George *et al.*
*Energy, Sustainability and Society* (2024) 14:19
https://doi.org/10.1186/s13705-024-00450-7

Energy, Sustainability
and Society

**RESEARCH** **Open Access**

# Balancing the books: unveiling the direct impact of an integrated energy system model on industries, households and government revenues

Jan Frederick George[1,2*], Alexander Marx[3], Anne Held[1], Jenny Winkler[1], Anke Bekk[1] and Mario Ragwitz[2,4,5]

## Abstract

**Background** The transition towards a sustainable energy system is reshaping the demand for final energy, driven by the diffusion of new end-use technologies. This shift not only impacts consumers' energy expenses, but also holds implications for the public budget. Building on data from a German energy transition scenario, we analyse the direct impact of energy costs on industries, low-income households, and changes in government revenues from the taxes and levies on final energy carriers. Our analysis considers the impact of current policies and explores a scenario introducing additional excise tax rates to offset potential revenue losses.

**Results** We found that substantial carbon price increases could generate revenues that offset the losses from excise taxes on fossil fuels while enabling the financing of renewable support from the public budget by the end of this decade. Nevertheless, a decline in government revenues from taxes and levies is anticipated after 2030 until the middle of the century due to the declining use of fossil fuels. Maintaining current excise tax revenues during the transition could be achieved by introducing additional excise taxes on fossil fuels and electricity. Lastly, our analysis indicated a continuous decline in household energy expenditures until 2050, whereas energy-intensive industries face adverse impacts due to decarbonisation.

**Conclusions** This research provides valuable insights into the fiscal implications of the energy transition, shedding light on different industrial sectors and households while considering the evolving impact on the public budget. Policymakers may need to consider systemic reforms or alternative financing mechanisms outside the energy system to balance the books.

## Highlights

- Micro-simulations analysing the impact of taxes and levies on final energy
- Decreasing fossil final energy demand leads to substantial losses of government revenues
- Energy-intensive industries are adversely affected by decarbonisation
- Household energy costs are expected to decline

*Correspondence:
Jan Frederick George
jan.george@isi.fraunhofer.de
Full list of author information is available at the end of the article

**Keywords** Carbon prices, levies, taxes on final energy, Consumer impact, Industry decarbonisation, Government revenues and sectoral distribution, Real unit energy costs

## Background

Climate change mitigation requires substantial changes in energy conversion and utilisation [1]. Detailed system models consistently indicate that decarbonisation efforts will be characterised by the integration of renewable electricity in the industrial, transport, heating and cooling sectors, thereby forming an integrated energy system [2, 3].

However, as [4] argues, increasing electrification using emerging technologies poses challenges to various stakeholders and has become a focal point for resistance. There needs to be a greater understanding of the potential consequences of this transition for individual consumers [5]. However, impact analyses usually focus on aggregated welfare losses and do not cover detailed distributional consequences [6–9].

Given the heterogeneity among energy consumers, ranging from energy-intensive manufacturing industries with high annual production hours to low-income households in poorly insulated dwellings, it can be assumed that the impact of the energy transition is likely to vary among consumers. Rising energy costs during the transition can increase production costs, affecting industries' competitiveness as well as exacerbating energy poverty. Indirect effects, such as carbon leakage (industries moving to countries with cheaper energy prices) or weakened global market competitiveness, may also result [7, 10].

Therefore, this study's *first research topic* aims to assess the potential impact of energy costs on individual consumers, such as firms and households, over time as emerging electricity-based technologies are deployed. By examining the energy expenses of individual consumers during the transition, the findings will provide a foundation to identify which consumers and sectors are likely to experience particularly heavy burdens from rising energy costs and need support to facilitate their successful integration into a sustainable energy future.

The energy costs for individual consumers are determined by the retail prices for final energy. These not only comprise wholesale prices and mark-ups for procurement, supply and margins, but also taxes and other levies such as state-induced components (SIPC), for example, excise taxes, carbon prices and grid fees. As the prevailing SIPC architecture evolved within a fossil-dominated energy system, there may be challenges for consumers and different distributional impacts in different sectors as they switch to renewable electricity-based technologies.

Moreover, many SIPC on final energy have provided stable government revenues due to the inelastic energy demand [11]. However, as the energy system transitions towards an increasing use of renewable electricity, targeted reductions of $CO_2$-emitting final energy carriers mean changes in the contribution of SIPC revenues to the public budget. This can substantially affect the public budget, as observed in a Slovenian case study on the transport sector [12]. In addition, as different sectors have distinct energy end-uses, the transition is likely to change the sectoral distribution of SIPC payments.

To steer energy demand towards climate neutrality, many countries have introduced emissions trading systems (ETS) as market-based policy instruments to internalise external costs and incentivise a shift from fossil to renewable energy by increasing carbon prices as part of the SIPC [13]. Rising carbon prices could provide additional government revenues, which could be used to finance policies supporting the energy transition. At the same time, however, carbon prices also represent an additional financial burden on consumers during the transition. Although they are similar to excise taxes on fossil fuels, carbon price revenues will actually decrease to zero as fossil fuels are phased out of energy systems. Nonetheless, increasing carbon prices can supplement government revenues in the medium term [14].

Consequently, because the energy transition is likely to burden consumers and decrease government revenues, policymakers should seek to balance the books when developing strategies and policies that provide subsidies or reductions and exemptions for SIPC in order to mitigate the impact of increasing energy costs on consumers while maintaining stable finances in the transition towards an electricity-based energy system.

