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Different Responses of European Economies to Carbon Tax: Insights from National CGE Models for Poland, Germany, France, and the UK

Odmienne reakcje europejskich gospodarek na podatek węglowy. Wnioski z krajowych modeli CGE dla Polski, Niemiec, Francji i Wielkiej Brytanii

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Abstract

This paper compares the different responses of four European countries – Poland, Germany, France, and the UK – to carbon taxation through the lens of open-source national Computable General Equilibrium (CGE) ThreeME models. It investigates the medium-term impacts of a linearly increasing carbon tax from 2020 to 2035 on emissions reduction, energy consumption, and economic growth within these countries. The study reveals significant emissions reductions across all nations by 2035, with Poland experiencing the most substantial decrease, highlighting the influence of energy and carbon intensity on the effectiveness of carbon taxes. Investment growth spurred by carbon taxation emerges as a pivotal driver for economic resilience, notwithstanding the despite nuanced adverse effects on final consumption and trade balances. The paper underscores the dual nature of carbon taxes: as a potent mechanism for decarbonization decarbonisation and as a complex economic influencer necessitating nuanced fiscal strategies to mitigate potential adverse effects on economic performance. Through a rigorous comparison of carbon tax impacts across different economic structures, this study contributes valuable insights into the trade-offs and synergies between environmental and economic objectives, underlining the necessity for integrated policy approaches to achieve sustainable growth and climate targets in the European context.

Streszczenie

W niniejszym artykule porównano różne reakcje czterech krajów europejskich – Polski, Niemiec, Francji i Wielkiej Brytanii – na opodatkowanie emisji dwutlenku węgla, wykorzystując krajowe modele ThreeME (Computable General Equilibrium – CGE) o otwartym kodzie źródłowym. Zbadano średnioterminowy wpływ liniowo rosnącego podatku węglowego w latach 2020–2035 na redukcję emisji, zużycie energii i wzrost gospodarczy w analizowanych krajach. Badanie ujawniło znaczące redukcje emisji do 2035 r. we wszystkich krajach, wśród których to Polska doświadczyła najbardziej znaczącego spadku, oraz wpływ energochłonności i intensywności emisji dwutlenku węgla na skuteczność podatków węglowych.

Wzrost inwestycji stymulowany przez opodatkowanie emisji dwutlenku węgla okazuje się kluczowym czynnikiem napędzającym odporność gospodarczą pomimo zróżnicowanych negatywnych skutków dla konsumpcji końcowej i bilansu handlowego. W artykule podkreślono dwoistą naturę podatków węglowych: jako silnego mechanizmu dekarbonizacji i jako złożonego czynnika wpływającego na gospodarkę, wymagającego zniuansowanych strategii fiskalnych w celu złagodzenia potencjalnego negatywnego wpływu na wyniki gospodarcze. Poprzez dokładne porównanie wpływu podatku węglowego na różne struktury gospodarcze badanie wpisuje się w dyskutowane kompromisy i synergie między celami środowiskowymi a gospodarczymi i dowodzi konieczności zintegrowanego podejścia politycznego do osiągania zrównoważonego wzrostu i celów klimatycznych w kontekście europejskim.

Słowa kluczowe:
podatek węglowy, polityka klimatyczna, modelowanie CGE, modelowanie makroekonomiczne

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Introduction

Climate change has emerged as a paramount concern for our generation. The 2023 Intergovernmental Panel on Climate Change report [IPCC, 2023] underscored the risk that the emissions targets in 2030 set by Nationally Determined Contributions (NDCs) might fall short of keeping global warming under 1.5°C, complicating efforts to limit warming to below 2°C. This discrepancy between current policies and the ambitious mid-term goals necessitates more robust and effective strategies to combat global warming.

The European Commission's pledge to cut emissions by at least 55% from 1990 levels [European Commission, 2023] demands concerted efforts from its member states. Yet, climate change mitigation efforts often face resistance from economic stakeholders due to the anticipated profound societal, economic, and technological upheavals [Fragkos et al., 2021; Landis et al., 2021]. The widely recognised economic distortions caused by carbon taxes [Fragkos, Fragkiadakis, 2022; Fragkos, Fragkiadakis, Paroussos, 2021] underline the importance of assessing their impacts on both economies and societies, particularly within the European Union, where the countries' economic and emissions structures vary significantly.

Computable General Equilibrium (CGE) models, which incorporate environmental aspects, are invaluable for simulating the effects of carbon taxes [An et al., 2023]. They account for the interplay between environmental, energy, and economic dynamics. Studies on climate policies with CGE models have already been conducted for European countries and the Europe Union. Saveyn's [Saveyn et al., 2011] research within the EU highlights that high-income countries face relatively consistent costs from carbon pricing, whereas costs for lower-income countries are more variable. The study suggests that emission permit auctions and emission taxes, with revenue recycling to offset labour taxes, are preferred for promoting GDP growth and employment.

Callonnec et al. [2023] used a CGE model to simulate the National Low-Carbon Strategy of France, revealing the potential for a carbon tax to simultaneously benefit the environment and the economy, suggesting a double dividend effect. For Poland, Rokicki et al. [2023] contrasts the carbon tax and cap-and-trade systems, finding that, due to the country's emission structure, a carbon tax may not effectively reduce greenhouse gas emissions in the short term. Additionally, Böhringer and Rutherford [2013] indicate that the average cost of emissions abatement in Poland is twice as high as the EU average, attributed to the country's substantial dependence on coal.

Turner's study [Turner et al., 2022] for the UK demonstrates that the carbon tax, in the absence of additional policy measures, can significantly reduce emissions but may also result in GDP losses. The economic impact is influenced by the labour market's adaptability to the carbon tax. Employing a CGE model for Germany, Böhringer et al. [2021] predicts a notable reduction in greenhouse gas (GHG) emissions from the carbon tax. The study also emphasises the critical role of international trade in assessing the economic costs of carbon pricing policies in Germany.

Existing research demonstrates the effectiveness of carbon taxes in reducing emissions, but also highlights their negative economic impacts. However, most studies focus on single countries, leaving a gap in comparative research on the effects of identical carbon taxes across economies, especially in terms of economic structure. To address this, we use open-source national CGE models – the ThreeME model – for four European countries: Germany, France, Poland, and the UK. These models are calibrated using the same database and methodology to offer a more rigorous comparison of carbon tax impacts on different countries. Our study aims to provide insights into the sensitivity of European economies to carbon taxes, and to identify potential trade-offs and synergies between environmental and economic objectives according to different specifications for each country. The paper is structured as follows: first, we introduce our modelling framework and scenario settings; next, we present our simulation results and discuss the economic and environmental impacts of identical carbon taxes across the four countries. The paper concludes with a discussion of key findings.

