energy- and emission-intensive economic activity and lower energy tax rates, revised EU energy tax floors lead to regressive wage (see Fig. 2) and income-side welfare impact patterns at the EU level, reflecting the heterogeneity across countries. Earlier model-based studies based on a coarse labour market representation, such as Landis et al. (2021) and Mayer et al. (2021), find progressive impacts of carbon pricing due to the sources-side impacts, while empirical findings suggest regressive sources-side impacts (Vona, 2023). Our results suggest that considering heterogeneity across space and sectors (here disaggregated by 27 countries and six sectors) can result in regressive sources-side (income) impacts, providing a potential bridge between the diverging results in modelling and empirical studies.

When additional tax revenue is recycled (within the country) via lump sum transfers, the regressivity of the reform at the EU-wide level (panel g) is completely reverted (panel h). Compared to the results after transfer that focused on within-country distributional impacts (panel d), the welfare gains are now larger for the first decile, but also more concentrated towards the bottom of the income distribution. Decile-average impacts from the third EU-level income decile onwards are slightly negative across all scenarios. Per-capita transfers are uniform within a country but differ across countries, resulting in a non-monotone impact pattern after transfers.

As in the case of within-country distributional effects, average welfare effects per EU-wide decile hide substantial heterogeneity across households in the same income group (Figure SI-19 in Appendix B). The welfare effect before transfer in the bottom two deciles (i.e. poorest 20 % of the EU population) ranges between −1.5 to 0.8 % in the *Energy* scenario, from −3 % to 1 % in the *Climate*, and from −4.2 % to 1.8 % in the ***Air*** scenario. In addition to heterogeneity across household characteristics in dimensions other than income, these horizontal equity impacts are now also due to the fact that EU-wide deciles pool individuals living in households with similar incomes but residing in different countries. Differences in existing tax rates across countries therefore contribute to the impact dispersion within EU-wide deciles. While on average the first decile is better off after revenue recycling via lump sum transfer to households, about 25 % of the poorest decile still experiences a welfare loss after transfer.

5. Conclusions

One of the overarching questions of the paper is whether proposed energy taxation reforms are aligned with a just transition to climate neutrality. While getting energy prices right – reflecting externalities and reducing fossil fuel subsidies – can facilitate a transition towards sustainable energy use (Jewell et al., 2018; Parry et al., 2014), tax reforms often face acceptability challenges related to equity concerns within and between countries.

Fig. 5 combines results discussed in previous sections to enable an integrated perspective on environmental and distributional outcomes. Without compensatory measures (revenue recycling), the ETD reform introduces a trade-off between social and environmental outcomes: emission reductions come at the cost of raising poverty in all countries and inequality in some. With revenue recycling, proposed reforms can jointly reduce emissions and income inequality within all countries, and bring down poverty in most countries, highlighting the potential for synergies across social and environmental dimensions. The results furthermore indicate largely synergistic environmental effects, as climate-based taxation reduces air pollutant emissions, and air pollution-based energy taxation tends to strengthen climate change mitigation (despite trade-offs at a more granular level). The analysis thus suggests that careful policy design can pursue environmental and social targets at the same time, reducing greenhouse gas emissions, air pollution, poverty, and inequality simultaneously.

At the same time, our findings illustrate that lump sum transfers leave large impact heterogeneity within income groups unaddressed. These horizontal equity impacts are important to consider in a broader context of societal acceptability of policy reforms (van der Ploeg et al., 2022; Vandyck et al., 2022). Alternative policy packages could consider more targeted transfers, social tariffs, as well as other instruments, such as (means-tested) subsidy schemes (Hänsel et al., 2022; Lin and Lin, 2025). As our results indicate potential negative impacts for workers, complementary labour market policies (e.g. employment transition programs, re-skilling, upskilling) could play a role in cushioning distributional concerns. While alternative revenue recycling schemes are beyond the scope of this paper, earlier work illustrates the potential of earned income tax credits in addressing equity concerns of carbon pricing (Cronin et al., 2019). Our results also show that households in energy poverty risk negative welfare losses in the absence of compensatory measures, indicating that energy poverty concerns require dedicated policy responses (Vandyck et al., 2023). Further exploring policy approaches that tackle energy poverty and vertical and horizontal equity concerns jointly is an important avenue for future research.

Moreover, we have identified substantial cross-country impact heterogeneity, which is relevant from the point of view of the ongoing convergence and territorial cohesion challenges in the EU, as well as for political economy reasons, since revisions of the Energy Taxation Directive need to be agreed with a unanimity of votes in the Council of the European Union. At the same time, our analysis disregards other regional policy initiatives and dedicated policies to support regions in transition, such as the Just Transition Fund. In addition, our assessment ignores potential benefits from avoided climate damages and improved air quality, and the associated economic gains and distributional impacts (Dechezleprêtre et al., 2019; Emmerling et al., 2024; Young-Brun et al., 2025).

A broader policy package can also consider careful sequencing of policy measures. A timely phase-in of subsidies and taxes potentially limits the exposure of vulnerable households to strong price effects by enhancing energy efficiency and shifting to low-carbon sources of energy. This paper illustrates the importance of policy sequencing for distributional impacts: strong climate policy measures (in the baseline and via CO_2-based energy taxes) can lead to a shift towards biomass for residential heating; then, introducing air pollution-based taxation that raises the cost of biomass use gives rise to regressive impacts as residential energy expenditure shares decline with income. A joint consideration of multiple environmental externalities together with equity considerations is therefore important to avoid socio-political lock-in effects that prevent further progress towards climate neutrality and clean air.

CRediT authorship contribution statement

Sofia Maier: Writing – original draft, Methodology, Formal analysis. **Toon Vandyck:** Writing – original draft, Visualization, Supervision, Methodology, Formal analysis, Conceptualization. **Mattia Ricci:** Methodology, Formal analysis. **Luis Rey:** Methodology, Formal analysis. **Marie Tamba:** Methodology, Formal analysis. **Fabian Wagner:** Methodology.