To the best of our knowledge, the expected changes to national and sectoral government revenues from SIPC in the transition towards an integrated electricity-based energy system have not yet been comprehensively analysed. Therefore, this study's *second research topic* aims to assess the development of government revenues from SIPC and the sectoral contributions of SIPC payments in this transition. Both dimensions, energy costs for consumers and government revenues, are of interest to policymakers who need to identify the cost burdens for consumers and gain an advance overview of the implications for government revenues due to the energy transition.

To conduct the impact analysis on industries, households, and government revenues, we used energy demand data from a bottom-up model that identifies pathways towards an integrated energy system. Unlike macroeconomic models that rely on uncertain substitution elasticities [15, 16], the results of bottom-up models provide more precise information, accounting for technological substitution, the existing technology stock, investment cycles, and the diffusion of emerging electricity-based process routes and technologies [15, 17]. Consequently, the detailed transition paths of bottom-up models enable the allocation of final energy demand to industrial subsectors and household income segments, which enables an assessment of the associated energy costs.

We focus our study on Germany, an economically strong country in the European Union with considerable industrial value creation, comprehensive SIPC policies providing various exemptions and reductions for manufacturing industries, and ambitious climate protection goals [18]. Additionally, excise taxes on final energy contribute substantially to Germany's public budget with around €47 bn (around 6% of the total public budget in each year between 2018 and 2020 [19]).

Furthermore, Germany introduced a levy on electricity prices to finance the support for renewables with the launch of its Renewable Energy Act in 2000. In principle, every unit of electricity was charged equally, and the German transmission grid operators determined the levy rate yearly. However, there were substantial reductions for industrial consumers with high electricity demand (see §64 EEG).

In the past, all taxes and levies came with substantial reductions and exemptions for industrial users [20, 21]. Given these tax privileges, excise tax reforms resulting in higher SIPC rates in Germany show that these effectively reduced industrial energy demand while having low adverse employment effects [22]. Additionally, in the German manufacturing sector, no differences in competitiveness could be observed between firms receiving and those not receiving an electricity excise tax rebate [23]. In an empirical study, Rosenberg et al. [24] found that raising industries' SIPC on electricity had no noticeable impact on firms' performance. Nonetheless, the responses in a survey of 1500 executives of German industrial firms indicated that raising the electricity excise tax could hamper the future of Germany's energy-intensive industries, among which the metal processing and basic chemicals producing industries have the highest risks [25].

Lutz et al. [26] use a macroeconomic model to demonstrate how changes of SIPC can be employed to reach climate targets and show effects for different industries. Großmann et al. [27] extend this model and incorporate more detailed SIPC privileges. Their results suggest that SIPC can be raised on industrial consumers without decreasing their competitiveness. However, this model does not explicitly account for switching from fossil fuels to electricity-based production technologies. Using a regional input–output model, Többen [28] examines the direct and indirect effects of the renewable levy on German industries, but without considering substitution elasticities between electricity and fossil fuels.

Implementing the European Emissions Trading Scheme (EU ETS) in 2005 and the national ETS in 2021 have generated additional government revenues from carbon prices. The intention is to use these revenues to partially fund the renewable support scheme, which became part of the state budget in 2022 [29]. The renewable support scheme was projected to costs approximately €23 bn in 2022 [30], with expected future cost reductions [31]. However, it is expected that the revenues from carbon pricing will probably remain below the volume required to finance the renewable support until 2025 [32].

Consequently, the analysis of Germany provides insights into a comprehensive SIPC architecture, which makes it possible to transfer the analysis to nations with different SIPC regulations.

This paper aims to investigate the direct impacts of Germany's energy transition towards an integrated, electricity-based energy system on industrial subsectors, low-income households, and the public budget and how these impacts evolve over time. We conduct micro-simulations to reproduce government revenues and sectoral contributions. Further, we calculate the direct cost impacts of two SIPC policies on industrial and low-income household segments based upon wholesale price projections and grid charge developments from the literature. We simulate two scenarios: Scenario A reflects the current stated policies. In scenario B, we simulate an additional excise tax on final energy. This helps policymakers to identify consumers especially burdened by energy costs and the potential development of government revenues from SIPC over the course of the energy transition.

The paper is structured as follows. Methods section explains our modelling approach to calculating government revenues and the sectoral distribution of SIPC payments and measuring the direct impact on consumers. Results section presents the simulation results and we close with a discussion and conclusions part in Discussion section.

## Methods

For Germany, as part of the European energy system, various bottom-up system studies have evaluated potential pathways for achieving climate neutrality [33–37]. These scenario studies differ, especially in the expected share of direct electrification and use of synthetic energy carriers [38]. By comparing different technology diffusion scenarios, the authors of [33] found that large-scale direct electrification of processes and applications is the most cost-efficient energy supply option. Due to the comprehensive data provided, we base our contribution on the scenario studies described in [33]. We use the scenario "TN Strom", which reaches net-zero emissions in 2050 primarily through electrification, as it meets final energy demand at the lowest energy system cost compared to other scenarios.

This scenario study employs an extensive bottom-up approach to ensure a sustainable and resilient European energy system. Starting from the historical technology stock and consumption behaviour in 2020, the scenario study simulates the diffusion of technologies and energy efficiency measures across all demand sectors to achieve climate neutrality by 2050.

In the following section, we outline our approach to simulate the impact of the final energy demand from this scenario study on the public budget. We consider the SIPC on final energy, including relevant reductions and exemptions of the current taxation scheme on final energy and the distribution of payments among the sectors of industry, commerce trade and services (CTS), households and public transport in Germany. We present our modelling approach to measure the direct impacts on industrial subsectors and households. Subsequently, we simulate two SIPC policy scenarios. In the analysis, we use real values with the base year of 2020, abstracting from inflation.

