The Distributional Effects of EU Carbon Pricing

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The Distributional Effects of EU Carbon Pricing

By Marek Antosiewicz, Michał Burzyński, Piotr Lewandowski, Joël Machado, Sebastian Rausch, Jakub Sokołowski*

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The EU member states have committed to achieving climate neutrality, i.e. net-zero greenhouse gas (GHG) emissions, by mid-century. The two emissions trading systems (ETSs) in the EU—ETS1 and ETS2—are the lead instruments of EU climate policy to steer the transition to a carbon-neutral economy. Declining emission caps under ETS1 and ETS2 imply increasing carbon prices raising the question of aggregate economic cost and the distribution of costs among EU member states, regions, sectors, workers and households. Yet, given the enormous scale of the required transformation, surprisingly little is known about the distributional effects of future EU carbon pricing. This report provides an ex-ante analysis of the macroeconomic, labor market, distributional, and inequality effects caused by ETS1 and ETS2. We develop and apply novel structural simulation models, including a dynamic multi-country multi-sector general equilibrium with endogenous innovation in energy services, which fully integrates a micro-simulation module, a micro-simulation model to perform in-depth analyses of household, labor income, and inequality impacts in four EU countries (France, Germany, Poland, and Spain), and a spatial general equilibrium model to study worker re-allocation across occupations, sectors, and 100 EU regions. We find that achieving deep emissions reductions using the market-based instrument of emissions trading need not be costly at an aggregate EU level, but entails distributional effects of considerable magnitude and dispersion across different economic entities and market participants. This report provides new quantitative evidence on various distributional dimensions. Overall, our findings suggest that to increase the social acceptance and political feasibility of EU carbon pricing policies, targeted measures may be needed to address the unintended distributional consequences and policy-induced inequality.

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A. Introduction

A.1. Overview and Focus

The EU member states have committed to achieving climate neutrality, i.e. net-zero greenhouse gas (GHG) emissions, by mid-century. Carbon markets, defined by emissions trading systems (ETSs), are the lead instrument of EU climate policy to steer the transition to a carbon-neutral economy. Introduced in 2005, the EU Emissions Trading Scheme (EU ETS or ETS1) is the world's first carbon market and remains one of the largest in the world. It requires polluters to pay for their GHG emissions, covering emissions from the electricity and heat generation, industrial manufacturing and aviation sectors—which account for roughly 40% of total GHG emissions in the EU. From 2027, a new, second ETS will be introduced for emissions from fuels used for combustion in buildings, road transport and other sectors (mainly small industry, which is not covered by the existing EU ETS). The declining emission caps under ETS1 and ETS2 will lead to an increasing scarcity of emission allowances, implying trajectories of higher carbon prices associated with the use of fossil energy. While the market-based instrument of cap-and-trade is generally considered an efficient and effective policy instrument for decarbonization, the ambitious objective of "deep" emissions reductions and the structural transformation of EU economies required to achieve them, raise the fundamental question for society and policy of the economic costs and, in particular, the distribution of the costs among EU member states, industries, sectors, workers and households.

Environmental policies like ETSs affect companies, workers and households in heterogeneous ways. By increasing firms' marginal cost of production, they may affect prices and employment levels or cause a spatial relocation of economic activity and workers across occupations, sectors, and geographical regions. These adjustment mechanisms are particularly facilitated in areas of free mobility such as the European Union. By affecting product and factor prices and employment levels, carbon pricing impacts households' utility, with likely heterogeneous impacts across the household income distribution.

This report provides an ex-ante analysis of the macroeconomic, labor market, distributional, and inequality effects caused by ETS1 and ETS2, thereby contributing to the surprisingly scarce evidence on the likely economic and welfare effects of the key EU climate policies on carbon pricing.

In three distinct (but methodologically related) chapters, we examine various dimensions of the distributional effects of EU carbon pricing, focusing both on different propagation channels for the effects of carbon prices and on different economic entities and market participants which are exposed directly and indirectly to EU carbon pricing. Methodologically, we develop novel structural economic models—including a macroeconomic model of the EU economy, a spatial equilibrium model with 100 EU regions, and a micro-simulation model providing an in-depth analysis of selected EU countries—that together facilitate a detailed investigation of the distributional effects. The three models each make a new and innovative contribution to the existing literature and to economic modeling for the analysis of EU climate policy. The three models are soft-linked: the macroeconomic model determines endogenous carbon prices, based on a detailed representation of EU emissions trading policy, and changes in sectoral output, which serve as the basis for scenario variation in the micro-simulation and spatial equilibrium models.

Chapter B examines the distributional effects of ETS1 and ETS2 across EU countries, sectors, and heterogeneous households, and investigates the role of endogenous innovation and unemployment for assessing the distributional effects. We develop and apply a novel dynamic multi-country multi-sector macroeconomic general equilibrium model of EU carbon markets and economic activity that incorporates a number of key features with high relevance for the ex-ante analysis of EU climate policy. These include a multi-sector and -commodity structure, resolving the supply and use of fossil fuels and renewable energy and sectors with varying energy (carbon) intensity, endogenous innovation (based on directed technical change) in industry and household energy services, unemployment and regional labor markets, and household heterogeneity in terms of consumption and income patterns, based on integrating 240,000 households of a representative sample of the EU household population.

Chapter C examines the economic and social implications of the EU's carbon pricing mechanisms, specifically focusing on the ETS2 and national emissions markets under the Effort Sharing Regulation (ESR). The focus is on how the carbon pricing created by ETS2 and ESR affects living standards, including households' (labor and disposable) income, household expenditure spending across the income distribution, and how it affects inequality. We answer these questions by combining macroeconomic and microsimulation models to examine, in depth, the case of four selected EU countries (France, Germany, Poland and Spain). By highlighting the specific challenges that carbon pricing poses for the economies in the south, in Central and Eastern Europe, the two largest economies in the EU, these cases provide valuable insights into the broader distributional implications of EU carbon pricing.

Chapter D examines the cross-regional allocation of workers and activities and discusses the importance of sorting across labor markets, migration, and different fiscal transfer schemes. We build a static structural spatial general equilibrium model that focuses on workers' sorting across occupations, sectors and geographical regions as adjustment mechanisms to environmental policies. Importantly, our model enables us to quantify how labor market dynamics can serve as an additional channel through which environmental policies can affect a given population within a relatively short period of time. We simulate a counterfactual increases in carbon prices, as driven by EU ETS policies, across all regions and sectors, accounting for exogenous region-sector-specific TFP adjustments to the policy shock which are driven by the macroeconomic model. Counterfactual policies considered also investigate different scenarios on redistribution of carbon revenues, including no redistribution, uniform per-capita distribution across EU regions, and no cross-country but unifirm within-country distribution.

A.2. Summary of Main Findings and Policy Implications

Our analysis suggests that achieving the EU's climate policy targets through the market-based instrument of emissions trading need not be costly in terms of the aggregate EU-27 welfare impacts when the benefits of endogenous innovation related to the use of fossil and (renewable) electricity are realized. This suggests that climate policies should also strengthen incentives for private sector R&D investments. At the same time, however, even if the positive effects of endogenous productivity improvements materialize, the distributional effects of carbon pricing across EU countries, EU regions below the country level, economic sectors, workers, and different household types are substantial. Therefore, to increase the social acceptance and political feasibility of EU climate policy, targeted measures may be needed to address the unintended consequences of carbon pricing in terms of policy-induced distributional inequality.

Chapter B makes the point that aggregate welfare effects obscure a considerable variation in welfare effects between and within countries. When ETS2 is introduced in 2027, aggregate welfare effects at the country level range from -0.8 to +2.7%. The welfare gains for some countries are due, among other factors, to a high share of carbon revenues from ETS1 and ETS2 flowing back to the member states, as well as to relatively low abatement costs. By 2050, the welfare effects are negative for almost all countries, ranging to up to -2.1%. The variation in utility impacts at the household-level significantly exceeds the variation in aggregate impacts at the country level. When ETS2 is introduced in 2027, households' utility impacts in the EU household population range from around -10% to +20%, with impacts at the 25th and 75th percentiles of -0.55% and +3.3%. The household-level distribution of utility impacts widens considerably over time, with the standard deviation rising from 3.8% in 2017 to 10% in 2050. Assuming that carbon revenues within a country are returned as a uniform lump-sum transfer to households, the household-level incidence from future EU carbon pricing policies are neutral to slightly progressive when considering the mean impacts across income deciles. Variation in utility impacts within income groups, however, is substantial and exceeds the variation in means across income groups. While, unsurprisingly, the sectoral effects in terms of output reductions are large for energy and energy-intensive sectors, the impacts on total sectoral output are small (-3% by 2050) due to labor reallocation and substitution effects. While the EU-average unemployment rate increases from 5.9% in 2027 to 7.0% in 2050, employment (aggregated across skill types of labor and sectors) remains largely unaffected.

Overall, the policy implications that emerge from this chapter suggest that public policy should look to harness the potential of innovation to reduce the cost of future carbon abatement. If the aim is to reduce the distributional effects of high carbon prices on households, targeted measures are needed that go beyond blanket rebates. In particular, the study points to significant impacts on horizontal equity (i.e. within household income groups) that are at least as important as vertical impacts (i.e. between income groups). This suggests that targeted, means-tested rebate programs may be needed.

Chapter C points to substantial differences in the impact of carbon pricing, through the existing ESR and the introduction of ETS2, on the living standards of households in the four EU countries considered. Poland benefits most from these policies, with lump-sum transfers driving significant income gains for lower-income households, reducing household income inequality substantially. Spain also exhibits progressive outcomes, with lump-sum transfers increasing disposable incomes across all deciles, particularly benefiting the lower-income groups by 2040. Conversely, France experiences the most pronounced regressive effects and widening inequality, primarily due to increased expenditures on goods and services, including transportation, disproportionately impacting lower-income households under ETS-2. Germany demonstrates progressive income gains under ESR, while ETS-2 results in moderate losses for higher-income groups, reflecting the varied influence of direct and labor market effects. Overall inequality, as measured by changes in the Gini coefficient of household disposable income, declines in Poland, Germany, and to a lesser extent in Spain. In contrast, it widens in France where lump-sum transfers of carbon revenues are low and do not offset the regressive increase in living costs.

These findings underscore the importance of tailoring carbon pricing policies to national contexts, ensuring that compensatory mechanisms such as lump-sum transfers are designed to support vulnerable populations effectively. Policymakers should consider the distributional impacts and balance short-term social equity concerns with long-term climate objectives to foster a just and sustainable low-carbon transition.

Chapter D finds that the manufacturing, construction, and transport sectors face overall the largest increase in carbon pricing, whereas service sectors are much less affected. Considerung the model resolution of 100 EU regions, GDP can decrease up to 14%, with the strongest losses materializing in Greece and Eastern European countries. In contrast, GDP is least negatively affected in most German regions, Luxembourg, and Switzerland. Beyond impacting sectors, workers switch occupations, moving from less-educated elementary tasks to service and professional tasks. Simultaneously, higher carbon prices increase the marginal cost of production and thereby prices. Some firms are no longer profitable and leave the market, reducing the number of available product varieties, but increasing the average productivity level of incumbents. We show that redistribution mitigates losses in almost all regions, except for some highly productive capitals. Uniform redistribution in the EU benefits mainly the least productive areas in Eastern and Southern Europe, whereas most regions in the productive countries are net contributors. In contrast, redistributing taxes collected in a country to its own national regions implies that the least productive areas in highly productive countries receive more transfers. Less productive regions in the lower productivity countries receive less transfers and inequality across European regions is less mitigated. Finally, we show that occupational sorting acts as an adaptation channel when migrating across regions is costly.

A.3. Structure of this report

The remainder of this report is organized as follows. In Chapter B, we present the novel dynamic macroeconomic model, including data and model calibration, and present and discuss our results from analyzing the distributional effects of ETS1 and ETS2 across EU countries, heterogeneous types of households, and economic sectors. In Chapter C, we feed the outputs from these simulations into a micro-simulation model to quantify the impact of the policy change on the incomes of different types of households and on measures of inequality. We present and discuss our results of an in-depth analysis of the EU countries France, Germany, Poland and Spain, and draw policy conclusions. In Chapter D, we present the novel structural general equilibrium model with spatial detail that features workers' sorting across occupations, sectors and geographical regions as an important adjustment mechanism to EU carbon pricing policies. We present and discuss our results from counterfactual simulations of a large future increase in EU carbon prices and various carbon revenue redistribution rules for the average income of 100 EU regions (below the country level), as well as the importance of migration and occupational sorting channels as adjustment mechanisms.

In what follows, we have written each chapter as a self-contained, standalone contribution, allowing the interested reader to jump directly to the area(s) of interest.

B. The distributional effects of EU carbon pricing through two emissions trading systems (ZEW/Sebastian Rausch)

B.1. Introduction

The EU member states have committed to achieving climate neutrality, i.e. net-zero greenhouse gas (GHG) emissions, by mid-century, Carbon markets, defined by emissions trading systems (ETSs), are the lead instrument of EU climate policy to steer the transition to a carbon-neutral economy. Introduced in 2005, the EU Emissions Trading Scheme (EU ETS or ETS1) is the world's first carbon market and remains one of the largest in the world. It requires polluters to pay for their GHG emissions, covering emissions from the electricity and heat generation, industrial manufacturing and aviation sectors—which account for roughly 40% of total GHG emissions in the EU. From 2027, a new, second ETS will be introduced for emissions from fuels used for combustion in buildings, road transport and other sectors (mainly small industry, which is not covered by the existing EU ETS). The decreasing emission caps under ETS1 and ETS2 will lead to an increasing scarcity of emission allowances, implying trajectories of higher carbon prices associated with the use of fossil energy. Given the magnitude of the structural change required, there is surprisingly little evidence on the macroeconomic and distributional effects of ETS1 and ETS2.

This chapter contributes by developing and applying a novel structural economic equilibrium model to provide an ex-ante analysis of the two main EU carbon pricing policies. Existing studies either use static models, ignoring endogenous investments and capital accumulation (Landis, Fredriksson and Rausch, 2021; Abrell and Rausch, 2021), simple micro-simulation models focused on household incidence, abstracting from behavioral responses to climate policy and economy-wide effects (Feindt et al., 2021), quasi-experimental methods to estimate the cost of past climate policy (Dechezleprêtre, Nachtigall and Venmans, 2023; Metcalf and Stock, 2023; Känzig, 2023), or dynamic general equilibrium models assuming a single, representative household and/or ignoring the role of endogenous innovation and unemployment (Bretschger et al., 2017; Beestermöller, 2017; Baumstark et al., 2021; Kettner et al., 2024).

The novel dynamic general equilibrium model of EU carbon markets and economic activity developed in this chapter incorporates a number of key features with high relevance for the ex-ante analysis of EU climate policy. I integrate a multi-sector structure, resolving the supply and use of fossil and renewable energy supply and multiple economic sectors with varying energy (carbon) intensity, in a recursive-dynamic macro model. The model adapts a directed technical change (DTC) mechanism, building on Acemoglu et al. (2012), for endogenous innovation in energy services which use fossil fuels and (renewable-based) electricity. Decarbonization through increased electrification is an important channel for mitigating climate change in the future (Davis, 2023), which in turn determines the macroeconomic costs of decarbonization. To study the distributional consequences of EU carbon pricing, the model resolves all EU countries and a representative sample of the EU household population, comprising 240,000 heterogeneous households. I use statistical matching, based on Landis, Abrell and Rausch (2021), to integrate micro-household data from (Eurostat, 2023*a*) Household Budget Survey (HBS) and EU statistics on income and living conditions (EU-SILC) (Eurostat, 2023*b*). The 240,000 heterogeneous households are integrated as individual economic agents, using a decomposition algorithm for solving high-dimensional equilibrium models with heterogeneous households (Rutherford and Tarr, 2008). The heterogeneity of households refers to both consumption and income patterns, including a differentiation of labor by skill type. Unemployment on the regional and skill-specific labor markets is modeled using a wage-curve approach, which makes it possible to investigate the labor market effects of EU climate policy in some detail. The two EU ETSs are represented separately, with a focus on the time trajectory of emissions caps, sectoral coverage, and the redistribution of carbon revenues between EU countries.

In this chapter, the model is applied to analyze the distributional effects of future EU carbon pricing policies, represented by ETS1 and the new ETS2. The main findings are as follows. Accounting for endogenous innovation through directed technical change in energy services, which combine knowledge capital with fossil fuels and (green) electricity in industry sectors and for household demand, considerably reduces the carbon prices in ETS1 and ETS2 and the welfare cost of achieving the EU climate targets in 2050. Using carbon pricing as the lead instrument, reaching EU climate goals entails a welfare loss of 0.5% in 2050 for the aggregate EU-27 economy; costs are 1-2 orders of magnitude higher, when estimated with a model that excludes endogenous innovation in energy services.

The aggregate welfare effects, however, obscure a considerable variation in welfare effects between and within countries. When ETS2 is introduced in 2027, aggregate welfare effects at the country level range from -0.8 to +2.7 percent. The welfare gains for some countries are due, among other factors, to a high share of carbon revenues from ETS1 and ETS2 flowing back to the member states, as well as to relatively low abatement costs. By 2050, the welfare effects are negative for almost all countries, ranging to up to -2.1%. The variation in utility impacts at the household-level significantly exceeds the variation in aggregate impacts at the country level. When ETS2 is introduced in 2027, households' utility impacts in the EU household population range from around -10% to +20%, with impacts at the 25th and 75th percentiles of -0.55% and +3.3%. The household-level distribution of utility impacts widens considerably over time, with the standard deviation rising from 3.8% in 2017 to 10% in 2050. Assuming that carbon revenues within a country are returned as a uniform lump-sum transfer to households, the household-level incidence from future EU carbon pricing policies are neutral to slightly progressive when considering the mean impacts across income deciles. Variation in utility impacts within income groups, however, is substantial and exceeds the variation in means across income groups.

While, not surprisingly, the sectoral effects in terms of output reductions are large for energy and energy-intensive sectors, the impacts on total sectoral output are small (-3% by 2050) due to labor reallocation and substitution effects. While the EU-average unemployment rate increases from 5.9% in 2027 to 7.0% in 2050, employment (aggregated across skill types of labor and sectors) remains largely unaffected.

Overall, the key findings suggest that achieving the EU's climate policy targets through the market-based instrument of emissions trading need not be costly in terms of EU-27 and country welfare impacts when the benefits of endogenous innovation related to the use of fossil and (renewable) electricity are realized. This suggests that climate policies should also strengthen incentives for private sector R&D investments. Even if the positive effects of endogenous productivity improvements materialize, the distributional effects of carbon pricing across EU countries and different household types are substantial. Therefore, to increase the social acceptance and political feasibility of EU climate policy, targeted measures (beyond uniform lump-sum transfers) may be needed to address the unintended consequences of carbon pricing in terms of policy-induced distributional inequality.

The remainder of this chapter is structured as follows. Section B.2 presents the model. Section B.3 presents and discusses the data, model calibration, and computational strategy. Section B.4 describes and discusses the main results of quantitative analysis. Section B.5 concludes.

B.2. The Model

SETS.—I study a discrete-time economy where time is indexed by t. Sectoral goods are indexed by $i, j \in \mathcal{I}$, where $\mathcal{I} = \mathcal{E} \cup \mathcal{N}$ comprises disjoints subsets of energy $\mathcal{E}$ and non-energy $\mathcal{N}$ goods. Energy goods $\mathcal{E} = \mathcal{F} \cup \mathcal{C}$ include the fossil fuels coal, natural gas, and oil, indexed by $f \in \mathcal{F}$, and electricity, indexed by $e \in \mathcal{C}$. Technologies to produce electricity from fossil fuels, nuclear, and various renewable (hydro, solar, and wind) resources are indexed by $n \in \mathcal{N}$. Natural resources are indexed by $z \in \mathcal{Z}$, where $\mathcal{Z} = \mathcal{F} \cup \mathcal{N}$ comprises resources used in the extraction of fossil fuels and non-fossil electricity generation. Different skill types of labor are indexed by $l \in \mathcal{L}$. Regions are indexed by $r, s \in \mathcal{R}$. Households in the population of region r are indexed by $h_{(r)} \in \mathcal{H}_r$.

Technologies and production

NON-ENERGY GOODS AND ENERGY SERVICES.—The output Y_{irt}, $i \in \mathcal{N}$, of non-energy good i

in region r at time t is produced competitively from K_{irt} units of capital, L_{ilrt} units of labor of skill type l, an energy services Q_{irt}, and intermediate non-energy inputs M_{jirt} from other sectors j. The representative firm's production function is a nested CES:

$$(1) \qquad Y_{irt} = \Big(\alpha_{ir} F_{irt}^{\frac{\sigma-1}{\sigma}} + (1-\alpha_{ir}) \underbrace{\big[\sum_{j\in\mathcal{M}} \beta_{jir} M_{jirt}^{\frac{\mu-1}{\mu}}\big]^{\frac{\mu}{\mu-1}}}_{\text{Composite of non-energy intermediate inputs}}{}^{\frac{\sigma-1}{\sigma}}\Big)^{\frac{\sigma}{\sigma-1}}$$

which, at the top-level, trades off a capital-labor-energy services composite given by:

$$(2) \qquad F_{irt} = \Big(\gamma_{ir} \underbrace{\big[K_{irt}^{\delta_{ir}} \prod_{l} L_{ilrt}^{\kappa_{lir}(1-\delta_{ir})}\big]}_{\text{Value-added}}{}^{\frac{\epsilon-1}{\epsilon}} + (1-\gamma_{ir}) \underbrace{Q_{irt}}_{\text{Energy services}}{}^{\frac{\epsilon-1}{\epsilon}}\Big)^{\frac{\epsilon}{\epsilon-1}}$$

with a composite of non-energy intermediate inputs. Capital and labor are nested with a Cobb-Douglas function. $\alpha_{ir} \in (0,1)$, $\beta_{jir} \in (0,1)$, with $\sum_j \beta_{jir} = 1$, $\gamma_{ir} \in (0,1)$, $\delta_{ir} \in (0,1)$, and $\kappa_{lir} \in (0,1)$, with $\sum_l \kappa_{lir} = 1$ are distribution (or share) parameters. σ, μ, and ϵ is the elasticity of substitution between F_{ir} and the intermediate-input composite, between intermediate inputs, and between value-added and energy services, respectively.

Energy services can be generated from both fossil fuels and electricity, with the latter representing the key decarbonization pathway that reduces dependence on fossil fuels through electrification combined with electricity from carbon-neutral renewables. As electrification of production processes is not possible for all sectors, I treat energy services from electricity and fossil (indexed by $q =$ *electricity, fossil*) fuels as imperfect substitutes:

$$(3) \qquad Q_{irt} = \Big(\sum_q \kappa_{qir} \hat{Q}_{qirt}^{\frac{\phi-1}{\phi}}\Big)^{\frac{\phi}{\phi-1}}$$

where $\kappa_{qir} \in (0,1)$, with $\sum_q \kappa_{qir} = 1$, are distribution parameters and $\phi < \infty$ is the elasticity of substitution between different types of energy services.

Energy services are produced by combining energy inputs with machine inputs. Machines services convert energy to energy services and embody knowledge capital, i.e. the best available technology of producing energy services with a given amount of energy. Knowledge capital is accumulated through a directed technical change mechanism in which successful scientists "stand of the shoulder of giants", enhancing future knowledge capital. Production of energy services $\hat{Q}_{qirt}$ from electricity or fossil fuels for use in sector i and region r has the following CES form:

$$(4) \qquad \hat{Q}_{qirt} = \Big(\eta_{qir} \underbrace{\big[\sum_{j\in\mathcal{E}} \zeta_{qjir} E_{qjirt}^{\frac{\rho-1}{\rho}}\big]^{\frac{\rho}{\rho-1}}}_{\text{Electricity or fossil energy inputs}}{}^{\frac{\chi-1}{\chi}} + (1-\eta_{qir}) \underbrace{X_{qirt}}_{\text{Machine inputs}}{}^{\frac{\chi-1}{\chi}}\Big)^{\frac{\chi}{\chi-1}}$$

where E_{qjirt} is the input of energy type j (i.e., coal, natural gas, oil, and electricity) for producing energy services q for sector i in region r at time t. ρ is the elasticity of substitution between different types of energy inputs.[1] $\eta_{qir} \in (0,1)$ and $\zeta_{qjir} \in (0,1)$, with $\sum_j \zeta_{qjir} = 1$, are distribution parameters.

The elasticity of substitution between energy and machine inputs is χ. Following Lemoine (2024), I call machines energy-using when energy and machines are gross complements ($\chi < 1$),

[1] In (4), if $q =$ *fossil*, ρ is the elasticity of substitution between different fossil fuels. If $q =$ *electricity*, electricity is the only energy input (so the energy sub-nest collapses to a single input). Instead of bundling fossil fuels, energy services could be differentiated by the type of fossil fuel used as input.

and I call machines energy-saving when energy and machines are gross substitutes ($\chi > 1$).

DIRECTED TECHNICAL CHANGE IN ENERGY SERVICES.—Machine services X_{qirt} are produced in a Dixit-Stiglitz environment of monopolistic competition from machines of varying quality:

$$X_{qirt} = \int_0^1 (A_{vqirt})^{1-\lambda} (x_{vqirt})^{\lambda} dv \tag{5}$$

where $\lambda \in (0, 1)$. The machines x_{vqirt} that work with energy q to produce energy services $\hat{Q}_{qirt}$ at time t are divided into a continuum of types, indexed by v. The quality (or efficiency) of machine x_{vqirt} is given by A_{vqirt}. Machines of type v are produced by monopolists who each take the price of machine services as given (each is sufficiently small) but recognize their ability to influence the price of machines of type v. The cost of producing a machine is in units of the investment good.

Scientists choose which energy service q in which sector i they want to study and are then randomly allocated to a machine type v. Scientists in region r at time t working on energy services of type qi are of measure s_{qirt}. Each scientist succeeds in innovating with probability $\eta \in (0, 1]$. If they fail, scientists earn nothing and the quality of that type of machine is unchanged. As in Acemoglu et al. (2012) and Hart (2019), among others, successful scientists receive a one-period patent to produce their type of machine. Successful scientists improve the quality of their machine type to:

$$A_{vqirt} = A_{vqir(t-1)} + \gamma A_{vqir(t-1)} \tag{6}$$

where $\gamma > 0$ is a parameter measuring productivity in quality improvement.

If a number of s_{qirt} scientists research machines used for energy services qi, the average quality of these machines evolves according to:

$$\begin{aligned} \overline{A}_{qirt} &= \int_0^1 [\eta s_{qirt}(1+\gamma)A_{vqir(t-1)} + (1-\eta s_{qirt})A_{vqir(t-1)}] dv \\ &= (1+\eta\gamma s_{qirt})\overline{A}_{qir(t-1)} \,. \end{aligned} \tag{7}$$

A scientist who succeeds in innovating exercises her patent to obtain the monopoly profit Π_{qirt} for the researched energy service of type qi in region r. The allocation of scientists is based on relative profits created by the payoffs from doing successfully researching different types of energy services. The first-order condition for a producer of machine services yields demand for machines of type v related to energy services $qirt$:

$$x_{vqirt} = \left(\frac{p^X_{qirt}}{p^x_{vqirt}} \right)^{\frac{1}{1-\lambda}} A_{vqirt} \,. \tag{8}$$

The monopolistic producer of x_{vqirt} thus faces an isoelastic demand curve and accordingly marks up its price. In equilibrium, the produce of machine type v used to produce energy services qi earns profits:

$$\pi_{vqirt} = \lambda(1-\lambda)(p^x_{vqirt})^{\frac{1}{1-\lambda}} A_{vqirt} \,. \tag{9}$$

The expected profits of scientists choosing to research machines that work to produce energy services of type qi in region r at time t is therefore:

$$\Pi_{qirt} = \eta\lambda(1-\lambda)(p^x_{vqirt})^{\frac{1}{1-\lambda}} (1+\gamma)\overline{A}_{qir(t-1)} \,. \tag{10}$$

Households in region r at time t supply a fixed measure of research effort in aggregate $\overline{S}_{rt}$

which is allocated to research on energy services of type qi:

(11) $$\overline{S}_{rt} = \sum_q \sum_i s_{qirt} \, .$$

ELECTRICITY AND FOSSIL ENERGY PRODUCTION.—To capture cross-country differences in the electricity generation mix, and the resulting heterogeneity in the carbon intensity and cost of electricity before and after climate policy, electricity is produced from fossil-based, renewable (wind, solar, hydro) and other carbon-neutral (nuclear) energy sources.