Methodology

Modelling framework

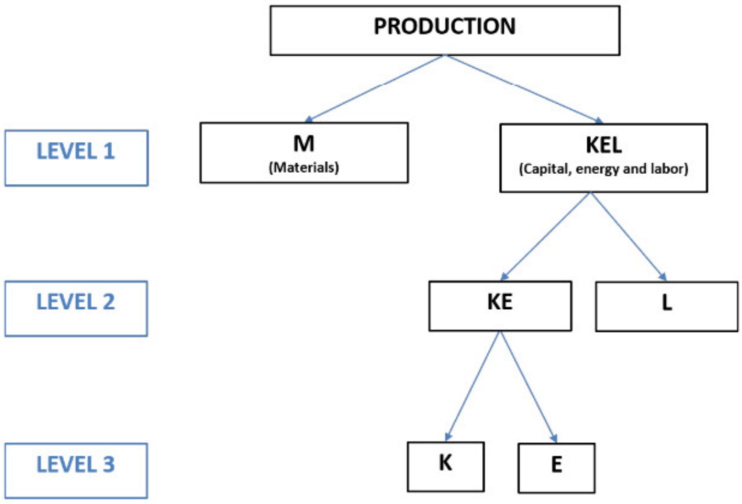
The ThreeME model [**Reynes et al., 2021**] is a national, multi-sectoral Computable General Equilibrium (CGE) model devised for the evaluation of the medium- and long-term repercussions of environmental and energy policies at both macroeconomic and sectoral dimensions. Its application spans various countries, including France, where it has been utilised to assess the economic and environmental ramifications of its National Low-Carbon Strategy [**Callonnec et al., 2023**]; Mexico, for projecting the mid- to long-term consequences of proposed energy policies [**Landa Rivera et al., 2016**]; and the Netherlands, focusing on the macroeconomic impacts associated with job creation [**Bulavskaya, Reynès, 2018**].

Characterised by its neo-Keynesian hypotheses, the ThreeME model emphasises the gradual adjustment of prices and quantities to their equilibrium levels, diverging from the assumption of immediate market responses. This aspect reflects the real-world scenarios where market adjustments are often delayed due to uncertainties, adjustment costs and other temporal constraints. Furthermore, the model's hybrid structure, which blends bottom-up and top-down simulations, allows for a more nuanced analysis of energy consumption and its impacts on the economy.

The key features of the ThreeME model include:

- **Hybrid Simulation Approach**: In macroeconomic modelling, the top-down approach starts with aggregate economic variables and works down to smaller sectors, useful for broad policy analysis. In contrast, the bottom-up approach begins with detailed data on individual agents, aggregating to understand the overall economy, providing granular insights into specific sectors. By merging top-down and bottom-up simulations, ThreeME provides a realistic portrayal of energy consumption that moves beyond the simplistic assumptions of standard top-down models where energy consumption is directly proportional to consumer income. This method allows for an accurate depiction of the evolution of an economy's energy mix, as well as the examination of the interplay between energy and other factors of production.
- **Neo-Keynesian CGE Framework**: Unlike conventional Walrasian CGE models, the ThreeME model adopts a neo-Keynesian approach accounting for the slow adjustment of prices and quantities. This framework acknowledges market imperfections and the possibility of supply-demand disequilibrium, such as involuntary unemployment, providing a more realistic perspective on economic transitions and the long-term impacts of policy interventions. Further details about this feature can be found in the full description of the ThreeME model [**Reynes et al., 2021**].
- **Nested Constant elasticity of substitution (CES) production function**: In this study, we adopted a nested CES production function to enhance the model's realism. At the first level, materials input (M) can be substituted with aggregated capital input (K), energy input (E), and labour input (L). At the second level, substitution is possible between L and KE. Finally, at the third level, substitution occurs between capital and energy. This approach allows the ThreeME model to more accurately simulate the demand for factors of production, reflecting real-world economic dynamics.

Figure 1. Structure of nested CES production function



Source: Author's own elaboration.

Through its advanced features and flexible application across different national contexts, the ThreeME model serves as a critical tool for policymakers and researchers aiming to understand and evaluate the complex interrelations between environmental policies, energy consumption, and economic development.

In this study, we applied ThreeME models to four European countries: France, Germany, Poland and the UK. The principal data for model calibration, including supply and use tables, energy balances and GHG emissions, were obtained from Exiobase 3 [**Stadler et al., 2018**], supplemented with energy data from the IEA [**International Energy Agency, 2022**] and additional necessary data from Eurostat. The models were calibrated to the base year 2019. The four ThreeME models simulate 32 sectors, including nine electricity sectors and four other energy sectors. They also incorporate 28 products, including five energy sources: crude oil, transport oil, natural gas, coal and coal products, and electricity.

Baseline scenario

The baseline scenario, often referred to as "business as usual" (BAU), is predicated on the absence of any climate policy interventions, serving as a reference point for comparing other counterfactual scenarios. In the study, the baseline scenario is calibrated to the year of 2019, and it is assumed as a steady state where all the economic indicators grow at a constant rate. In this study, we assume an annual productivity growth rate of 0.95%, along with a population growth rate of 0.25% for all the studied countries. In terms of elasticities in the nested CES production function, we choose 0 for level 1 (between M and KEL), 0.5 for level 2 (between L and KE), and 2.5 for level 3 (between K and E).

Table 1 presents key indicators for the base year across the four analysed countries. Poland stands out with its high emissions intensity relative to GDP, alongside a significant reliance on coal within its electricity mix. Conversely, France exhibits the lowest emissions intensity and boasts the highest proportion of nuclear power in its electricity mix. Positioned between these two extremes, Germany and the UK display varied energy profiles: Germany has a higher coal dependency in its electricity generation compared to the UK, which leans more on gas-fired electricity production. It is crucial to note that this study maintains the electricity mix as constant and exogenous, deliberately overlooking the technical advancements in electricity generation. Such a methodology enables a concentrated examination of the carbon tax's direct effects on both the economy and the environment.

Table 1. Key indicators at calibration, in 2019

Country	GHG emissions (million tCO_2eq)	GDP (billion USD)	Degree of openness (percentage of GDP)	Electricity mix
Poland	356	541	2.5	73% Coal, 14% Other thermal plant, 13% Renewable
Germany	733	3521	5.0	38% Renewable, 32% Coal, 16% Other thermal plant, 14% Nuclear
France	396	2472	–2.2	72% Nuclear, 20% Renewable, 8% Thermal plant
UK	432	2562	–2.3	41% Gas, 27% Renewable, 18% Nuclear, 14% Other thermal plant

Source: Author's own elaboration.