### Model description to simulate the effects on the public budget

To analyse the government revenues and their sectoral distribution from SIPC on final energy prices, we consider fiscal income $I_i^f(t)$ in euro per year $t$ from the most relevant revenue streams $i$, comprising excise taxes on fossil energy [Energy Tax Act (2017)] and electricity [Electricity Tax Act (2019)], and from carbon prices as described in Eq. (1):

$$I_i^f(t) = \sum_{\varepsilon} E_{\varepsilon,\rho}(t) * p_{\varepsilon,\rho}^s(t). \tag{1}$$

There are (partial) exemptions and special regulations for specific end-uses, processes and consumers, such as manufacturing industries facing international competition. We cover the most relevant SIPC rates $p_\rho^s$, indicated by $\rho$ either as the regular rate or a privileged rate.

The annual final energy demand $E_\varepsilon(t)$ is distinguished by the final energy carrier $\varepsilon$. Resulting $CO_2$ emissions $Q_\varepsilon\left(E_\varepsilon, ef_\varepsilon, t\right)$ are calculated by multiplying the emission factor $ef_\varepsilon$ of the final energy carrier by the final energy demand.

We use official data from [39] and [19, 40–43] to allocate the historical final energy demand to the regular and privileged income streams of the industry, CTS, households, and transport sectors. The development of final energy demand until 2050 is taken from [33].

We align the privileged categories to existing laws and regulations in Germany. To enhance practicality and provide a more comprehensive overview of the reduced tax rates, we convert the statutory reduced tax rates into percentages relative to the regular tax rates. For the excise tax, apart from the regular rate, we distinguish between full tax exemptions for specific processes and a 25% reduction from the regular rate for both fossil fuels and electricity for manufacturing industries. Additionally, we consider a peak tax compensation rate for the manufacturing industry that reduces the regular excise tax rate by 73%. There are exemptions on regular tax rates for public transport and air traffic for electricity, gasoline, diesel, kerosene, and natural gas. Based on the current reduction rates, we consider a reduced rate for each mobility fuel. Synthetic final energy carriers, e.g. kerosene, are taxed as their fossil counterparts. SIPC are not applied to evolving synthetic energy carriers like hydrogen.

The renewable support levy (Renewable Energies Act) is considered for 2019 and 2020 as a balanced budget policy until its financing reform in 2022.[1] After 2022, we consider this under public expenses. Privileged categories for the renewable levy on electricity are divided into full exemption and a special compensation scheme. In some instances, full exemption is granted for the self-consumption of on-site power plants. Reduced self-consumption rates imply an 80% reduction for modernised existing plants and a 60% reduction for renewable and efficient gas plants. The special compensation scheme applies to electricity-cost-intensive companies (BesAR) and represents a 95% reduction from the regular rate.

Table 1 displays an overview of all income streams considered.

To allocate the final energy demand to each fiscal income stream, we considered the share of final energy demand granted privileged energy tax rates in the reference year (further explanations in Appendix). For fossil energy demand, we assumed the share of privileged final energy demand remains constant over time. Concerning direct electrification technologies, we allocated and updated the electricity demand to the income streams

---

[1] We define a balanced budget policy as one that generates sufficient income to finance its expenditure and, therefore, does not draw on the public budget.

**Table 1** Considered fiscal income streams from state-induced price components

| **Income stream *i*** | **Excise tax** | | | | | **Carbon price** | **Renewable support** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **SIPC rate $\rho$, reductions in % of the regular rate** | **Regular rate** | **Privileged process** | **Producing industries** | **Peak compensation** | **Public transport** | **Regular** | **Regular** | **Self-consumption** | **BesAR (95%)** | **80%** | **60%** |
| Coal | €/MWh | 0% | – | – | – | €/$t_{CO2}$ | – | – | – | – | – |
| Diesel | €/MWh | – | – | – | 11% | €/$t_{CO2}$ | – | – | – | – | – |
| Electricity | €/MWh | 0% | 75% | 27% | 50% | Included in wholesale price[a] | €ct/kWh | 0% | 5% | 20% | 40% |
| Gasoline | €/MWh | – | – | – | 8% | €/$t_{CO2}$ | – | – | – | – | – |
| Heating oil | €/MWh | 0% | 75% | – | | €/$t_{CO2}$ | – | – | – | – | – |
| Kerosene | €/MWh | – | – | – | 0% | – | – | – | – | – | – |
| Natural gas | €/MWh | 0% | 75% | – | 7% | €/$t_{CO2}$ | – | – | – | – | – |

*Excise tax:* regular excise tax rates for fossil final energy are based on the §2 Energy Tax Act and converted to €/MWh with lower heating values. The regular excise tax rate for electricity according to §3 Electricity Tax Act. Processes according to §51 Energy Tax Act and §9a Electricity Tax Act; manufacturing industries according to §54° Energy Tax Act and §9b Electricity Tax Act; public transport according to §56 Energy Tax Act and combined rate for §§9 Abs. 2 and 9c Electricity Tax Act. *Carbon price:* only kerosene is exempt. *Renewable support*: privileges for self-generated final consumption depend on the type of plant and when it began operation according to §§61—61f Renewables Energy Act. For the specific compensation scheme BesAR, a uniform rate is assumed as an average reduction according to the §64 Renewables Energy Act. [a]It is assumed that electricity generators forward carbon prices to the wholesale electricity market over time according to the share of electricity used in processes. The share of electrified processes is further described in Appendix. The regular rate is allocated to the residual final energy demand from the total demand.