Electricity output Y_{nrt} from technology n is produced competitively combining a technology-specific factor R_{nrt} with inputs of capital, labor and materials:

(12) $$Y_{nrt} = \Big(\underbrace{\theta_{nr} R_{nrt}^{\frac{\lambda_{nr}-1}{\lambda_{nr}}}}_{\substack{\text{Natural resource}\\ \text{factor}}} + \underbrace{(1-\theta_{nr}) \hat{Y}_{nrt}^{\frac{\lambda_{nr}-1}{\lambda_{nr}}}}_{\substack{\text{Non-resource inputs of}\\ \text{capital, labor, materials}}} \Big)^{\frac{\lambda_{nr}}{\lambda_{nr}-1}}$$

where $\hat{Y}_{nrt}$ represents non-resource inputs with a similar nested structure as in (1)–(4).[2] With the resource factor being in fixed supply at any point in time, the price elasticity of supply of electricity produced by technology n, is related to the share parameter $\theta_{nr} \in (0,1)$ and the elasticity of substitution λ_{nr} according to:

(13) $$\lambda_{nr} = \eta_{nr} \frac{\theta_{nr}}{1-\theta_{nr}} \, .$$

For example, by appropriately choosing θ_{nr} and λ_{nr} based on data, it is possible to calibrate a supply curve for renewable electricity from wind and solar which approximates the empirical distribution of size and quality of wind and solar sites (i.e., resources) in a specific region.

While electricity output generated from different technologies is constrained by the availability and costs of resource factors, Y_{nrt} from different technologies are perfect substitutes, implying that:

(14) $$\sum_{n \in \mathcal{N}} Y_{nrt} = Y_{ert} \, .$$

where Y_{irt}, $i \in \mathcal{C}$ is the aggregate electricity produced in region r.

Fossil energy production Y_{frt} of $f = \{$*coal*, *natural gas*, *crude oil*$\}$ follows a similar CES structure as (12), with the difference that, unlike for renewable energy resource, the fossil-fuel specific resource factor R_{frt} is depletable, i.e. the resource endowment at time t diminishes over time based on cumulative use prior to t.

Heterogeneous households

PREFERENCES AND ENDOWMENTS.—Each region is inhabited by a household population $\mathcal{H}_r$ comprising workers (differentiated by skill type), entrepreneurs, and scientists. The composition of household populations differs among regions. $h_{(r)} \subset \mathcal{H}_r$ indexes an individual household in region r. Households have heterogeneous preferences over final consumption goods c_{iht}, comprising non-durable consumption and energy services related to mobility and housing, and

[2] I assume that directed technical change only occurs in the production of energy services for non-energy sectors, but not in electricity and fossil energy-producing sectors.

leisure time ℓ_{ht}. The instantaneous utility function for household $h_{(r)}$ is given by:

$$(15) \qquad U_{h_{(r)}t}\left(c_{iht}, l_{ht}\right) = \Big(\omega_h \underbrace{\big[\sum_{j\in\mathcal{M}} \xi_{ih} c_{iht}^{\frac{\vartheta_h-1}{\vartheta_h}}\big]^{\frac{\vartheta_h}{\vartheta_h-1}\frac{\nu_h-1}{\nu_h}}}_{\text{Non-durable goods and energy services}} + (1-\omega_h) \underbrace{\ell_{ht}}_{\text{Leisure consumption}}^{\frac{\nu_h-1}{\nu_h}}\Big)^{\frac{\nu_h}{\nu_h-1}}$$

where $\omega_h \in (0,1)$ and $\xi_{ih} \in (0,1)$, with $\sum_i \xi_{ih} = 1$, $\forall h$, are distribution parameters. ϑ_h and ν_h is the elasticity of substitution between consumptions goods, and between material and leisure consumption, respectively.

Households maximize utility (15) subject to income (16) derived from supplying labor differentiated by skill type, shares of profits from physical, knowledge, and natural resource capital, shares of profits accruing to scientists, and transfers from the government, including potential rebates from carbon pricing.

Income of household $h_{(r)}$ at time t is given by:

$$(16) \qquad M_{h_{(r)}t} = \underbrace{p^{\ell}_{ht}\overline{L}_{ht}}_{\text{Value of time endowment}} + \underbrace{\Theta^l_h \sum_i \sum_q \Pi_{qirt}}_{\text{Share in scientists' profits}} + \underbrace{\Theta^k_h \Omega_{rt}}_{\text{Share in aggregate capital income}} + \underbrace{T_{ht}}_{\text{Transfers and carbon rebates}}$$

where $\overline{L}_{ht}$ is the household's time endowment at time t, and p^{ℓ}_{ht} the household-specific value of time at t. Θ^l_h is the share of scientists' profits in region r accruing to household h. Θ^k_h represents the household's claim on the aggregate payments to the different types of capital in region r, with $\sum_{h(r)} \Theta^k_{h(r)} = 1$, $\forall r$. Aggregate capital income in region r at time t

$$\Omega_{rt} = \underbrace{p^k_{rt} K_{rt}}_{\text{Physical capital}} + \underbrace{\sum_z p^r_{zrt} R_{zrt}}_{\text{Natural resource capital}} + \underbrace{\sum_i \sum_q p^a_{qirt} \overline{A}_{qirt}}_{\text{Knowledge capital}},$$

comprises income from physical capital K_{rt}, natural resource z, and knowledge capital of type d. p^k_{rt}, p^r_{zrt}, and p^a_{qirt} denote the respective prices for each type of capital. T_{ht} denotes income from government transfers, including revenues collected from carbon pricing (depending on climate policy).

ENDOGENOUS LABOR SUPPLY BY SKILL TYPE.—Solving a household's utility maximization problem and applying the envelope theorem (i.e. Shephard's Lemma) yields the optimal demand for leisure at the household level ℓ_{ht}. ℓ_{ht} represents voluntary unemployment. Given the household's time endowment, the total time allocated to supplying labor to firms is given by:

$$(17) \qquad \hat{n}_{ht} = \overline{L}_{ht} - \underbrace{\frac{\partial p^u_{ht}}{\partial p^{\ell}_{ht}} U_{ht}}_{\ell := \text{Leisure consumption}}$$

where $p^u_{ht}(\mathbf{p}^c_t, p^{\ell}_{ht})$ is the unit expenditure function of household h given a vector of prices $\mathbf{p}^c_t$ for non-durable goods and energy services and the household-specific valuation of time (i.e., the price of leisure). Households generate income from supplying labor, which is differentiated by skill type. The allocation of total time devoted to labor supply across skill types is described by a CET transformation function:

$$(18) \qquad \hat{n}_{ht} = \Big(\sum_l k_{lh}\, n_{lht}^{\frac{1+\upsilon}{\upsilon}}\Big)^{\frac{\upsilon}{1+\upsilon}}$$

which implicitly defines household-level skill-specific labor supply n_{lht}. k_{lh} is a distribution parameter that reflects the proportion of time household h allocates to skill type l (in a benchmark equilibrium), with $\sum_l k_{lh} = 1$, $\forall h$.[3] If the elasticity of transformation υ is zero, there is no mobility across skills types; $0 < \upsilon < \infty$ reflects that the allocation of time across skills types is flexible to a certain degree.

SAVINGS.—Each period, household save a share of their current income with savings rate $s_{h(r)}$. The household-specific savings rate is exogenous, constant over time, and invariant to climate policy.[4] Savings of household h at time t are thus given by $s_h M_{ht}$.

ENDOWMENTS OVER TIME.—I assume that the time endowments of households and the number of scientists in a given region grow at rate γ_{rt} over time[5], implying that the following laws of motions:

$$\overline{L}_{h(t+1)} = (1+\gamma_{rt})\overline{L}_{ht} \quad \text{and} \quad \overline{S}_{r(t+1)} = (1+\gamma_{rt})\overline{S}_{rt}\,. \tag{19}$$

Aggregate investment $I_{rt} = \sum_{h\in\mathcal{H}_r} s_h M_{ht}$ in region r is determined by the sum of household-level savings. Aggregate physical capital in region r increases through investment I_{rt} and depreciates at rate δ_r:

$$K_{r(t+1)} = (1-\delta_r)K_{rt} + I_{rt}\,. \tag{20}$$

Labor markets and unemployment

Workers with a particular skill type are fully mobile across sectors within a region, but cannot move across national borders.[6] Supply and demand on the market for skill type l of labor in region r determine the equilibrium wage rate w_{lrt}:

$$\underbrace{(1-\Lambda_{lrt})}_{\substack{\text{“Rationing”}\\ \text{due to un-}\\ \text{employment}}}\underbrace{\sum_h n_{lh_{(r)}t}}_{\substack{\text{Aggregate of}\\ \text{households'}\\ \text{labor supply}}} = \underbrace{\sum_i \frac{\partial c_i^Y(\mathbf{p}_{rt})}{\partial w_{lrt}} Y_{irt}}_{\substack{\text{Labor demands by}\\ \text{production sectors}}}\,, \tag{21}$$

where the RHS exploits Shephard Lemma's to derive optimal labor demand by sector given a representative firm's cost function $c^Y(\mathbf{p}_{rt})$, which incorporates profit maximization subject to production technologies (1)–(4) (and (12) and (14) in the case of electricity) taking input prices $\mathbf{p}_t$ as given.

Λ_{lrt} is the unemployment rate for labor type l in the regional labor market r. To model involuntary unemployment, I build on the “wage curve” literature (Blanchflower and Oswald, 1994, 2005; Card, 1995), which supports the empirical observation (see Nijkamp and Poot, 2005, for a meta study) that real wages are lower in labor markets with higher unemployment.[7]

[3]For most households, the data for labor earnings show only one positive entry for one occupation (skill type). However, there may be several earners in a household who work more than one job, or a single earner may have income from different jobs in different occupations.

[4]While this precludes forward-looking behavior and the possibility that the savings rate changes in response to climate policy, this is not an uncommon assumption in the directed technical change macro literature (Lemoine, 2024; Acemoglu et al., 2012; Golosov et al., 2014). The endogenous savings rate in fully intertemporal, rational-expectations macro models applied to the analysis of climate change mitigation policies (Nordhaus, 1992, 2017; Bretschger et al., 2017) typically does not vary much.

[5]Hence, while this growth rate can vary over time and by region, there are no demographic shifts which change the relative size of household types in a region's population.

[6]I thus abstract from migration. To the extent that the cross-country mobility of labor is an effective margin of adjustment to climate policy, this is an important simplification. As it is beyond the scope of this paper, I leave it to future research to examine the implications of this assumption. While not directly related to the focus of this paper, Alsina-Pujols (2025) shows that migration increases the local social cost of carbon (SCC) in regions with an inflow of migration, while the local SCC of regions with an outflow of migration and the global SCC remain largely unaffected.

[7]This provides a reduced-form representation of equilibrium unemployment that sidesteps the complexity of structural explicit theories of unemployment and wage dynamics (i.e., search and matching (Pissarides, 1990), efficiency wages (Shapiro and Stiglitz, 1984), and collective wage bargaining (McDonald and Solow, 1981)) and, importantly, their potential pitfalls related to empirical specification in a multi-sector, multi-country model. Given that the focus of my analysis on long-run effects until 2050, modelling in a “deeper” structural way micro-frictions on the labor market is not of first order importance.

Expressed using objects of this model, the wage curve thus describes a negative relationship between the real wage, given by the nominal wage w_{lrt} divided by the average utility price index $\hat{p}^u_{rt}$ (based on household-level price indexes p^u_{ht} and respective weights given by income M_{ht}), and the regional unemployment rate Λ_{lrt}. Given an empirical estimate for the unemployment elasticity of pay $\eta_{lr} < 0$ and assuming a constant elasticity form, Λ_{lrt} is determined by the following wage curve for the regional labor market lr:

$$\frac{w_{lrt}}{\hat{p}^U_{rt}} = b_{lr}(\Lambda_{lrt})^{\eta_{lr}} \tag{22}$$

where b_{lr} is a parameter used to benchmark (22) to observed unemployment rates in regional labor markets. With positive unemployment, the factor $(1 - \Lambda_{lrt})$ in (21) reflects that fewer workers are effectively available for work than without unemployment, causing the equilibrium wage rate to be above the market-clearing wage rate that would obtain in the absence of unemployment.

International trade and the supply of final goods

All energy and non-energy goods are tradable. Sector-specific bilateral international trade is represented following the standard Armington (1969) approach where goods produced at different locations are treated as imperfect substitutes. The Armington aggregation produces final goods that differ according to their use as intermediate inputs in the production of sectoral output, for household consumption and investment, and for government consumption.

The amount of the Armington composite good i supplied in region r for use category $q = \{\textit{intermediate input in sector j, consumption, investment, government}\}$ at time t, H^q_{irt}, is given by a CES composite of sectoral outputs produced domestically and abroad:

$$H^q_{irt} = \Big[\Theta_{qir} D_{qirt}^{\frac{\kappa_{ir}-1}{\kappa_{ir}}} + (1-\Theta_{qir})\underbrace{\{(\sum_{s\neq r} m_{qisr} \hat{M}_{qisrt}^{\frac{\psi_{ir}-1}{\psi_{ir}}})^{\frac{\psi_{ir}}{(\psi_{ir}-1)}}\}}_{=\text{ CES import aggregate}}{}^{\frac{(\kappa_{ir}-1)}{\kappa_{ir}}}\Big]^{\frac{\kappa_{ir}}{\kappa_{ir}-1}} \tag{23}$$

where D_{qirt} denotes domestic supply and $\hat{M}_{qisrt}$ represents imports of sectoral good i from region s to region r for use final use category q. κ_{ir} and ψ_{ir} are elasticity of substitution parameters as observed from national accounts data.

Θ^q_{ir} and m^q_{isr} are distribution parameters which enable incorporating rich bi-lateral, sector- and final use-specific international trade patterns. For example, an energy-intensive manufacturing sector in region r may source an energy good, used as an input in production, differently from domestic and foreign markets than a similar sector in region s or than a household for private consumption in the same or a different region.

Final goods for investment are further aggregated in a CES fashion into a composite good; likewise for government consumption goods.

Markets and pricing

To characterize equilibrium prices, I define additional market clearing and pricing conditions.

GOODS MARKETS.—The market for sectoral output clears if produced output equals domestic and export demand from use of the sectoral good as intermediate inputs in production, for private and government consumption, and for investment:

$$\underbrace{Y_{irt}}_{\substack{\text{Supply of}\\ \text{sectoral output}}} = \underbrace{\sum_q D_{qirt}}_{\substack{\text{Domestic demand}\\ \text{for final use}}} + \underbrace{\sum_q \sum_{s\neq r} \hat{M}_{qirst}}_{\substack{\text{Export demand}\\ \text{for final use}}} . \tag{24}$$

Finals good markets determine the price of the Armington goods p^q_{irt}. Aggregate supply of consumer goods of type i must equal the total consumption by households in a given region:

$$H_{irt}^{consumption} = \sum_{h\in\mathcal{H}_r} c_{iht}\,. \tag{25a}$$

Aggregate supply of intermediate input good i for use in sector j:

$$H_{irt}^{intermediate\ input\ sector\ j} = \frac{\partial c_j^Y(\mathbf{p}_{rt})}{\partial p_{irt}^{intermediate\ input\ sector\ j}} Y_{jrt}\,. \tag{25b}$$

The markets for the composite investment and government consumption goods clear if:

$$H_{irt}^{investment} = \frac{\partial c^I(\mathbf{p}_{rt})}{\partial p_{irt}^{investment}} I_{rt} + \sum_j \sum_q \int_0^1 x_{vqjrt} dv \tag{25c}$$

$$H_{irt}^{government} = \frac{\partial c^G(\mathbf{p}_{rt})}{\partial p_{irt}^{government}} G_{rt} \tag{25d}$$

where $c^I(\mathbf{p}_{rt})$ and $c^G(\mathbf{p}_{rt})$ denote the cost function for the composite investment and government consumption good, respectively.

CAPITAL MARKETS.—The rental markets for physical and for natural resource capital clear if:

$$K_{rt} = \sum_i \frac{\partial c_i^Y(\mathbf{p}_{rt})}{\partial p_{rt}^k} Y_{irt} \quad \text{and} \quad R_{zrt} = \sum_i \frac{\partial c_i^Y(\mathbf{p}_{rt})}{\partial p_{zrt}^r} Y_{irt}\,. \tag{26}$$

Climate policies: carbon pricing and emissions trading

Carbon pricing drives a wedge between the user price for fossil energy e in consumption and production $\tilde{p}_{ert}^q$ and the respective producer price according to:

$$\tilde{p}_{ert}^q = p_{ert}^q + \underbrace{\mathbb{I}_{qr}^{\mathcal{S}}}_{\substack{\text{Indicator for}\\ \text{scope of ETS}}} \times \underbrace{\Phi_e \tau_t^{\mathcal{S}}}_{\substack{\text{Surcharge proportional}\\ \text{to } CO_2 \text{ content}}} \tag{27}$$

where Φ_e is the carbon content of fossil fuel e. $\mathbb{I}_{qr}^{\mathcal{S}}$ is an indicator variable that has the value 1 if the emissions caused by using fossil fuels in demand category q in region r are subject to an emissions price $\tau_t^{\mathcal{S}}$, and 0 otherwise.

Endogenous carbon prices $\tau_t^{\mathcal{S}}$ are determined by emissions trading systems (ETSs). Let $\mathcal{S}$ index a specific ETS. The different regimes of carbon pricing in the EU (i.e., ETS1, ETS2, and ESR) are characterized by three key features: (1) their targeted emissions reductions $\Upsilon_t^{\mathcal{S}}$, defining the cap over time, (2) the scope of their coverage, with $\mathcal{S}_r \subset \mathcal{R}$ and $\mathcal{S}_q$ defining the regional and sectoral scope of the ETS $\mathcal{S}$, and (3) a scheme for distributing the revenues from the ETS to individual regions, where $\Phi^{\mathcal{S}_r}$, with $\sum_{r\in\mathcal{S}_r} \Phi_r^{\mathcal{S}} = 1$, is the share of carbon revenues allocated to region r.

The carbon market for ETS $\mathcal{S}$ determines the endogenous carbon price $\tau_t^{\mathcal{S}}$ by relating supply of and demand for emissions certificates at time t according to:

$$\underbrace{\sum_{r\in\mathcal{S}_r} \Phi_r^{\mathcal{S}} \Upsilon_t^{\mathcal{S}}}_{\substack{\text{Emissions cap of ETS}\\ \text{(=supply of certificates)}}} = \underbrace{\sum_{r\in\mathcal{S}_r} \sum_{i\in\mathcal{S}_i} \sum_e \Phi_e E_{eirt}}_{\substack{\text{Demand for certificates}\\ \text{conditional on scope of ETS}}} \qquad (\tau_t^{\mathcal{S}})\,. \tag{28}$$

The formulation in (28) enables to represent multiple ETSs with different regional and sectoral coverage. For example, if $\mathcal{S}_r$ and $\mathcal{S}_q$ comprise all regions and demand categories, a fully integrated carbon market where emissions are priced uniformly across all emitters is implemented.

Existing carbon pricing schemes in the EU (i.e., ETS1, ETS2, and the ESR) are represented by appropriately choices of $\mathcal{S}_r$ and $\mathcal{S}_q$, together with the time trajectories of the cap and revenue allocation rules.

Competitive equilibrium

Given climate policy choices ($\Upsilon_t^{\mathcal{S}}$, $\mathcal{S}_r$, $\mathcal{S}_q$, $\Phi_r^{\mathcal{S}}$) and initial endowments of labor (time), physical, resource and knowledge capital, a decentralized equilibrium consists of sequences of quantities

$$\{Y_{irt}, Y_{nrt}, M_{jirt}, K_{irt}, L_{lirt}, Q_{irt}, \hat{Q}_{qirt} E_{qjirt}, X_{qirt}, x_{vqirt}, H^q_{irt}, D_{qirt}, \hat{M}_{qisrt},$$

$$c_{iht}, \ell_{ht}, \hat{n}_{ht}, n_{lht}, \Lambda_{lrt}, K_{rt}, \overline{S}_{rt}, s_{qirt}, R_{zrt}, \overline{A}_{qirt}, A_{vqirt}, \overline{L}_{ht}, G_{rt}, T_{ht}\}$$

and prices

$$\{p^Y_{irt}, p^h_{irt}, p^\ell_{ht}, w_{lrt}, p^k_{rt}, p^x_{rt}, p^r_{zrt}, p^a_{qirt}, \tilde{p}^q_{ert}, \tau_t^{\mathcal{S}}\}$$

such that *(i)* sectoral outputs of non-energy and energy goods Y_{irt} and electricity production Y_{nrt} and inputs used in production K_{irt}, L_{lirt}, M_{jirt}, Q_{irt}, $\hat{Q}_{qirt}$, E_{qjirt}, X_{qirt}, R_{irt} maximize firms' profits subject to (1)–(4) and (12)–(14), *(ii)* machine x_{vqirt} and knowledge inputs A_{vqirt} maximize monopoly profits (9) given technology (5), *(iii)* the supply of Armington goods H^g_{irt}, domestically and internationally sources inputs D_{qirt} and $\hat{M}_{qisrt}$ in the Armington aggregation maximize profits Π^h_{qirt} subject to (23), *(iv)* households' material consumption c_{iht}, leisure consumption ℓ_{ht}, total labor supply $\hat{n}_{ht}$, and labor time allocation (skill-type specific labor supply) n_{lht} decisions maximize utility U_{ht} in (15) subject to income (16), *(v)* the unemployment rate Λ_{lrt} on the regional labor market segment lr is determined by the wage curve (22), *(vi)* regional physical capital stocks K_{rt} evolve according to the law of motion (20), *(vii)* time endowments of households $\overline{L}_{ht}$ and the number of scientists $\overline{S}_{rt}$ evolve according to (19), *(viii)* government expenditures G_{rt} and transfers T_{ht} grow at rate γ_{rt}, *(ix)* the allocation of scientists s_{qirt} across research activities linked to energy services of type qi maximizes expected profits of scientists given by (10) and satisfies the aggregate resource constraint (11), *(x)* knowledge capital $\overline{A}_{qirt}$ for producing energy services of type qi in region r accumulates according to (7) *(xi)* prices for sectoral output p^Y_{irt} are determined by market-clearing conditions (24), *(xii)* prices for final goods by use category q p^q_{irt} clear respective final goods markets (25a)–(25d), *(xiii)* household-level prices of leisure (valuations of time) p^ℓ_{ht} are determined by the resource constraint for time given by (17), *(xiv)* wages on regional labor markets by skill type l w_{lrt} are determined by market-clearing conditions (21), *(xv)* rental rates of physical capital p^k_{rt} and resource prices p^r_{zrt} clear respective markets given by (26), *(xvi)* the price of fossil energy gross of regulatory charges from carbon pricing $\tilde{p}^q_{ert}$ is determined by (27) *(xvii)* endogenous carbon prices $\tau_t^{\mathcal{S}}$ are determined by emissions markets defined by (28) *(xviii)* the price of knowledge capital p^a_{qirt} is determined by supply, i.e. the law of motion of knowledge accumulation (7), and demand for knowledge capital utilized by monopoly producers (8).

B.3. Data and Calibration

I present and discuss the resolution of the quantitative model, the data for the calibration, the calibration of model parameters, and the computational strategy for solving counterfactual equilibria.

Macro and micro data

Model resolution.—Table 1 reports the model resolution in terms of regions, sectors (including different technologies for electricity generation), heterogeneous households, goods for final demand, primary production factors, and the differentiation of labor by skill type. This model resolution is made possible by combining several comprehensive data sources, yielding

Table 1. **Quantitative model resolution: sectors and goods, regions, and primary factors.**

Sectors ($i \in \mathcal{I}$)	**Countries and regions** ($r \in \mathcal{R}$)
Energy sectors ($i \in \mathcal{E}$)	*EU27 countries*[1]
Coal	Austria (AUT), Belgium (BEL),
Crude oil	Bulgaria (BGR), Croatia (HRV, Cyprus (CYP),
Natural gas	Czechia (CZE), Denmark (DNK), Estonia (EST),
Refined oil products	Finland (FIN), France (FRA), Germany (DEU),
Electricity, with technologies ($n \in \mathcal{N}$)	Greece (GRC), Hungary (HUN), Ireland (IRL),
fossil-based	Latvia (LVA), Lithuania (LTU), Netherlands (NLD),
hydro	Poland (POL), Portugal (PRT), Slovakia (SVK)
renewables (wind & solar)	Slovenia (SLN), Spain (ESP), Sweden (SWE)
nuclear	*Other regions*
Energy-intensive & trade-exposed sectors	Rest of Europe (REU)
Energy-intensive trade goods	Rest of the World (ROW)
Other manufactured goods	
Transport sectors	**Primary production factors**
Air transport	*Capital*
Water transport	Physical capital
Road transport	Knowledge capital (accumulated through DTC)
Other sectors	Fossil energy resource capital ($z \in \mathcal{Z}$)
Agriculture	Coal
Services	Oil
	Natural gas
Goods for final demand	*Labor, differentiated by skill type* ($l \in \mathcal{L}$)
Private consumption by 240,798 households	Officials and managers
($h_{(r)} \in \mathcal{H}_r$, representative sample	Technicians and associate professionals (incl. scientists)
of EU27 household population)	Clerks
Investment	Service and market sales workers
Government consumption	Unskilled and agricultural workers

Notes: Sectoral and regional classifications shown above are direct aggregations of the 65 sectors and 141 countries/regions contained in the GTAP11 database (Aguiar et al., 2022). The sectoral mapping is available on request from the author. [1]:Due to small economic size, Malta and Luxembourg are assigned to the REU region.

an unusually rich data foundation for the empirical-quantitative model.[8]

MACRO DATA: NATIONAL INCOME AND PRODUCT ACCOUNTS.—All EU27 countries and two regional aggregates representing the rest of Europe and the non-European countries are included in the model as individual regions. The multi-sectoral economic structure for each of the countries (and regional aggregates) as well as bi-lateral international trade linkages between them are based on regional social accounting matrix (SAM) data. I use SAM data from version 11 of the Global Trade Analysis Project (GTAP, Aguiar et al., 2022) which provides a consistent set of country-level national income and product accounts of sectoral production, intermediate input-output use, consumption, investment, bilateral trade in monetary values as well as underlying energy flows in physical terms and information on CO_2 emissions for the base-year 2017.[9] To account for sectoral heterogeneity with respect to energy use (and carbon intensity), the model distinguishes between energy-intensive sectors, including road, air and water transportation, as well as services and agriculture. The sectoral breakdown comprises a detailed representation of production and use of fossil fuels (coal, natural gas, crude oil, refined oil) and electricity. Initial endowments of primary productions factors are based on GTAP data which also provides information on labor earnings by skill type by sector by country.

ELECTRICITY.—Country-level electricity generation by type of energy source (i.e., fossil-based and carbon-neutral, including hydro, renewables, and nuclear power) is based on Global Change Data Lab (2024). The information on the costs of inputs in the various types of electricity generation is based on Abrell, Rausch and Streitberger (2019).

MICRO HOUSEHOLD DATA: HBS AND EU-SILC.—While the GTAP data is used to parametrize the macroeconomic and sectoral structure, the model includes household micro-data, based on publicly available data from Eurostat, to capture heterogeneity in household expenditure

[8]For example, I have information on labor earnings by occupation in a given sector and region, how these earnings accrue to heterogeneous households, and how households spend their income on final consumption goods according to idiosyncratic, i.e. household-specific, preferences for more than 240,000 households that collectively form a representative sample of the EU's household population.