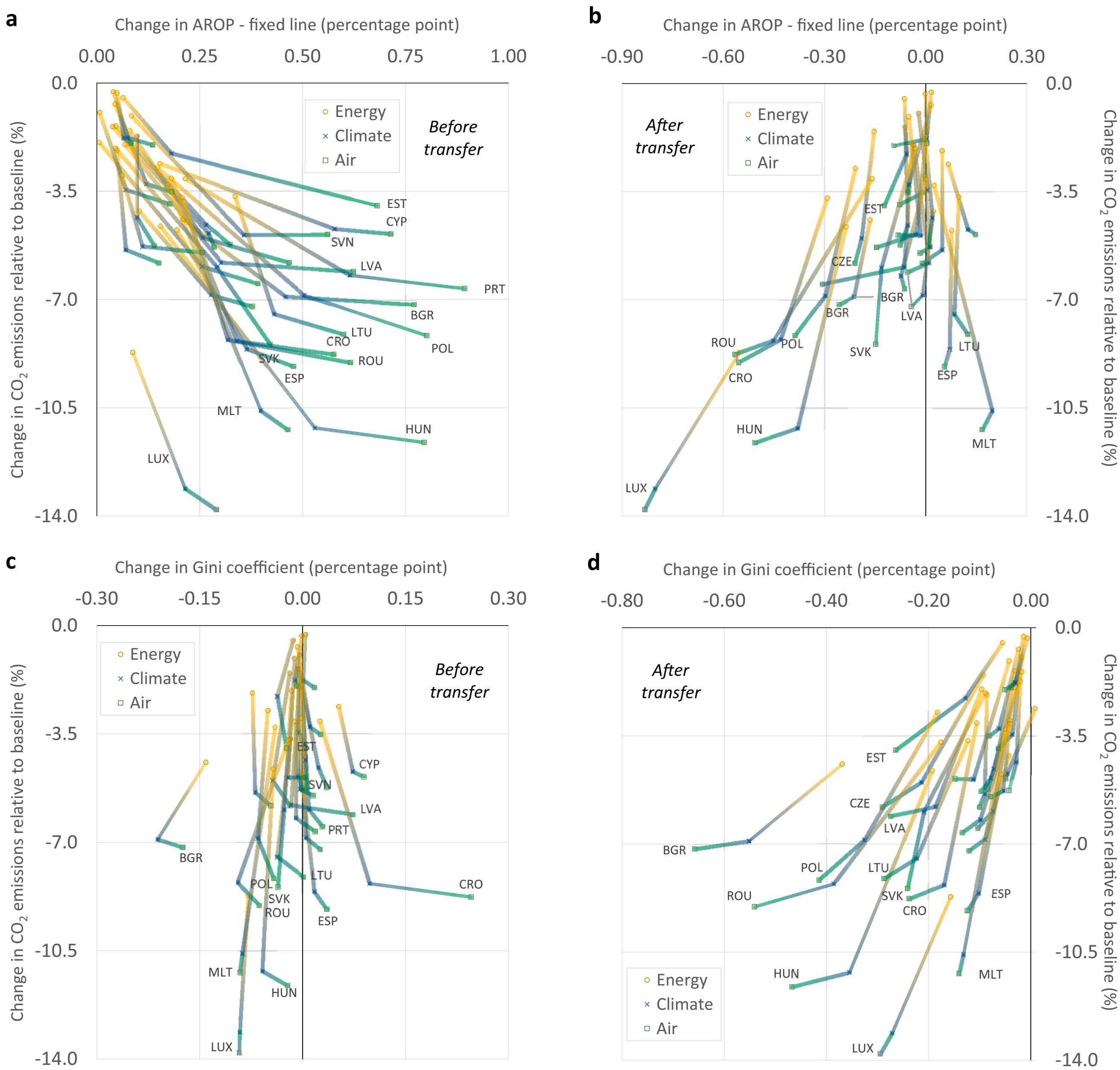

Fig. 5. Synergies and trade-offs between social and environmental outcomes. CO_2 emissions reduction vs. a) poverty, before transfer, b) poverty, after transfer, c) inequality, before transfer, d) inequality after transfer.

Declaration of competing interest

The authors declare no conflict of interest.

Acknowledgements

The views expressed here are purely those of the authors and may not, under any circumstances, be regarded as an official position of the European Commission. We would like to thank all colleagues who have contributed indirectly to this paper by working on the development of the JRC-GEM-E3 and EUROMOD models. We thank participants at the EMP-E 2021 conference, the European Commission's Annual Research 2022 Conference, Belgian Environmental Economics Day (BEED) 2024, the 29th Annual Conference of the European Association of Environmental and Resource Economists (EAERE), the 28th GTAP conference on Global Economic Analysis, and three external referees for valuable comments. We are furthermore particularly grateful to Ignacio Hidalgo González for his input on industry tax base and effective rates, as well as to Bianey Palma for her help with the original codes developed to analyse the distributional effects. Toon Vandyck acknowledges financial support of the KU Leuven BOF-ZAP grant (3H230637).

Appendix A. Methods

This Appendix provides further background to the methodological framework laid out in Section 2, schematically represented in Fig. A1 below. In particular, the following subsections elaborate further on (1) the computable general equilibrium model JRC-GEM-E3, (2) welfare measurement in EUROMOD_ITT, and (3) the procedure to match microdata on expenditures and income.

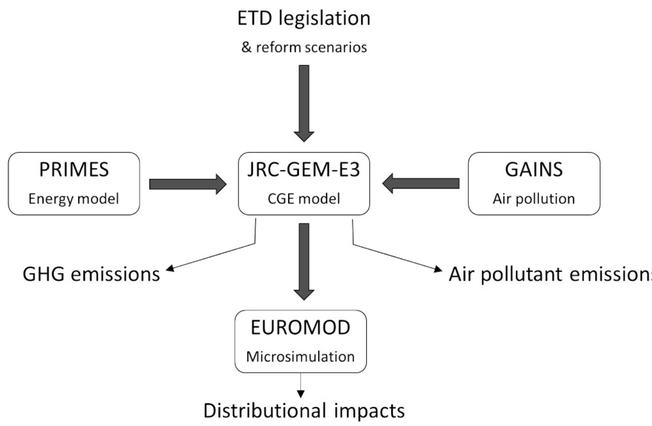

Fig. A1. Schematic overview of modelling toolbox.

A.1. JRC-GEM-E3

The JRC-GEM-E3 model provides a global and economy-wide scope, with economies disaggregated into 31 sectors, for which input-output connections and international trade are modelled. Sectoral activities map onto the 14 product categories listed in Table A1.