Carbon tax scenarios

In our research, we implement a consistent carbon tax across the ThreeME models for Poland, Germany, France, and the UK. This tax progressively increases from $ 0 in 2020 to $ 250 per ton of CO2 by 2035. The scope of this carbon pricing encompasses all CO2-emitting economic activities, including the consumption of fossil fuels by households and companies, and other CO2-emitting processes. We adopt a revenue-neutral policy for the carbon tax, channelling its fiscal revenues towards offsetting public debt. This strategy is deliberate, enabling us to isolate the effects of the carbon tax from those associated with other fiscal policies. By doing so, we focus exclusively on the carbon tax's direct impacts on the economy and the environment.

Results and discussions

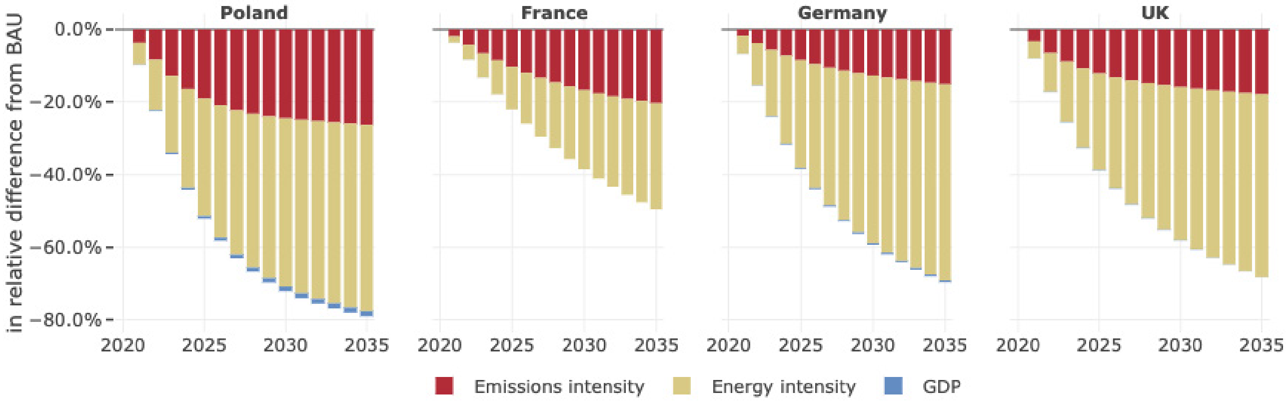
Emissions and energy consumption

Following the enactment of a carbon tax, our simulations reveal that Poland, Germany, and the UK experience immediate and rapid decarbonisation, a trend that persists until around 2030 (Fig. 2). Beyond this point, the rate of carbon emissions reduction slows down, whereas in France, the pace of decarbonisation remains steady throughout the period. However, the continuous increase in the tax rate suggests a diminishing sensitivity to the policy across all examined countries. By 2035, carbon emissions have decreased by 79.1% in Poland, 69.6% in Germany, 68.3% in the UK, and 49.4% in France, relative to the baseline scenarios.

The variance in emissions reduction rates underscores the differing responsiveness of CO_2 emissions to policy interventions across nations. Metrics such as emissions intensity per GDP and energy intensity per GDP are key to understanding these discrepancies: countries with higher emissions and energy intensities tend to be more responsive to carbon taxes. In 2019, Poland had the highest emission and energy intensities per GDP among the studied countries, with values of 0.66 tCO2eq/USD and 2.52 kWh/USD respectively, followed by Germany (0.21 tCO2eq/USD and 1.17 kWh/USD), the UK (0.17 tCO2eq/USD and 0.91 kWh/USD), and France (0.16 tCO2eq/USD and 0.82 kWh/USD). By 2035, after the implementation of the carbon tax, emissions intensity per GDP is projected to decrease to 0.15 tCO2eq/USD in Poland, 0.07 tCO2eq/USD in Germany, 0.06 tCO2eq/USD in the UK, and 0.08 tCO2eq/USD in France.

Drawing from the Kaya identity [**Kaya, Yokobori, 1997**; **Zhang et al., 2022**], we decompose emissions evolution into three drivers: GDP, energy intensity of GDP, and emissions intensity of energy. This makes it possible to better understand the various efforts in emissions reduction. The reduction in energy and emissions intensities emerges as the principal driver behind emissions abatement (Fig. 2), while the GDP driver's contribution seems to be marginal. Our findings suggest that the carbon tax has prompted economies to enhance energy efficiency and transition towards less carbon-intensive energy consumption, aligning with other similar studies [**He et al., 2024**; **Mashhadi Rajabi, 2023**]. Although technological drivers primarily facilitate emissions reductions, the contributions of energy and emissions intensities vary by country. In France, the contributions of energy intensity and emissions intensity to total emission reduction are relatively closer, with energy intensity contributing 20.4% and emissions intensity 29.2%. Conversely, in Poland, Germany, and the UK, improvements in energy efficiency play a more significant role in reducing total emissions.

Figure 2. GHG emissions and the contributions of different drivers, results expressed in relative difference from BAU



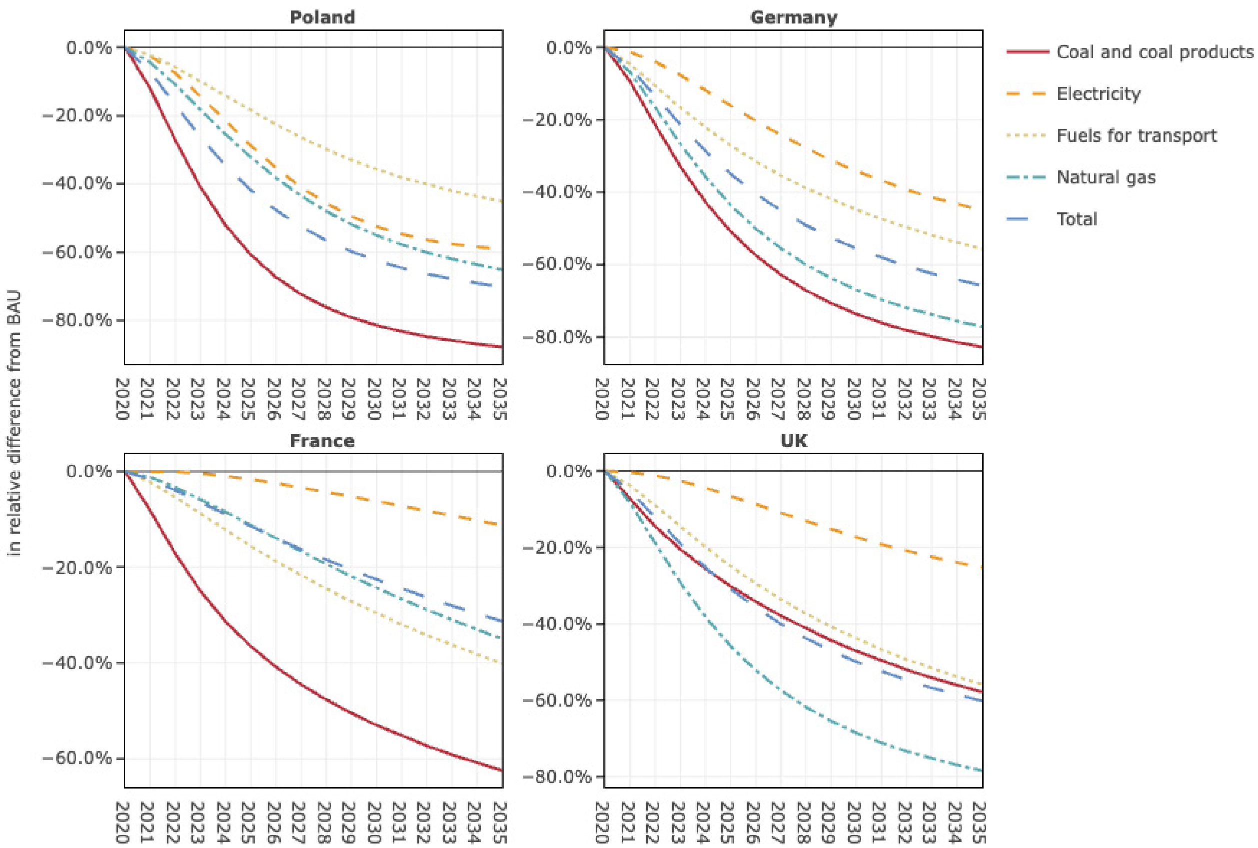
Source: Author's own elaboration.