[9]In addition, I incorporate data on taxes and subsidies on sectoral outputs and inputs, factor taxes, consumption taxes, and commodity- and country-specific tariffs on bi-lateral imports and exports.

patterns (preferences) and income. The Household Budget Survey (HBS) data (Eurostat, 2023*a*) comprises data collected from national surveys for different EU Member States focusing mainly on mainly on household expenditure on goods and services. I use the HBS data from the 2020 wave. The EU statistics on income and living conditions (EU-SILC) (Eurostat, 2023*b*) collect cross-sectional and longitudinal data on income, poverty, social exclusion, and living conditions, from which I extract information on total annual income and income by source (capital, labor, transfer income). I use the EU-SILC micro-data for the year 2020.

STATISTICAL MATCHING.—To combine HBS and EU-SILC data, I rely on previous work carried out under a project for the EU Commission's Joint Research Center (Landis, Abrell and Rausch, 2021) which developed a statistical matching procedure for merging both datasets based on common socio-economic variables for the respective 2010 waves of HBS and EU-SILC.[10]

Calibration

CALIBRATION LOGIC.—Table 2 reports the parameters that need to be chosen for the quantitative model.

For calibration, I distinguish between four types of parameters: (1) distribution parameters in CES functions are chosen based on direct, observable equivalents from macro or microdata, (2) substitution elasticities calibrated either to empirical supply responses (for example, in labor or energy supply) or based on empirical values from the literature, (3) other parameters, governing exogenous aspects of intertemporal dynamics (for example, population growth, capital depreciation) or the specification of directed technical change, are selected based on the literature, and (4) climate policy parameters that reflect the scope and ambition of EU carbon pricing regulations are directly taken from legislative documents.[11]

DISTRIBUTION PARAMETERS.—I follow the standard calibration procedure in multi-sectoral general equilibrium modeling (see, for example, Rutherford, 1995; Harrison, Rutherford and Tarr, 1997; Böhringer, Carbone and Rutherford, 2016) to determine distribution parameters. Distribution parameters for non-energy production (α_{ir}, β_{jir}), γ_{ir}, δ_{lir}), energy services (κ_{qir}, η_{qir}, ζ_{qijr}), and international trade (Θ_{qir}, m_{qisr}) are calibrated based on macro data from GTAP. Together with information on the value of output of each activity, this calibrates the multi-sector input-output structure of the model. Distribution and share parameters for households (ω_h, ζ_{ih}, k_{lh}, Θ^l_h, Θ^k_h) are calibrated based on the micro data from HBS and EU SILC. Together with information on the value of household-level consumption and income by source, this determines households' preferences and base-year income patterns.

SUBSTITUTION ELASTICITIES.—Elasticity of substitution parameters σ, μ, ϵ, ϕ, ρ, and ζ are set to values taken from the MIT EPPA model (Chen et al., 2015). The substitution elasticity between the natural resource factor n and capital inputs λ_{nr} is calibrated using (13) to match an own-price supply elasticity of 2.5 for renewables (wind and hydro) and .2 for nuclear and hydro power.[12]

I follow Boeters and Savard (2013) to calibrate the endogenous labor-leisure choice parameter ν_h together with the time endowment targeting the uncompensated income elasticity of labor

[10]In a nutshell, the matching approach is based on the idea of minimizing the Hellinger distance between the statistical distributions of common variables across different categories in the two surveys and uses a random hot deck sampling procedure in an iterative process to find observations in the donor dataset for previously unassigned recipient observations. Further details, including documentation of the statistical matching procedure, are available from the author on request.

[11]Given the country, sector, and household detail of the model, it is not feasible to adopt a methods of moments approach (as, for example, in Fried, 2018, in a quantitative macro model for climate policy analysis) for calibrating some of the "free" parameters. This would require time series data on prices and outputs at the sectoral, country, and household levels which do not exist at this level of detail. The calibration approach adopted here thus involves calibrating the model to replicate a one-period equilibrium that represents the base year for which comprehensive data is available. A reference path without climate policy is then obtained by recursively simulating the model given intertemporal parameters and the laws of motion for physical and knowledge capital stocks and labor endowments.

[12]The low elasticity for nuclear and hydro power reflects the fact that building new nuclear plants is typically not strongly driven by economic considerations (as represented in the model) and that in the case of hydro, the resource potential for new hydro power plants is more limited relative to renewables from wind and sun. A future extension of the model needs to incorporate estimates of country-specific supply elasticities that reflect the actual renewable resource potentials and spatially differentiate the quantity and quality of wind and solar locations to capture the regional heterogeneity among EU countries.

TABLE 2. **Parameters and data sources.**

Parameter	Source
Non-energy production	
Sectoral output elasticity of substitution: σ	Calibrated: Chen et al. (2015)
Non-energy intermediate inputs elasticity of substitution: μ	Calibrated: Bretschger et al. (2017)
Capital-labor-energy services elasticity of substitution: ϵ	Calibrated: Chen et al. (2015)
Distribution parameter: α_{ir}	Data: GTAP (Aguiar et al., 2022)
Distribution parameter: β_{jir}	Data: GTAP
Distribution parameter: γ_{ir}	Data: GTAP
Distribution parameter: δ_{lir}	Data: GTAP
Energy services	
Energy inputs elasticity of substitution: ρ	Calibrated: Chen et al. (2015)
Machine inputs elasticity of substitution: ξ	Calibrated: Acemoglu et al. (2012)
Energy and machine inputs elasticity of substitution: χ	Calibrated to match implied knowledge growth rate of 2–3.5% per year
Distribution parameter: κ_{qir}	Data: GTAP
Distribution parameter: η_{qir}	Data: GTAP
Distribution parameter: ζ_{qijr}	Data: GTAP
Supply price elasticity: η_{nr}	Data: GTAP
Energy production	
Natural resource elasticity of substitution: λ_{nr}	Calibrated to match fuel supply elasticity
Distribution parameter: θ_{nr}	Calibrated to match fuel supply elasticity
International trade	
Import elasticity of substitution: ψ_{ir}	Calibrated: Narayanan et al. (2012)
Armington elasticity of substitution: κ_{ir}	Calibrated: Narayanan et al. (2012)
Distribution parameter: Θ_{qir}	Data: GTAP
Distribution parameter: m_{qisr}	Data: GTAP
Research and innovation	
Innovation success probability: η	Normalized
Productivity in quality improvement: γ	Calibrated: Lemoine (2024)
Distribution parameter: λ	Calibrated: Lemoine (2024)
Labor markets	
Unemployment elasticity of pay: η_{lr}	Calibrated: Nijkamp and Poot (2005)
Wage curve parameter: b_{lr}	Calibrated: EU Labor Force Survey (2022)
Households	
Consumption goods elasticity of substitution: ϑ_h	Calibrated: Chen et al. (2015)
Material-leisure elasticity of substitution: ν_h	Calibrated: labor supply elasticity
Distribution parameter: ω_h	Data: Eurostat HBS-SILC (2023*a*; 2023*b*)
Distribution parameter: ξ_{ih}	Data: Eurostat HBS-SILC
Share in scientists profits: Θ^l_h	Calibrated: earnings from high-skilled labor
Share in capital income: Θ^k_h	Data: Eurostat HBS-SILC
Elasticity of transformation between labor types: ν	Exogenous
Distribution parameter: k_{lh}	Data: Eurostat HBS-SILC
Emissions and climate policy	
Carbon content of fossil fuel e: Φ_e	Data: GTAP
Emissions cap by ETS system $\mathcal{S}$ over time: $\Upsilon^{\mathcal{S}}_t$	Based on European Commission regulations[a]
Share of carbon revenue for region r: $\Phi^{\mathcal{S}}_r$	Based on European Commission regulations[a]
Growth	
Effective labor growth rate (comprising Harrod-neutral technological progress and population growth): γ_{rt}	Population projections (Eurostat, 2024*a*) and average 2019-2024 labor productivity growth (European Central Bank, 2024)
Capital depreciation rate: δ_r	Exogenous: 5% per year

Notes: [a]See Section B.4 for more detail on the European Commission (EC) regulations that define the policy parameters.

supply and the uncompensated wage elasticity of labor supply.[13] For these labor supply elasticities, I choose values of $\eta^I = -0.05$ and $\eta^W = 0.2$ (independently of household type and EU region), which fall within the range of empirical estimates reported in the literature (Blundell and MaCurdy, 1999; Chetty, 2012; Bargain and Peichl, 2016).

DIRECTED TECHNICAL CHANGE.—As only the product $\gamma \times \eta$ matters, I normalize the success probability of scientists η to one. The base case assumes $\gamma = 1$ for the productivity of scientists based on the parametrization in Lemoine (2024). In light of the parametrization used in similar modelling exercises in the literature, this choice implies a relatively low value for γ (for example, Fried (2018) and Acemoglu et al. (2023) set $\gamma = 1.07$ and $\gamma = 3.96$, respectively). In my model, $\gamma = 1$ implies that knowledge related to improving energy services roughly doubles over a period of 20–30 years (depending on sector, type of energy service, region, and policy scenario; see Section B.4), which in turn implies an average growth rate of about 2–3.5% per year. Since empirical estimates of annual growth rates in knowledge (Jones, 1995; Kortum, 1997; Comin and Mestieri, 2018; Bloom et al., 2020) are typically in the range of 2–6%, the model's knowledge growth rates implied by $\gamma = 1$ can be considered a conservative parametrization.

INTERTEMPORAL PARAMETERS.—To parametrize the growth rate of effective labor (including population and Harrod-neutral productivity growth) γ_{rt}, I incorporate population projections by country by time period $\overline{\gamma}_{rt}^{Pop}$ based on the baseline projection from Eurostat (2024*a*) and information on labor productivity growth in the EU $\overline{\gamma}^{Prod}$. Using data from European Central Bank (2024) on labor productivity growth by hour in 2019–2024, I compute an annual average growth rate in labor productivity of $\overline{\gamma}^{Prod} = 1.07\%$ for the EU area which is uniformly applied to all EU countries. The total growth rate of effective labor is calculated as: $\gamma_{rt} = \overline{\gamma}_{rt}^{Pop} + \overline{\gamma}^{Prod}$. In the model, this implies an average growth rate of EU GDP of about 1.6% per year in the absence of climate policy, which is in the range of the realized average growth rate of about 1.63% per year in the EU between 1996 and 2024 (Eurostat, 2024*b*). γ_{rt} for non-EU regions is set at 4% per year. The depreciation rate of capital δ_r is set at 5% per year. Households transfers T_{ht} and government expenditures G_{rt} grow with the region-specific population rate $\overline{\gamma}_{rt}^{Pop}$, implying that transfers and government expenditures per household remain constant over time (and policy counterfactuals) in each region.

I solve the model from 2017 until 2050. 2017 is the base year for which macroeconomic social accounting data is available from GTAP. I forward-calibrate the economy to 2027 using the observed GDP growth rate at the country level for the period 2017-2025 and assume growth for 2026-2027 based on 2025 growth rates. The years 2027 (ETS2 starts) and 2030 (the year for which the EU climate targets are set in EU climate legislation) are explicitly modeled, implying a model time step of three years between 2027-2030. For all periods after 2030, the model is solved in time steps of five years.

WAGE CURVE.—Based on Nijkamp and Poot (2005), who conduct a meta-analysis on a survey of 208 studies providing empirical estimates of the wage curve elasticity, I assume $\eta_{lr} = -0.07$ for all regional labor markets. The second wage curve parameter b_{lr} is used to calibrate the wage curve for each regional labor market lr to observed unemployment rates. I use the most recent available estimates for country-specific unemployment rates by occupation $\overline{\Lambda}_{lr}$ in the EU27 from the EU Labor Force Survey (2022). In the base-year equilibrium with prices normalized to one, the constant elasticity function of the wage curve (22) can be calibrated to observed

[13]Formally, and based on Boeters and Savard (2013), the income elasticity of labor supply η^I and the wage elasticity of labor supply η^W are related to the household's time endowment $\overline{L}_h$ as follows:

$$\overline{L}_h = (1 - \eta^I/[(1+\eta^I)M_h - \eta^I \hat{M}_h)]\hat{n}_h$$

where $\hat{M}_h$ denotes non-labor income. The substitution elasticity between material and leisure consumption ν_h is then given by:

$$\nu_h = \frac{\eta^W - \frac{\overline{L}_h - \hat{n}_h}{\hat{n}_h}\left[(1-\theta^W)\frac{\overline{L}_h}{\overline{L}_h + \hat{M}_h}\right]}{\frac{\overline{L}_h - \hat{n}_h}{\hat{n}_h}\theta^W}$$

where θ^W is the share of consumption in extended income (the latter including observed household reference income and the value of time).

unemployment rates by setting $b_{lr} = (\overline{\Lambda}_{lr})^{-1}$.

Computational strategy

equilibrium formulation and computation.—I formulate the model as a mixed complementarity problem associating quantities with zero-profit and prices with market-clearing conditions (Mathiesen, 1985; Rutherford, 1995). I use the General Algebraic Modeling System (GAMS) software and the GAMS/MPSGE higher-level language (Rutherford, 1999) together with the PATH solver (Dirkse and Ferris, 1995) to compute the equilibrium.

heterogeneous households and overcoming dimensionality.—Solving for the single period equilibrium of the multi-sector multi-country model with a representative household is easily achieved with standard software and solvers. However, incorporating 240,000 heterogeneous households raises dimensionality issues that render standard tools ineffective. I use a decomposition algorithm developed by Rutherford and Tarr (2008), which makes it possible to integrate all households as individual economic agents into the general equilibrium model.[14] Along with the transition path of the macro variables, the model thus solves the utility optimization problems for each of the 240,000 households comprising material and leisure consumption and labor supply decisions, in response to counterfactual climate policies.

The core idea of the algorithm is to break down the numerical problem of calculating general equilibrium prices and quantities into two sub-problems, one of which represents the multi-country multi-sector macro part and the other represents the utility maximization problems of households. By iterating between the two sub-problems and using candidate prices and quantities from the household problems to sequentially recalibrate the preferences of an artificial representative agent in the macro-problem, mutually consistent responses from firms and households are obtained that represent a general equilibrium. The preferences of the 240,000 "real" households, which are calibrated on the basis of the EU HBS-SILC microdata, always remain unchanged.

B.4. Results

Counterfactual Experiments

I analyze carbon pricing in the EU by evaluating the introduction of ETS2, while continuing the EU ETS. Welfare effects are compared relative to a (hypothetical) baseline without any ETS policies. I also explore the interaction between endogenous innovation in energy services and climate policy, as well as the role of unemployment for the costs of climate policy.

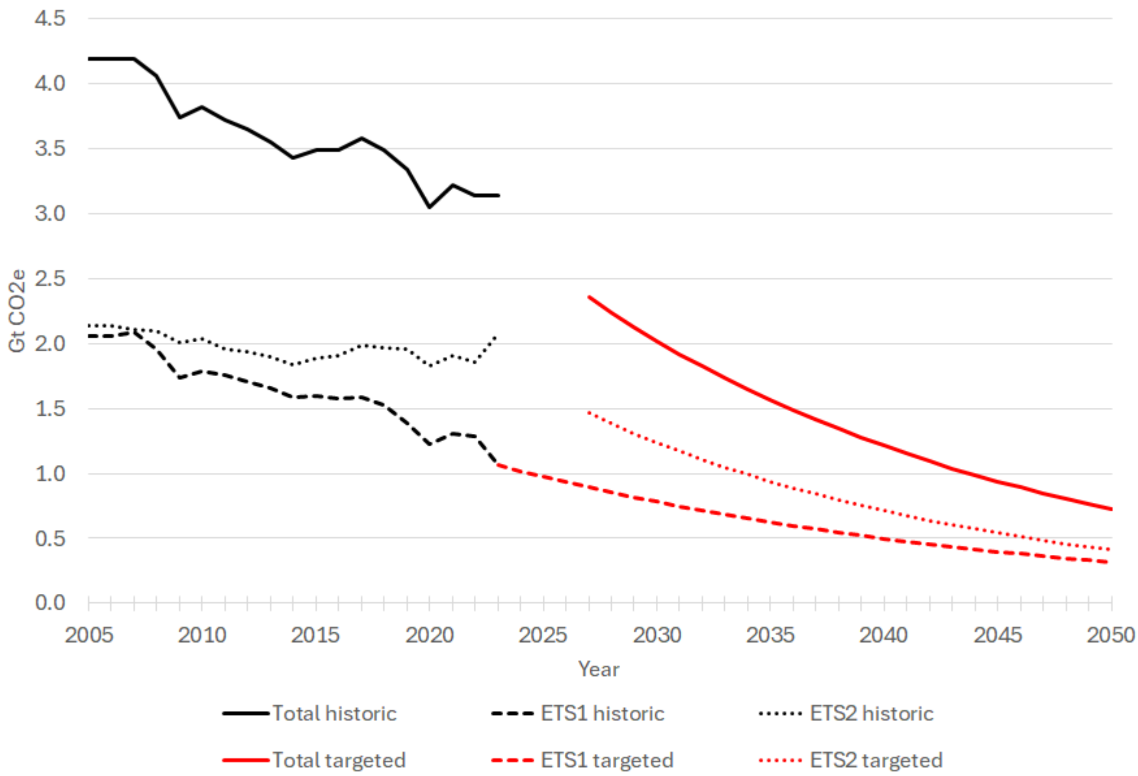
The emission caps of the different ETS policies are available until 2030 from legal documents (European Commission 2020, 2021*a*, 2021*c*, 2023*b*). The ETS1 (ETS2) cap will be set to bring emissions down by 62% (42%) by 2030 compared to 2005 levels. Figure 1 shows the historic and targeted emission reductions for ETS1 and ETS2.[15] In calculating reduction targets for after 2030, I assume constant linear annual reduction factors for ETS1 and ETS2, based on the values for 2030 already implemented in EU climate legislation. This defines $\Upsilon_t^{\mathcal{S}}$, where $\mathcal{S} = \{ETS1, ETS2\}$. Assuming an identical sectoral coverage for ETS2 and ESR, the trajectory of targeted emissions is also identical, i.e. $\Upsilon_t^{ETS2} = \Upsilon_t^{ESR}$.

Under current regulation (i.e., in the absence of ETS2), emissions not covered by the ETS1 are subject to the ESR for which national emissions targets are set by policy (European Commission, 2023*c*). Using the targets set for 2030, I can calculate a country's share in the EU's overall

[14] Rutherford and Tarr (2008) apply the algorithm to study the poverty effects of Russia's accession to the WTO using a general equilibrium model that incorporates real households with heterogeneous income and consumption patterns. Rausch, Metcalf and Reilly (2011) develop a general equilibrium model incorporating heterogeneous households based on consumer expenditure and income data for the United States with state-level detail to study the distributional effects of carbon pricing. Rausch and Rutherford (2010) adapt the decomposition algorithm to solve overlapping generations models with a large number of heterogeneous households.

[15] Based on data shown in Figure 1, this implies that combined emissions from ETS1 and ETS2 will reduce by 52% by 2030 compared to 2005 levels. Since I exclude emissions from waste as well as land use, land use change and forestry (LULUCF) from the analysis, this differs somewhat from the EU's overall climate target of reducing GHG emissions by 55% by 2030 compared to 2005 levels.

Figure 1. **EU-27 carbon budgets in ETS1 and ETS2: historical and targeted GHG emissions**



Notes: The figure presents historical annual GHG emissions and reductions targets, aggregated for the EU-27 countries. Historical emissions are taken from the European Environment Agency data viewer (Agency, 2024). Targeted emissions trajectories are based on legal documents by the European Commission (2023*b*). The linear reduction factor in the ETS1 is 4.3% per year for 2024-2027 and increases to 4.4% from 2028 onwards. The linear reduction factor for the ETS2 is 5.1% and increases to 5.38% per year from 2028. The gap for 2024–2026 in the plots results from the fact that historical emissions data is only available up to 2023, while ETS2 does not start until 2027.

targeted ESR emissions, which determines Φ_r^{ESR}. The targeted ESR emissions budget of country r over time is then given by $\Phi_r^{ESR} \times \Upsilon_t^{ESR}$. The final piece to represent EU carbon pricing policies in the model is to specify how carbon revenues under ETS1 and ETS2 are handed back to countries. For ETS1 this information is sourced from European Commission (2023*a*) and for ETS2 from European Commission (2018, 2021*b*). I also use information from the Social Climate Fund (SCF) and assume that 25% of the ETS2 revenues are distributed to countries based on the SCF redistribution rule and 75% based on the ETS2 redistribution rule.

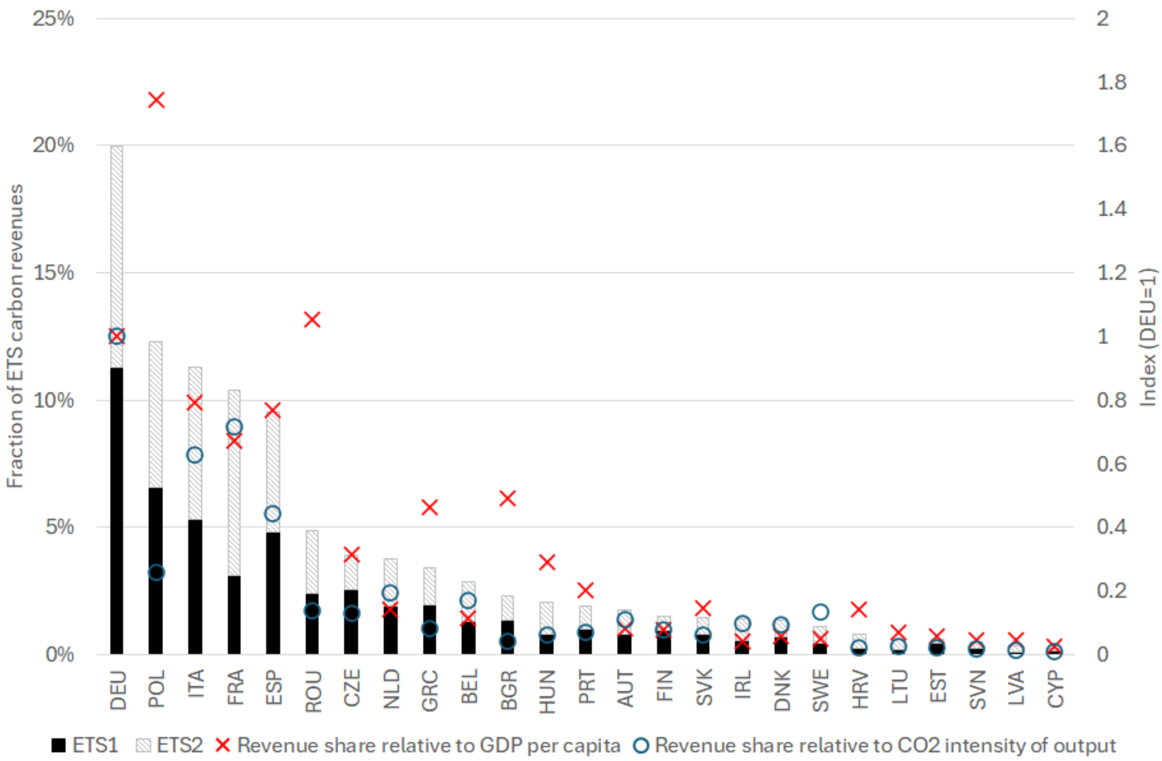
Figure 2 shows the effective share of carbon revenues collected from ETS1 and ETS2 flowing back to the EU countries. While countries with larger economies and populations receive larger shares of carbon revenues, the distribution of carbon revenues across countries under the existing ETS regulations is roughly proportional to GDP per capita and the CO_2 emission intensity of output.

Aggregate EU-27 welfare and the role of unemployment and endogenous innovation

Before turning to the distributional effects of future EU carbon pricing, I provide evidence on the relative importance of including unemployment and endogenous innovation for quantitatively assessing the welfare cost of climate policy.

Figure 3 reports the change in EU-27 aggregate welfare of the future ETS regulation (ETS1 + ETS2) relative to a baseline without carbon pricing. The aggregate welfare change is compared over time and across different model specifications, which differ in the inclusion of unemployment and endogenous innovation (directed technical change). The costs of achieving the EU's climate policy targets through carbon pricing are significantly overestimated if innovation is ignored.

Figure 2. **Effective carbon revenue shares by country as defined by EU ETS regulations**



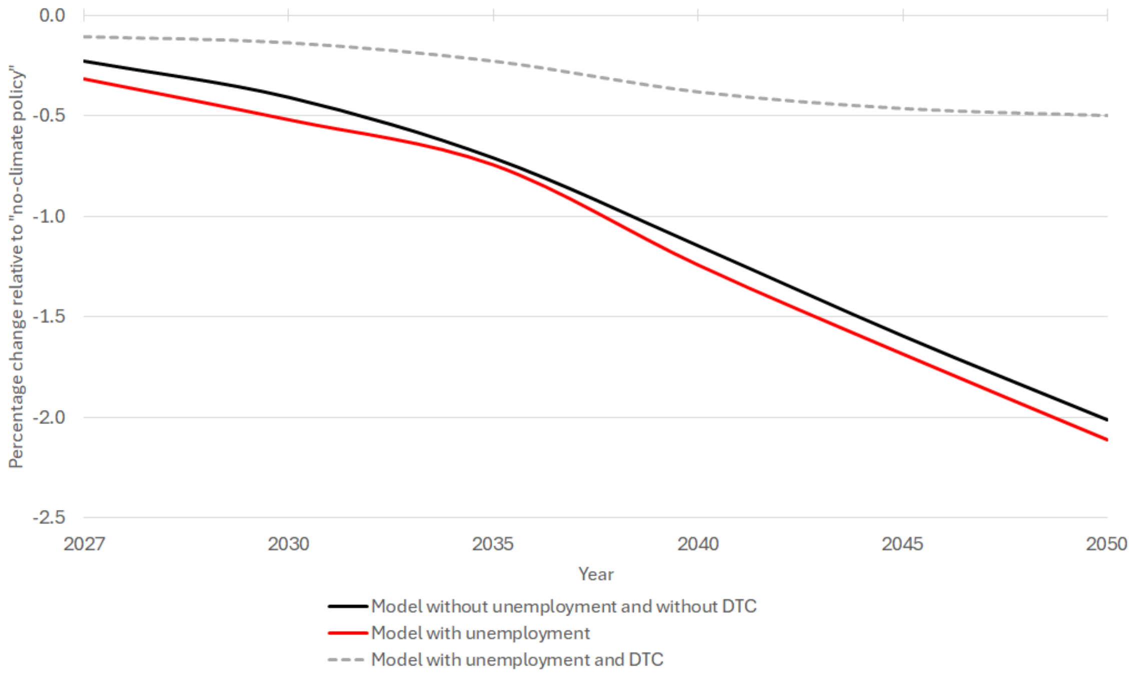
Notes: The figure shows the share of CO_2 revenues from ETS1 and ETS2 that are returned to EU countries, as defined by the European Commission's ETS regulations (2018, 2021*b*,2023*a*). Revenue shares are differentiated by ETS1 and ETS2 and are shown by the bars (left vertical axis). The total height of a bar shows a country's share of combined revenues from ETS1 and ETS2, ordering countries from left to right in descending order. The crosses and circles (right vertical axis) show the share of combined revenues relative either to a country's GDP per capita or to the CO_2 emission intensity of output, respectively, with each data series indexed to Germany (i.e., DEU=1). For GDP per capita and the emission intensity of output, I use data for 2017 from the model (see Section B.3).

While further exploration of the innovation channel is not per se the focus of this chapter, the main intuition is that carbon pricing shifts demand from fossil fuels to renewable energy, electricity (which is increasingly generated from renewable sources), and to non-energy inputs, including (physical and knowledge) capital and labor. In the model with directed technical change, this shift in demand increases innovation related to (a) the electrification of energy services and (b) a higher efficiency in using fossil energy to provide energy services. This lowers the relative price of energy services produced with low carbon intensity compared to those produced with high carbon intensity.