In JRC-GEM-E3, firms are cost-minimizing with Constant Elasticity of Substitution production functions. Sectors are interlinked by providing goods and services as intermediate production inputs to other sectors. Households are the owner of the factors of production (labour and capital) and thereby receive income, used to maximize Stone-Geary utility through consumption. Government behaviour is considered largely exogenous, although budget balance is maintained in the scenarios by endogenously adjusting transfers to households. Bilateral trade-flows adjust to prices according to a standard Armington specification. The model is recursive-dynamic, achieving an equilibrium for goods and services markets, and for factors of production through adjustments in prices in 5-year steps. The model and its mathematical equations are documented in Capros et al. (2013), and the underlying input-output data is described in Aguiar et al. (2019). Given the relevance of aviation in the ETD reform proposal (coverage extending to intra-EU aviation, see Section 2.4), we update the elasticity of substitution (see Table 1) between energy and the capital-labour bundle in this sector to values used (0.1) in similar models with a dedicated focus on air transport (Winchester et al., 2015). The model covers existing tax systems, including the EU Emission Trading System (ETS), which is represented by the carbon price signal in this paper.

The 31 sectors of the JRC-GEM-E3 model (second column of Table A2) are aggregated from the more granular sectoral disaggregation in the GTAP database, as indicated in the third column of Table A2. For the ease of visual representation, these 31 sectors are further aggregated to eight sectors (fourth column) in Fig. 1 (household residential and household transport are shown in addition). The mapping from the JRC-GEM-E3 sectors to the NACE classification used in the micro-data is shown in the fifth column. As this is a many-to-many mapping, we retain six aggregated sectors (sixth column in Table A2) for the macro-micro connection of sectoral wage changes.

The production structure of these sectors is governed by nested Constant Elasticity of Substitution (CES) functions. For most sectors, the structure follows the representation shown in Fig. A2. In response to changes in relative prices, firms may adjust the inputs into the production process. The ease at which sectors can shift to alternative inputs – deviating from the input structure in the current-policy Reference – is captured by the elasticities of substitution at various levels in the CES nest. These are represented by sigma’s in Fig. A2, for which the corresponding values are listed in Table A2. For further background on the model and its parameters, we refer to the more detailed description in Capros et al. (2013).

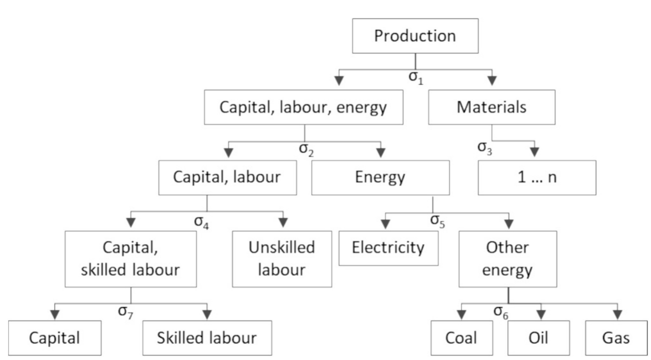

Fig. A2. Nesting structure for key sectors (not crude oil extraction, refineries, and electricity).

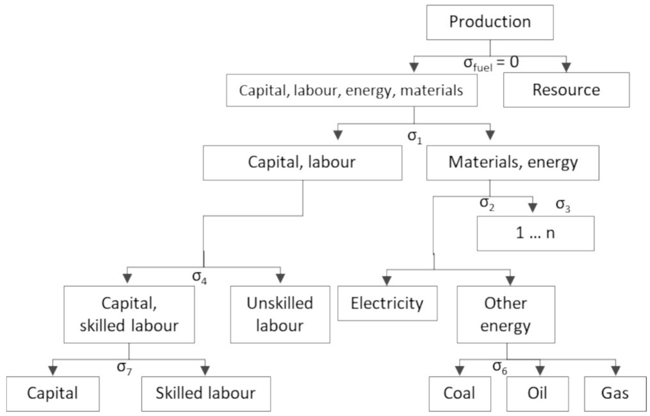

Fig. A3. Nesting structure for crude oil (sector 3 in Table A2).

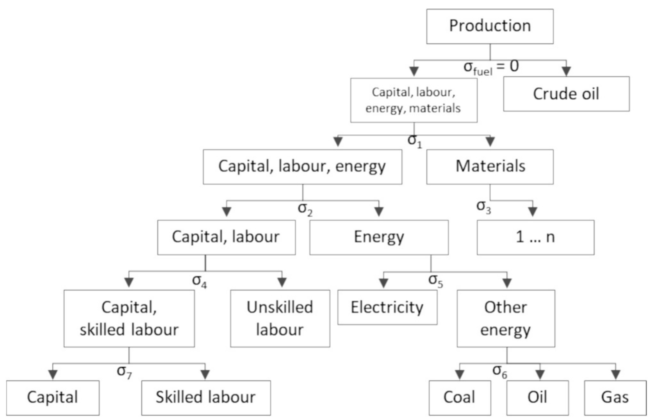

Fig. A4. Nesting structure for refineries (sector 4 in Table A2).

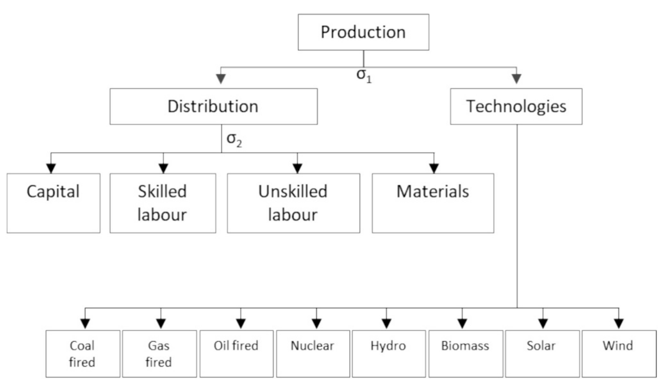

Fig. A5. Nesting structure for electricity sector (sector 6 in Table A2).

Table A1
Consumption categories in the JRC-GEM-E3 model.

01	Food, beverages, and tobacco	08	Purchase of vehicles
02	Clothing and footwear	09	Operation of personal transport equipment
03	Housing and water charges	10	Transport services
04	Fuels and power	11	Communication
05	Household equipment and operation	12	Recreational services
06	Heating and cooking appliances	13	Miscellaneous goods and services
07	Medical care and health	14	Education

Table A2
Sectors in the CGE model along with their mapping and elasticities (see also Fig. A2).