We derived individual sector allocation factors $\alpha f_s$ to distribute the national final energy demand of each income stream to a sectoral energy demand $E_i^s$ according to Eq. (2). The individual allocation of energy demand to the income streams in each sector is described in Appendix.

$$E_i(t) = \sum_s E_i^s(t) = \sum_s E_i(t) * \alpha f_s. \tag{2}$$

The values from 2019 serve as a pre-crisis reference. Revenues from carbon prices on fossil secondary energy carriers used for electricity generation are not included in this analysis.

### Simulation of the direct impact on consumers

We investigate the direct impact of the "TN Strom" scenario [33] on selected manufacturing industries and low-income households.

We use a bottom-up approach and calculate the final energy price $p_\varepsilon(j,t)$ in euro per megawatt-hour by adding consumer-specific price components. These consist of the SIPC rates, the market-based price component $p_\varepsilon^m(j,t)$ and, if applicable, infrastructure-related levies $p_\varepsilon^g(j,t)$ for consumer type $j$ distinguished into households and industries at a subsector level. Assumptions about the developments of price components and consumer-specific calculations of SIPC rates can be found in Appendix.

We study the consequences of the energy transition scenario for each industry by looking at the real unit energy costs RUEC. This approach is recommended by several authors (e.g. [44, 45]). The RUEC are defined as the energy costs relative to the value added (see Eq. 3):

$$\mathrm{ruec}^k(t) = \frac{C_E^k(t)}{\mathrm{GVA}^k(t)}, \tag{3}$$

where $C_E^k$ represents the annual costs of final energy and $\mathrm{GVA}^k(t)$ the gross value added. To show the impact of changes in energy costs on the gross value added, we first add back the energy costs to the value added in 2019 in Eq. (3).

The growth rate underlying the scenario "TN-Strom" is used to extrapolate the gross value added into the future. We then use the output growth rate $g$ underlying the scenario study "TN Strom" to extrapolate each subsector. Then we deduct the calculated energy costs. The derivation of the energy costs $C_E^k$ are explained in Appendix. Therefore, the value added at time $t$ for industry $k$ is:

$$\begin{aligned}\mathrm{GVA}^k(t) = & \left(\mathrm{GVA}^k(2019) + C_E^k(2020)\right) \\ & * \left(1 + g(t)\right)^{t-2020} - C_E^k(t).\end{aligned} \tag{4}$$

Vulnerable households are of special interest when analysing energy cost impacts from the transition towards an integrated energy system. To analyse the cost impacts, we conduct micro-simulations of the real cost share of total final energy costs $\mathrm{rcse}^d$ distinguished for equivalent disposable income (EDI) deciles $d$ of households, as described in Eq. (5). This metric was used in studies [46–49] to analyse the cost impacts and distributional effects of the SIPC framework on households. The EDI is determined by dividing a household's total net disposable income by an equivalence factor, assigning each household to an EDI decile using the modified OECD equivalence factor[2] [50]. This widely used approach ensures the equalisation of incomes across different household compositions:

$$\mathrm{rcse}^d(t) = \frac{C_E^d(t)}{I^d(t_{2019})} \tag{5}$$

The energy costs $C_E^d(t)$ are obtained by multiplying the demand by the energy prices, including the respective SIPC of different SIPC policy scenarios. The energy costs within each EDI decile are calibrated for 2019 based upon historical energy demand and energy prices. For this purpose, the module takes the average energy demand of each final energy carrier per EDI decile from [47] and the income $I^d$ per EDI decile household from [51]. The average energy demand, energy cost and income per EDI decile make it possible to simulate the vertical distributional effects of SIPC impact in the household sector.

We extend this approach to analyse the cost impacts of SIPC policies on EDI households by accounting for future energy demand in the transition towards an integrated energy system. To incorporate this development, annual changes in final energy demand for each EDI decile are extrapolated based on the relative change in final energy demand observed in the household sector of scenario studies. In accordance with the other calculations, we based this on the "TN Strom" scenario defined in the official German Long-Term Scenarios study. More details on the assumptions and sources for the development of final energy demand and grid fees are provided in Appendix.

---

[2] The EF is a sum of weights that take into account the age and number of household members. The first member is assigned a weight of 1, while each additional household member aged 14 or older is assigned a weight of 0.5, and younger members are assigned a weight of 0.3.

**Table 2** Assumed carbon price developments

| Sensitivity | ETS | year | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Low | nETS | €$_{2020}$/t$_{\mathrm{CO2}}$ | – | 38.7 | 96.9 | 140.2 | 174.2 | 200.4 | 220.0 |
| | EU ETS | €$_{2020}$/t$_{\mathrm{CO2}}$ | 24.6 | 90.0 | | | | | |
| High | nETS | €$_{2020}$/t$_{\mathrm{CO2}}$ | – | 38.7 | 130.0 | 225.0 | 300.0 | 300.0 | 300.0 |
| | EU ETS | €$_{2020}$/t$_{\mathrm{CO2}}$ | 24.6 | 100.0 | | | | | |

Assumption that carbon prices from EU ETS and nETS are merged in 2030. Sources: carbon price nETS: value in 2025 according to the German Fuel Emissions Trading Act. Carbon price EU ETS: value in 2020 based on [52], value in 2025 based on ETS futures of [53] accessed 14th of July 2023; sensitivity with low carbon prices real values for 2020 from [52]; sensitivity with high carbon prices from scenario [33]

### Scenario description

We investigate the impact of two SIPC policy scenarios and calculate each with two carbon price developments as depicted in Table 2.

As of July 2022, renewable support is financed outside the energy system from the public budget and is no longer applied as an SIPC on electricity.

#### *Scenario A: stated policy*

This scenario follows the stated SIPC policies on final energy prices. We try to model tax exemptions and reductions for industries as closely as possible to the current tax law. We do not consider changes in the SIPC policies over time.