Overall, endogenous innovation in the model with DTC strengthens the price incentives created by carbon pricing, implying that the same emissions reduction can be achieved at a lower cost. Importantly, endogenous innovation helps to sustainably and permanently reduce the relative costs of low-carbon production technologies, which keeps the costs of future abatement options low in the long run. Figure 3 shows that around 2040-2050, unlike in the model without endogenous innovation, the costs of climate policy do not continue to rise.

In addition, a model with endogenous innovation yields considerably lower carbon prices to achieve the same emissions reductions at the EU-27 level. Table 3 shows that in 2030, when policy stringency is still modest, the ETS1 (ETS2) carbon price obtained from a model with endogenous innovation is 24% (36%) below the respective price under a model without endogenous innovation. As climate targets become more ambitious over time, endogenous innovation has a large positive impact on carbon prices and welfare costs. For example, by 2050, carbon prices obtained from a model with endogenous innovation are about 2-4 times lower than in a model without endogenous innovation.

FIGURE 3. **Aggregate EU-27 welfare change for alternative model specifications**



Notes: This table compares the effects of the new ETS regulation, which includes ETS1 and, from 2027, ETS2, on the EU-27 economy relative to a hypothetical "no climate policy" baseline. Aggregate welfare refers to the sum of Hicksian equivalent variation based on household-level utility $U_{h_{(r)}t}$. When calculating the change in welfare in the EU-27, we take a utilitarian approach, i.e. each household is given the same weight in aggregate welfare.

TABLE 3. **Model specifications: the effects of including unemployment and endogenous innovation (directed technical change)**

	Model specifications								
	no unemployment & DTC			unemployment			unemployment & DTC		
	2030	2040	2050	2030	2040	2050	2030	2040	2050
Welfare change per year									
in %	-0.4	-1.1	-2.0	-0.5	-1.2	-2.1	-0.1	-0.4	-0.5
in bill. EUR	-59	-183	-350	-76	-202	-375	-21	-65	-93
in EUR per capita	-133	-410	-784	-171	-452	-840	-46	-144	-208
Carbon prices									
ETS1	112	276	725	116	283	741	85	174	340
ETS2	206	762	2'468	211	780	2'527	131	337	660
Unemployment rate									
in %	–	–	–	6.6	7.6	10.4	6.4	6.6	7.0
% change	–	–	–	12.4	28.7	76.6	7.7	12.3	17.8

Notes: This table compares the effects of the new ETS regulation, which includes ETS1 and, from 2027, ETS2, on the EU-27 economy relative to a hypothetical "no climate policy" baseline.

Figure 3 and Table 3 also suggest that including unemployment in the model has less impact on the estimate of the costs of climate policy than including endogenous innovation. Welfare cost are slightly larger if unemployment is included. There are two counteracting effects. On the one hand, including unemployment means that in the policy-induced transition from fossil energy to low- or carbon-neutral inputs, additional labor is pulled out of unemployment and brought to bear on the labor market. This has a positive effect on welfare. On the other hand, the adverse impacts on energy- and carbon-intensity sectors of the economy imply, given limited mobility of labor across sectors and regions, that unemployment tends to increase, with a negative effect on welfare.

Endogenous innovation also significantly reduces the negative impact on the unemployment rate. While the model without DTC predicts an increase in the unemployment rate to 10.4% by 2050 (from 5.9% without climate policy), a model with endogenous innovation estimates that the increase is limited to 7.0% (see Table 3).

The remainder of the analysis focuses on the distributional and employment effects of EU climate policy using the preferred model specification with unemployment and endogenous innovation.

Distributional effects by country, household, and sector

The aggregate welfare effects mask substantial variation in the welfare effects across countries, heterogeneous households, and industries. Exploiting the rich country-, sector- and household-level heterogeneity of the model enables examining the magnitude of the distributional effects of future EU carbon pricing policies.

distributional effects by country.—Figure 4, Panel (a) shows the welfare effects by EU country for different years. Figure 5 uses a map to visualize the welfare changes for the years 2030 and 2050. Several insights emerge. First, carbon pricing through the EU system of ETSs leads to highly dispersed welfare impacts between EU countries. Some countries even gains from EU carbon pricing policies. To help understand the cross-country distribution of welfare impact, Panel (b) provides a scatter plot of (i) a country's share of ETS revenues (obtained from ETS1 and ETS2) in total EU-wide ETS revenues relative its economic output vs. (ii) a country's CO_2 emissions intensity of economic output. (i) is a measure of how a country is positioned in terms of the redistribution of carbon revenues, controlling for the economic size of the country. For example, a large country (Germany) would benefit less than a small country (Estonia) for a given share of carbon revenues. (ii) is an imperfect measure of the exposure to carbon pricing on a country. For example, a country with a high emissions intensity may be more affected than a country with a lower emissions intensity.[16] Countries with high revenues shares (for example, BGR, SVK) tend to be among the countries where carbon revenues overcompensate abatement cost, yielding welfare gains. Countries with low revenue shares and/or high emissions intensity tend to incur welfare losses. Second, the pattern of distributional effects among countries changes over time. Countries with welfare gains in 2027 (BGR, EST, CZE, ROU, SVK, POL) experience smaller gains or losses by 2040 and 2050, while some countries with initial losses in 2027 experience smaller losses in 2040 and 2050 (for example, DEU, FRA, HRV, SVN). This suggests that the cross-country distribution of impacts narrows over time: the standard deviation of country-level welfare changes in 2027 is 0.94, reducing to 0.64 (0.56) in 2040 (2050).

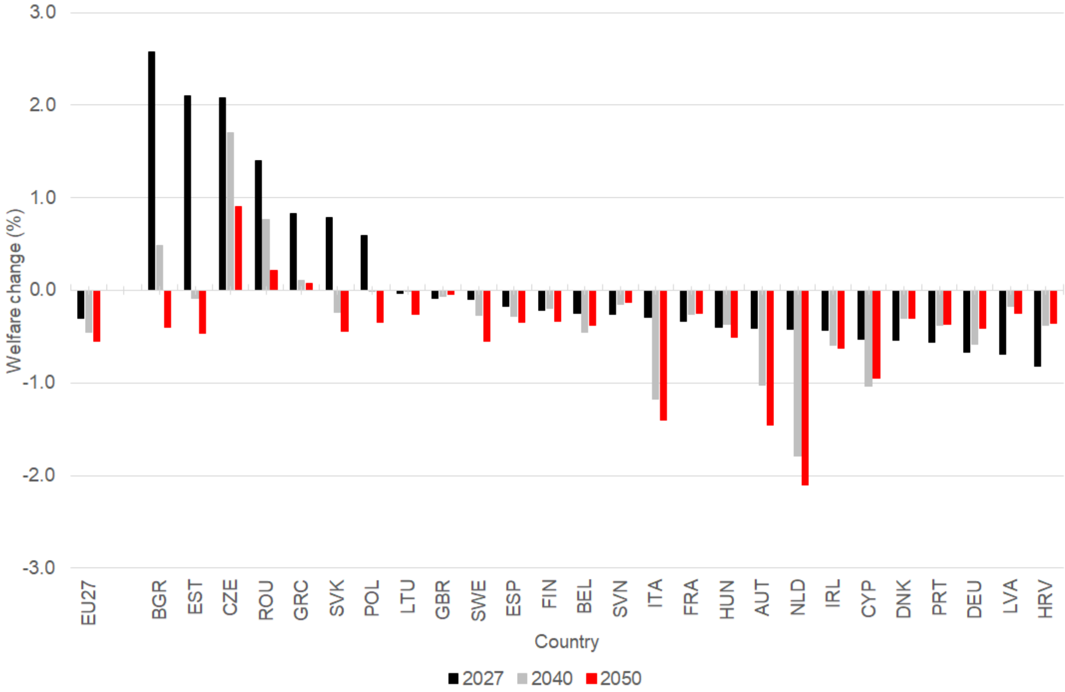
distributional effects by household.—Figure 6 shows empirical cumulative distribution functions of household-level utility changes for different years, pooling households from all EU countries. The striking result is that the range and dispersion of utility impacts at the household level significantly exceed the variation of welfare changes at the country level. For 2027, the impact on households ranges from -10.0% to over +20%, with a standard deviation of 3.8%, and the changes for utilities are -0.55% and 3.3% at the 25th and 75th percentiles, respectively. The distribution of household-level impacts, in contrast to country averages, widens considerably over time, with the standard deviation increasing to 8.7% and 10% in 2040 and 2050.

Figure 7 groups households (pooled from all EU countries) according to consumption deciles.[17] Several insights emerge. First, for the EU household population, the mean household utility impacts across income (as proxied by consumption) are neutral to slightly progressive. While the EU HBS data shows that the share of energy expenditure decreases with income, the neutral to slightly progressive outcome is driven by the uniform per-household rebating of

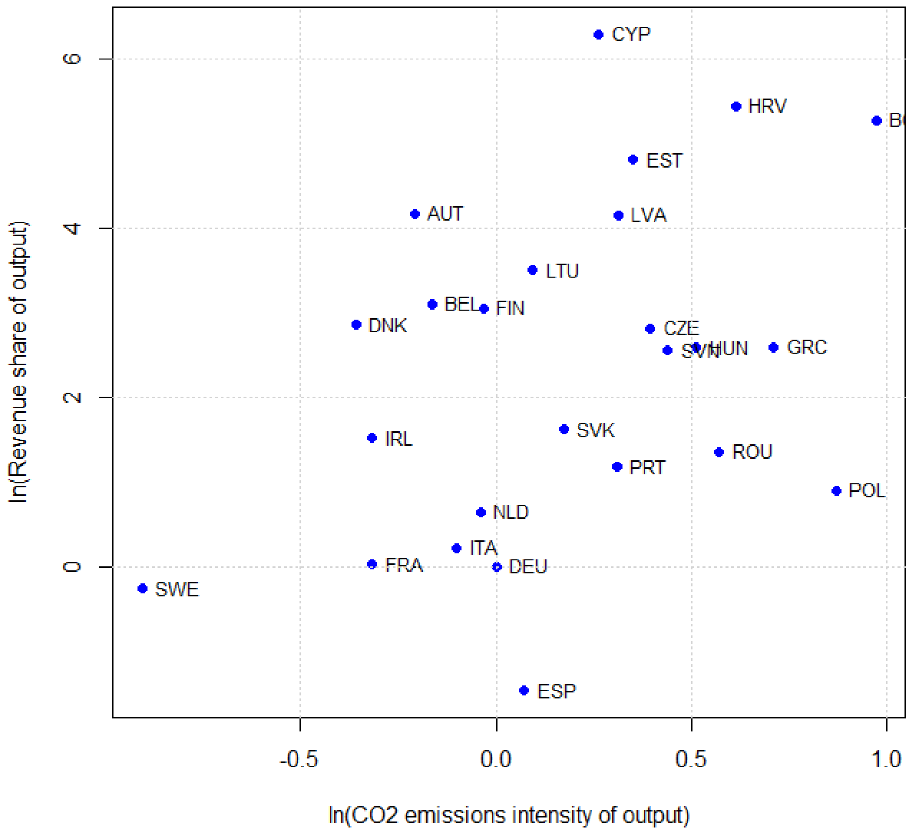
[16]Carbon intensity, shown in Panel (b) of Figure 4, is an imperfect measures as contains no information on a country's marginal abatement, i.e. how costly it is to move away from a pre-policy emissions intensity. It is precisely the virtue of the general equilibrium model to capture these costs in terms of a micro-founded consistent welfare analysis, taking into account the behavioral responses of firms and consumers to price and income changes on interlinked product, factor, and carbon markets.

[17]I rank households by consumption expenditure as a proxy for lifetime income because it provides a more stable and comprehensive measure of economic well-being than ranking by income group (due to several reasons, including income volatility, intertemporal borrowing and savings, under-reporting, and informal income.

FIGURE 4. **Welfare change, carbon revenue share, and CO_2 emissions intensity of output by country**



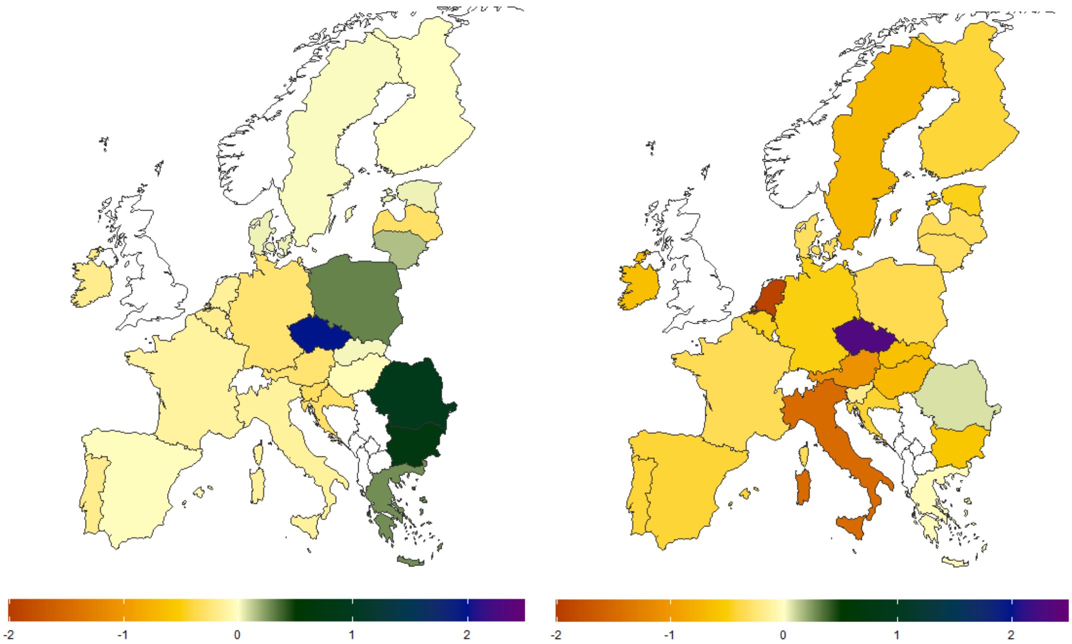
(a) Welfare change by country



(b) Cross-country distribution of ETS revenue share relative to output vs. CO_2 intensity of output

Notes: Panel (a) shows the aggregated welfare change (in %) by country under ETS1+ETS2 relative to "no-climate policy" for different years. Countries are ordered from left to right in descending order of their welfare impact in 2027. Panel (b) shows, using model data for the base year, a scatter plot showing a country's share of ETS revenues in total EU-wide revenues relative to economic output against its CO_2 emissions intensity of output.

FIGURE 5. **Welfare change by EU country from ETS1+ETS2 relative to "no-climate policy" (in %)**



(a) Year 2030

(b) Year 2050

carbon revenues within a country and progressive sources of income effects. Second, despite much higher carbon prices in 2050 (see Table 3), the degree of progressivity (in terms of mean impacts by consumption decile) is not much affected. Third, the variation within the deciles swamps the variation in the mean values between the decile groups. In fact, the EU-HBS-SILC data show considerable heterogeneity within consumption (income) deciles in terms of key characteristics such as a household's share of labor, capital, and transfer income, as well as the share of energy expenditure, which in turn drive the within-income group variation in utility impacts.

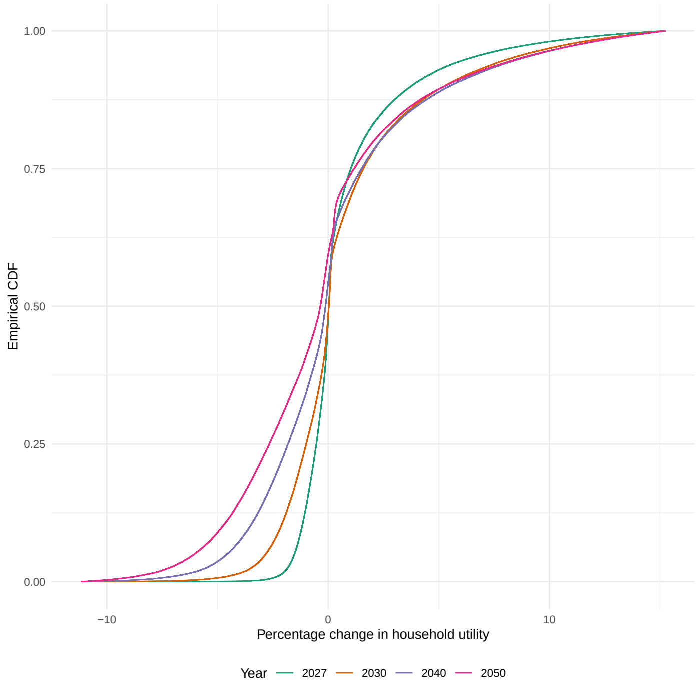
Figure 8 shows that the degree of progressivity in terms of the mean household impacts across income groups varies between countries. Progressivity tends to be more pronounced in countries that receive a larger share of carbon revenues (see Panel (b) in Figure 4) and have relatively low GDP per capita (e.g. BGR, GRC, POL, ROU), while progressivity tends to be lower in richer countries and those with a relatively low share of carbon revenues (such as DEU, FRA, ESP). For countries with positive welfare changes in 2027 at the aggregate country level (see Panel (b) in Figure 4), virtually all households gain, while in countries with a welfare loss (such as DEU and FRA) a substantial fraction of households is worse off from EU carbon pricing.

EFFECTS ON SECTORS, EMPLOYMENT, AND WAGES.—Table 4 the change in sectoral output, employment, and wages. Not surprisingly, the energy industry and energy-intensive sectors experience a significant decline in output and employment. At the same time, labor reallocation and substitution away from direct and indirect CO2-emitting activities, facilitated by endogenous innovation and targeted technical change, means that output and employment levels are not significantly affected or even increase slightly. The change in total sectoral production is slightly positive by 2050. Wages (on average across labor skill types and country) are also only moderately affected on average across all skill types and countries by the EU's future carbon pricing policies.

B.5. Conclusion

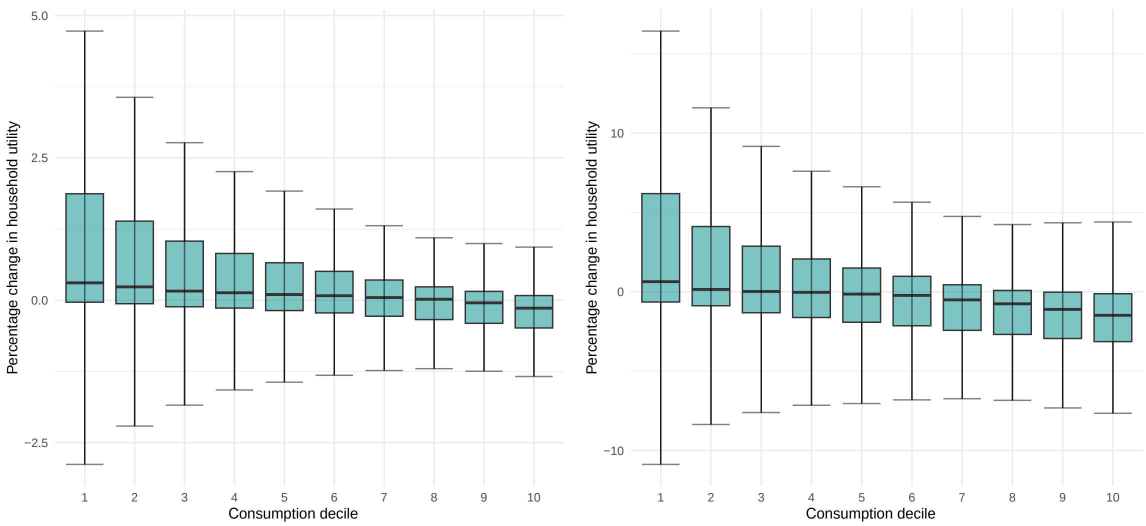
This chapter documents a novel dynamic general equilibrium model of the EU economy, fully developed under the WeLaR project, that is tailored to assess the macroeconomic, labor market and distributional implications of EU climate policy. The model combines the integration of a

Figure 6. **Distribution of household-level utility changes for pooled EU-27 household population by year: empirical CDFs**



Notes: This plots show the empirical cumulative distribution functions (CDF) of utility changes (in %) of households under ETS1+ETS2 relative to "no-climate policy" for different years pooling household from all member states.

Figure 7. **Within- and across-consumption quintile distribution of household utility changes under ETS1+ETS2 relative to "no-climate policy" (in %)**



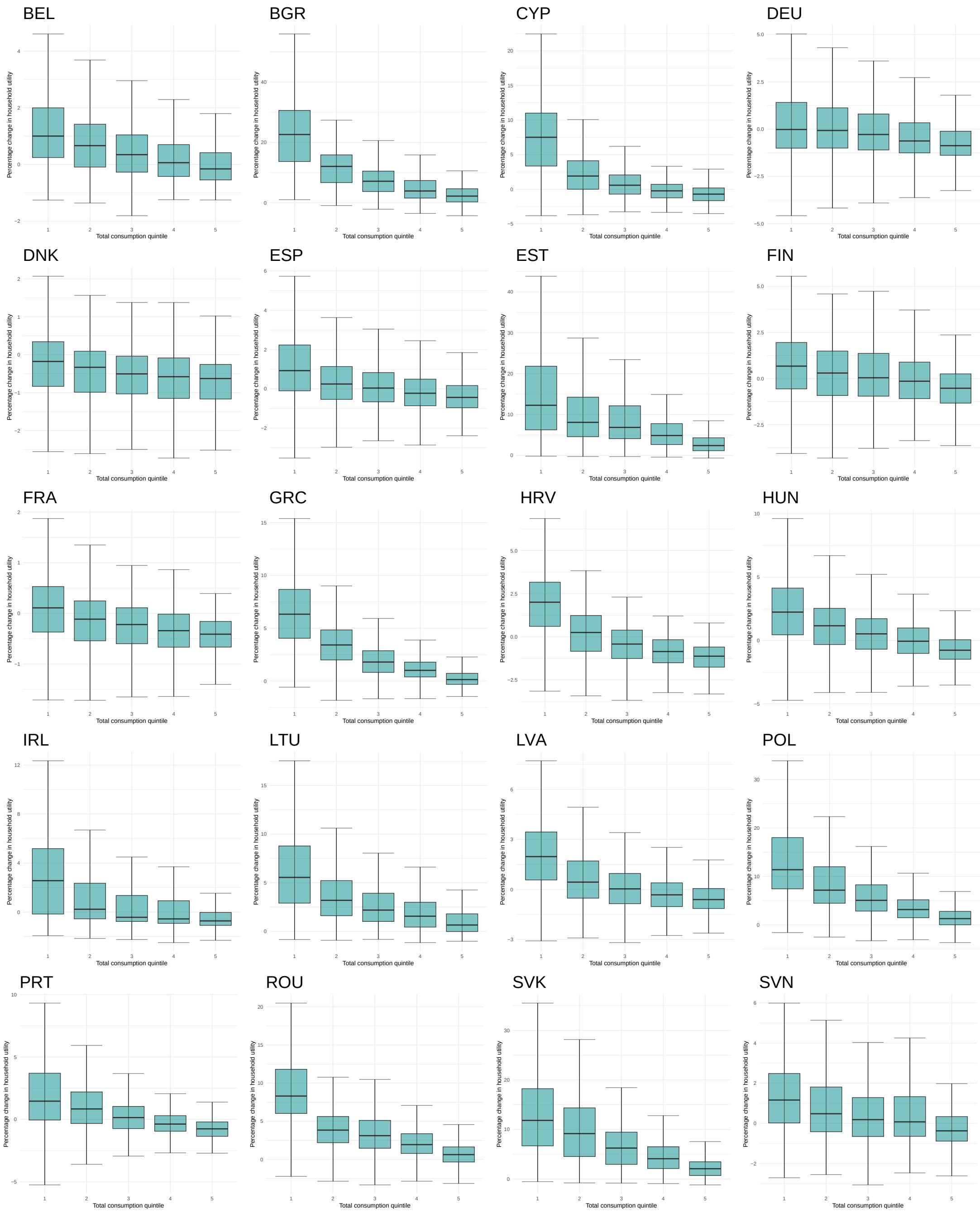
(a) EU27 pooled, 2027

(b) EU27 pooled, 2050

Notes: For each consumption decile, the box plots show the mean and inter-quartile range of the household-level utility impacts. The lower and upper ends of the whiskers show outliers below and above the 5th and 95th percentiles, respectively.

range of features that are both state-of-the-art from an academic research perspective and relevant for a comprehensive ex-ante analysis of EU climate policy. These include a multi-country

Figure 8. **Within- and across-consumption decile distribution of household utility changes under ETS1+ETS2 relative to "no-climate policy" in 2027 (in %)**



Notes: For each consumption decile, the box plots show the mean and inter-quartile range of the household-level utility impacts. The lower and upper ends of the whiskers show outliers below and above the 5th and 95th percentiles, respectively.

Table 4. **Changes in sectoral output, employment, and wages**

	Percentage change in			
	sectoral output		in employment	
	2030	2050	2030	2050
Sector				
Coal	-69	-88	-80.7	-94.6
Natural gas	-29	-44	-21.6	-31.1
Refined oil	-27	-57	-19.3	-38.2
Energy-intensive industries	-3	-6	-0.8	-0.7
Manufacturing	0	0	0.0	0.4
Services	-1	-2	-1.0	-1.5
Agriculture	-1	-1	-0.3	0.1
Transportation	-4	-10	-0.3	0.2
All sectors	-2	-3	-0.3	0.2
Changes in wages (in %)			-1.3	-3.6

Notes: This table compares the effects of the new ETS regulation, which includes ETS1 and, from 2027, ETS2, on the EU-27 economy relative to a hypothetical "no climate policy" baseline. All numbers refer to EU27 aggregates or averages, respectively.

multi-sectoral structure, the supply and use of different types of fossil and renewable energy, endogenous innovation in energy services, 240,000 heterogeneous households as separate economic agents based on a representative sample of micro-data for the EU household population, the differentiation of skill types of labor, regional labor markets and unemployment, and the representation of the EU's carbon markets and cross-country redistribution policies as defined by the existing EU Emissions Trading System (ETS) 1 and the new ETS 2 covering emissions from heat and road transport, which will come into force in 2027.

In this chapter, the model is used to analyze the distributional effects of future EU carbon pricing policies, represented by ETS1 and ETS2. The main findings are as follows. Accounting for endogenous innovation through directed technical change in energy services, which combine knowledge capital with fossil fuels and (green) electricity in industry sectors and for household demand, considerably reduces the carbon prices in ETS1 and ETS2 and the welfare cost of achieving the EU climate targets in 2050. Using carbon pricing as the lead instrument, reaching EU climate goals entails a welfare loss of 0.5% in 2050 for the aggregate EU-27 economy; costs are 1-2 orders of magnitude higher, when estimated with a model that excludes endogenous innovation in energy services.

The aggregate welfare effects obscure a considerable variation in welfare effects between and within countries. When ETS2 is introduced in 2027, aggregate welfare effects at the country level range from -0.8 to +2.7 percent. The welfare gains for some countries are due, among other factors, to a high share of carbon revenues from ETS1 and ETS2 flowing back to the member states, as well as to relatively low abatement costs. By 2050, the welfare effects are negative for almost all countries, ranging to up to -2.1%. The variation in utility impacts at the household-level significantly exceeds the variation in aggregate impacts at the country level. When ETS2 is introduced in 2027, households' utility impacts in the EU household population range from around -10% to +20%, with impacts at the 25th and 75th percentiles of -0.55% and +3.3%. The household-level distribution of utility impacts widens considerably over time, with the standard deviation rising from 3.8% in 2017 to 10% in 2050. Assuming that carbon revenues within a country are returned as a uniform lump-sum transfer to households, the household-level incidence from future EU carbon pricing policies are neutral to slightly progressive when considering the mean impacts across income deciles. Variation in utility impacts within income groups, however, is substantial and exceeds the variation in means across income groups.