	JRC-GEM-E3 sectors	Mapping to GTAP10 Sectors	Fig. 1	NACE	NACE, aggregated	σ_1	σ_2	σ_3	σ_4	σ_5	σ_6	σ_7
1	Crops	PDR,WHT,GRO,V_F,OSD, C_B,PFB,OCR	Agriculture	1	Agriculture	0.2	0.25	0.25	0.24	0.5	0.9	0.25
2	Coal	COA	Energy	2	Industry	0.2	0.25	0.25	0.2	0.5	0.9	0.21
3	Crude Oil	OIL	Energy	2	Industry	0.2	0.25	0.25	0.2	0.5	0.9	0.21
4	Oil	P_C	–	3	Industry	0.2	0.25	0.25	1.26	0.5	0.9	1.32
5	Gas	GAS,GDT	Energy	2,4	Industry	0.2	0.25	0.25	0.73	0.5	0.9	0.77
6	Electricity supply	TnD	Energy	4	Industry	0.0	0.00					
7	Ferrous metals	I_S	Industry	3	Industry	0.2	0.25	0.25	1.26	0.5	0.9	1.32
8	Non ferrous metals	NFM	Industry	3	Industry	0.2	0.25	0.25	1.26	0.5	0.9	1.32
9	Chemical Products	CHM,BPH,RPP	Industry	3	Industry	0.2	0.25	0.25	1.26	0.5	0.9	1.32
10	Paper Products	PPP	Industry	3	Industry	0.2	0.25	0.25	1.26	0.5	0.9	1.32
11	Non metallic minerals	OXT,NMM	Industry	2,3	Industry	0.2	0.25	0.25	0.73	0.5	0.9	1.32
12	Electric Goods	ELE,EEQ	Industry	3	Industry	0.2	0.25	0.25	1.26	0.5	0.9	1.32
13	Transport equipment	MVH,OTN	Industry	3	Industry	0.2	0.25	0.25	1.26	0.5	0.9	1.32
14	Other Equipment Goods	FMP,OME,OMF	Industry	3	Industry	0.2	0.25	0.25	1.26	0.5	0.9	1.32
15	Consumer Goods Industries	CMT,OMT,VOL,MIL,PCR, SGR,OFD,B_T,TEX,WAP,LEA, LUM	Industry	3	Industry	0.2	0.25	0.25	1.17	0.5	0.9	1.23
16	Construction	CNS	Construction	6	Construction	0.2	0.25	0.25	1.4	0.5	0.9	1.47
17	Transport (Air)	ATP	Air Transport	8	Transport	0.2	0.1	0.25	1.68	0.5	0.9	1.76
18	Transport (Land)	OTP	Land Transport	8	Transport	0.2	0.25	0.25	1.68	0.5	0.9	1.76
19	Transport (Water)	WTP	Water Transport	8	Transport	0.2	0.25	0.25	1.68	0.5	0.9	1.76
20	Market Services	WTR,TRD,AFS,WHS,CMN, OFI,INS,RSA,OBS,DWE	Services	7,9,10,11,12,13,14,18,19	Other services	0.2	0.25	0.25	1.32	0.5	0.9	1.46
21	Non Market Services	ROS,OSG,EDU,HHT	Services	5,15,16,17	Public services	0.2	0.25	0.25	1.26	0.5	0.9	1.32
22	Coal fired	CoalBL	–	4	Industry							
23	Oil fired	OilBL,OilP	–	4	Industry							
24	Gas fired	GasBL,GasP	–	4	Industry							
25	Nuclear	NuclearBL	–	4	Industry							
26	Biomass	OtherBL	–	4	Industry							
27	Hydro electric	HydroBL,HydroP	–	4	Industry							
28	Wind	WindBL	–	4	Industry							
29	PV	SolarP	–	4	Industry							
30	Livestock	CTL,OAP,RMK,WOL,FSH	Agriculture	1	Agriculture	0.2	0.25	0.25	0.23	0.5	0.9	0.24
31	Forestry	FRS	Agriculture	1	Agriculture	0.2	0.25	0.25	0.2	0.5	0.9	0.21

A.2. Microdata matching procedure

This section details the approach used to impute EU-HBS data into the standard EUROMOD datasets, primarily based on EU-SILC. This imputation process is key to constructing the EUROMOD-ITT dataset, which integrates household demographics, income, labor market details, and consumption patterns. Since SILC and HBS survey different households, a direct match between them is not possible. To bridge this gap, we apply an imputation method that pairs each SILC household with its closest counterpart in HBS.

For this, we use the semi-parametric procedure developed by Akoğuz et al. (2020), which builds on Engel curve estimation (as seen in Decoster et al., 2010) and incorporates matching techniques. This procedure consists of three main steps. Firstly, a common set of relevant covariates is identified in the source and in the recipient dataset, including socio-economic characteristics of the household (head). Secondly, in the source dataset, consumption goods are aggregated into 20 macro-category and expressed in terms of consumption shares of income. These aggregated consumption shares are then regressed against the set of covariates identified in the first step. Thirdly, the estimated coefficients are then used to construct fitted shares of consumption in both the source and in the recipient dataset (i.e in each of these dataset, 20 fitted consumption shares will be calculated for any household based on their covariate). A Mahalanobis distance metric is then used to find the closest match between any record in the source and in the recipient dataset. The following section outlines the method step by step (for more information and discussions based on recent applications also see Amores et al., 2023, 2025).

A household h's expenditure on a commodity i in the source dataset (the HBS, indexed by 's'), denoted by e_{shi}, is converted into a share, w_{shi}, of disposable income, y_{sh}, i.e.:

$$w_{shi} = \frac{e_{shi}}{y_{sh}}, i \in N,$$

where N is the set of indices of commodities at the most detailed level in the HBS.

The above expenditures as shares of income are aggregated under broad categories of commodities.[21] We index these categories by the vector X. Thus, the income share of expenditure category X, W_{shx}, is defined as:

$$W_{shX} \equiv \sum_{i \in N_X} w_{shi}.$$

Consumption shares of income for aggregated categories, W_{shx} are regressed against a relevant set of covariates common to both the source (HBS) and the recipient (SILC) datasets. Although there is no structural interpretation to the regression model, the selection of covariates is inspired by the specification of Engel curves.[22] Note that aggregated categories X may still contain a significant number of zero observations. At this level of aggregation, these are considered to be true zeros. To account for zero expenditures, a two-step regression is performed, as described in points a) and b) below.

a) The probability that a household exhibits positive expenditures on commodity aggregate X is modelled by a probit model, using the common variables in the source and recipient dataset as explanatory variables. Formally:

$$\Pr(W_{shX} > 0) = 1 - \varphi\left(-\gamma_X' x_{sh}\right) = \varphi\left(-\gamma_X' x_{sh}\right),$$

where $\varphi(\bullet)$ denotes the standard normal distribution function, x_{sh} is the vector of explanatory variables for household h in the source dataset s, and the vector γ_X' contains the parameters to be estimated.