On one hand, the energy intensity of GDP reflects the overall energy consumption efficiency of an economy, and the carbon tax compels economies to use energy more efficiently, by increasing fossil energy costs [Sen, Vollebergh, 2018]. Our simulations indicate a marked decrease in energy consumption across all countries (Fig 2). Similar to emissions trends, Poland, Germany, and the UK see a rapid reduction in total energy consumption until around 2030, after which the pace moderates. In contrast, France's total energy consumption decreases steadily. By 2035, total energy consumption in Poland, Germany, the UK, and France is projected to decrease by 70.2%, 65.8%, 60.2%, and 31.3% respectively, relative to baseline scenarios.

On the other hand, carbon-intensive energy sources, especially coal, show greater sensitivity to carbon taxes, leading to marked changes in the energy mix of the analysed countries. This shift notably diminishes the emissions intensity of total energy consumption. Coal and coal products, in particular, exhibit a steep decline in usage rates in Poland and Germany, two countries with a relatively heavy reliance on coal in their energy mix. By 2035, the carbon tax is projected to reduce coal consumption by 87.8% in Poland and 82.8% in Germany. Meanwhile, the UK is expected to see a significant drop in natural gas usage, by 78.4% compared to the baseline scenario by 2035, due to its predominant role in the country's energy mix. France, benefiting from a less carbon-intensive electricity mix, shows a modest reduction in electricity consumption of 11.2% by 2035. In Poland, electricity consumption is expected to fall by 59.0% during the same period.

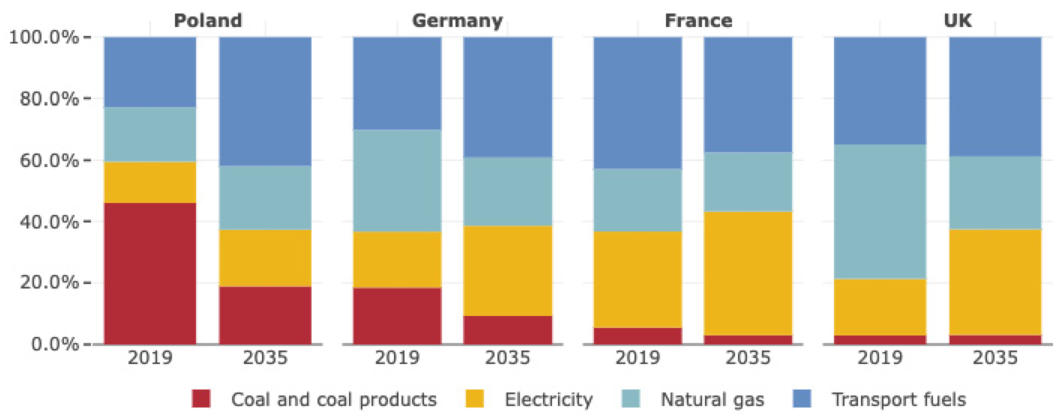
Figure 3 compares the 2019 and 2035 energy mixes of the studied countries. The imposed carbon tax leads to a significant coal phase-out in the energy mixes of Poland and Germany. The UK, with its minimal coal consumption (3.0% in 2019), sees no substantial reduction in coal use induced by the carbon tax. We also observe an electrification trend across the studied countries, particularly in France and the UK, where the share of electricity in the energy mix increases from 31.2% in 2019 to 40.2% in 2035 for France, and from 18.3% to 34.3% for the UK. Electrification in Germany and Poland is less pronounced, due to their greater dependency on fossil fuels and the assumption of the study where the technological progress of electricity generation is ignored.

Figure 3. Final energy consumption, results expressed in relative difference from BAU



Source: Author's own elaboration.

Figure 4. Share of final energy consumption in calibration year (2019) and at the end of simulation (2035)



Source: Author's own elaboration.

Table 2. Comparison between short-term GHG reduction objectives and simulation results, short-term referring to 2030 for Germany, France and Poland, and 2035 for the UK

Country	Short-term objective (GHG reduction below 1990 level)	Short-term emissions in ThreeME results (GHG reduction below 1990 level)
Germany	55%	63%
France	40%	20%
UK	78%	69%
Poland	20%	66%

Source: Author's own elaboration.

While the implementation of a carbon tax has demonstrated positive effects on emissions reductions, our simulation results reveal that, in the cases of France and the UK, the carbon tax alone falls short of achieving the short-term climate targets by 2030 (or 2035 for the UK) set forth in their Nationally Determined Contributions. This shortfall is likely attributable to the relatively low carbon intensity of their existing energy mixes, coupled with our model's exclusion of the possibility that the carbon tax boosts clean energy penetration and technological advancements. Therefore, to augment emissions abatement efforts effectively, it is imperative to adopt a multifaceted approach that encompasses both policy measures and technological progress for France and the UK.