While, not surprisingly, the sectoral effects in terms of output reductions are large for energy and energy-intensive sectors, the impacts on total sectoral output are small (-3% by 2050) due to labor reallocation and substitution effects. While the EU-average unemployment rate increases from 5.9% in 2027 to 7.0% in 2050, employment (aggregated across skill types of labor and sectors) remains largely unaffected.

The main findings of this chapter highlight that achieving the EU's climate policy targets through the market-based instrument of emissions trading need not be costly in terms of EU-27 and country welfare impacts when the benefits of endogenous innovation related to the use of fossil and (renewable) electricity are realized. This suggests that climate policies should also strengthen incentives for private sector R&D investments. Even if the positive effects of endogenous productivity improvements materialize, the distributional effects of carbon pricing across EU countries and different household types are substantial. Therefore, to increase the social acceptance and political feasibility of EU climate policy, targeted measures may be needed to address the unintended consequences of carbon pricing in terms of policy-induced distributional inequality.

C. The impact of climate policy on household income inequality in selected European countries (IBS/Marek Antosiewicz, Piotr Lewandowski, Jakub Sokołowski)

C.1. Introduction

Implementing carbon pricing mechanisms, such as the second phase of the Emissions Trading System (ETS-2), is central to the European Union's climate policy framework (Nysten, 2024). These measures have far-reaching economic and social implications, particularly in countries highly reliant on fossil fuels and deeply embedded in carbon-intensive industries. Regions heavily exposed to the costs of a low-carbon transition face significant challenges, including increased energy prices and labour market disruptions. Addressing the distributional impacts of carbon pricing is crucial to ensuring a just transition that mitigates adverse effects on vulnerable populations and maintains public support for ambitious climate policies (Green and Gambhir, 2020). The European Green Deal and ETS-2 may also affect other important sectors, such as transportation, which are economically and socially important in the EU. A key question is, therefore, how the ESR and ETS2 frameworks affect living standards, including labour incomes and disposable income, across the income distribution, and how they impact inequality.

In this chapter, we answer this question by combining macroeconomic and microsimulation modelling for four countries: France, Germany, Poland, and Spain. By leveraging insights driven by microdata analysis and aligning them with key regional and sectoral considerations, we aim to understand how these policies influence household incomes and inequality in countries that differ in varying economic structures and vulnerability to carbon taxation. Southern economies, such as Spain, represent an important case study due to their size and significance within the EU and the limited availability of granular data on the distributional effects of carbon pricing in the region. Similarly, Poland represents Central and Eastern Europe, where high carbon intensity and reliance on traditional industries exacerbate the risks of economic and social disparities. France and Germany, as the EU's largest economies, further illustrate the interaction between carbon pricing, income inequality, and social acceptance. France, which has experienced protests against climate policies through movements like the Yellow Vests, faces heightened risks of social polarisation from policies like ETS-2, particularly as lower-income households bear a disproportionate share of the economic burden (Douenne and Fabre, 2022). Meanwhile, Germany's economic influence is coupled with challenges in mitigating the effects of rising energy prices on household incomes. These cases provide valuable insights into the broader implications of European carbon pricing. Importantly, these four nations employ nearly half of all transportation workers in the EU, making them particularly susceptible to policy changes to reduce emissions in the sector.

We contribute to the literature by offering insights into the economic and social implications of carbon pricing policies in four EU countries: Poland, France, Germany, and Spain. First, we explore the diversity of impacts across EU countries with varying economic structures. We provide a detailed, comparative perspective, quantifying income changes under ETS-2 and highlighting how particular effects can burden lower-income households. Second, following Antosiewicz et al. (2022), Vona (2023), and Pollin (2023), we stress the role of labour market adjustments in shaping the distributional outcomes of carbon pricing. Our findings extend their conclusions by demonstrating how labour market impacts vary across countries and between higher- and lower-income subgroups with countries. Third, we show how indirect effects contribute to regressive outcomes under ETS-2, particularly in France, where increased expenditures on non-energy goods amplify income losses in lower deciles. Fourth, our findings align with Rausch, Metcalf and Reilly (2011) and Antosiewicz et al. (2022), who demonstrate the progressive potential of recycling carbon revenues as lump-sum transfers. Specifically, we provide a multi-country perspective on the effectiveness of these transfers, showing they substantially benefit low-income households, particularly in Poland and Spain, where they drive progressive income gains. Finally, we demonstrate how ETS-2 and ESR policies reduce inequality, as measured by the Gini coefficient in all four countries, with the most substantial reductions observed in Poland and Germany.

C.2. Methods and data

The distributional effects of the new Buildings and Road Transport Emission Trading System (ETS2) are calculated using a hybrid modelling approach consisting of a computable general equilibrium model soft-linked with a microsimulation model. In the first stage of the simulation procedure, the CGE model presented in Chapter B serves to simulate changes in employment, wages, consumption patterns, and prices of goods. These are used as inputs for the second stage of the simulation which uses a microsimulation model. This model provides results at the household level and yields the impact on the incomes of different types of households and on measures of inequality. In this section, we provide an overview of the modelling framework and simulation setup and describe the microsimulation model along with its data sources.

C.3. Microsimulation model

The microsimulation model simulates changes in the distribution of household income given the output of the CGE model. The microsimulation model for a specific country is built using the latest available dataset of the Household Budget Survey provided by Eurostat. For France, Germany and Spain, we use HBS for the year 2020, while for Poland we use the dataset for 2015. Each country follows a slightly different methodology when collecting data for the HBS,[18], but Eurostat unifies the country datasets, ensuring they are comparable across countries. The HBS include information on both the household as a whole and its members. On the household level, there is information on expenditures on various goods according to COICOP classification and on their socio-economic characteristics. For household members, we have information, among others, on age, occupation according to ISCO, sector according to NACE, labour market activity status and earnings. Table 5 contains a list of all the variables and symbols that are used in the model.

TABLE 5. Key variables and symbols used in the microsimulation model

Symbol	description
Δ_s^E	percent change in employment in sector s from CGE
Δ_s^W	percent change in wage in sector s from CGE
Δ_s^P	percent change in price of good in sector s from CGE
Δ_s^V	percent change in volume of goods purchased by household in sector s from CGE
T	per capita lump sum transfer from CGE model
SEC	sector of occupation consistent with MEMO
W	total labour income of individual
D	decile in labour income distribution of individual
$EQWH$	equivalised household size
EXP_s	total household expenditures on goods of sector s
EXP_{sEQ}	equivalised household expenditures on goods of sector s
INC	total household income
INC_{EQ}	equivalised household income
DE	direct consumption effect (energy)
IE	indirect consumption effect (other goods)
TE	lump-sum transfer effect
W'	total labour income of individual in a given scenario / simulation
EE	employment effect
S	set of sectors of CGE and microsimulation model
S^E	set of energy carrier sectors
S^{NE}	set of remaining sectors

The microsimulation procedure consists of the following steps:

- Calculation of selected statistics regarding households and household members;

[18]For example, the 2020 German HBS contains a sample of approx. 57.1 thousand households, while the figures for Poland, France and Spain stand at 37.1, 19.0, and 19.1.

- Conduct simulation of HBS dataset which consists of recalculation of employment status, wages, incomes and expenditures for a given output from the CGE model (the outputs are outlined in subsection C.4);
- Calculation of selected statistics for the simulated HBS dataset: statistics pertaining to incomes by deciles, and inequality: Gini coefficient, $D9/D1$ ratio.

In the exposition, h is used to index households, i is used to index individual household members, o is used to index occupation and s is used to index economic sectors.

Microsimulation model on the household budget survey data

At the household member level, we take the following steps:

- We define labour income W as the variable *EUR_MF099*, from the household member data table. We use this variable only for household members who are active on the labour market. This variable corresponds to income from all sources (net amount) which can be attributed to the household member, and as such it can also include non-labour income.
- We create variable SEC which maps the NACE sector (*ME04*) to the sector outlined in the CGE model codes the sector of occupation of the individual.
- We create variable OCC which maps the ISCO occupation variable (*ME908_Recoded*) to the five occupational categories in the CGE model.
- We define deciles D of sector-specific labour income distribution to which a given individual belongs. For each sector s:

  $$D = ecdf^{-1}(W_s) \tag{29}$$

  where W_s is the labour income truncated to sector s, and $ecdf^{-1}$ is the inverse of the empirical cumulative distribution function.

At the household level, we take the following steps:

- We use the variable *EUR_HH095* from the household data table as the variable for total household income. This variable is monetary net income from all sources minus income taxes.
- We map each consumption good for which expenditure data are available in the HBS (variables EUR_HH***: about 500 different goods) to particular sectors $s \in S$ present in CGE model. For each sector s we create a variable EXP_s as the sum of the household's expenditures on goods produced by this sector:

  $$EXP_s = \sum_{j \in s} R5_j \tag{30}$$

- We calculate equivalised household size, $EQWH$, using the modified OECD equivalence scale. In this scale the first adult is assigned a weight of 1, subsequent persons aged 14 or older are assigned a weight of 0.5, and children under age 14 are assigned a weight of 0.3.
- We calculate equivalised household income, INC_{EQ}, and equivalised household expenditure on sector goods EXP_{sEQ}.
- We assign each household to one of 10 bins defined as deciles of individual equivalised household income.[19]

[19] Each bin contains an equal number of individuals, but not necessarily the same number of households.

Soft-linking of macro- and micro- models

We use the following results of the CGE model as inputs in the microsimulation model. All inputs are expressed as percent deviations from the base year of 2017:

- $\Delta^{E,t}_{s,o}$ - employment in sector s and occupation o in year t
- $\Delta^{W,t}_{o}$ - wages in occupation o in year t
- $\Delta^{P,t}_{s}$ - price of sector goods / products of sector s in year t
- $\Delta^{V,t}_{s}$ - volume of household purchases of goods of sector s in year t

The variables, $\Delta^{E,t}_{s,o}$ and $\Delta^{W,t}_{o}$, are used to update the wage W of household members. The variables, $\Delta^{E,t}_{s}$ and $\Delta^{W,t}_{s}$, are used to update the expenditures EXP_s on goods.

Simulation procedure

In each simulation we calculate the change in equivalised: (i) labour income, (ii) lump-sum transfer income, and (iii) expenditures on energy and other goods, all conditional on the results obtained from the CGE model.

The labour income effect is composed of changes in the expected wage and employment probability. The employment effect results from adjusting sector-specific and occupation-specific employment status according to the labour market flows predicted by the macroeconomic model.

- For each sector s and occupation o for which the CGE model predicts a decrease in employment in comparison to the base year of 2017 ($\Delta^{E,t}_{s,o} < 0$), each individual working in this sector and occupation loses their job with the said probability. If the individual loses his or her job we set their labour market status to 'unemployed' and set the wage to zero:

$$W' = \begin{cases} 0 & \textit{if} \quad r < \Delta^{E,t}_{s,o} \\ W & \textit{if} \quad r \geq \Delta^{E,t}_{s,o} \end{cases} \tag{31}$$

- For sectors s and occupations o for which the CGE model predicts an increase in employment compared to the base year 2017 ($\Delta^{E,t}_{s,o} > 0$), we randomly select $N_{s,o}\Delta^{E,t}_{s,o}$ individuals from all household members whose labour market status is 'unemployed', where $N_{s,o}$ is the number of people employed in sector s and occupation o. These individuals become employed in sector s and occupation o. Next, we set their wage by sampling it from the empirical distribution of wages for workers currently employed in sector s and occupation o truncated to the decile of their previous position in the income distribution or the position of their household in the household income distribution.[20]

Wages of household members working in occupation o are simply adjusted according to the relative change predicted by the CGE model:

$$W' = W' * (1 + \Delta^{W,t}_{o}) \tag{32}$$

The labour effect, LE, is calculated as the sum of changes in equivalised labour income of all household members resulting from changes in wages and labour market status. We express it relatively to the base labour income:

$$LE_h = \left(\sum_{i=1}^{LOS_h} (W'_{ih} - W_{ih}) \right) / EQWH \tag{33}$$

[20] We adopt such a mechanism to avoid the situation in which low-skilled individuals, who previously held a low-paying job could randomly sample a wage from the top of the income distribution. Therefore, higher-skilled individuals are expected to take higher-skilled and better-paid jobs. However, there are many combinations of sectors and occupations, for which the decile-truncated empirical wage distribution would contain only a few elements. For such instances, we take the entire wage distribution and do not limit it to the relevant decile.

The transfer effect, TE, is calculated as the total equivalised income from the equal per-capita lump-sum transfers paid out to all household members, TE:

$$TE = LOS * T_t/EQWH, \tag{34}$$

where LOS is the total number of household members. Finally, we define the direct and indirect effects as the change in equivalised income resulting from changes in the prices of goods and changes in households' consumption patterns. We define the direct effect as the one resulting from energy carrier goods, and the indirect effect as the one resulting from all other goods:

- Direct effect. The set of energy carriers is as follows: $S^E = \{$*electricity, gas, heating oil, coal, heat, petrol and diesel fuel*$\}$. We calculate the direct price effect across energy goods, DE, using the formula:

$$DE = \sum_{s \in S^E} EXP_s * (\Delta_s^{P,t} + \Delta_s^{V,t} + \Delta_s^{P,t}\Delta_s^{V,t})/EQWH \tag{35}$$

- Indirect effect: The set of consumption goods is as follows: $S^{NE} = S \backslash S^E$. We calculate the indirect price effect across consumption goods, IE, using the formula:

$$IE = \left(\sum_{s \in S^{NE}} EXP_s * (\Delta_s^{P,t} + \Delta_s^{V,t} + \Delta_s^{P,t}\Delta_s^{V,t}) \right) /EQWH \tag{36}$$

All effects - labour, transfer, direct and indirect consumption effects - are then averaged for each income decile, and reweighted using household weights provided in the HBS data. Due to the stochastic nature of the simulation of labour market flows, we repeat each simulation 100 times and report average results.

C.4. Policy scenarios

For each country, we simulate two scenarios which are labelled *esr* and *ets*2. In the first one we assume that the new emission trading system for the buildings and road transport sector is not introduced and that all countries reduce their emissions according to the Effort Sharing Regulation. In the second scenario, we assume the introduction of the ETS2 system. For each scenario, we conduct a simulation for all years for which we have output from the CGE model starting with the year of introduction of the ETS2 system, that is for the years $T = \{2027, 2030, 2035, 2040, 2045, 2050\}$. Next, we compare the results of the two, to isolate the impact of the introduction of the ETS2 system. For brevity, we focus on the results for 2030 and 2040.

We assume that in each country the revenues from carbon taxation, as given by the CGE model, are distributed as lump-sum transfers. Table 6 shows the resulting values of lump-sum transfers in each country, conditional on the climate policy scenario. As a share of GDP, the carbon revenue and the resulting total transfer expenditure are the highest in Poland, exceeding 1% of GDP in 2030 and reaching 2% of GDP in 2040. In other countries studied, the carbon revenue and the resulting transfer expenditure do not exceed 1% of GDP. France is the country with the lowest carbon revenue, and the only one where revenues are lower in the ETS1 + ETS2 scenario than in the ETS1 + ESR scenario. As a consequence of high total carbon revenue, the annual transfer value per person in Poland expressed in Euro is comparable to those in Western European countries, even exceeding them by 2040 in the ETS1 + ETS2 scenario. Accounting for cross-country differences in income levels, the lump-sum transfer relative to GDP per capita is 2-3 times larger in Poland than in Germany and Spain, while in France is about half that in Germany and Spain.

For brevity, from now on we will refer to the ETS1 + ESR scenario as ESR, and to the ETS1 + ETS2 scenario as ETS2.

Table 6. Lump-sum transfer of carbon revenue across countries under ETS1 + ESR and ETS1 + ETS2 (2030 and 2040)

Country	**ETS1 + ESR**		**ETS1 + ETS2**	
	2030	**2040**	**2030**	**2040**
Total spending as a GDP share (in %)				
Germany	0.42	0.66	0.31	0.58
France	0.33	0.61	0.17	0.37
Poland	1.05	1.82	1.23	2.38
Spain	0.26	0.51	0.37	0.70
Annual transfer per person (in EUR)				
Germany	574	855	427	765
France	434	782	219	474
Poland	462	718	539	929
Spain	229	430	324	585

Source: own elaboration based on the CGE model results.

C.5. Distributional effects of climate policy in Germany, France, Poland, and Spain

Total impacts on household income

The overall effects of ESR and ETS-2 differ substantially between the four countries studied and across income groups within them (Figure 9). In terms of household incomes, Poland benefits the most, while France is the most negatively affected. In Poland, disposable incomes in the bottom deciles (D1-D3) would increase by 20–30% by 2030, compared to 5–10% increase in the top deciles (D8-D10). By 2040, these progressive impacts would intensify, with incomes in the bottom three deciles of the income distribution rising by 35–50%, compared to 5–15% in the top three deciles. In contrast, France would experience regressive income changes. By 2030, disposable incomes in the first decile would decline by almost 10% under the ESR and by more than 20% under the ETS-2. At the same time, households in the top decile would see losses of about 5% and 10%, respectively. By 2040, regressive effects persist under ETS-2, with the first decile reduction of 25% in disposable income and the tenth decile decreasing incomes by 15%.

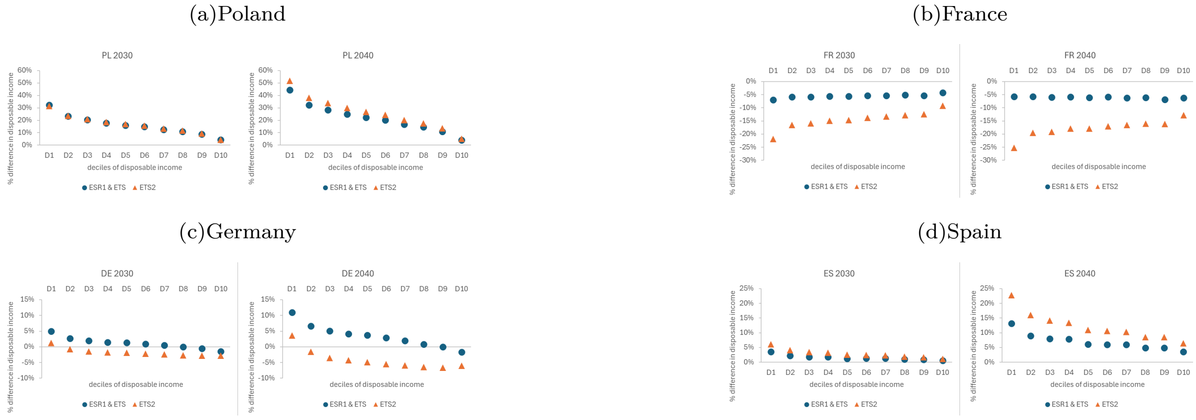
In Germany and Spain, the total impacts on household incomes are progressive under both scenarios, although with varying magnitudes. In Germany, ESR leads to gains of 1–5% below the median of the income distribution by 2030, while ETS-2 results in smaller gains (1%) for the first decile and losses (up to less than 5%) for higher deciles. In Spain, disposable incomes would increase by 5% in the first decile and 1% in the tenth decile by 2030, growing to 20% and 5% by 2040.

Labour market channel

Next, we assess the relative role of particular channels behind the climate policies' impact on household incomes, starting with labour income (Figures 10-11). The contribution of labour income varies between countries, but tends to be progressive as higher-income households exhibit higher shares of workers, especially those employed in sectors that pay above-median wages and are negatively affected by carbon taxation.

In Poland, the labour income contribution is negative, with higher-income groups (top three deciles) losing up to 5% of disposable income in 2030 and over 10% in 2040. In France, the effects are weaker but grow over time, causing additional income losses of 2% under ESR and 1% under ETS-2 by 2040. In Germany, the labour income losses are moderate in both scenarios, around 1-2% across the income distribution. By 2040, these losses intensify at the top of the income distribution, reaching 6% in the top decile. In Spain, the contribution of the labour market channel is less pronounced, but it assists the overall progressive effect of the policy.

Figure 9. Comparing ESR and ETS-2 impact on household incomes across the income distribution



Source: Own simulations based on the CGE model and the microsimulation model.

Such labour market impacts, particularly the progressive effects in Poland and Germany, resonate with the findings of Vona (2023), who emphasized that labour market adjustments play a critical role in shaping the distributional outcomes of carbon pricing. In coal-dependent regions, job losses in high-income groups due to transitioning away from fossil fuels were also documented by Pollin (2023).

Direct and indirect consumption channels

The direct and indirect consumption effects play a central role in shaping the distributional outcomes of ESR and ETS-2. In France, indirect effects dominate and they are regressive - lower-income households lose visibly more than higher-income households - particularly under ETS-2. Among the poorest households (the first decile), these effects reduce disposable income by 15% under ESR to 25% under ETS-2 by 2030. However, the increased expenditures on non-energy goods and services highlight a rise in consumption volume and prices. In Germany, the direct effects, i.e. spending on energy, are crucial, with ESR providing progressive gains across the income distribution. However, ETS-2 produces sharper losses for higher-income groups due to steeper energy price increases. The direct and indirect effects that we find, such as the regressive outcomes under ETS-2 in France, are consistent with findings by (Shang, 2023), who identified that indirect effects from carbon pricing could amplify inequalities, particularly in countries with high energy costs.

Lump sum effect

As introduced in Chapter B, lump-sum revenue recycling tends to act as a progressive mechanism because every household receives the same monetary payment, which is relatively larger for lower-income groups. In consequence, spending revenues from carbon taxation as lump-sum transfers is vital for the overall income effect of ESR and ETS-2 and their distributional consequences.

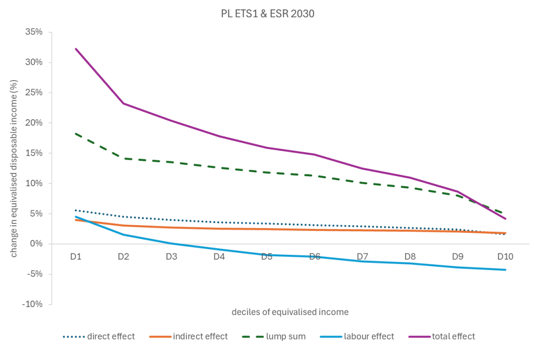
In Poland, lump-sum transfers are the main driver of income gains, increasing incomes by 20% in the bottom deciles and by 5% in the top deciles in 2030. By 2040, the value of these transfers would increase noticeably (Table 6), benefitting lower income households to an even larger extent. In Spain, lump-sum transfers drive the progressive impacts, with disposable incomes increasing steadily across all deciles. By 2030, the lowest decile would see an increase of 5% in disposable income, while the highest decile would gain 1%. By 2040, these impacts intensify, reaching 20% in the first decile and 5% in the tenth decile. In these two countries, the transfer expenditure is the largest as the share of GDP and it also grows over time (Table 6).

In Germany and France, lump-sum transfers cushion disposable income losses to a smaller extent than in Poland and Spain. Except for the ESR scenario in Germany, recycling carbon revenues as lump-sum transfers does not suffice to prevent net disposable income losses in Germany and France.

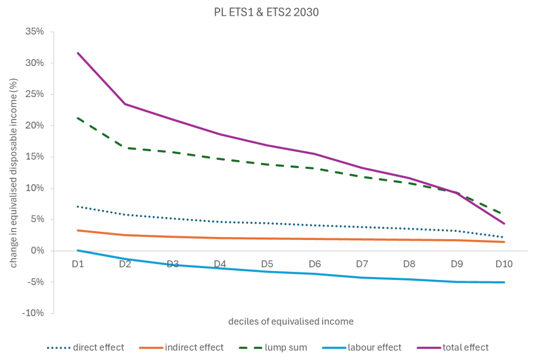
Our results indicating progressive income gains from lump-sum transfers align with the findings of Rausch, Metcalf and Reilly (2011), who used a static general equilibrium model to show that lump-sum recycling reduces regressivity in carbon tax policies. Similarly, Eisenmann et al. (2020) found that recycling carbon tax revenues through lump-sum transfers benefits low-income households the most. Specifically in Poland, a coal-reliant country, Antosiewicz et al. (2022) showed that a lump sum transfer of carbon tax revenues increases disposable incomes in the lowest deciles and compresses inequality. For Spain, Tomás et al. (2023) also highlighted the effectiveness of revenue recycling in reducing inequality through targeted transfers.

Figure 10. The effects of the lump-sum transfer scenario of the ETS and ESR (left panel) and ETS-2 (right panel) introduction on income by decile income groups in Poland and France, in relative terms in 2030 and 2040

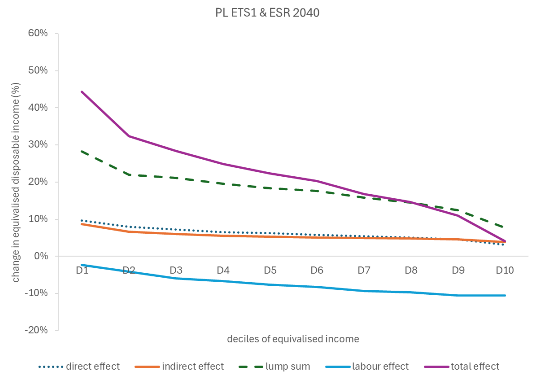
(a)Poland 2030



(b)Poland ETS-2 2030

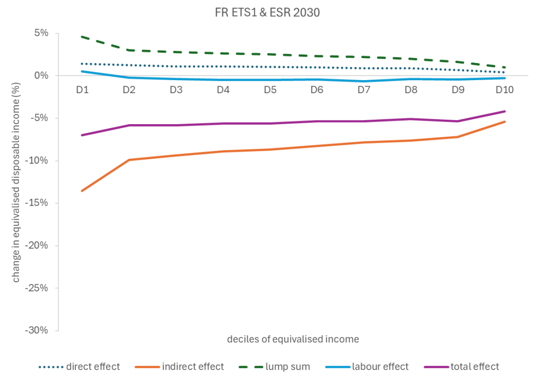


(c)Poland 2040

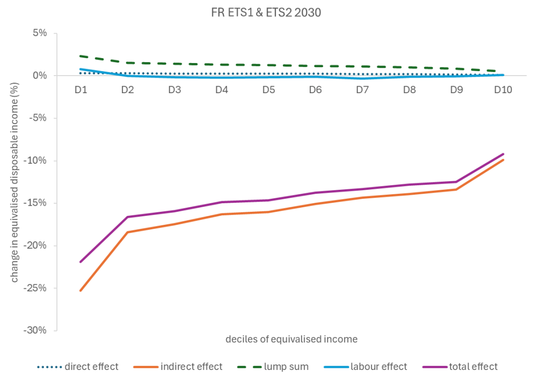


(d)Poland ETS-2 2040

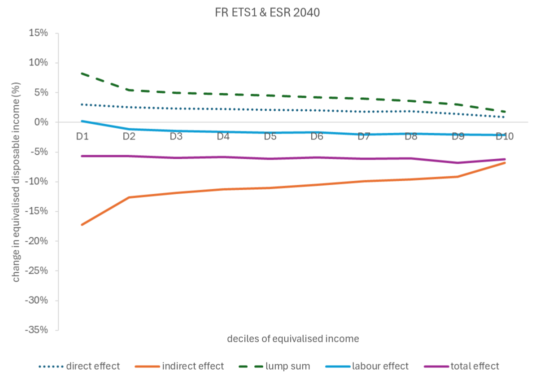
(e)France 2030



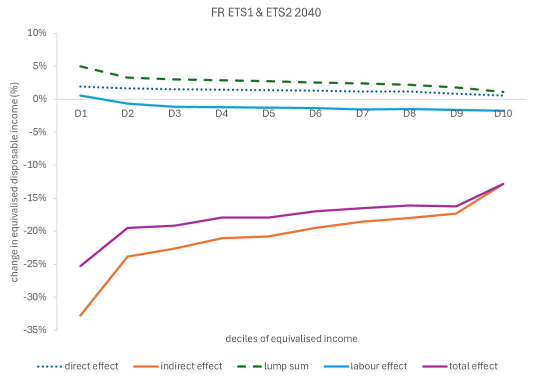
(f)France ETS-2 2030



(g)France 2040



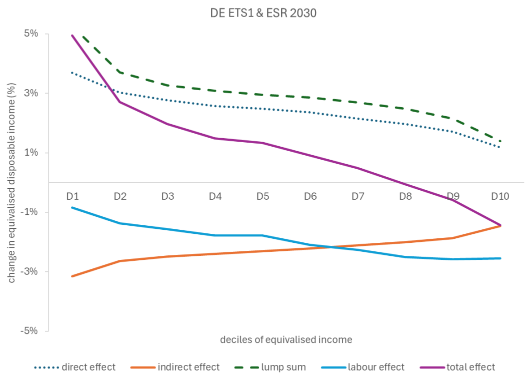
(h)France ETS-2 2040



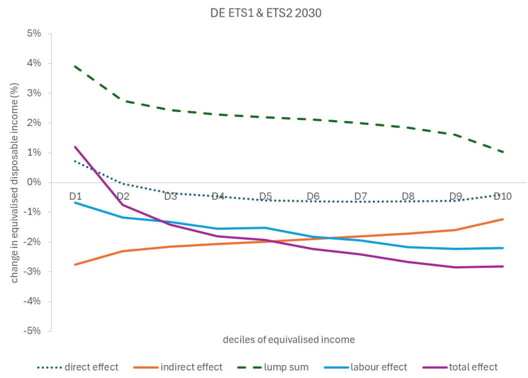
Source: Own simulations based on the CGE model and the microsimulation model.