Explanatory variables are selected based on data availability in both surveys and their significance and contribution to explaining consumption patterns. The covariates for all regressions (20 linear OLS regressions for positive expenditures and 20 probits for estimating the probability of positive expenditures) are the same per country. Household-level variables cover incomes (different sources), region (NUTS1), reference person being a farmer or not, number of male adults, number of HH members under age 14, number of employed individuals, etc.; whereas individual-level variables that are used to construct these variables are gender, citizenship, education level, current education status, employment status and age.

b) Next, an ordinary continuous regression model is formulated to assess the relation of positive income shares for broad expenditure categories with the common variables. Formally:

$$W_{shX} = \beta_X' X_{sh} + \varepsilon_h, W_{shX} > 0.$$

Using the estimated models, income shares spent on the broad categories X are fitted for all households in both the source ('s') and the recipient datasets ('r'), i.e.:

$$\widehat{W}_{dhX} = \varphi\left(-\widehat{\gamma_X' x_{dh}}\right)\widehat{\beta_X'} X_{dh}, \mathrm{d} = \mathrm{s}, \mathrm{r}.$$

Denote a vector (across aggregated commodity categories) of fitted shares retained as input for the distance by $\widehat{W}_{dh}$, where $d = s, r$. Using the Mahalanobis distance metric, the distance between a household h in the source data, and a household g in the recipient data is defined as:

$$dist(h, g) = \mathrm{dist}\left(\widehat{W}_{sh}, \widehat{W}_{rg}\right) = \sqrt{\left(\widehat{W}_{sh} - \widehat{W}_{rg}\right)' \Sigma^{-1} \left(\widehat{W}_{sh} - \widehat{W}_{rg}\right)},$$

where Σ stands for the variance-covariance matrix of the vector $\widehat{W}$, using data from both source and recipient.

A match for household g in the recipient dataset is defined as the household h in the source dataset that has the smallest distance to household g, where the distance is measured in terms of the equation above. For each match (h, g), income shares of expenditures at the most detailed level of goods disaggregation, $\mathrm{i} \in \mathrm{N}$ for the recipient household g, are obtained from the corresponding values of the source household h:

$$w_{rgi} = w_{shi}.$$

Table A3
Macro-categories used for the matching.

1. Food and non–alcoholic beverages	11. Private transportation
2. Housing (rental)	12. Public transportation
3. Housing (goods and services)	13. Travelling and holiday
4. Utilities	14. Education
5. Communications	15. Vehicles
6. Culture and recreation	16. Housing (durables)
7. Personal care	17. Clothing and personal items
8. Insurance	18. Health and care
9. Alcoholic beverages	19. Restaurants
10. Tobacco	20. Other

[21] These categories should be large enough to reduce the infrequent expenditure problem but small enough to allow household characteristics to explain differences in allocations of income across these goods.

[22] These covariates include the following household-level variables: disposable income (third degree polynomial), number of adult males, number of members aged ≤14, 15–29, 30–44, 45–59, ≤ 60, number of employed, number of unemployed, number of pensioned, number of disabled, number of students aged >14, number with higher education, number of non–EU citizens, reference person farmer, and regional dummies.

A.3. Welfare in EUROMOD-ITT

Expenditures in the micro-model are the sum of the cross product of the imputed household-level (h) income shares of expenditures from HBS to SILC ${s_{kt}}^{h}_{hbs-silc}$for each consumption category k and household disposable income from EUROMOD ($Y^h_{EM}t$) at time t. Total household expenditures are also the product of consumed quantities and consumer prices for the K-consumption basket:

$$X^h_t = \sum_{k=1}^{K} s^h_{kt} Y^h_{EMt} = \sum_{k=1}^{K} p_{kt} q^h_{kt}.$$

Baseline expenditures ($t = 0$) are expressed as X^h_0 – where we simplify the notation, to refer to the whole basket, as the product of quantities (q_0) and prices (p_0):

$$X^h_0 = p_0\, q^h_0.$$

The simulated fiscal policy reform (i.e., revision of minimum energy tax rates) raises consumer prices ($p_1 > p_0$). The shock in prices is heterogeneous across consumption categories but here we illustrate it with a consumption basket composed of one good – for parsimony reasons – the extension to the whole basket is straightforward and does not require any further assumption. With the rise in consumer prices, the after-reform expenditures ($t = 1$) under constant quantities (X_{1cq}) will therefore increase too ($X_{1cq} > X_o$), and are defined as:

$$X^h_{1cq} = p_1 q^h_0,$$

where q^h_0 is the initial quantity of goods consumed by household h, and p_1 is the new (after-reform) price level. The compensating variation (CV^h) is then defined as the additional income needed to keep the initial, pre-reform consumption basket under the new prices p_1:

$$CV^h = X^h_{1cq} - X^h_0.$$

The welfare-price effect (w_p) is the compensating variation after the shock in prices expressed as percentage of baseline disposable incomes:

$$w_p = \frac{CV^h}{Y^h_0} = \frac{X^h_0 - X^h_{Cq}}{Y^h_0} = \frac{p_0 q^h_0 - p_1 q^h_0}{Y^h_0}.$$

When we evaluate the price effect on income inequality and poverty, we simply use equivalent incomes (Y_{cv}), defined as the additional income that would be needed to pay for this compensating variation. Therefore, the after-reform disposable income under compensating variation is estimated as follows:

$$Y^h_{cv1} = Y^h_0 + CV^h_1.$$

Incomes (both baseline and under compensating variation) are equivalised with mod-OECD equivalent scales to account for differences in household composition. The redistributive effect and the impact on poverty are based on the comparison between these two income concepts Y^h_{cv1} and Y^h_0.