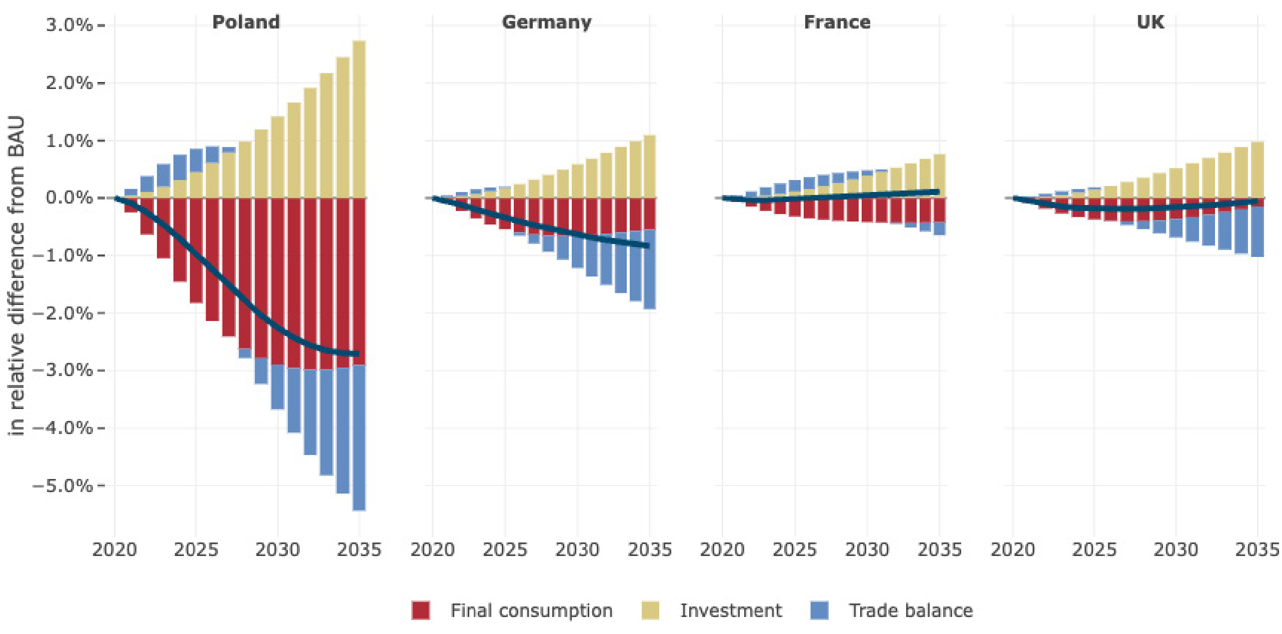
Macroeconomic implications

The implementation of the carbon tax has proven effective in reducing emissions, yet concerns about economic downturns persist, particularly in the absence of proper fiscal revenue redistribution [Frondel, Schubert, 2021; Mashhadi Rajabi, 2023]. These concerns are in line with our simulation results, which indicate that a carbon tax without appropriate redistribution scheme could precipitate an economic downturn.

For Poland, the introduction of the carbon tax leads to a sharp GDP decline until 2030, at 2.26% below the baseline scenario. The rate of decrease then moderates, culminating in a GDP that is 2.71% lower than the baseline by the end of the period. Germany experiences a steadier decline in GDP, ending the period at 0.83% below the baseline. In contrast, the UK's GDP dips initially, falling to 0.19% below the baseline by 2025, before it gradually recovers, closing the period at 0.06% below the baseline.

France, meanwhile, displays a double dividend after a short and slight economic recession. The carbon tax's impact on France's GDP is negative until 2025, but the negative impacts are limited with the largest reduction of –0.04% in 2023. Thereafter, the GDP under the carbon tax scenario begins to outperform the baseline, ending 0.11% higher by 2035. Regardless of the carbon tax's positive or negative impact on GDP, investment growth emerges as a crucial driver of economic growth, while declines in final consumption are responsible for economic contraction. The effects of trade balances on GDP appear to be variable over time.

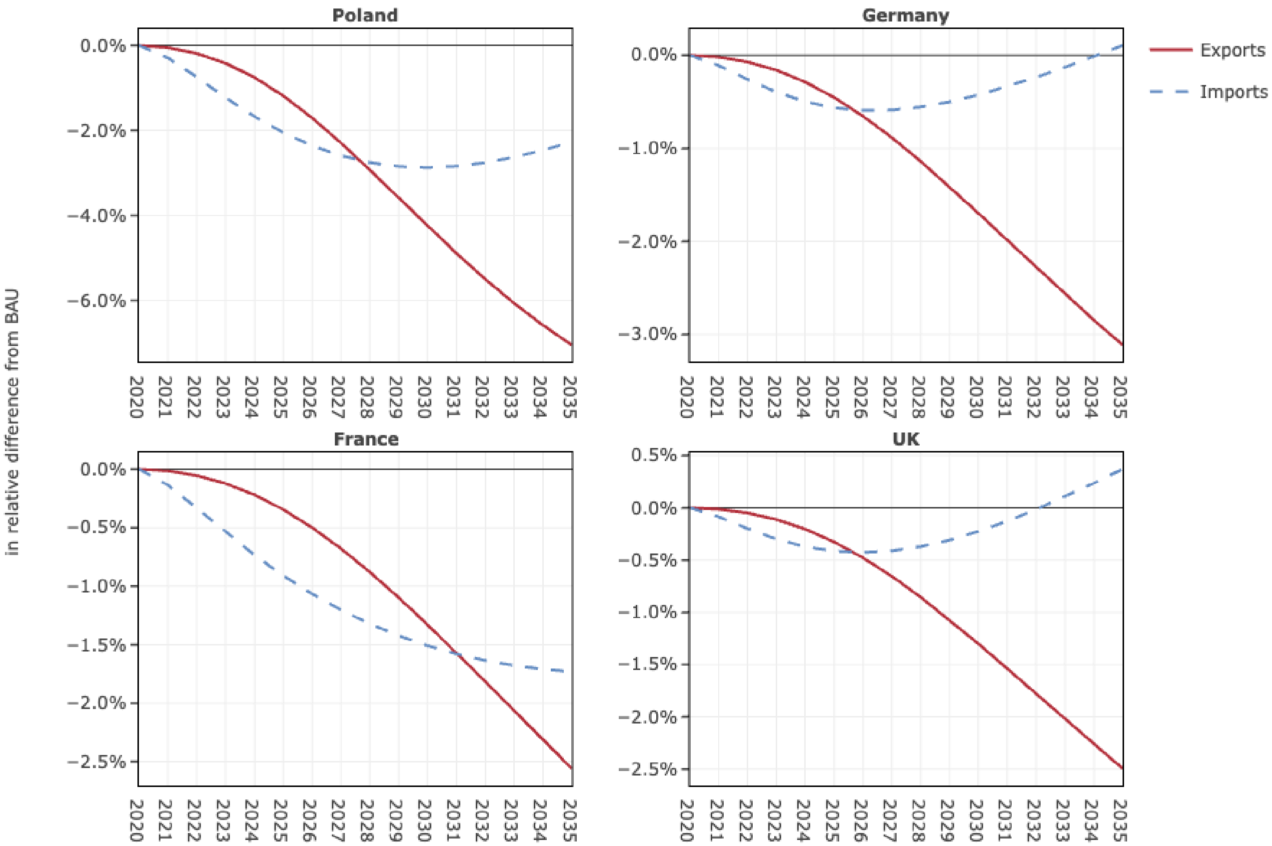
Figure 5. GDP evolution after carbon tax and the contributions of different components, results expressed in relative difference from BAU



Source: Author's own elaboration.