Figure 11. The effects of the lump-sum transfer scenario of the ETS and ESR (left panel) and ETS-2 (right panel) introduction on income by decile income groups in Germany and Spain in relative terms in 2030 and 2040

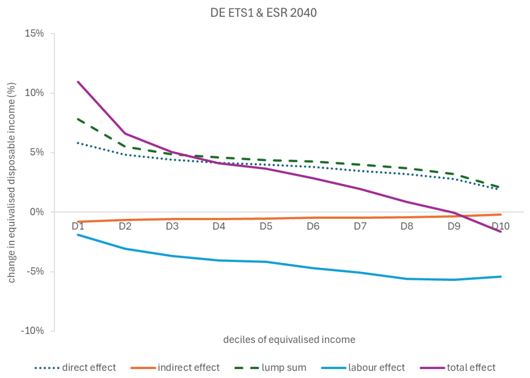
(a)Germany 2030



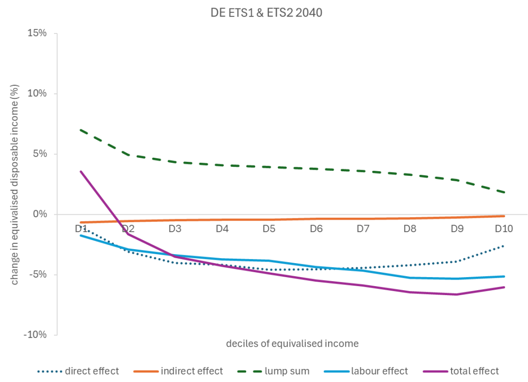
(b)Germany ETS-2 2030



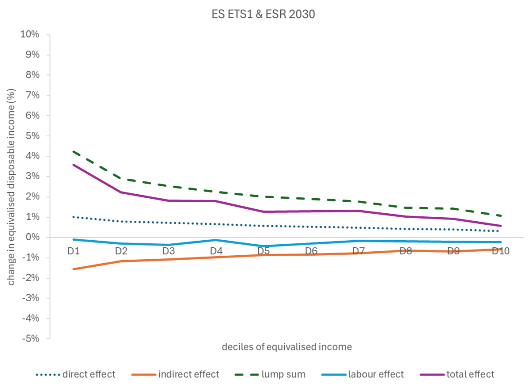
(c)Germany 2040



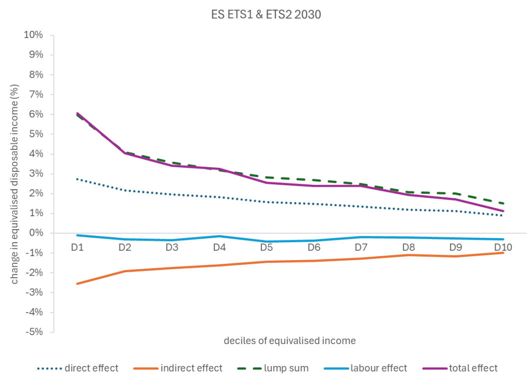
(d)Germany ETS-2 2040



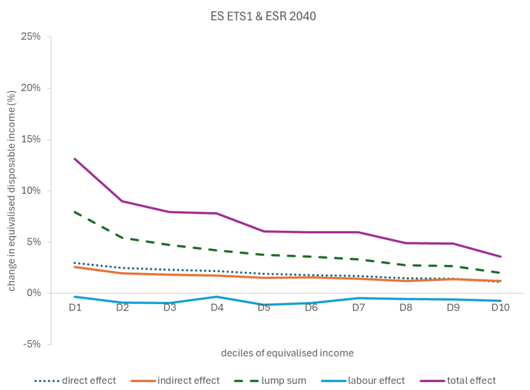
(e)Spain 2030



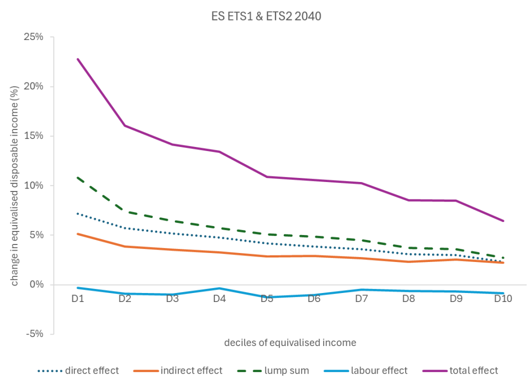
(f)Spain ETS-2 2030



(g)Spain 2040



(h)Spain ETS-2 2040



Source: Own simulations based on the CGE model and the microsimulation model.

Household income inequality

We find that both ESR and ETS-2 scenarios reduce income inequality in all countries except France, but the size of these effects differs noticeably between countries. The largest decreases in the Gini coefficient, by about 15%, are observed in Poland (Figure **??**). Such an equalising effect results mostly from (i) gains from lump-sum transfers being larger for lower-income households, and (ii) losses in labour income being stronger for higher-income households. The absolute declines in the Gini coefficient are also sizeable. For instance, Gini drops by more than 5 points in Poland, a large shift relative to its historical changes. This reflects that lump-sum transfers from ETS-2 revenues would account for about 2.5

In Spain, the reduction in inequality is smaller, at about 5% of the Gini coefficient. In Germany, the reduction in inequality is more modest, at around 1% of the Gini coefficient. This is primarily due to a substantial rise in consumption expenditures on goods other than energy among lower-income deciles, which drives overall expenditure growth. However, the inequality-reducing effect of this increase is offset by a decline in labour market income among the top deciles, mitigating the overall impact on income distribution. The observed reductions in Gini coefficients, particularly the substantial declines in Poland and Spain, corroborate the results of Fremstad and Paul (2019), who found that redistributive mechanisms in carbon pricing can substantially compress income inequality.

In contrast, France shows an increase in the Gini coefficient under the ETS-2 scenario, indicating a slight rise in income inequality. This widening inequality stems mainly from consumption expenditures growing the most in the bottom deciles of the income distribution. The redistributive mechanism in ETS-2, namely the lump-sum transfer of carbon revenues, also benefits the bottom deciles the most, but the value of transfers is insufficient to offset the regressive effects of carbon pricing in France.

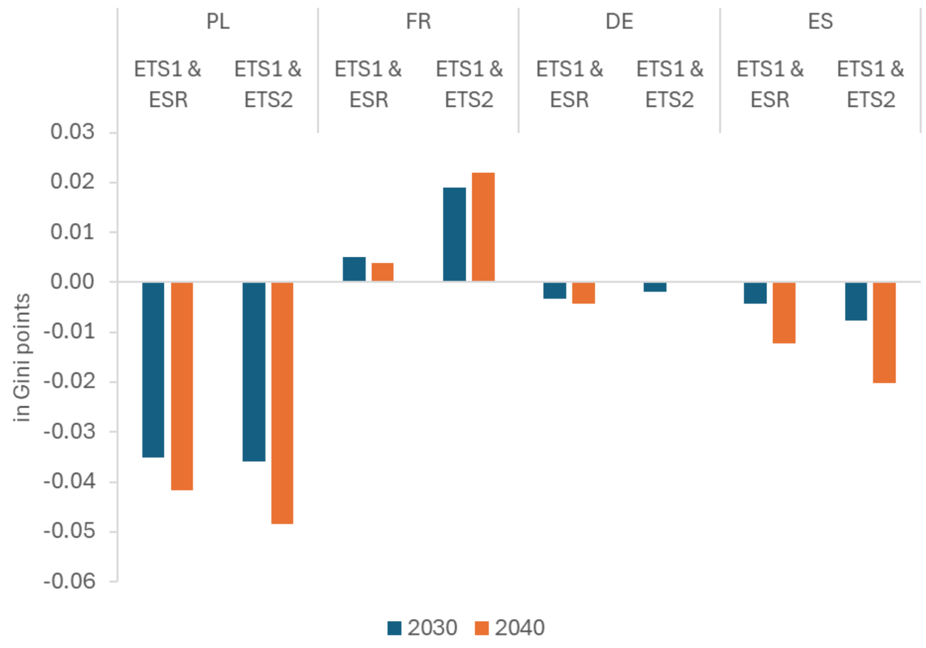
C.6. Summary and conclusions

In this chapter, we have studied the economic and social implications of the European Union's carbon pricing mechanisms, specifically focusing on the Emissions Trading System (ETS-2) and the Effort Sharing Regulation (ESR). By examining the impacts across four countries—France, Germany, Poland, and Spain—we have highlighted significant variations in outcomes based on income distribution, labour market effects, and the application of lump-sum transfers. We have studied the changes in household disposable income; they may differ in magnitude from similar policy scenarios described in other chapters using alternative indicators such as utility units.

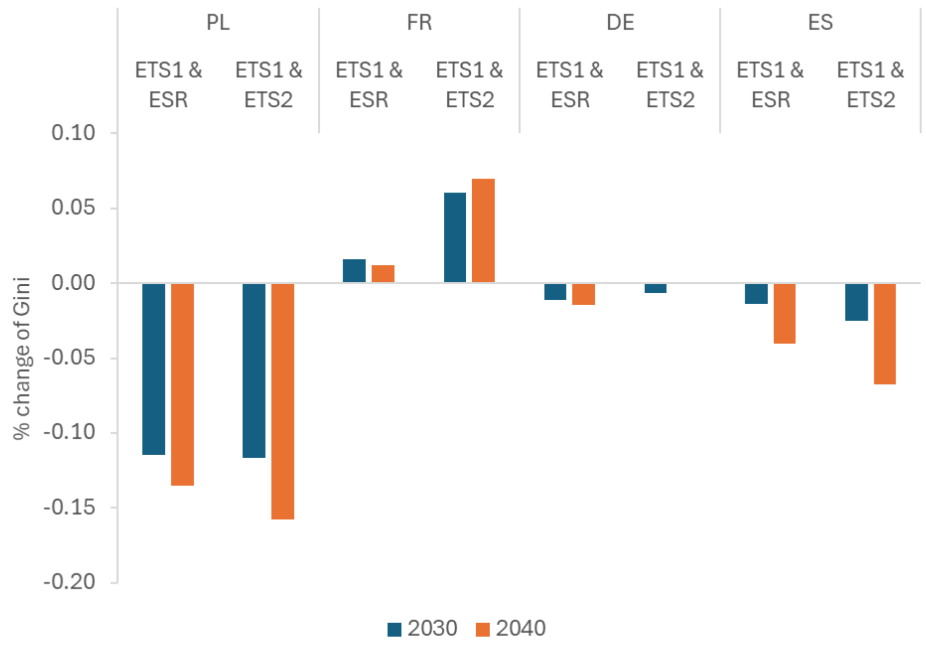
Our findings reveal that Poland benefits most from these policies, with lump-sum transfers driving significant income gains for lower-income households, reducing inequality substantially. Spain also exhibits progressive outcomes, with lump-sum transfers increasing disposable incomes across all deciles, particularly benefiting the lower-income groups by 2040.

Conversely, France experiences the most pronounced regressive effects, primarily due to increased expenditures on goods and services, including transportation, disproportionately impacting lower-income households under ETS-2. Germany demonstrates progressive income gains under ESR, while ETS-2 results in moderate losses for higher-income groups, reflecting the varied influence of direct and labour market effects.

Except for France, the introduction of ESR and ETS-2 reduces overall inequality, as measured by changes in the Gini coefficient. Poland and Spain experience the most substantial reductions, while the impact in Germany is less pronounced. In France, inequality widens as the cost of consumption increases the most (in relative terms) for lower-income households, while lump-sum transfers are too low to offset it because France's revenue from carbon taxation is lower than that of other countries. These findings underscore the importance of tailoring carbon pricing policies to national contexts, ensuring that compensatory mechanisms such as lump-sum transfers are designed to support vulnerable populations effectively. Policymakers should consider the distributional impacts and balance short-term social equity concerns with long-term climate objectives to foster a just and sustainable low-carbon transition.



(a)Absolute change



(b)Relative change

FIGURE 12. Changes in the Gini coefficient of equivalised household incomes compared to the base year

Source: Own simulations based on the CGE model and the microsimulation model.

D. The effect of climate policies on the spatial allocation of workers and production in Europe (LISER/Michał Burzyński, Joël Machado)

D.1. Introduction

Environmental policies like emissions trading systems affect companies and workers in heterogeneous ways. By increasing firms' marginal cost of production, higher environmental taxation might not only cause a relocation of firms' activity but also lead workers to change i) occupations, ii) sectors, and iii) geographical regions. These adjustment mechanisms are particularly facilitated in areas of free mobility such as the European Union. Environmental policies thereby affect the spatial distribution of economic activity and income with heterogeneous effects across sectors, regions, and countries.

In this chapter, we build a structural general equilibrium model that focuses on workers' sorting across occupations, sectors and geographical regions as adjustment mechanisms to environmental policies. A burgeoning literature uses spatial dynamic general equilibrium models incorporating trade, migration or technological innovation as adaption channels to climate change (Desmet and Rossi-Hansberg, 2024). Complementing this approach, we focus on the effects of environmental policies on labor market sorting across occupations and sectors within a static framework. This allows us to quantify how labor market dynamics can serve as an additional channel through which environmental policies can affect a given population within a relatively short period of time.

We build a model that accounts for multidimensional distributions of worker skills that lead to endogenous sorting across heterogeneous occupations and sectors. In addition, workers are differentiated along two education groups (tertiary-educated or less) and three origins (natives, EU-immigrants, and non-EU immigrants). The model further accounts for alternative adjustment channels highlighted in the existing literature, including inactivity, migration across European regions, firm creation, and trade. We use it to simulate counterfactual environmental policies and analyze their effects on the location of workers and sector-level production, immigration across regions and sorting across occupations and sectors at a regional level within Europe. We simulate a tenfold increase in CO2 certificate prices relative to 2018, accounting for exogenous region-sector-specific TFP adjustments to the policy shock. Despite a homogeneous CO2 certificate price, shocks are therefore sector-region specific.

We find that the manufacturing, construction, and transport sectors face overall the largest increase in environmental taxation, whereas service sectors are much less affected. As a result, GDP decreases up to 14%, with the strongest losses registered in Greece and Eastern European countries. In contrast, GDP is least negatively affected in most German regions, Luxembourg, and Switzerland. Beyond changing sectors, workers switch occupations, moving from less-educated elementary tasks to service and professional tasks. Simultaneously, higher CO2 prices increase the marginal cost of production and thereby prices.

In our baseline, environmental taxes represent a pure loss of part of the firms' production. In a second step, we use our model to simulate two different types of redistributive policies. Environmental taxes are either redistributed uniformly across all European regions or uniformly across regions within a country. We show that redistribution mitigates losses in almost all regions, except for some highly productive capitals. Uniform redistribution in the EU benefits mainly the least productive areas in Eastern and Southern Europe, whereas most regions in the productive countries are net contributors. In contrast, redistributing taxes collected in a country to its own national regions implies that the least productive areas in highly productive countries receive more transfers. Less productive regions in the lower productivity countries receive less transfers and inequality across European regions is less mitigated. Finally, we show that occupational sorting acts as an adaptation channel when migrating across regions is costly.

We contribute to three main strands of the literature. The first strand aims to quantify the consequences of climate change in general, including temperature increases, heatwaves and droughts, hurricanes and related climate policies (Deschênes and Greenstone, 2011; Deryugina, Kawano and Levitt, 2018; Bilal and Rossi-Hansberg, 2023; Hsiang and Jina, 2015; Roth Tran and

Wilson, 2024). A rapidly growing part of this literature relies on spatial general equilibrium models to assess the effects of climate change and climate policies (see e.g., Bilal and Rossi-Hansberg, 2023; Cruz and Rossi-Hansberg, 2022, 2024; Desmet et al., 2021; Balboni, 2024; Burzyński et al., 2022; Bilal and Känzig, 2024 and Desmet and Rossi-Hansberg, 2024 for an excellent review). Within this literature, only a few papers address sector heterogeneity and worker reallocation caused by climate change. In models of the world economy Conte et al. (2021); Conte, Desmet and Rossi-Hansberg (2022); Desmet and Rossi-Hansberg (2015) divide firms into an agricultural and non-agricultural sector. Cruz (2024) details the world economy into 287 subregions and 6 sectors to study the region-sector allocation of labor caused by climate change. In a US context, Rudik et al. (2022) provides an analysis at the state level for 20 industries within 3 sectors, while Colantone, Ottaviano and Schmitz (2024) accounts for 130 commuting zones and 21 industries.

Building on Burzynski (2024), we include worker sorting as an adaptation channel to environmental policies in a static general equilibrium model that accounts for 8 sectors and 100 European regions. Our model defines workers along three characteristics: origin (native, EU immigrant, non-EU immigrant), education (tertiary educated, less educated) and five different skills (four occupation skills and a preference for inactivity). This rich heterogeneity in worker characteristics allows us to study sorting across occupations, sectors and regions on European labor markets. We thereby connect the literature on the spatial geography of climate change with the literature on worker self-selection across markets (Roy, 1951; Burstein, Morales and Vogel, 2019; Burstein et al., 2020; Costinot and Vogel, 2015).

A second strand of literature has focused on quantifying the optimal global carbon taxation to reduce emissions, abstracting from the economic geography and labour market dynamics (Nordhaus, 2010; Golosov et al., 2014; Acemoglu et al., 2016; Barrage, 2020; Hassler and Krusell, 2012; Kotlikoff et al., 2024). Rather than defining optimal policies to meet specific emission targets, our objective is to quantify the impact of increasing environmental taxation, in line with existing empirical research (Metcalf and Stock, 2023; Känzig, 2023; Känzig and Konradt, 2023). Closer to our quantitative theoretical approach, only a few spatial integrated assessment models (SIAMs) address the general equilibrium effects of energy taxation and CO2 reduction. In a US context, Colantone, Ottaviano and Schmitz (2024) apply a spatial general equilibrium model to analyze the effects of the US Clean Air Act across industries and local labor markets by comparing those that were either already meeting the targets (attainment zones) with those forced to reduce emissions (non-attainment zones). They stress the importance of accounting for general equilibrium effects and find that the 10.5% decrease in polluting employment in non-attainment commuting zones was partially compensated by a 4.1% increase in employment in attainment commuting zones. Cruz and Rossi-Hansberg (2024) study the effect of CO2 taxation and abatement mechanisms in a global setting that features population growth, costly migration and trade, and technology investments, but abstracts from sectoral and worker heterogeneity. They highlight the strong regional heterogeneity in welfare costs of global warming.

Closest to our paper, Conte, Desmet and Rossi-Hansberg (2022) use a multisector dynamic spatial integrated assessment model with endogenous trade and migration. Similarly to our setting, the production sectors are differently affected by carbon taxation in their model. In contrast to us, they allow for externalities of global warming. They simulate the introduction of a carbon tax in the EU and find that if the generated revenues are rebated locally, the size of Europe's economy can increase because economic activity agglomerates in its high-productivity non-agricultural core and immigration to the EU increases. In our paper, we simulate the effects induced by environmental taxation on the short-term structural composition of European labor markets. While our framework is static, we add worker sorting across occupations, sectors and regions as an additional adjustment channel.

Finally, our paper contributes to the literature that focuses on the potential redistributional effects of environmental policies in different types of households. From the consumers' perspective, carbon taxes tend to be regressive because poorer households consume a higher fraction of their income on energy-intensive goods (e.g., Goulder et al., 2019). From an income perspective, the redistributive effects of a carbon tax depend on its effect on relative prices of the factors of production, the sectoral distribution of workers and the way in which revenues are rebated (Rausch, Metcalf and Reilly, 2011; Känzig, 2023). Our model features spatial and worker heterogeneity and therefore allows to simulate the redistributive effects of different tax schemes.

The remainder of this paper is organized as follows. In Section D.2, we introduce our model. In Section D.3, we detail our calibration strategy and define our counterfactual scenarios. In Section D.4, we first simulate a scenario with increased environmental taxation, then we introduce two different redistribution mechanisms. We quantify the importance of the migration and occupational sorting channels as adaptation mechanisms in Section D.5. In Section D.6, we provide a conclusion.

D.2. Theoretical Framework

We build a model with endogenous worker sorting across occupations and sectors, migration of workers, firm creation and trade. We extend the model developed in Burzynski (2024) along two main dimensions. First, we introduce environmental taxation on the production of goods and services that heterogeneously affects the marginal cost of production across country-sectors. This tax structure leads to heterogeneous changes in taxation across regions due to the region-specific sectoral composition of economic activity. Second, we allow for redistribution of the taxes collected and use the model to assess the distributional effects of three different redistribution schedules: no redistribution, a uniform redistribution across EU countries, or a country-specific redistribution.

Our model covers 100 European NUTS1 regions, 8 production sectors, 4 occupations, 2 skills of workers who are regrouped into 3 distinct origins (native, EU-migrants, and non-EU). Furthermore, within each region-occupation cell, natives are characterized by continuous distributions of wages. This level of detail allows us to generate insights about distributive effects across workers, sectors, and geographical regions. Below, we first describe the different building blocks of the model. We detail the extensions and refer the reader to Burzynski (2024) for a technical exposition of the general model.

Producer perspective

Each firm employs capital and labor to produce a differentiated firm-specific good. The technology used in production varies across sectors and regions, which implies differences in the intensity of factor usage, relative factor productivities, and factor prices. The latter are affected by the exogenous supply of capital and the endogenous supply of workers' skill levels. Physical capital is composed of two distinct categories. Structures (including dwellings, vehicles, and other non-ICT assets) are assumed to be imperfect substitutes to labor tasks whereas automation capital (including ICT assets, such as hardware and software) is assumed to be substitutable to labor tasks.

The production function is modeled as a constant elasticity of substitution (CES) function of two aggregated inputs: structures and tasks. Tasks combine labor composite and automation capital in a linear way. Assuming imperfect substitution between structures and tasks, the is-specific production is modeled as a constant elasticity of substitution (CES) function:

$$\bar{Q}_{is} = \bar{\beta}_{is}\left(\theta_{is}S_{is}^{\frac{\sigma_s-1}{\sigma_s}} + (1-\theta_{is})T_{is}^{\frac{\sigma_s-1}{\sigma_s}}\right)^{\frac{\sigma_s}{\sigma_s-1}}, \quad (37)$$

with θ_{is} representing the relative productivity of structures versus tasks, σ_s is the elasticity of substitution between both factors, and S_{is} (T_{is} respectively) stand for the supply of structures (task inputs respectively). $\bar{\beta}_{is}$ represents the productivity residual. Multiplying the quantities of goods produced by the marginal cost of production gives the nominal GDP in sector s and region i: $Y_{is} = c_{is}\bar{Q}_{is}$. Total GDP produced in all sectors S of the regional economy $i \in J$ is denoted as $Y_i = \sum_{s\in S} Y_{is}$.

Each sector's production process requires a specific set of occupational tasks which are executed by workers endowed with occupation-specific skills. Workers are heterogeneous across occupations and within the same occupation. This dual-tier heterogeneity allows us to aggregate all workers into a multidimensional continuous distribution, summarizing the skill supply within a regional labor market.

Based on the available skill supply, firms hire workers to perform occupation-specific tasks, leading to equilibrium wage rates for each type of occupational skill. The structure of occupation-specific tasks within the sectoral labor composite is assumed to be predetermined. Furthermore, we assume that the aggregated input of tasks follows a Cobb-Douglas function, stressing a complementarity among all occupational inputs: $T_{is} = \prod_o L_{ios}^{\gamma_{ios}}$. Hence, all necessary tasks must be completed to produce a unit of value added.

Workers can either be low-educated (LE) or highly-educated (HE). Although all workers can perform all tasks, workers in the two skill groups differ in their levels of occupation-specific skills. This generates distinct comparative advantages across the various tasks. As a result, low-skill and high-skill workers are not perfect substitutes within the production function. They occupy different ends of the skill spectrum and are assigned to different tiers of occupation-specific tasks. Similarly, native and immigrant workers at both levels of education are treated as imperfect substitutes because of their different characteristics and qualifications. This differentiation implies that within the task-based production framework, the skills supplied and wage rates differ between these groups. Within the same occupation and region, there are no barriers to mobility between sectors. Therefore, by construction, workers in a given occupation in a given region, with the same level of education and the same origin, have the same occupation-specific wages in all sectors, given that they have the same level of occupational skill.

A key novelty of our model is the inclusion of exogenously defined environmental policies, and in particular changes in CO2 emission prices. In our benchmark model, we assume that emission abatement translate into an increase of the marginal cost of production which is equivalent to a reduction of firm-level productivity (in line with Colantone, Ottaviano and Schmitz, 2024).

Cost-minimizing firms take market prices of structures and tasks as given, which implies an is-specific production cost equal to:

$$c_{is} = \bar{\beta}_{is}^{-1} \left(\theta_{is}^{\sigma_s} R_n^{1-\sigma_s} + (1-\theta_{is})^{\sigma_s} W_{is}^{1-\sigma_s} \right)^{\frac{1}{1-\sigma_s}} , \tag{38}$$

with R_n (W_{is}) representing the price of one unit of structures (tasks). Assuming that each firm has to forfeit a share λ_{is} of its production to meet emission targets, we can rewrite the productivity term as:[21]

$$\bar{\beta}_{is} = \beta_{is}(1-\lambda_{is}). \tag{39}$$

The interest rate R_n is country-specific and identical across all regions i in country n. In each is-specific cell, production (GDP) equalizes factor remunerations: $Y_{is} = W_{is}T_{is} + R_i S_{is}$.

In the baseline scenario, carbon costs are sunk, such that: $\sum_{i,s} \lambda_{i,s} Y_{i,s}$ is a sheer loss of production in the economy. In other scenarios, this amount constitutes a lump sum transfer to all workers, so that their total income equals: $w_{io}^*(x) = w_{io}(x) + t_{is}$, where i, o, and s indicate region, occupation and sector allocation of a worker with skill level x. Of course, in all cases: $\sum_{is} \lambda_{is} Y_{is} = \sum_{ios} t_{is} L_{ios}$, where L_{ios} indicates the number of workers in a specific labor market cell, aggregating them across education levels and origins.

Labor Markets - Firms operating in a given sector and region demand occupation-specific skills supplied by workers who are characterized by a dual heterogeneity (education and origin). We assume that natives in each regional labor market are characterized by a continuous distribution of multidimensional skills. Each individual has a unique bundle of four market skills for occupation-specific jobs and a non-market skill representing their preference for inactivity.

[21] Note that our focus lies on the impact of environmental policies on the spatial allocation of production, workers and their welfare. We do not explicitly model emissions or externalities linked to emissions.