#### *Scenario B: additional excise tax*

This scenario considers an additional excise tax on final energy prices to provide an additional income $\hat{I}$, to keep the revenues from excise taxes on fossil final energy and electricity at the 2019 level of €46 bn [40, 41]. This scenario shows how the tax regime in the energy sector would have to change in order to maintain the same level of state revenues.[3] The required income from the additional excise tax is calculated as described in Eq. (6):

$$\hat{I}(t) = I_{\mathrm{tax}}(t) = I_{\mathrm{tax}}(t_{2019}) - I_{\mathrm{tax}}(t), \quad \text{if } I_{\mathrm{tax}}(t) > 0. \tag{6}$$

The additional excise tax considers the current privileged tax rates described in Model description to simulate the effects on the public budget section. The financing volume is divided between fossil final energy and electricity, each according to its share in the total final energy volume according to Eq. (7), (8) and (9):

$$\hat{I}(t) = \hat{I}_{\mathrm{elec}}(t) + \hat{I}_{\mathrm{fossil}}(t) = (\alpha r_{\mathrm{elec}}(t) + \alpha r_{\mathrm{fossil}}(t))\hat{I}, \tag{7}$$

$$\alpha r_{\mathrm{elec}} = \frac{E_{\mathrm{elec}}}{\sum_{\varepsilon} E_{\varepsilon}}, \tag{8}$$

$$\alpha r_{\mathrm{fossil}} = \frac{E_{\mathrm{fossil}}}{\sum_{\varepsilon} E_{\varepsilon}}. \tag{9}$$

The additional income from the excise tax on fossil final energy $\widehat{I}_{\mathrm{fossil}}$ is distributed according to the share $\alpha Q_{\varepsilon}$ of total $CO_2$ emissions caused by the energy carriers in Eq. (10):

$$\alpha Q_{\varepsilon} = \frac{Q_{\varepsilon}}{\sum_{\mathrm{fossil}} Q_{\varepsilon}}. \tag{10}$$

This excludes synthetic fossil energy carriers from the additional excise tax. To obtain the additional regular tax rate $\widehat{p}_i^s$ while considering the current privileged categories described in Model description to simulate the effects on the public budget section, we rearrange Eq. (11) and Eq. (12), which leads to the additional excise tax rates per kilowatt-hour:

$$\hat{I}_{\mathrm{fossil}}(t) = \sum_i E_{\varepsilon,i}(t)\hat{p}^s_{\varepsilon,i}(t), \quad \text{for } \varepsilon = \text{fossil fuels}, \tag{11}$$

$$\hat{I}_{\mathrm{elec}}(t) = \sum_i E_{\varepsilon,i}(t)\hat{p}^s_{\varepsilon,i}(t), \quad \text{for } \varepsilon = \text{electricity}. \tag{12}$$

Appendix also contains the description of a sensitivity analysis to estimate the influence of demand response to rising energy prices due to the additional excise taxes.

## Results

This section presents the results of the impact on consumers, the total fiscal revenues and the sectoral distribution of SIPC payments.

### Direct impact on the public budget

Figure 1 shows the results of simulating the national fiscal income due to applying SIPC to final energy in both scenarios.

---

[3] Alternatively, the state might have to increase or reallocate revenues from other sectors. Analysing the effects of such more structural changes is, however beyond the scope of this paper. Depending on the political setting, reallocating budgets might also prove difficult [54].