The welfare-income effect (w^h_y), expressed as share of pre-reform income, is defined as:

$$w^h_y = \frac{Y^h_1 - Y^h_0}{Y^h_0}.$$

Incomes after the shock (Y^h_1), expressed in disposable income, depend on the shock in gross wages across J sectors ($w_{j0} - w_{j1}$) and capital income ($c_0 - c_1$), but also on household characteristics (HHc_0) and tax-benefit rules (tb_0) of each country, which remain fixed at baseline values:

$$Y^h_0 = f(w_{j0}, c_0, tb_0, HHc_0),$$

$$Y^h_1 = f(w_{j1}, c_1, tb_0, HHc_0).$$

The total welfare effect (w^h_T) can then be expressed as the sum of welfare-price effect (w^h_p) and the welfare-income effect (w^h_y):

$$w^h_T = w^h_p + w^h_y = \frac{CV^h_1}{Y^h_0} + \frac{Y^h_1 - Y^h_0}{Y^h_0}.$$

A.4. Further background on the calculation of tax rates in the Air scenario

To clarify the tax rates based on air pollution, we provide more insight on the general philosophy and illustrate for the example of natural gas for heating. The *Air* scenario adds 0.32 EUR/GJ in this case, as illustrated in Table 1. Here we show the derivation of this number.

The idea here is to factor the damages associated with air pollution into the energy tax rates. This requires quantifying four components: (A) air pollutant emission factors, (B) physical damages from air pollution, here restricted to mortality impacts expressed as years of life lost, (C) emissions, to quantify damages for tonne of emissions, and (D) a monetary valuation of physical damages from air pollution. These components, along with their sources, are listed in Table A4. The combination of these factors (A*B/C*D) gives tax rates of 0.07 EUR/GJ and 0.25 EUR/GJ for $PM_{2.5}$ and NOx, respectively, summing to 0.32 EUR/GJ found in Table 1.

For the calculation of damages per tonne of emissions (B/C), it is important to ensure that both the numerator and denominator have the same coverage. As mortality is based on $PM_{2.5}$ *concentrations* rather than primary anthropogenic emissions, natural sources as well as secondary particulate matter have to be accounted for in the emissions in the denominator. Table A5 provides the corresponding emissions data (highlighted cells show the values used in Table A4).

Table A4
Detailed calculations of tax rates in the Air scenario: illustration for natural gas used for heating.

	Natural gas (2016)	PM2.5	NOx	Unit	Source / note
A	Emission factor	0.7	31	g / GJ	EMEP/EEA guidebook 2019*
B	Mortality	3,530,400	564,500	Years of Life Lost	EEA Air quality in Europe - 2019 report
C	Emissions	3678	7011	kt	EMEP centre on emission inventories and projections**
D	Mortality valuation	100,068	100,068	EUR / life year lost	EUR2019
		79,500	79,500		EUR2005 (Based on OECD)
		25.87	25.87		Inflation 2005–2019, Eurostat
A*B/C*D		0.07	0.25	EUR / GJ	

* Tier 1, gaseous fuels, Residential plants.
** https://www.ceip.at/webdab-emission-database/reported-emissiondata

Table A5
Emissions and the calculation of PM2.5 emissions including secondary emissions.

Emissions (kt, 2016, EU27)	NMVOC	NH3	NOx	PM2.5	SOx	Total
PublicPower	41.42	4.03	938.22	33.88	780.23	
Industry	477.69	43.33	908.51	159.64	686.43	
OtherStatComb	1228.75	45.47	578.16	957.62	340.09	
Fugitive	359.32	5.53	22.88	7.64	112.62	
Solvents	2331.42	4.13	2.20	21.17	0.95	
RoadTransport	565.84	48.83	2840.49	135.01	4.24	
Shipping	31.65	0.04	228.38	13.25	53.75	
Aviation	5.87	0.15	62.10	2.26	3.87	
Offroad	155.95	0.33	559.75	40.33	4.29	
Waste	60.74	51.42	68.80	95.95	4.01	
AgriLivestock	1219.75	1500.34	43.06	21.54	0.00	
AgriOther	388.18	1952.23	736.58	17.19	0.50	
Other	0.00	34.34	0.05	0.41	0.00	
Natural	2385.07	4.76	21.82	26.62	947.37	
Total	9251.64	3694.93	7011.00**	1532.51	2938.35	
PM2.5 Conversion factor*	0.009	0.194	0.067	1	0.298	
PM2.5-equivalent, Total	83.26	716.82	469.74	1532.51	875.63	3677.96**

Source: EMEP emission inventories.
* Source of PM2.5 conversion factors: TSAP report #15.
** Values used in Table A4

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2025.109001.

References

Aguiar, A., Chepeliev, M., Corong, E.L., McDougall, R., Van Der Mensbrugghe, D., 2019. The GTAP data base: version 10. J. Glob. Econ. Anal. 4, 1–27.

Akoğuz, E.C., Capéau, B., Decoster, A., De Sadeleer, L., Güner, D., Manios, K., Paulus, A., Vanheukelom, T., 2020. A New Indirect Tax Tool for EUROMOD - Final Report.

Allcott, H., Mullainathan, S., Taubinsky, D., 2014. Energy policy with externalities and internalities. J. Public Econ. 112, 72–88.

Amann, M., Bertok, I., Borken-Kleefeld, J., Cofala, J., Heyes, C., Höglund-Isaksson, L., Klimont, Z., Nguyen, B., Posch, M., Rafaj, P., et al., 2011. Cost-effective control of air quality and greenhouse gases in Europe: modeling and policy applications. Environ. Model Softw. 26, 1489–1501.

Amores, A.F., Maier, S., Ricci, M., 2023. Taxing household energy consumption in the EU: the tax burden and its redistributive effect. Energy Policy 182, 113721.

Amores, A.F., Basso, H., Bischl, J.S., De Agostini, P., De Poli, S., Dicarlo, E., Flevotomou, M., Freier, M., Maier, S., García-Miralles, E., Pidkuyko, M., 2025. Inflation, fiscal policy, and inequality: the impact of the post-pandemic Price surge and fiscal measures on European households. Rev. Income Wealth 71 (1), e12713.

Böhringer, C., Fischer, C., 2023. Tax, kill or bill: an analysis of unilateral CO_2 price floor options in multilateral emissions trading systems. J. Environ. Econ. Manag. 119, 102816.

Böhringer, C., Peterson, S., Rutherford, T.F., Schneider, J., Winkler, M., 2021a. Climate policies after Paris: pledge, trade and recycle: insights from the 36th energy modeling forum study (EMF36). Energy Econ. 103, 105471.