Our simulation results have shown that the positive contribution of investment to GDP grows with the carbon tax rate, suggesting that the carbon tax fosters investment growth. This observation is particularly relevant in light of the previous section's findings, which highlighted the carbon tax's significant role in reducing energy consumption across the economy. So the observed investment growth, notably of construction and manufacturing goods, reflects the fact that the carbon tax effectively encourages industries to move from energy-intensive to capital-intensive production methods, thereby facilitating economic growth and reducing CO_2 emissions. However, the degree to which energy and capital can be substituted for each other varies from country to country. Under a uniform carbon tax rate, the magnitude of aggregated investment growth is observed to be most pronounced in Poland, followed by Germany, the UK, and France.

Figure 6. Imports and exports changes induced by carbon tax, results expressed in relative difference from BAU



Source: Author's own elaboration.

While the carbon tax exerts an overall beneficial effect on investment, its implication for the trade balance across the studied nations is multifaceted. Initially, alterations in the trade balance positively influence GDP growth; however, this beneficial effect gradually diminishes, eventually exerting a negative impact and contributing to economic downturn pressures. The unilateral enactment of a carbon tax diminishes the competitiveness of domestic products, either narrowing the trade surplus or exacerbating the trade deficit. Figure 3 illustrates the aggregated impact on imports and exports, expressed as a percentage deviation from a baseline scenario. Directly, the carbon tax affects exports by elevating the production costs of domestic goods, leading to a marked reduction in exports in all simulated countries, and this decline correlates with the carbon tax rate. Nonetheless, the carbon tax's effect on imports is more complex and indirect. Initially, aggregated imports decline in all countries, likely due to an overall demand decrease induced by the carbon tax. Subsequently, the reduction in imports decelerates and may even reverse in Germany and the UK, a trend potentially attributable to substitution effects between imported and domestic goods. This combination of export reduction and import increase negatively affects GDP growth in Poland, Germany, and the UK. Conversely, in France, the negative impact of the trade balance on GDP growth is mitigated, as imports consistently decline throughout the simulation period, unlike in other countries.

Moreover, the carbon tax demonstrates negative impacts on final consumption. However, our simulations reveal that the reduction in final consumption is not a perpetual trend, even as the carbon tax rate increases. Beyond the initial recession phase, the magnitude of the final consumption loss begins to decline in all the studied countries. Our results indicate a decrease in the consumption of domestic products attributable to the carbon tax, alongside an increase in the consumption of all imported goods except energy products. Specifically, by 2035, domestic goods consumption is projected to decrease by 8.6% in Poland and less than 2% in Germany, France, and the UK, compared to the baseline scenario. Conversely, the consumption of imported goods is expected to increase by 7.2% in Poland, 3.8% in the UK, 1.8% in France, and 2.9% in Germany.

The carbon tax results In an Incre"se i' the price of domestic consumption, thereby diminishing household purchasing power, particularly in the absence of fiscal revenue recycling mechanisms. Concurrently, the rise in domestic consumption prices renders imported goods more competitively priced, as the latter are less impacted by the tax. The increase in the consumption of imported goods partially offsets the negative impacts of the carbon tax on household consumption, but this compensatory effect is limited, and the carbon tax ultimately undermines the purchasing capacity of the economy.

Sensitivity tests

The elasticity of substitution (ES) between capital and energy inputs in production is a critical parameter in modelling frameworks. Different ES values can lead to significantly varied outcomes [**Antimiani et al., 2015**]. In this study, we employed a nested production function (see Fig. 1), adding complexity to the choice of elasticity. To provide a deeper understanding of the ThreeME model and our simulation results, we conducted sensitivity tests using a range of ES values between capital and energy. While varying the ES, we maintained a consistent carbon tax trajectory and assumptions. The main results of these tests for 2035 are displayed in Table 3, expressed as relative differences from the baseline scenario (BAU).

Table 3. Main results of sensitivity test for 2035 using different elasticities of substitution between capital and energy inputs, expressed in relative difference from BAU

Country	Indicator	es = 3	es = 2.5	es = 1	es = 0.5
Poland	Gross domestic product	−2.16%	−2.71%	−4.58%	−5.62%
	Investment	17.49%	13.94%	−1.83%	−8.04%
	Energy consumption of households	−71.60%	−72.76%	−73.08%	−73.70%
	Energy consumption of companies	−65.94%	−63.24%	−44.98%	−35.90%
France	Gross domestic product	0.31%	0.11%	−0.55%	−0.79%
	Investment	4.89%	3.86%	0.74%	−0.38%
	Energy consumption of households	−35.62%	−35.64%	−36.22%	−36.39%
	Energy consumption of companies	−35.87%	−32.38%	−21.11%	−16.80%
Germany	Gross domestic product	−0.65%	−0.83%	−1.53%	−1.81%
	Investment	6.99%	5.37%	0.52%	−1.24%
	Energy consumption of households	−54.52%	−54.01%	−53.98%	−54.01%
	Energy consumption of companies	−66.19%	−62.19%	−47.48%	−41.09%
UK	Gross domestic product	0.19%	−0.06%	−0.84%	−1.13%
	Investment	7.63%	5.93%	1.03%	−0.68%
	Energy consumption of households	−58.28%	−57.92%	−57.92%	−57.90%
	Energy consumption of companies	−60.83%	−57.10%	−45.61%	−41.34%

Source: Author's own elaboration.

The sensitivity test results reveal significant variations in gross domestic product (GDP), investment, and energy consumption across different countries and elasticity scenarios. In all four countries, lower elasticities (es = 1 and es = 0.5) negatively impact GDP, with Poland being the most sensitive (–5.62% compared to BAU). France (–0.79%) and the UK (–1.13%) show moderate changes, while Germany's response (–1.81%) is stable but consistently negative. Investment levels exhibit an interesting trend where higher elasticities (es = 3 and es = 2.5) lead to increased investment, particularly in Poland and Germany. Conversely, lower elasticities (es = 1 and es = 0.5) generally result in reduced investment.