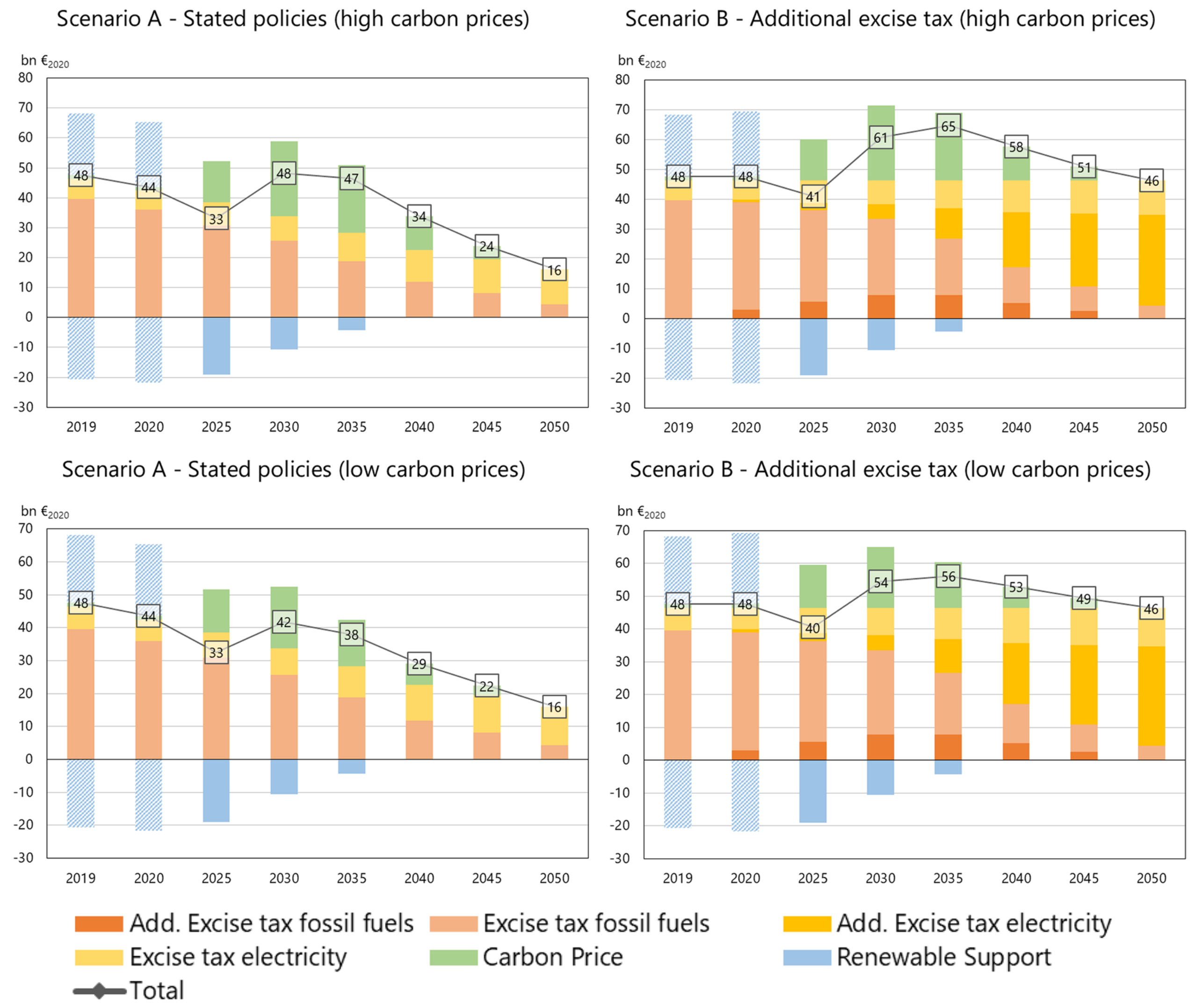


**Fig. 1** Direct impact on public budget of energy-related taxes and other levies for Germany 2020 to 2050. *Note:* Renewable support in 2019 and 2020 is considered as a balanced budget, afterwards financed from the public budget (Source: own calculation)

The results show changes in revenues from excise taxes on fossil fuels and electricity, the carbon price and the amount of funding required for the renewable support. In 2019, the reference year for this analysis, the fiscal revenues from excise taxes on electricity and fossil final energy as well as the EU ETS on fossil final energy demand in the industrial sector amounted to €48 bn. Together with the renewable support paid by electricity consumers via the renewable levy on electricity, the total government revenues from SIPC were €68 bn. From this point onwards, the two scenario simulations show that the development of fiscal income could veer in different directions in the short to medium term.

Scenario A, with high carbon prices, shows fiscal revenues of €52 bn from SIPC in 2025, with 26% of this from the EU ETS and nETS carbon prices. The net balance of SIPC revenues and expenses of renewable support is €33 bn. Compared to 2019, the net contribution to the public budget decreases by 22%. This effect is similar to the lower carbon prices applied in scenario A, but net payments in both carbon price cases diverge afterwards.

With the expected decrease in renewable support, net payments increase compared to 2025 by €15 bn to €48 bn with high carbon prices (and by €9 bn to €42 bn with low carbon prices) to the highest net revenues in 2030.

From 2040 onwards, it is assumed that no further renewable support is needed. However, there is a further shift away from fossil final energy to electricity in the energy demand considered in the scenario study "TN Strom". This means strong decreases in revenues from

**Table 3** Regular and additional excise tax rates on final energy carriers in scenario B

| €/MWh (LHV) | Regular rate | Additional tax rate in | | |
|---|---|---|---|---|
| | | 2030 | 2040 | 2050 |
| Diesel | 47.2 | 9.4 | 24.7 | – |
| Electricity | 20.5 | 12.2 | 35.4 | 53.5 |
| Gasoline | 72.6 | 8.0 | 21.0 | – |
| Heating oil | 6.2 | 10.4 | 30.9 | – |
| Kerosene | 0.0 | 4.1 | 10.9 | – |
| Natural gas | 5.5 | 7.8 | 21.9 | – |

Source: own calculations

the excise taxes on fossil fuels. These drop to €12 bn in 2040, equivalent to 30% of the excise tax revenues from fossil fuels in 2019. At the same time, revenues from the excise tax on electricity increase, but do not compensate for the reduced income from excise taxes on fossil fuels. This is due to the projected increases in energy efficiency measures and technology diffusion of the underlying scenario study "TN Strom". With the increasing use of electricity in heat pumps and battery electric vehicles, final energy demand decreases compared to conventional applications, as sector coupling provides higher efficiencies for final energy conversion. Therefore, total revenues from excise taxes on fossil fuels and electricity decrease with increasing decarbonisation of the energy system. Furthermore, carbon prices will no longer contribute to government revenues once sustainable energy carriers fully cover final energy demand. Consequently, total SIPC revenues reduce to €16 bn in both carbon price paths of scenario A in 2050, which is 34% of the contribution to the public budget compared to 2019.

In scenario B, an additional excise tax on fossil fuels and electricity is assumed to maintain the excise tax revenues of €46 bn from 2019. Tax rates need to increase annually to fill the gap of decreasing excise tax revenues. The necessary tax rates for the additional excise tax are displayed in Table 3.

The additional excise tax on electricity has to increase to €53.5/MWh in 2050, which is around 2.6 times higher than under current policies (€20.5/MWh). The additional excise tax for fossil fuels reflects the total $CO_2$ emissions of each energy carrier. This approach leads to significant increases in SIPC, especially for natural gas and heating oil used as final energy for heating applications, but also for kerosene for aviation. As synthetic fuels are carbon–neutral, no additional excise tax will be applied to them. Consequently, the additional excise tax in 2050 is only assumed for electricity.

Applying these additional tax rates keep the revenues from excise taxes on final energy at €46 bn until 2050. The estimated changes to government revenues as the result of demand response with price elasticities from literature values remain below 0.3% (see Fig. 9 in Appendix). To understand the distribution of SIPC payments among the sectors of industry, CTS, households and transport, the following section shows the simulation results for both scenarios.