This discrete set of occupational skills constitutes the first tier of labor heterogeneity. The second tier is characterized by worker heterogeneity in their skill endowments. We assume that the logarithms of these endowments follow a five-dimensional normal distribution within each region-specific worker population.

Each individual aims to maximize their returns from supplying occupation-specific skills given their skill endowments and the market prices for these skills across all occupations. A key feature of the model is that each individual selects a single occupation, which leads to occupational sorting based on each worker's comparative advantage in a specific occupational task. Their choice is determined by demand factors (market returns to different skills) and supply factors (individual endowments of discrete skills). Hence, individuals that sort into a given occupation are not randomly selected from the general population. This self-selection bias affects all moments of the observed post-sorting wage distributions.

The log wage distributions across occupations after sorting can be represented as a normal distribution conditioned on other correlated normal distributions (see Burzynski (2024) for further details). This set of conditions defines a Unified Skew-Normal distribution (SUN), as developed and analyzed by Azzalini (2005) and Arellano-Valle and Azzalini (2006). The SUN distribution fully characterizes the wage distributions across occupations and regions after sorting.

Consumers' Perspective - Each individual allocates their income to purchase goods differentiated by sector, region and firm-level heterogeneity within sectors. In order to increase tractability, we divide the consumption problem into outer and inner decisions.

First, individuals determine their sectoral spending by maximizing utility from aggregated consumption under a budget constraint that equates consumption expenditures and income. They choose optimal expenditure shares based on their preferences for sector-specific items and goods' market prices. We summarize the outer utility as a CES function:

$$\max_{Q_{is}} Q_i = \left(\sum_{s\in S} \alpha_{is} Q_{is}^{\frac{\varepsilon-1}{\varepsilon}}\right)^{\frac{\varepsilon}{\varepsilon-1}} \qquad \text{s.t.} \quad \sum_{s\in S} P_{is} Q_{is} = X_i. \tag{40}$$

We assume that individuals in a given region i have identical preferences for all types of goods (α_{is}) and share a common elasticity of substitution between sector-specific goods (ε). Given that the consumption problem is homothetic, it can be easily aggregated across all residents of region i, yielding total demand Q_i, total sectoral demands Q_{is} and total incomes, X_i, that equal demand.

The solution of the maximization program yields sector-specific demands, with an overall price index P_i that is a function of sectoral prices P_{is} and preference parameters:

$$Q_{is} = Q_i \left(\alpha_{is} P_i / P_{is}\right)^{\varepsilon}, \quad P_i = \left(\sum_{s} \alpha_{is}^{\varepsilon} P_{is}^{1-\varepsilon}\right)^{\frac{1}{1-\varepsilon}}. \tag{41}$$

The solution to the utility maximization problem yields sector-specific demands and determines sectoral price levels.

After solving the outer utility maximization problem, consumers decide on the consumption structure across goods within each sector, which are differentiated by their region of origin and the firms that produce them. Therefore, the inner utility maximization problem boils down to selecting the consumption structure within each region-sector pair, given sectoral prices and demands determined in the outer utility maximization step. Sectoral goods from different origins are imperfect substitutes and characterized by a constant elasticity of substitution that exceeds the one from the outer utility. Moreover, consumers incur iceberg trade costs that vary by sector and origin country when they import sector-specific goods from other regions.

Combining the solutions to the inner and outer utility maximization problems generates the equilibrium in the goods market, where the total supply of goods produced in a sector within a region equals the demand for those goods.

Firms - Similar to Melitz (2003), firms in a given region are subject to a uniform, sector-specific fixed cost of production. However, they are characterized by an individual productivity level which is determined through a variable production cost. Leveraging their local monopoly power, firms internalize demand for their products and optimize prices, which are set as a mark-up over marginal production costs. These costs depend on the costs of the three production factors (labor and the two types of capital), the firm-specific productivity, and the elasticity of substitution across goods within a region-sector. We further assume that environmental taxes translate into an increase of firms' marginal cost.

Potential entrepreneurs have to pay a fixed cost in order to draw their productivity level from a given distribution. They decide to produce on the market if their productivity draw is high enough for them to generate an operational profit (which defines the free entry condition). However, expected net profits also account for the sunk cost and no firm chooses to enter the market if their expected net profit is negative (which defines the zero expected profit condition).

The free entry condition, which dictates the threshold productivity level distinguishing firms that remain from those that exit the market, and the zero expected profit condition, which determines the mass of firms in a specific region-sector cell, jointly define the equilibrium market size of firms.

Assuming Pareto distributions for firm productivity, with a determined minimal productivity level within specific sector-region cells, we model the distribution of firm characteristics among market participants. This allows us to compute sector-specific averages of expected revenues, operational profits, and net profits.

Migration - Each worker's utility in a given region is the sum of three components. First, the logarithm of the expected real wage in a specific occupation within the region represents the objective measure of welfare. Second, individuals have preferences for living in different regions, represented by a subjective taste shock which is modeled as a random variable. Third, moving between regions encompasses a utility cost, which captures factors such as language barriers, distance costs, and emotional ties to local communities, family, and friends that migrants have to pay. These migration costs depend on the education level.

Each individual optimizes their utility by selecting their preferred place of residence, considering economic conditions, personal preferences and migration costs. Assuming preference shocks follow an extreme value type one probability distribution (Gumbel distribution), the solution to the spatial utility maximization problem can be derived analytically. Following McFadden (1973), the probability of moving to a destination region relative to staying in the origin region is proportional to the ratio of real wage rates between the destination and origin regions, multiplied by the migration costs.

In response to a shock affecting a regional labor market, native workers (within the same country) and within-EU immigrants (across different countries) adjust their labor supplies in both origin and destination regions.[22] The equilibrium condition requires that expected utilities equalize across regions and hence individuals are indifferent between staying in their current region of residence and moving elsewhere. Formally, labor market equilibrium is achieved by balancing the supply and demand of efficient labor across occupation-sector cells within each region, which implies sorting of workers into occupations within sectors and their migration across regions within specific occupations.

In formal terms, the economy is in a general equilibrium if and only if all markets clear and total expenditure in a given region equals total income earned by workers in that region.

[22]Non-EU immigrants' behavior is exogenous. These immigrant stocks are therefore constant across occupations, sectors and regions.

Table 7. The Structure of the Economy: Occupations and Sectors

Occ. Number	Occ. Code	ISCO1D	Sec. Number	Sec. Code	NACE1D
1	MAN	1	1	MANU	A, B, C, D, E
2	PRO	2, 3	2	CONS	F
3	SER	4, 5	3	SALE	G
4	ELE	6, 7, 8, 9	4	TRAN	H
5	INA	0*	5	LSER	I, N, R, S
			6	FSER	K, L
			7	PSER	J, M
			8	PUBL	O, P, Q

Notes: Occupations 1: Managers (MAN); 2: Professionals (PRO), 3: Clerical, Service and Sale Workers (SER), 4: Less-Skilled and Elementary Occ. (ELE), 5: Inactive on Labor Market (INA). Sectors: 1: Manufacturing (MANU), 2: Construction (CONS), 3: Wholesale and Retail Trade (SALE), 4: Transport and Storage (TRAN), 5: Low-Skilled Services (LSER), 6: Financial Services (FSER), 7: Professional Services (PSER), 8: Public Administration, Education, and Health (PUBL). Source: ISCO, NACE (Eurostat).

D.3. Calibration and definition of counterfactual scenarios

In this section, we summarize our calibration strategy and the assumptions underlying our counterfactual scenarios. We calibrate our model on the reference period 2018, for which all necessary data inputs are available for the different dimensions required:

- Geography: The model is calibrated on data for 100 geographical regions (at the NUTS1 level) from 31 European countries. We list the regions included in Online Appendix A1.

- Production sectors: Firms' are aggregated into eight different production sectors based on the NACE 1-digit classification: manufacturing, construction, sales, transportation, low-skilled services, financial services, professional services, and public services. Table 7 provides the correspondence between our model aggregates and the NACE categories.

- Occupation tasks: The labor market differentiates between four types of occupations that correspond to four specific types of tasks. These occupations, obtained by combining ISCO 1-digit occupations (see Table 7 for the correspondence), are: managers, professionals, service and elementary jobs (coded by $o = 1, ..., 4$ respectively). Workers can also choose inactivity, which is a non-market occupation indexed by $o = 5$.

- Individual characteristics: Each native worker is characterized by a five-dimensional vector of skills that define their ability to fulfill four market and one non-market (i.e., inactivity) occupational tasks. These skills are summarized by multidimensional Normal densities backed out from wage distributions obtained from the data. Skill distributions differ for low- and high-educated workers. We further control for workers' origin and define separate wage distributions for natives, while EU-immigrants and non-EU immigrants are summarized by the average values.

Data sources

Labor Market - The calibration of the model is based on several data sets provided by Eurostat. We compute the exogenous supply of workers by type (i.e. 2 education levels x 3 origin groups x 4 occupations) and region using the Labor Force Survey (LFS). We use non-parametric kernel estimates across 100 regions to generate education- and occupation-specific wage distributions from the Structure of Earnings Survey (SES). The estimated densities serve as reference for the estimation of the parameters defining the labor market module.[23] We apply an algorithm that minimizes distances between the empirical and the model (SUN) wage distributions. Then, relying on the European Union Statistics on Income and Living Conditions (EU-SILC) database, we calibrate the differences in location and spread of wage distributions across the three origin groups for all regions and occupations. Furthermore, the aggregated LFS data also provides region-specific inactivity rates.

[23] To eliminate extreme observations, all wage distributions from SES are censored at the 1st and 99th percentile. Smoothing of the Epanechnikov kernel takes place with parameter equal to 2.

Migration - We need to compute region-by-region migration matrices by occupation and education level. We start with country-level migration data from all European countries from Eurostat (based on census 2010) and complement it with the OECD DIOC database for 2010. In the first step, we impute region-pair-specific flows across countries in 2018 using gravity regressions. In the second step, we rely on a similar procedure to determine within-country region-pair-specific movements. Burzynski (2024) provides further details.

Regional Trade by Sectors - We use the Trade in Value Added (TiVA) dataset by the OECD to compute trade matrices by region pairs for the eight aggregated sectors in our model. We then use the EU regional trade database created by JRC and PBL (Thissen, Lankhuizen and Jonkeren, 2015) to decompose aggregated trade into sectors. Finally, we unify the eight unbalanced NUTS1-pair-specific trade matrices obtained such that: (i) regional GDP values equal the sums of produced value added in the model, (ii) regional consumption of sectoral goods equal the sums over all regions of production by sector, (iii) aggregate production equates aggregate consumption.

Macro Indicators - We use different additional datasets from Eurostat: data on stocks of labor and capital by sectors (including structures and automation capital), the 2018 sectoral GDP values decomposed into employees' compensation, capital compensation, and corporate profits by eight aggregated sectors, data on price levels (PPP indexes), interest rates and firm demography (stocks of active firms, survival and exit rates).

Exogenous Parameters - We rely on the literature to set the values for several parameters. We set the elasticity of substitution between sector-specific goods to 3 and the elasticity of substitution between goods within each sector to 4, following Simonovska and Waugh (2014). The elasticity of substitution between labor and automation capital equals 1 for ICT and 3 for MNT. Following Ottaviano and Peri (2012), we use an elasticity of substitution between education groups equal to 2 and an elasticity of substitution between origin groups equal to 20. The minimal level of productivity in each sector is standardized to one. We set sector-specific elasticities of substitution between structures and tasks to $\sigma_s = (0.6, 0.41, 0.74, 0.36, 0.63, 1.16, 0.24, 0.27)$, following Chirinko and Mallick (2017).

Calibration Algorithm - A detailed description of the calibration procedure is presented in Burzynski (2024). In a nutshell, the algorithm consists of: (1) determine the parameters of multidimensional SUN skill distributions from the data on wage densities; (2) identify the technological parameters (i.e. the relative productivities of all inputs) using the hierarchical CES production function, data on sectoral GDPs, carbon taxation and average wage rates; (3) use data on trade flows and consumption to identify trade cost matrices across all region pairs; (4) calibrate migration costs matrices using data on migration shares for all region pairs, wage rates and prices; (5) use the utility functions with price and consumption data to determine the value of preference parameters.

Simulation Algorithm - To compute the counterfactual equilibrium of the model, we apply the algorithm detailed in Burzynski (2024). The key steps include: (1) shock the environmental policy parameters of the model; (2) compute the new labor market equilibrium using wage equations (determined by the hierarchical CES production function), supplies of labor by occupation and tasks by occupation-sector; (3) compute the aggregates of firm characteristics, including firm masses, real production, productivity distributions, GDP aggregates, transfers (if applicable) and prices; (4) obtain the migration flows.

Defining the counterfactual scenarios

Our baseline scenario is calibrated with data for the year 2018. We use data on country-sector specific environmental taxes, that include costs linked to CO2 emissions, provided by Eurostat to assess the baseline tax rate (labelled T1) and assume that these taxes represent a pure cost for firms. Hence, the baseline does not feature a redistribution of the environmental taxes (labelled R1). Our baseline scenario thus combines observed environmental taxation and no redistribution (T1R1).

The price of CO2 increased from around 7.5€/tCO2 in January 2018 to close to 25€/tCO2 in December 2018, setting the yearly average price at around 15-16€/tCO2. By the end of 2021, the price had reached 80€/tCO2. In May 2024, BloombergNEF forecasted a price of 146€/tCO2 by 2030 (BloombergNEF, 2024).[24] Using multiple models with varying underlying assumptions, Abrell et al. (2024) estimate that in order to reach the EU emission targets, the CO2 price would need to be 130 to 286 €/tCO2 in the EU ETS, and range from 175 to 360 €/tCO2 for the energy-related ESR (ESR-E) emissions, depending on the model's underlying assumptions.

Given the historical and projected evolution of CO2 prices, we simulate a counterfactual 'High CO2 prices' (labelled T2) scenario. We assume an exogenous tenfold price increase of CO2 certificate prices across all regions and sectors. This implies a price exceeding 200 €/tCO2, which is in line with the values projected for 2030/2040 in Chapter B (see Table 3).[25] However, such a shock likely leads to a sector-specific readjustment of their energy input mix, which we do not model explicitly. To account for this adaptation channel, we rely on the sectoral changes in emission cost per value added produced with the CGE simulations in Chapter B. In essence, this boils down to deflating the tax increase by a country-sector-specific factor that accounts for efficiency gains. The country-sector specific taxation changes are provided in Appendix A3. Unsurprisingly, the manufacturing and transport sectors adjust their production technology more strongly than the service sectors. The pass-through increase in CO2 prices ranges from 55.9% in the Romanian manufacturing sector to 85.9% in the Lithuanian services sectors. As each region has a different sectoral structure, this country-specific adjustment means that the rate of pass-through of the CO2 price increase varies across all regions.

This scenario on CO2 price increases is combined with three possible scenarios on redistribution:

- No redistribution (labeled R1), is used in the baseline. In this scenario, higher CO2 prices imply higher marginal production costs which cause foregone production.

- Uniform redistribution of environmental taxes across European regions (labeled R0) implies the same lump sum transfer per capita, independently on the region of residence of the worker in Europe. Hence, environmental taxes are collected at European level and redistributed across European regions independently of where the taxed economic activity took place. As we detail in Section D.4, this scenario provides the highest redistributive mechanism.

- Uniform redistribution within countries (labelled R2) assumes that taxes are collected at the country level and redistributed homogeneously across regions within the country. Hence, there is no cross-country redistribution.

D.4. Simulation results

In this section, we use the model detailed in Section D.2 to simulate counterfactual changes in CO2 certificate prices which lead to country-sector specific changes in environmental taxation. In the multi-occupations multi-sector general equilibrium model, a change in environmental taxation affects the marginal cost of all production factors. Given that each region has its own structure of production sectors, country-sector specific changes in the production costs result in heterogeneous changes across the 100 regions. We first quantify the effects of increasing taxation, absent any redistribution channel. Then, we analyze to what extend two different redistributive schemes mitigate the negative consequences of higher CO2 prices.

[24] Last viewed on September 12th 2024.
[25] Trade in CO2 certificates ensures a homogeneous price of CO2 certificates across regions and sectors.

The Benchmark Scenario: increasing taxes with no redistribution

We start by discussing the pure effects of increasing taxes, without any redistribution (T2R1), displayed in Figure 13. As could be expected, Panel a) shows that GDP decreases in most regions because increasing environmental taxation increases the part of the production that is devoted to reduce pollution. The marginal cost of production increases which translates into a lower remuneration of the tasks used for production (see Panel c). Losses in nominal GDP reach up to 14.5% of the baseline GDP in Latvia. Production is most negatively impacted in the Baltic states, Greece and Romania, whereas the regions facing the lowest negative impact are mainly located in Germany, Luxembourg and Switzerland. As the United Kingdom is not directly affected by the environmental regulations, higher environmental taxes in the European Union have slight positive spillover effects on its production. In contrast, regions suffering the strongest decrease are mainly located in Eastern and Southern Europe.

Higher environmental taxation leads to a sectoral reallocation of labor, as sectors most affected by the changes (i.e., the manufacturing and transportation sectors) become relatively less attractive for workers compared to less affected sectors, particularly the service sector (see discussion below and Figure 14). Due to the sectoral structure of their labor market, Luxembourg and Switzerland witness the strongest increase in their labor force, followed by the south-east of Germany and Austria. The UK benefits from an increase in its relative attractiveness for workers because it is not part of the system. On the opposite, the regions facing the strongest decline in their labor force are in Croatia, Slovakia, Latvia, Estonia and Ireland. We show in Section D.5 that the increase in labor is highly correlated to net migration movements, which points to the fact that there is not a substantial increase in inactivity.

However, labor reallocation is not enough to compensate for the increase in marginal costs of production, which can reach up to 18%. The decrease in the task remuneration across all regions (Panel c) drives the negative shocks observed in nominal GDP in Panel a).

Simultaneously, as production costs increase, the least productive firms leave the market and the number of varieties decreases which translates in a higher regional price index in most regions. Panel d) shows that the strongest price increases, up to 1.7%, are registered in Italy, Greece and Eastern European regions. In contrast, the Paris area, regions in Northern France and Northern Spain register a slight decrease of their price index.

Workers in our model are either highly-educated (HE) or less-educated (LE). They work in one of four types of occupations in one of eight sectors (or are inactive). As Figure 13 shows, changes in environmental taxation differently affect the 100 European regions. In Figure 14, we dig deeper into the mechanisms of the model. Panel a) depicts the changes in GDP by region and sector. The transport sector is most frequently affected by reductions in production, followed by the manufacturing and construction sectors in some countries. These sectors are the most affected by the higher environmental taxation. In contrast, service sectors and public administration, which are not affected by the tax increases, generally benefit from higher production.

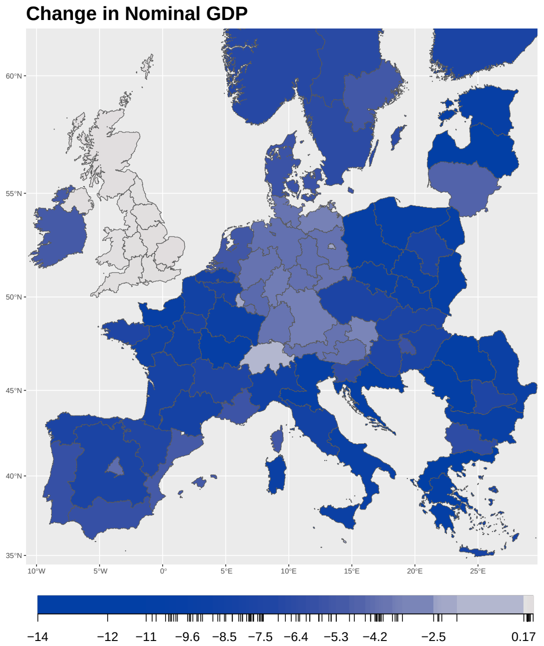
Panel b) highlights that employment of less educated natives decreases in elementary occupations, which are over-represented in the manufacturing, transport and construction sectors. In contrast, less-educated native employment increases in the service and professional occupations, more prevalent in the service sectors and public administrations. This highlights the sorting of workers who leave affected sectors for less affected ones until education-occupation specific wages equalize across sectors.

Panel c) highlights that immigration does not substantially change, with a few exceptions.[26] In particular, the share of less-educated immigrant workers in elementary occupations increases in the United Kingdom, which is unaffected by the shock. Luxembourg and Switzerland reinforce their attractiveness for immigrant workers, in particular highly educated professionals.

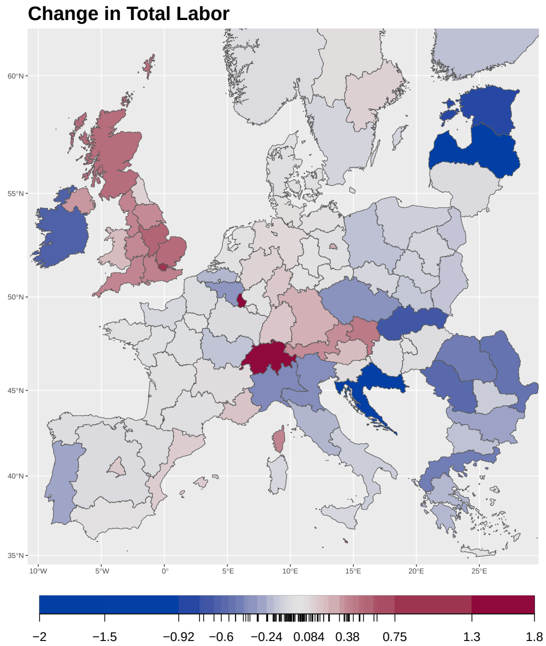
Panel d) shows the cumulative effect of increased environmental taxation on real wages for

[26] As we detail in Section D.5, one reason stems from the fact that migration is costly, in contrast to changing sectors or even occupations (which are both free).

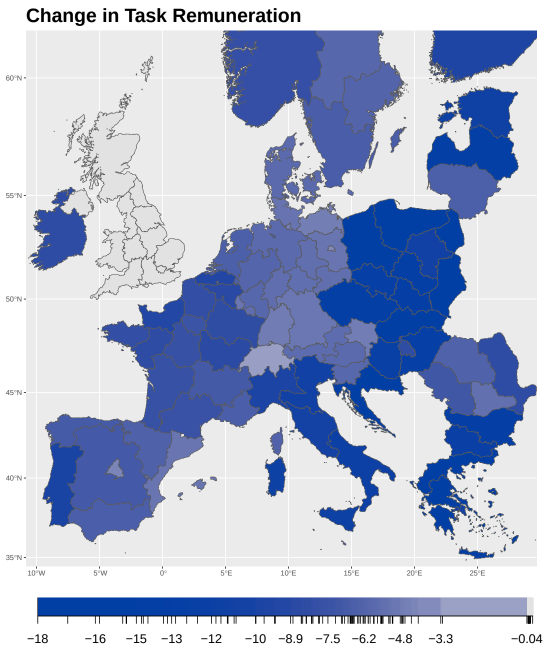
Figure 13. Effects of Increasing Environmental Taxes on GDP, Labor Composite, Task Remuneration and Prices in the Benchmark Scenario



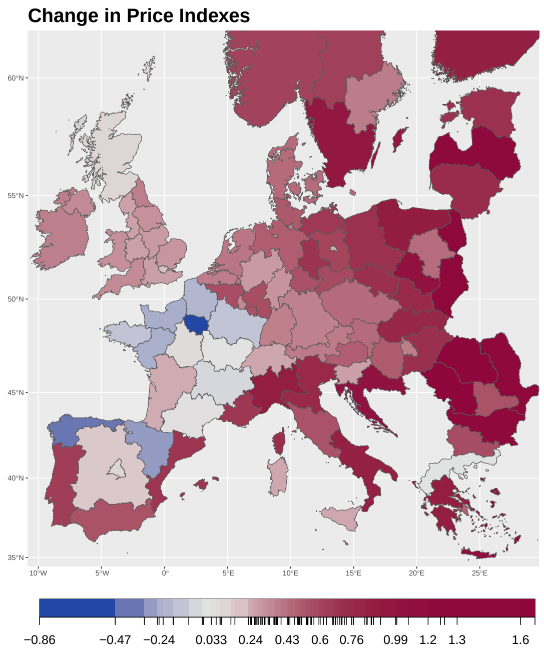
(a)Change in GDP (in %)



(b)Change in labor composite (in %)



(c)Change in task remuneration (in %)



(d)Change in prices (in %)

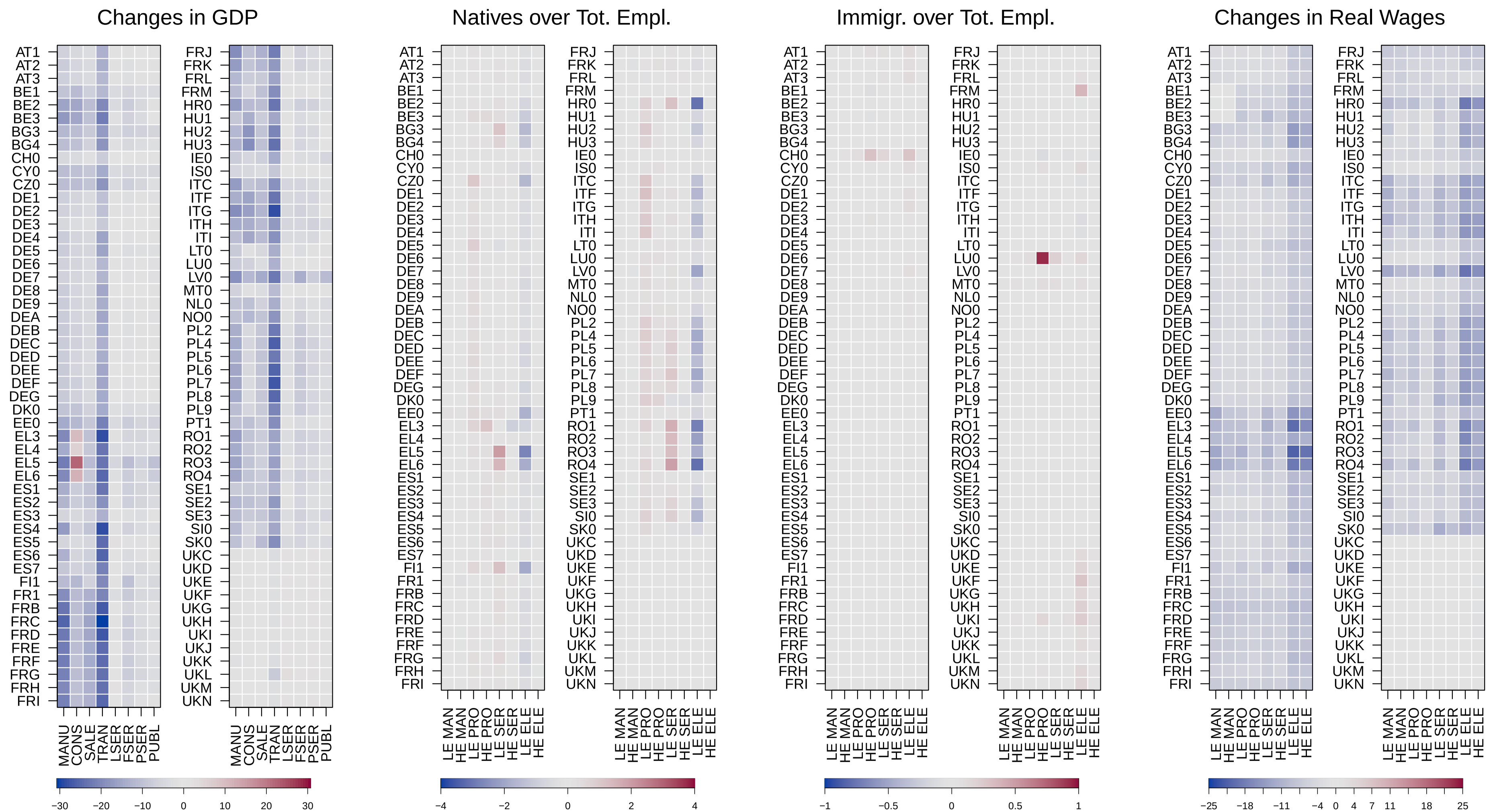
Note: Panel (a) shows changes in regional GDP (in %); Panel (b) shows changes in regional efficient labor composite (in %); Panel (c) shows changes in regional task remuneration (in %); and Panel (d) shows changes in regional price indexes (in %). All results include the difference between the benchmark scenario (T2R1, high-tax, no redistribution) and baseline equilibrium.

the eight types of workers (2 educations x 4 types occupations). The increase in the marginal cost of production lowers the remuneration of workers. At the same time, prices increase. Both channels lead to lower real wages, in particular for workers in elementary occupations which tend to be concentrated in the sectors most affected by the policy change. In contrast, workers in the service sectors are the least affected.