In terms of energy consumption, household behaviour appears less sensitive to changes in the ES between capital and energy. However, for companies, the reduction rate relative to BAU diminishes as the ES value decreases. A lower (higher) ES implies a reduced (greater) ability to substitute between capital and energy, aligning with our simulation results. A higher ES facilitates stronger substitution effects from energy to capital, leading to increased investment and mitigating GDP losses due to the loss of purchasing power. This trend is evident in all studied countries, with higher carbon intensity economies such as Poland showing greater sensitivity to ES variations compared to lower carbon intensity economies such as France.

The weak sensitivity of household energy consumption to ES variations is understandable. The ES between capital and energy for production influences the production inputs of these two factors, subsequently impacting production costs and consumption prices. These effects are indirect compared to measures with direct impacts on household energy consumption.

Conclusion

Using the open-source CGE model ThreeME, we simulated the economic and environmental impacts of a carbon tax that grows linearly from $ 0 in 2020 to $ 250 per ton of CO_2 by 2035 in four European countries – Poland, Germany, France, and the UK. The implementation of the carbon tax significantly reduced CO_2 emissions by 2035, with the greatest reduction observed in Poland (79.1% compared with BAU), followed by Germany (69.6% compared with BAU), the UK (68.3% compared with BAU), and France (49.4% compared with BAU). The variance in reduction rates can be attributed to differences in energy intensity and the carbon intensity of each country's energy mix. Countries with higher energy intensity and a more carbon-intensive energy mix are more responsive to the carbon tax, resulting in greater emissions reductions. In contrast, for countries like France, which already have a lower-carbon energy mix, additional measures – such as the adoption of clean electricity and integrated climate policies – are necessary to meet climate targets.

Investment growth spurred by the carbon tax had a positive impact on GDP in all studied countries. However, declines in final consumption and negative trade balance effects contribute to economic downturns. Countries with higher emissions reductions, such as Poland, are more prone to recessions, and those with trade deficits, such as Poland and Germany, are more affected by the carbon tax compared to countries with trade surpluses, like France and the UK. Additionally, our study highlights that a unilateral carbon tax can lead to carbon leakage through increased imports, underscoring the need for complementary policies that promote international cooperation and address leakage risks.

The sensitivity test results indicate that the energy-saving effects and economic costs of a carbon tax are highly dependent on the elasticity of substitution between capital and energy inputs. In this study, we adopted an ES value of up to 2.5, which produced relatively optimistic outcomes in terms of GHG abatement costs. However, lowering the ES to 0.5 resulted in less favourable results – for example, a 35.9% emissions reduction and a 5.62% GDP decline relative to BAU in Poland by 2035. Moreover, countries with higher carbon intensity in their GDP, such as Poland, exhibit greater sensitivity to changes in the ES compared to lower-carbon-intensity countries like France.

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Data availability statement

All the data used to calibrate ThreeME models could be found on the official website of the databases:

Exiobase 3: https://www.exiobase.eu/

Eurostat: https://ec.europa.eu/eurostat/web/main/data/database

International Energy Agency (IEA): https://www.iea.org/data-and-statistics

The ThreeME model is an open-source CGE model; for more information please visit the official website: https://www.threeme.org/

For other data generated or analysed during the study, please contact the author by email: wang@neo-observatory.nl

Appendix

Table S1. Macroeconomic results of simulation for France

Year	GDP (million \$)	I (million \$)	CH (million \$)	X (million \$)	M (million \$)	PCH (2019 = 1)	UNR	EMS (thousand tons CO_2eq)
2020	2503960	491393,3	1305277	790849,2	847687,4	1,04	8,21%	401,7
2021	2533710	497576,3	1320520	799670,1	856988,9	1,07	8,14%	392,8
2022	2563112	503853,3	1334616	808369,2	865565,3	1,09	8,09%	378,7
2023	2592784	510325,1	1348645	816923,6	873957,3	1,12	8,06%	363,6
2024	2622870	517040,8	1362967	825325,8	882422,5	1,14	8,05%	349,1
2025	2653344	524013	1377643	833579,5	891068,5	1,17	8,05%	335,7
2026	2684151	531237,4	1392651	841698,5	899936,9	1,20	8,07%	323,4
2027	2715261	538705,7	1407963	849703,9	909043,6	1,23	8,10%	312,1
2028	2746673	546411,2	1423563	857622,6	918395,5	1,26	8,14%	301,7
2029	2778409	554349,2	1439449	865484,4	927995,8	1,29	8,18%	292,2
2030	2810499	562516,7	1455625	873320,4	937845,9	1,33	8,22%	283,4
2031	2842974	570910,8	1472092	881160,9	947945,4	1,36	8,27%	275,3
2032	2875866	579528,2	1488852	889034,7	958292,1	1,39	8,32%	267,8
2033	2909198	588364,8	1505902	896968,1	968882,3	1,43	8,36%	260,9
2034	2942992	597415,8	1523238	904984,6	979711	1,46	8,40%	254,5
2035	2977263	606675,2	1540854	913105	990772,3	1,50	8,44%	248,5

Notes: GDP – Gross domestic product, I – Investment, CH – Household final consumption, X – Exports, M – Imports, PCH – Household consumption price, UNR – Unemployment rate, EMS – GHG emissions.

Source: Author's own elaboration.

Table S2. Macroeconomic results of simulation for the UK

Year	GDP (million \$)	I (million \$)	CH (million \$)	X (million \$)	M (million \$)	PCH (2019 = 1)	UNR	EMS (thousand tons CO_2eq)
2020	2595122	426316,8	1654194	788690,1	848789,2	1,04	3,53%	438,3
2021	2625355	431769,3	1673437	797504,1	858687,6	1,07	3,45%	409,8
2022	2655031	437415,3	1691532	806208,9	868156,6	1,09	3,40%	374,7

cont. Table S2

Year	GDP (million $)	I (million $)	CH (million $)	X (million $)	M (million $)	PCH (2019 = 1)	UNR	EMS (thousand tons CO_2eq)
2023	2684974	443366,3	1709676	814774,7	877649	1,12	3,37%	342,1
2024	2715378	449662,3	1728231	823185,6	887360,3	1,14	3,36%	314,0
2025	2746243	456297,2	1747276	831439,8	897362,4	1,17	3,36%	290,2
2026	2777545	463248,6	1766823	839549,2	907680,7	1,20	3,37%	269,9
2027	2809285	470492,9	1786881	847536,8	918324,3	1,23	3,38%	252,7
2028	2841483	478009,4	1807461	855433,6	929293,8	1,26	3,40%	237,8
2029	2874168	485780,7	1828565	863274,9	940583,8	1,29	3,42%	224,9
2030	2907366	493791,3	1850187	871097,5	952182,8	1,32	3,44%	213,7
2031	2941095	502026,4	1872307	878937,6	964074,4	1,35	3,46%	203,8
2032	2975366	510471,2	1894893	886829,2	976238,1	1,38	3,48%	195,0
2033	3010180	519111,2	1917909	894803,4	988651,5	1,42	3,49%	187,2
2034	3045535	527931,8	1941313	902888,1	1001292	1,45	3,50%	180,3
2035	3081425	536919,2	1965067	911107,5	1014136	1,48	3,51%	174,1

Source: Author's own elaboration.