Böhringer, C., Rutherford, T.F., Schneider, J., 2021b. The incidence of CO_2 emissions pricing under alternative international market responses: a computable general equilibrium analysis for Germany. Energy Econ. 101, 105404.

Böhringer, C., García-Muros, X., González-Eguino, M., 2022. Who bears the burden of greening electricity? Energy Econ. 105, 105705.

Cai, M., Vandyck, T., 2020. Bridging between economy-wide activity and household-level consumption data: matrices for european countries. Data in Brief 30, 105395.

Capros, P., Van Regemorter, D., Paroussos, L., Karkatsoulis, P., Fragkiadakis, C., Tsani, S., Charalampidis, I., Revesz, T., Perry, M., Abrell, J., 2013. GEM-E3 model documentation. In: JRC Scientific and Policy Reports 26034.

Cronin, J.A., Fullerton, D., Sexton, S., 2019. Vertical and horizontal redistributions from a carbon tax and rebate. J. Assoc. Environ. Resour. Econ. 6, S169–S208.

Dechezleprêtre, A., Rivers, N., Stadler, B., 2019. The Economic Cost of Air Pollution: Evidence from Europe. OECD Economics Department Working Papers.

Decoster, A., Loughrey, J., O'Donoghue, C., Verwerft, D., 2010. How regressive are indirect taxes? a microsimulation analysis for five European countries. J. Policy Anal. Manage. 29, 326–350.

Douenne, T., 2020. The vertical and horizontal distributive effects of energy taxes: a case study of a French policy. Energy J. 41 (3).

Drupp, M.A., Kornek, U., Meya, J.N., Sager, L., 2025. The economics of inequality and the environment. J. Econ. Lit. 63 (3), 840–874.

Emmerling, J., Andreoni, P., Charalampidis, I., Dasgupta, S., Dennig, F., Feindt, S., Fragkiadakis, D., Fragkos, P., Fujimori, S., Gilli, M., Grottera, C., Guivarch, C., Kornek, U., Kriegler, E., Malerba, D., Marangoni, G., Méjean, A., Nijsse, F., Piontek, F., Simsek, Y., Soergel, B., Taconet, N., Vandyck, T., Young-Brun, M., Zhao, S., Zheng, Y., Tavoni, M., 2024. A multi-model assessment of inequality and climate change. Nat. Clim. Chang. 14 (12), 1254–1260.

ESABCC (European Scientific Advisory Board on Climate Change), 2024. Towards EU climate neutrality: Progress, policy gaps and opportunities. In: Assessment Report 2024. https://doi.org/10.2800/216446.