The role of tax redistribution

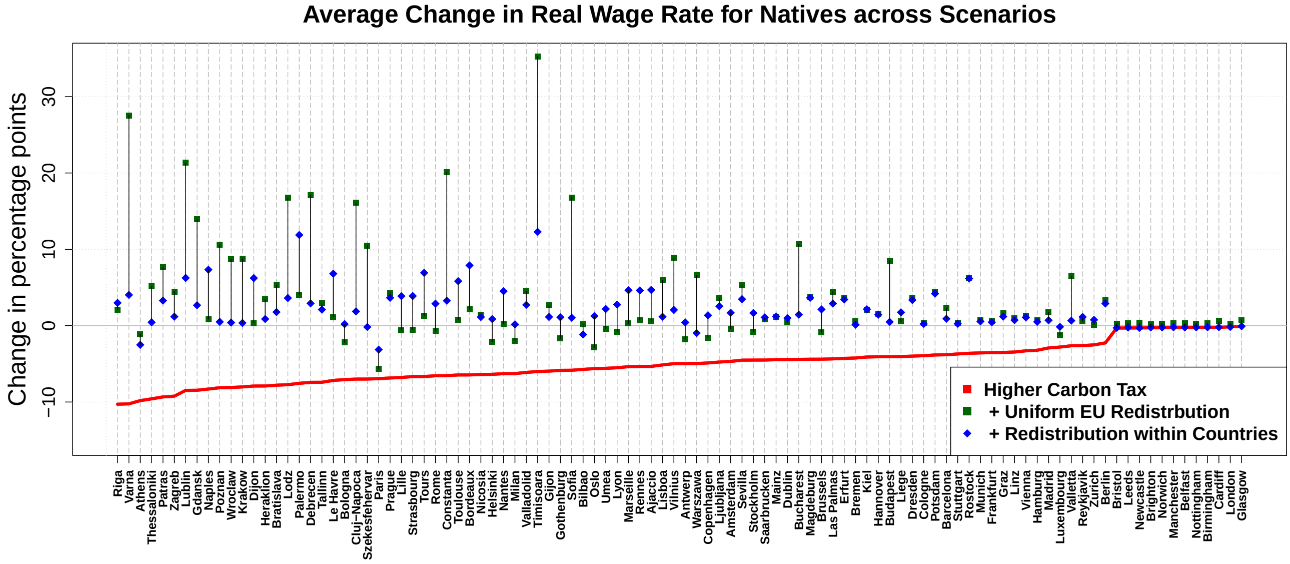
In this section, we explore the role of environmental tax redistribution. Unlike the benchmark scenario, where environmental taxes are treated as a pure production loss, we assume that the generated revenues are entirely redistributed to workers. We consider the two scenarios detailed in Section D.3: i) a uniform transfer across European regions (T2R0) and ii) a uniform transfer across regions within each country based on the nationally collected taxes (T2R2).

Figure 14. Effects of Environmental taxes on Sector-Specific Aggregates in the Benchmark Simulation



Note: Figure 14 details the change in nominal GDP (production) by region and sector in panel a). Sectors: MANU: Manufacturing, CONS: Construction, SALE: Wholesale and Retail Trade, TRAN: Transport and Storage, LSER: Low-Skilled Services, FSER: Financial Services, PSER: Professional Services, PUBL: Public Administration, Education, and Health. Panels b) to d) show changes at the skill-occupation-region level: the evolution of the share of natives in employment in panel b), the evolution of the share of immigrants in employment in panel c) and changes in real wages in panel d). Workers belong to one of two skill groups: highly-educated (HE) and less-educated (LE), and one occupation: MAN, PRO, SER, ELE. For the region codes, please refer to Table A2. All results display the difference between the T2R1 scenario (higher taxes without redistribution) relative to the reference scenario. Source: authors' calculations.

FIGURE 15. Effects of Environmental taxes on Sector-Specific Aggregates in the Benchmark Simulation



Note: Figure 15 shows the average change in real wages for the different scenarios. The red line highlights our benchmark scenario (higher taxes without redistribution). The green squares add uniform redistribution across all EU regions to the benchmark scenario. The blue lozenge add uniform redistribution within each country to the benchmark scenario.

The red line in Figure 15 compares our benchmark scenario with high taxes but no redistribution on real wages to the baseline with observed levels of environmental taxes in 2018. Higher environmental taxes imply a median (and average) decrease in real wages of around 5%, while workers in the most affected regions face around 10% lower real wages. Higher environmental taxes most negatively affect Eastern European regions, such as Riga and Varna, and the Greek regions of Athens, Thessaloniki, and Patras. Interestingly, these Greek regions have a relatively low share of employment in the manufacturing, construction and transport sector, and hence the negative effect emerges mainly from the competition that arises from the occupational sorting of affected workers towards sectors that employ most of the labor force (public and services sectors). Regions least affected include capital regions, characterized by a sectoral distribution that is less affected by environmental policies (see Figure A1) : Berlin, Zurich, Reykjavik, Valletta and Luxembourg.[27]

In our benchmark simulation, environmental taxes represent a pure production cost which is used to abate pollution without any measurable return for workers. Instead, when these taxes are redistributed, the losses from higher environmental taxation are, by construction, mitigated everywhere. However, redistribution affects workers' welfare to very different extends across regions. Figure 15 highlights the effects of a uniform tax across the EU (green squares) and uniform redistribution within countries (purple diamond). The design of the redistribution scheme thereby impacts the total effect of the environmental policy change, in line with Conte, Desmet and Rossi-Hansberg (2022).

Intuitively, uniform redistribution across EU regions (green circles) benefits most the poorest European areas, as they perceive transfers collected from activity taxed in more productive regions. Eastern and Southern European regions are among the main beneficiaries (Varna, Timisoara, Lublin, Constanta and Sofia). In a majority of areas, the transfers even allow to turn the impact of higher environmental taxes to a net increase in welfare relative to the baseline taxation scenario. In contrast, regions such as Paris, Oslo, Madrid, Milan and Bologna are net contributors. Although the transfers mitigate the losses relative to the benchmark scenario without transfers, the higher taxes still negatively impact the net welfare in these regions relative to the levels observed under baseline tax levels.

[27]Note that real wages in the United Kingdom are only marginally affected by worker reallocation and trade, as they are not subject to the environmental policy changes.

When taxes collected within a country are redistributed solely within its regions, regions in Eastern and Southern Europe are much less compensated for the negative impact of higher environmental taxes. The most productive areas within these countries are worse off then in a scenario with transfers across countries, given that they are the net contributors (whereas they might be a net beneficiary when redistribution is uniform across European areas). Less productive areas receive transfers from the more productive areas within the country, but these are below the levels of EU-wide transfers in the least developed EU regions. In contrast, less developed regions within the most productive countries have higher welfare gains when transfers remain in the country. Areas which are net contributors at EU level but beneficiaries within the national borders include Bologna, Bilbao, Brussels, Oslo and Antwerp among others.

D.5. Disentangling the importance of labor sorting and migration

The main contribution of our framework is to jointly account for sorting across occupations and industries as well as across space (i.e., migration) as an adaptation mechanism to changes in environmental policies. In this section, we disentangle the importance of these two mechanisms.

Regional migration

Figure 16 shows how environmental taxation affects migratory patterns. Changes in net migration closely mimic the change in the labor composite shown in Panel b) of Figure 13.[28] Overall, higher environmental taxes spark a marked increase in labor movements (200.000 additional migrants relative to the baseline, representing around a 2% increase in the within-EU migrant workforce). The high-productivity regions in Europe, including Luxembourg (+4.000), Switzerland (+60.000), some regions of South-East Germany and Austria, with an economic structure that is not much affected by the higher taxes become relatively more attractive for workers. Similarly, net immigration increases in the United Kingdom (+140.000 in total) because it is unaffected by the environmental policy.

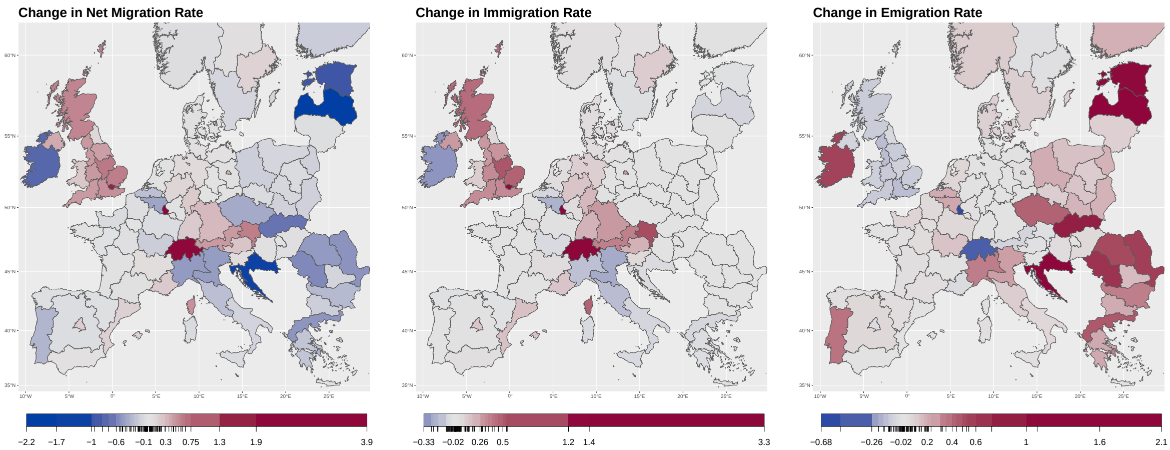
In contrast, net migration decreases most in Eastern and Southern European regions, including Northern Italy, Prague and Bratislava (exceeding -20.000 in each), and Baltic states, Romania, Croatia and Bulgaria (exceeding -10.000 in each). Panel b) and c) highlight that population movements go in opposite directions. Regions that become less attractive for immigrants also register an increase in emigration, and vice versa. Immigration decreases mostly in Ireland, Northern Italy and Southern Belgium. Panel c) shows that emigration increases mostly from Ireland, Eastern European countries, Portugal and Northern Italy.

In order to quantify the effect of the migration option as an adaptation channel to higher environmental taxes, we simulate our benchmark scenario without cross-regional mobility (i.e., migration costs are assumed to be infinite). The black line in Figure 17 provides the change in real wage rates for our baseline result, discussed in Section D.4. The green squares refer to a scenario without the regional mobility channel. Migration per se does not substantially affect the welfare effects generated by higher CO2 prices. In most regions, blocking migration has only a marginal negative additional impact. Regions where this effect is strongest are Riga, Tallinn, Zagreb, Constanta and Timisoara.[29] In contrast, the negative welfare effects are only mitigated by the migration channel in a few regions, mostly located in high-productive regions such as Zurich, Brussels, Linz, and Vienna. Inter-regional migration is costly in terms of utility, which explains why workers rather resort to occupational sorting as an adaptation mechanism, as detailed below.

[28]The minor differences stem from the fact that the latter also accounts for native workers that move from employment to inactivity, whereas only employed migrants move within their occupation

[29]Note that these are the regions where the joint effect, shown in red circles, is lower than the pure occupation sorting effect (the blue lozenge).

FIGURE 16. Effects of Increasing Environmental Taxes on Immigration and Emigration Rates in the Benchmark Scenario



(a)Net immigration (b)Immigration (c)Emigration

Note: Figure 16 shows the regional change in net immigration rate (Panel a), the immigration rate (Panel b) and the emigration rate (Panel c). All numbers are expressed as percentage point changes (p.p.) and depict the change in the number of immigrants (or emigrants) relative to the total working population.

Labor sorting allows workers to adjust

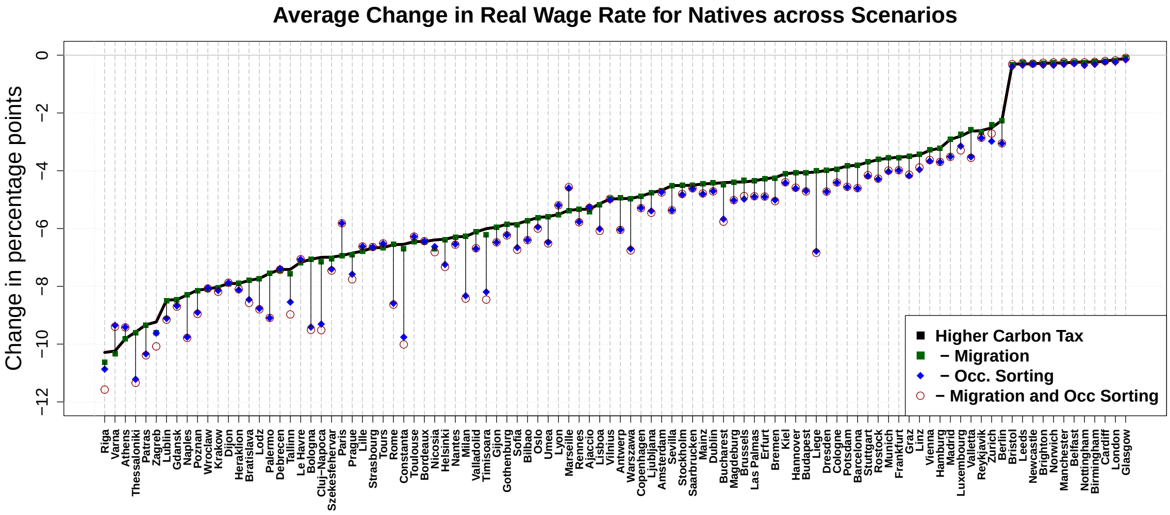
In a next step, we simulate the model without allowing for sorting across occupations. Each worker possesses a five-dimensional distribution of skills that can be valorized on the labor market. Higher CO2 prices affect sectors with different skill requirements in heterogeneous ways. An increase in the marginal cost of production in these sectors will thereby affect disproportionally workers in certain occupations (i.e. using a specific skill). Higher CO2 prices in our benchmark scenario impact primarily the manufacturing, transportation and construction sectors, which hire an important share of workers in elementary occupations. If we no longer allow workers to change their occupation, they can only switch to better paying sectors. Incumbent workers in the same occupations in these sectors therefore face increased wage competition.

As the blue tiles in Figure 17 show, blocking sorting across occupations reinforces the negative effects in most regions. Workers are particularly affected in regions where the sectors mostly hit by the policy change represent a high share of the employment. As workers in occupations most prevalent in these sectors face a decrease in wages, preventing them to switch to occupations where they could earn higher wages reinforces the negative welfare shock. The regions most negatively affected are concentrated in Eastern European countries (Constanta, Warsaw) and Italy (Rome, Milan, Bologna). Surprisingly, blocking workers' sorting across occupations can lead to less negative effects in some regions (e.g. Paris, Lyon). When workers cannot change their occupation, competition decreases in the new occupations that affected workers would have chosen. At the same time, affected workers are more likely to change sectors. Thereby, they increase competition in these sectors for workers in the same occupations and improve the productivity of workers in complementary occupations. The average welfare effect is a result of these different channels and is affected by the occupation-sector composition of the workforce.

D.6. Conclusion

In this Chapter, we quantify the regional effects of a EU-wide increase in CO2 emission prices on workers' welfare. Our model contributes to the literature by accounting for workers' sorting across occupations, sectors and 100 European regions as an adaptation mechanism to environmental policy shocks. Inter-regional migration remains limited in Europe, despite important wage differences. This points to the fact that, despite free-mobility agreements, it's costly for workers to leave their origin area in terms of utility (i.e. well-being). In contrast,

FIGURE 17. Effects of Environmental taxes on Sector-Specific Aggregates in the Benchmark Simulation



Note: Using our benchmark scenario characterized by higher carbon taxes without redistribution, Figure 17 decomposes the impact of cross-regional migration and occupational sorting in workers' real wages. The black line replicates the benchmark results from Figure 15. The green squares show the effects without migration, the blue lozenges the effects without occupational sorting and the red circles the cumulative effect of both.

switching occupation or sector within the region of residence following a sector-specific shock is a relatively less costly adaptation mechanism.

Increasing CO2 emission prices without a redistributive mechanism for the collected taxes has significant and heterogeneous impacts across regions. Marginal production costs rise up to 18%, particularly in manufacturing-intensive regions. GDP declines in most regions, with losses reaching 14% in Eastern Europe. The most productive areas located in Germany, Luxembourg, and Switzerland, experience smaller negative effects or even gains due to their structure of production that is less affected by the higher environmental taxes. In our simulations, workers move from declining sectors like transport and manufacturing to expanding ones like services, highlighting the role of occupational and sectoral shifts in adapting to environmental taxation. The least productive firms are pushed out of the market, which reduces firm diversity and increases regional price indices, notably in Italy, Greece, and Eastern Europe.

The redistribution of environmental taxes mitigates the negative effects of higher CO2 prices to varying degrees depending on the scheme. EU-wide redistribution benefits poorer regions in Eastern and Southern Europe, turning potential losses into welfare gains for areas like Varna and Timisoara. In contrast, productive regions like Paris and Milan are net contributors and suffer a welfare loss. Hence, a European-level redistributive scheme reduces inequalities across European regions and countries. In contrast, national-level redistribution within countries reduces inequality across regions but provides less support to poorer EU regions. The most productive areas within countries act as net contributors, while the least productive regions benefit from transfers. The two types of redistribution mechanisms influence labor movements, firm dynamics, and regional welfare differently, highlighting the significance of policy design in addressing the welfare consequences of environmental taxation and its impact on inequality.

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Appendix A: Additional Figures and Tables

A1. Section B: Definition of the different units

Table A1. European Country Codes

ISO	Country	ISO	Country	ISO	Country	ISO	Country
AT	Austria	EE	Estonia	IS	Iceland	PL	Poland
BE	Belgium	EL	Greece	IT	Italy	PT	Portugal
BG	Bulgaria	ES	Spain	LT	Lithuania	RO	Romania
CH	Switzerland	FI	Finland	LU	Luxembourg	SE	Sweden
CY	Cyprus	FR	France	LV	Latvia	SI	Slovenia
CZ	Czechia	HR	Croatia	MT	Malta	SK	Slovakia
DE	Germany	HU	Hungary	NL	Netherlands	UK	United Kingdom
DK	Denmark	IE	Ireland	NO	Norway		

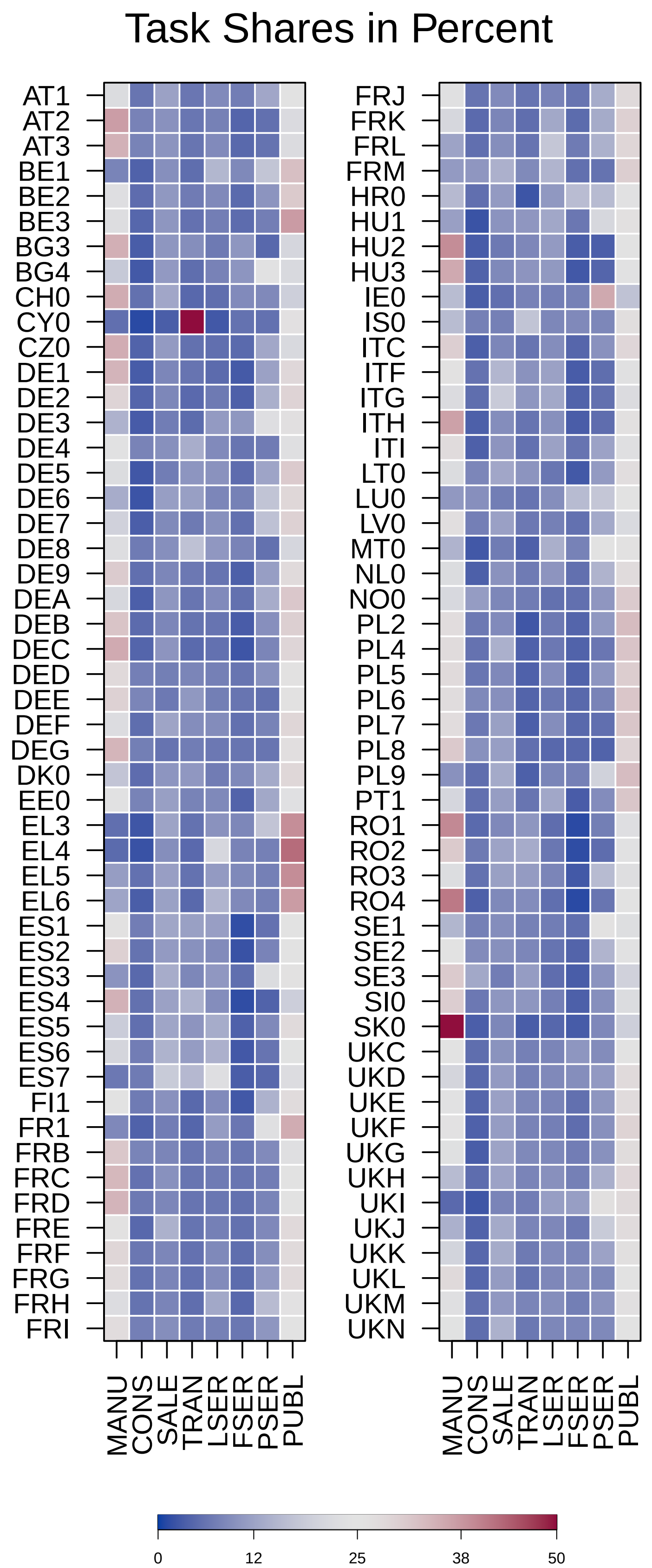
Table A2. European NUTS1 Region Codes

Region	City	Region	City	Region	City	Region	City
AT1	Vienna	DEF	Kiel	FRJ	Toulouse	PL7	Lodz
AT2	Graz	DEG	Erfurt	FRK	Lyon	PL8	Lublin
AT3	Linz	DK0	Copenhagen	FRL	Marseille	PL9	Warszawa
BE1	Brussels	EE0	Tallinn	FRM	Ajaccio	PT1	Lisboa
BE2	Antwerp	EL3	Athens	HR0	Zagreb	RO1	Cluj-Napoca
BE3	Liege	EL4	Heraklion	HU1	Budapest	RO2	Timisoara
BG3	Varna	EL5	Thessaloniki	HU2	Szekesfehervar	RO3	Bucharest
BG4	Sofia	EL6	Patras	HU3	Debrecen	RO4	Iasi-Constanta
CH0	Zurich	ES1	Gijon	IE0	Dublin	SE1	Stockholm
CY0	Nicosia	ES2	Bilbao	IS0	Reykjavík	SE2	Gothenburg
CZ0	Prague	ES3	Madrid	ITC	Milan	SE3	Umea
DE1	Stuttgart	ES4	Valladolid	ITF	Naples	SI0	Ljubljana
DE2	Munich	ES5	Barcelona	ITG	Palermo	SK0	Bratislava
DE3	Berlin	ES6	Sevilla	ITH	Bologna	UKC	Newcastle
DE4	Potsdam	ES7	Las Palmas	ITI	Rome	UKD	Manchester
DE5	Bremen	FI1	Finland	LT0	Vilnius	UKE	Leeds
DE6	Hamburg	FR1	Paris	LU0	Luxembourg	UKF	Nottingham
DE7	Frankfurt	FRB	Tours	LV0	Riga	UKG	Birmingham
DE8	Rostock	FRC	Dijon	MT0	Valletta	UKH	Norwich
DE9	Hannover	FRD	Le Havre	NL0	Amsterdam	UKI	London
DEA	Cologne	FRE	Lille	NO0	Oslo	UKJ	Brighton
DEB	Mainz	FRF	Strasbourg	PL2	Krakow	UKK	Bristol
DEC	Saarbrucken	FRG	Nantes	PL4	Poznan	UKL	Cardiff
DED	Dresden	FRH	Rennes	PL5	Wroclaw	UKM	Glasgow
DEE	Magdeburg	FRI	Bordeaux	PL6	Gdansk	UKN	Belfast

TABLE A3. Adjustment factors

	Sector							
Country	MANU	CONS	SALE	TRAN	LSER	FSER	PSER	PUBL
BEL	0.6702	0.8545	0.8416	0.6649	0.8416	0.8416	0.8416	0.8416
BGR	0.5919	0.8440	0.8373	0.6868	0.8373	0.8373	0.8373	0.8373
CZE	0.5975	0.8428	0.8435	0.6254	0.8435	0.8435	0.8435	0.8435
DNK	0.6666	0.8194	0.8071	0.6504	0.8071	0.8071	0.8071	0.8071
DEU	0.6113	0.8580	0.8355	0.6532	0.8355	0.8355	0.8355	0.8355
EST	0.7445	0.8360	0.8324	0.7205	0.8324	0.8324	0.8324	0.8324
IRL	0.6055	0.8511	0.8440	0.6981	0.8440	0.8440	0.8440	0.8440
GRC	0.6083	0.8343	0.8306	0.6949	0.8306	0.8306	0.8306	0.8306
ESP	0.6777	0.8377	0.8330	0.6328	0.8330	0.8330	0.8330	0.8330
FRA	0.6926	0.8472	0.8416	0.6830	0.8416	0.8416	0.8416	0.8416
HRV	0.6837	0.8228	0.8217	0.7098	0.8217	0.8217	0.8217	0.8217
ITA	0.6949	0.8427	0.8370	0.6986	0.8370	0.8370	0.8370	0.8370
CYP	0.6425	0.8350	0.8298	0.6453	0.8298	0.8298	0.8298	0.8298
LVA	0.6965	0.8402	0.8372	0.6522	0.8372	0.8372	0.8372	0.8372
LTU	0.7249	0.8513	0.8583	0.6384	0.8583	0.8583	0.8583	0.8583
REU	0.8423	0.8412	0.8373	0.8528	0.8373	0.8373	0.8373	0.8373
HUN	0.7001	0.8394	0.8459	0.6036	0.8459	0.8459	0.8459	0.8459
NLD	0.7563	0.8487	0.8460	0.6728	0.8460	0.8460	0.8460	0.8460
AUT	0.6039	0.8244	0.8164	0.6467	0.8164	0.8164	0.8164	0.8164
POL	0.6973	0.8470	0.8330	0.6764	0.8330	0.8330	0.8330	0.8330
PRT	0.6993	0.8344	0.8268	0.6799	0.8268	0.8268	0.8268	0.8268
ROU	0.5587	0.8174	0.8159	0.6493	0.8159	0.8159	0.8159	0.8159
SVN	0.5998	0.8409	0.8251	0.7019	0.8251	0.8251	0.8251	0.8251
SVK	0.5873	0.8319	0.8459	0.6423	0.8459	0.8459	0.8459	0.8459
FIN	0.7154	0.8220	0.8163	0.6620	0.8163	0.8163	0.8163	0.8163
SWE	0.7111	0.8350	0.8344	0.6920	0.8344	0.8344	0.8344	0.8344

Figure A1. Sectoral distribution of tasks in the Baseline



Note: Figure A1 shows the sectoral distribution of tasks in the baseline equilibrium.

WeLaR is Horizon Europe research project examining the impact of digitalisation, globalisation, climate change and demographic shifts on labour markets and welfare states in Europe. It aims to improve the understanding of the individual and combined effects of these trends and to develop policy proposals fostering economic growth that is distributed fairly across society and generates opportunities for all.

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