Table S3. Macroeconomic results of simulation for Germany

Year	GDP (million $)	I (million $)	CH (million $)	X (million $)	M (million $)	PCH (2019 = 1)	UNR	EMS (thousand tons CO_2eq)
2020	3565858	725644,4	1916791	1537040	1361101	1,04	2,94%	743,0
2021	3607108	735016,1	1937930	1554179	1376114	1,07	2,88%	704,1
2022	3646802	744625,2	1956848	1570945	1390425	1,09	2,85%	648,4
2023	3686135	754609,9	1975480	1587262	1404839	1,12	2,85%	591,7
2024	3725715	765083,7	1994727	1603111	1419743	1,15	2,88%	540,2
2025	3765774	776090	2014897	1618512	1435278	1,18	2,92%	495,6
2026	3806371	787618,9	2036030	1633516	1451467	1,21	2,98%	457,6
2027	3847517	799635	2058068	1648196	1468281	1,24	3,04%	425,3
2028	3889223	812097,2	2080934	1662640	1485678	1,28	3,11%	397,7
2029	3931517	824967,8	2104548	1676943	1503612	1,31	3,19%	374,2
2030	3974435	838214,9	2128836	1691203	1522038	1,34	3,26%	353,8
2031	4018015	851811,3	2153725	1705513	1540912	1,38	3,34%	336,2
2032	4062288	865732,9	2179142	1719962	1560195	1,42	3,41%	320,8
2033	4107283	879957,9	2205020	1734627	1579850	1,45	3,48%	307,3
2034	4153019	894465,8	2231296	1749576	1599843	1,49	3,55%	295,4
2035	4199514	909237,2	2257917	1764867	1620145	1,53	3,61%	284,9

Source: Author's own elaboration.

Table S4. Macroeconomic results of simulation for Poland

Year	GDP (million $)	I (million $)	CH (million $)	X (million $)	M (million $)	PCH (2019 = 1)	UNR	EMS (thousand tons CO_2eq)
2020	547629,5	107145,2	315529,4	284391,6	270830,9	1,04	3,13%	360,7
2021	553654,1	108678,7	318122,6	287481,7	273306,6	1,07	3,13%	330,3
2022	559214,7	110327,5	319838,5	290359,3	275286,7	1,10	3,21%	288,5
2023	564489,1	112114,4	321259,3	292975,1	277149,1	1,14	3,36%	248,5
2024	569588,8	114064	322698	295308,5	279099,5	1,17	3,57%	214,9
2025	574585,1	116180,2	324309	297363,8	281229,3	1,21	3,80%	188,0
2026	579539,9	118454,3	326170,6	299169	283574,8	1,25	4,07%	166,8
2027	584521,9	120876	328327,8	300771,9	286149,4	1,29	4,35%	150,3

Year	GDP (million $)	I (million $)	CH (million $)	X (million $)	M (million $)	PCH (2019 = 1)	UNR	EMS (thousand tons CO_2eq)
2028	589608,7	123438,1	330807,8	302234,1	288957,6	1,33	4,64%	137,4
2029	594878,3	126136,9	333623,8	303624,1	291999,5	1,38	4,93%	127,3
2030	600399,8	128970,6	336774,4	305009,7	295270,8	1,42	5,21%	119,3
2031	606222,8	131939,4	340238,7	306451,1	298761,7	1,46	5,47%	112,9
2032	612374,5	135042,9	343981	307996,2	302456,9	1,51	5,70%	107,7
2033	618863,2	138276,5	347960,3	309680,3	306337,9	1,55	5,89%	103,5
2034	625682,3	141632	352134,9	311526,8	310385,1	1,59	6,05%	99,9
2035	632816,1	145099,1	356466,6	313549,3	314579,4	1,63	6,17%	96,9

Source: Author's own elaboration.

Table S5. Macroeconomic results of sensitivity tests for 2035, expressed in relative difference from BAU

Country	Indicator	ES = 3	ES = 2.5	ES = 1	ES = 0.5
Poland	Gross domestic product	−2.16%	−2.71%	−4.58%	−5.62%
	Final consumption	−5.04%	−5.03%	−4.80%	−4.82%
	Investment	17.49%	13.94%	−1.83%	−8.04%
	Imports	−2.01%	−2.27%	−3.17%	−3.42%
	Exports	−7.07%	−7.05%	−5.83%	−5.71%
	Energy consumption of households	−71.60%	−72.76%	−73.08%	−73.70%
	Energy consumption of companies	−65.94%	−63.24%	−44.98%	−35.90%
France	Gross domestic product	0.31%	0.11%	−0.55%	−0.79%
	Final consumption	−0.79%	−0.82%	−0.89%	−0.92%
	Investment	4.89%	3.86%	0.74%	−0.38%
	Imports	−1.79%	−1.73%	−1.44%	−1.32%
	Exports	−2.67%	−2.56%	−2.28%	−2.18%
	Energy consumption of households	−35.62%	−35.64%	−36.22%	−36.39%
	Energy consumption of companies	−35.87%	−32.38%	−21.11%	−16.80%
Germany	Gross domestic product	−0.65%	−0.83%	−1.53%	−1.81%
	Final consumption	−0.94%	−1.02%	−1.27%	−1.37%
	Investment	6.99%	5.37%	0.52%	−1.24%
	Imports	0.35%	0.10%	−0.51%	−0.70%
	Exports	−3.33%	−3.11%	−2.65%	−2.52%
	Energy consumption of households	−54.52%	−54.01%	−53.98%	−54.01%
	Energy consumption of companies	−66.19%	−62.19%	−47.48%	−41.09%
UK	Gross domestic product	0.19%	−0.06%	−0.84%	−1.13%
	Final consumption	−0.13%	−0.24%	−0.55%	−0.67%
	Investment	7.63%	5.93%	1.03%	−0.68%
	Imports	0.50%	0.37%	0.10%	0.03%
	Exports	−2.68%	−2.50%	−2.06%	−1.92%
	Energy consumption of households	−58.28%	−57.92%	−57.92%	−57.90%
	Energy consumption of companies	−60.83%	−57.10%	−45.61%	−41.34%

Source: Author's own elaboration.