European Commission, 2020a. Stepping up Europe's 2030 climate ambition: investing in a climate-neutral future for the benefit of our people. In: Communication COM/2020/562.
European Commission, 2020b. The 2021 Ageing Report: Underlying Assumptions and Projection Methods. Institutional Paper 142. Directorate-General for Economic and Financial Affairs.
European Commission, E.C, 2021a. Proposal for a council directive restructuring the union framework for the taxation of energy products and electricity. Impact Assessment Report. Staff Working Document SWD 641.
European Commission, E.C, 2021b. Second clean air outlook. Impact Assessment Report. Staff Working Document SWD 3.
Feindt, S., Kornek, U., Labeaga, J.M., Sterner, T., Ward, H., 2021. Understanding regressivity: challenges and opportunities of European carbon pricing. Energy Econ. 103, 105550.
Flachsland, C., Pahle, M., Burtraw, D., Edenhofer, O., Elkerbout, M., Fischer, C., Tietjen, O., Zetterberg, L., 2020. How to avoid history repeating itself: the case for an EU emissions trading system (EU ETS) price floor revisited. Clim. Pol. 20, 133–142.
Goulder, L.H., Hafstead, M.A., Kim, G., Long, X., 2019. Impacts of a carbon tax across us household income groups: what are the equity-efficiency trade-offs? J. Public Econ. 175, 44–64.
Hänsel, M.C., Franks, M., Kalkuhl, M., Edenhofer, O., 2022. Optimal carbon taxation and horizontal equity: a welfare-theoretic approach with application to German household data. J. Environ. Econ. Manag. 116, 102730.
International Energy Agency, 2020. Extended World Energy Balances, IEA World Energy Statistics and Balances (Database). IEA.
Jacobsen, M.R., Sallee, J.M., Shapiro, J.S., Van Benthem, A.A., 2023. Regulating untaxable externalities: are vehicle air pollution standards effective and efficient? Q. J. Econ. qjad016.
Jenkins, S.P., 2009. Distributionally-sensitive inequality indices and the gb2 income distribution. Rev. Income Wealth 55, 392–398.
Jewell, J., McCollum, D., Emmerling, J., Bertram, C., Gernaat, D.E., Krey, V., Paroussos, L., Berger, L., Fragkiadakis, K., Keppo, I., Saadi, N., Tavoni, M., van Vuuren, D., Vinichenko, V., Riahi, K., 2018. Limited emission reductions from fuel subsidy removal except in energy-exporting regions. Nature 554 (7691), 229–233.
King, M.A., 1983. Welfare analysis of tax reforms using household data. J. Public Econ. 21, 183–214.
Kiuila, O., Markandya, A., Ščasný, M., 2019. Taxing air pollutants and carbon individually or jointly: results from a cge model enriched by an emission abatement sector. Econ. Syst. Res. 31, 21–43.
Köppl, A., Schratzenstaller, M., 2023. Carbon taxation: a review of the empirical literature. J. Econ. Surv. 37 (4), 1353–1388.
Landis, F., Fredriksson, G., Rausch, S., 2021. Between- and within-country distributional impacts from harmonizing carbon prices in the EU. Energy Econ. 103, 105585.
Lin, B., Lin, Z., 2025. The distributional effects of inclusive energy-efficiency subsidies: an empirical study of multi-dimensional Matthew effects. J. Environ. Manag. 394, 127500.
Maier, S., Ricci, M., Almeida, V., Christl, M., Cruces, H., De Poli, S., Grünberger, K., Hernández, A., Hufkens, T., Hupteva, D., et al., 2022. EUROMOD Baseline Report. European Commission.
Mantzos, L., Wiesenthal, T., Matei, N.A., Tchung-Ming, S., Rozsai, M., Russ, P., Soria Ramírez, A., 2017. JRC-IDEES: Integrated Database of the European Energy Sector - Methodological Note, Luxembourg, 2017.
Mardones, C., Mena, C., 2020. Economic, environmental and distributive analysis of the taxes to global and local air pollutants in Chile. J. Clean. Prod. 259, 120893.
Mayer, J., Dugan, A., Bachner, G., Steininger, K.W., 2021. Is carbon pricing regressive? Insights from a recursive-dynamic CGE analysis with heterogeneous households for Austria. Energy Econ. 104, 105661.
Newbery, D.M., Reiner, D.M., Ritz, R.A., 2019. The political economy of a carbon price floor for power generation. Energy J. 40.
OECD, 2022. Pricing greenhouse gas emissions: turning climate targets into climate action. In: OECD Series on Carbon Pricing and Energy Taxation. OECD Publishing, Paris. https://doi.org/10.1787/e9778969-en.
Parry, I., Vollebergh, H.R., 2016. Reforming the eu energy tax directive: assessing the options. CESifo working paper series no. 5749. Available at SSRN https://ssrn.com/abstract=2747273.
Parry, I.W., Heine, M.D., Lis, E., Li, S., 2014. Getting Energy Prices Right: From Principle to Practice. International Monetary Fund. https://doi.org/10.5089/9781484388570.071.
Parry, I., Veung, C., Heine, D., 2015. How much carbon pricing is in countries' own interests? The critical role of co-benefits. Climate Change Econ. 6, 1550019.
Parry, I., Black, S., Roaf, J., 2021. Proposal for an international carbon price floor among large emitters. In: IMF Staff Climate Notes 2021/001. International Monetary Fund, Washington, DC.
Piketty, T., Saez, E., Zucman, G., 2018. Distributional national accounts: methods and estimates for the United States. Q. J. Econ. 133 (2), 553–609.
Pizer, W.A., Sexton, S., 2019. The distributional impacts of energy taxes. Rev. Environ. Econ. Policy 13 (1), 104–123.
Proost, S., Van Regemorter, D., 1995. The double dividend and the role of inequality aversion and macroeconomic regimes. Int. Tax Public Financ. 2, 207–219.
Rausch, S., Metcalf, G.E., Reilly, J.M., 2011. Distributional impacts of carbon pricing: a general equilibrium approach with micro-data for households. Energy Econ. 33, S20–S33.
Rocchi, P., Serrano, M., Roca, J., 2014. The reform of the European energy tax directive: exploring potential economic impacts in the EU27. Energy Policy 75, 341–353.
S&P Global Platts, 2019. World Electric Power Plants Database, 2019. https://www.spglobal.com/platts/en/products-services/electric-power/world-electric-power-plants-database.
Semieniuk, G., Holden, P.B., Mercure, J.F., Salas, P., Pollitt, H., Jobson, K., Vercoulen, P., Chewpreecha, U., Edwards, N.R., Viñuales, J.E., 2022. Stranded fossil-fuel assets translate to major losses for investors in advanced economies. Nat. Clim. Chang. 12 (6), 532–538.
Shang, B., 2023. The poverty and distributional impacts of carbon pricing: channels and policy implications. Rev. Environ. Econ. Policy 17, 64–85.
Stiglitz, J.E., 2019. Addressing climate change through price and non-price interventions. Eur. Econ. Rev. 119, 594–612.
Sutherland, H., Figari, F., 2013. EUROMOD: the European Union tax-benefit microsimulation model. Int. J. Microsimul. 6, 4–26.
Tamba, M., Krause, J., Weitzel, M., Ioan, R., Duboz, L., Grosso, M., Vandyck, T., 2022. Economywide impacts of road transport electrification in the EU. Technol. Forecast. Soc. Chang. 182, 121803.
van der Ploeg, F., Rezai, A., Reaños, M.T., 2022. Gathering support for green tax reform: evidence from German household surveys. Eur. Econ. Rev. 141, 103966.
van der Ploeg, F., Rezai, A., Reaños, M.T., 2025. Third-Best Carbon Taxation: Trading off emission cuts, equity, and efficiency. J. Assoc. Environ. Resour. Econ. 12 (4), 1023–1058.
Vandyck, T., Van Regemorter, D., 2014. Distributional and regional economic impact of energy taxes in Belgium. Energy Policy 72, 190–203.
Vandyck, T., Keramidas, K., Kitous, A., Spadaro, J.V., Van Dingenen, R., Holland, M., Saveyn, B., 2018. Air quality co-benefits for human health and agriculture counterbalance costs to meet Paris Agreement pledges. Nat. Commun. 9, 4939.
Vandyck, T., Weitzel, M., Wojtowicz, K., Los Santos, L.R., Maftei, A., Riscado, S., 2021. Climate policy design, competitiveness and income distribution: a macro-micro assessment for 11 EU countries. Energy Econ. 103, 105538.
Vandyck, T., Temursho, U., Landis, F., Klenert, D., Weitzel, M., 2022. Prices and standards for vertical and horizontal equity in climate policy. Working paper (Available at SSRN 4144282).
Vandyck, T., Della Valle, N., Temursho, U., Weitzel, M., 2023. EU climate action through an energy poverty lens. Sci. Rep. 13, 6040.
Vona, F., 2023. Managing the distributional effects of climate policies: a narrow path to a just transition. Ecol. Econ. 205, 107689.
Weitzel, M., Vandyck, T., Keramidas, K., Amann, M., Capros, P., den Elzen, M., Frank, S., Tchung-Ming, S., Díaz Vázquez, A., Saveyn, B., 2019. Model-based assessments for long-term climate strategies. Nat. Clim. Chang. 9, 345–347.
Weitzel, M., Vandyck, T., Rey Los Santos, L., Tamba, M., Temursho, U., Wojtowicz, K., 2022. A comprehensive socio-economic assessment of EU climate policy pathways. Ecol. Econ. 204, 107660.
Winchester, N., Malina, R., Staples, M.D., Barrett, S.R., 2015. The impact of advanced biofuels on aviation emissions and operations in the us. Energy Econ. 49, 482–491.
Wojtowicz, K., Rey, L., Temursho, U., Saveyn, B., Vandyck, T., Tamba, M., Weitzel, M., 2019. PIRAMID: a new method to generate future input-output tables for baseline building. In: GTAP 2019 Conference Paper.
Young-Brun, M., Dennig, F., Errickson, F., Feindt, S., Méjean, A., Zuber, S., 2025. Within-country inequality and the shaping of a just global climate policy. Proc. Natl. Acad. Sci. 122 (39), e2505239122.