## Sectoral distribution of SIPC payments

The sectoral distribution of SIPC payments for both scenarios with high carbon prices is shown in Fig. 2 for 2019, 2030, 2040, and 2050. The results with lower carbon prices can be found in Appendix (Fig. 10), as the results do not differ substantially.

In 2019, households contributed the most to the fiscal income from SIPC on final energy with €33 bn, which also includes the final energy for private mobility such as gasoline and diesel. The second highest SIPC payments of €13 bn came from the transport sector, almost entirely from the excise taxes on fossil fuels and covering all the final energy used for commercial mobility, including public transport. The highest share of SIPC payments in the CTS and industrial sectors were related to renewable support payments, summing up to €13 bn and €8 bn, respectively. CTS and households contributed the most to renewable support payments with €9 bn and €8 bn, respectively, followed by industry with €4 bn, while the transport sector contributed less than 1%.

In 2030, the SIPC payments of households decrease slightly in scenario A with high carbon prices compared to 2019 and increase by €3 bn in scenario B. In the following decades, the household payments decrease in both scenarios to €4 bn (scenario A) and €14 bn (scenario B) in 2050. The notable decrease in excise tax payments on fossil fuels within the household sector is linked to the projected reduction in the demand for gasoline and diesel due to the widespread adoption of battery electric vehicles as outlined in the scenario study "TN Strom".

Until 2030, the SIPC payments of the CTS sector decrease by 51% and 45% in scenario A and scenario B, respectively, with high carbon prices compared to 2019. This indicates to the relatively low use of fossil fuels in this sector. While in scenario B, SIPC payments of the CTS sector stay at the same level, scenario A shows a further decrease to €2 bn until 2050.

In the industrial sector in 2030, SIPC payments in scenario A remain at similar levels as in 2019, even without further payments for renewable support. Instead, this gap is filled by payments from rising carbon prices.

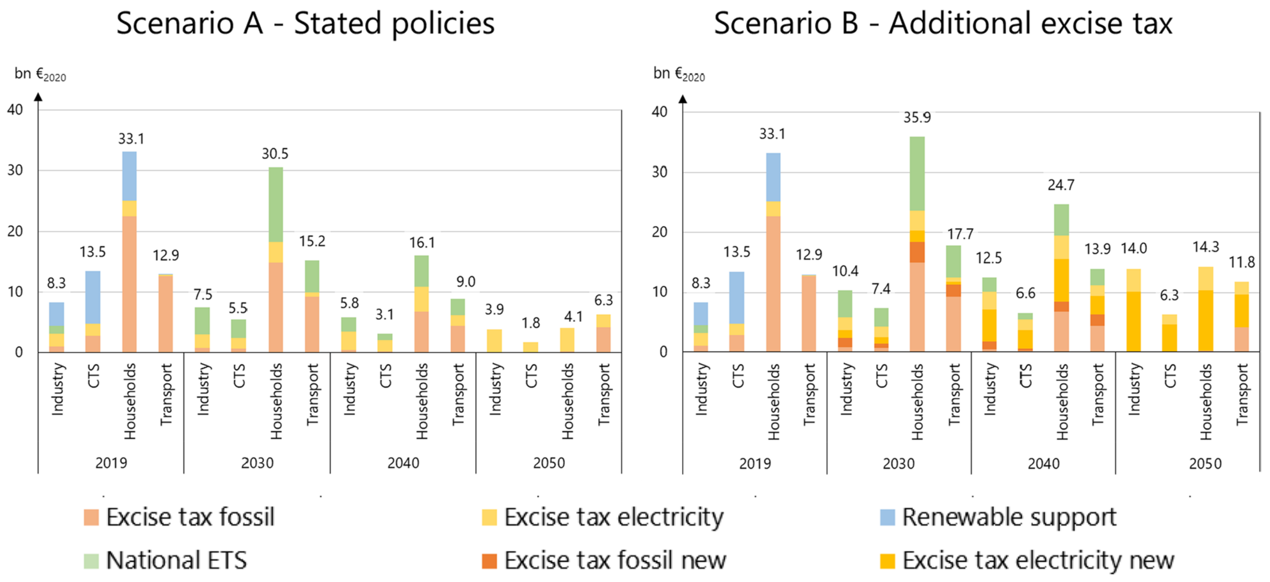


**Fig. 2** Sectoral distribution of SIPC payments—high carbon prices (Source: own calculations)

In the following decades, SIPC payments of the industrial sector decrease by 53% until the middle of the century in scenario A. Changes in industrial energy demand between 2019 and 2030 have a minimal impact on excise tax payments within the industry sector due to significant exemptions or reductions in the excise tax on electricity and fossil fuels. In scenario B, there is a continuous increase in SIPC contributions from industry until the middle of the century by 68% in total. In this scenario, the industry contributes €10 bn in 2030, €12 bn in 2040 and €14 bn in 2050, increasing its share in government revenues from energy-related SIPC. While industry contributed 12% to the total SIPC revenues in 2019, this value almost triples until 2050. In 2050, most of these contributions are due to the additional excise tax on electricity, even with the excise tax exemptions on electricity in industrial processes.

In scenario A, SIPC contributions from the transport sector rise by €2 bn until 2030 and decrease after 2030, reducing by 46% until 2050 compared to 2019. In scenario B, SIPC payments increase in the transport sector to €18 bn in 2030. Further transport electrification until 2050 in scenario B then reduces these payments to similar levels as in 2019 with €12 bn.

Consequently, the energy transition reduces SIPC costs in all sectors under stated policies compared to 2019. The abolishment of the renewable levy makes significant cuts to SIPC payments in the industry, CTS and household sectors. Until 2050, the additional excise tax on final energy only leads to increases in payment in the industrial sector when taking into account the current regulations on SIPC exemptions and reductions.

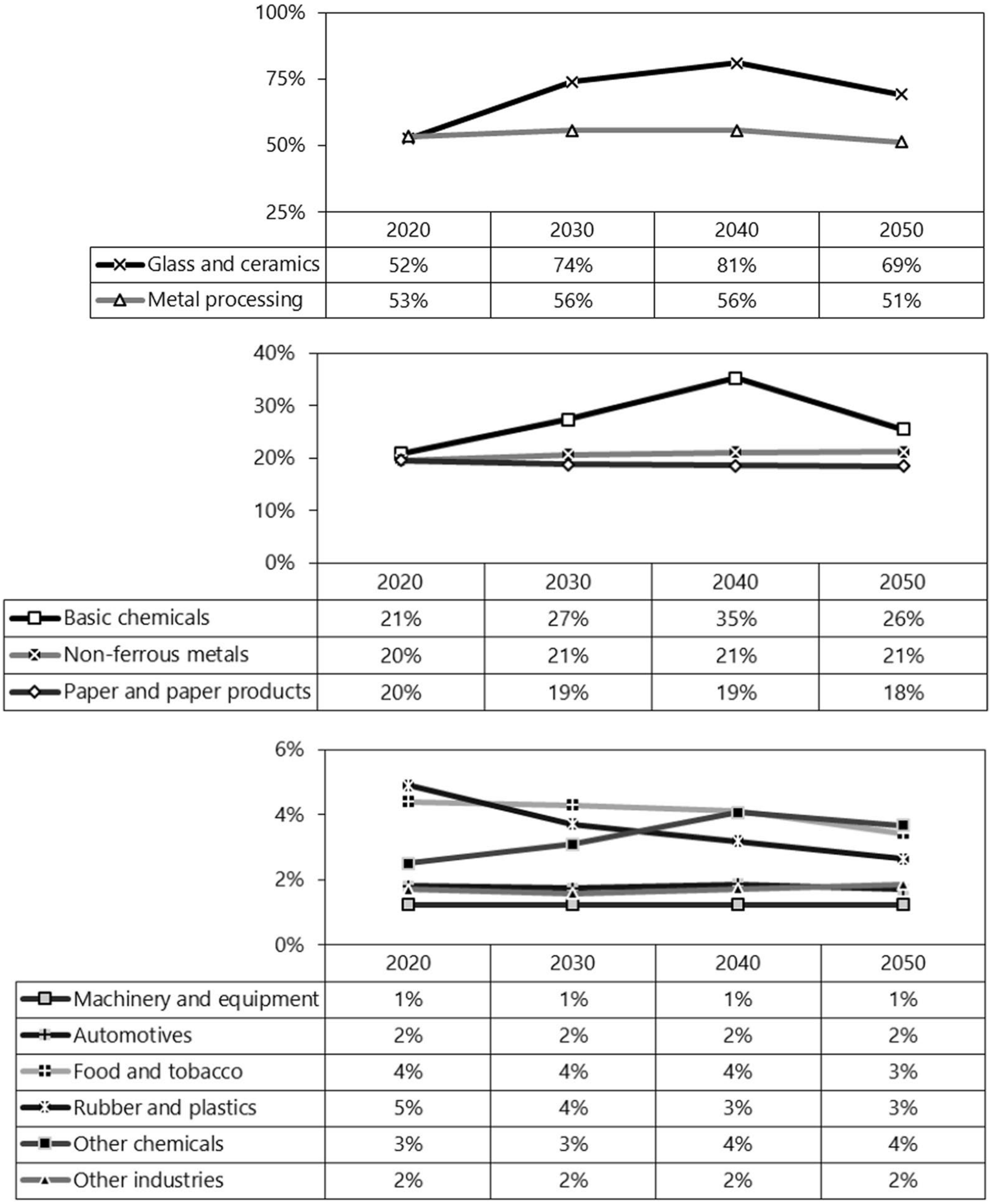
### Direct impact on manufacturing industries

The level of impact of RUEC is heterogeneous for different manufacturing industries. Figure 3 illustrates the impact of current regulations and Fig. 4 the impact of additional excise taxes under a high carbon price for the industrial sector.

The results under a low carbon price regime can be found in Appendix (Figs. 11 and 12). Under a high carbon price, the energy costs increase in almost all industries until 2040 and decline thereafter. However, large increases in RUEC are the exception and limited to a small number of industries. The introduction of the additional excise tax changes the results only slightly.

In Scenario A, the RUEC for glass and ceramics and basic chemicals increase substantially from 52% to 69% and from 21% to 26% between 2020 and 2050, respectively. The RUEC in other industries, such as metal processing, non-ferrous metals and other chemicals increase by between 1 and 2 percentage points, which corresponds to a 50% increase in RUEC. The RUEC in all other industries increase by less than 1 percentage point or even decrease. On the contrary, the paper and paper products, rubber, and plastics, as well as the food and tobacco industries are even better off in 2050 than in 2020.

The additional excise taxes on electricity introduced in scenario B impact the metal processing industry most heavily, with an RUEC increasing by 11 percentage points in 2050 compared to scenario A. The RUEC for glass and ceramics, and paper and paper products increase by 2 percentage points in 2050 in comparison to scenario A. All other industries' RUEC change by 1 percentage point



| | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|
| Glass and ceramics | 52% | 74% | 81% | 69% |
| Metal processing | 53% | 56% | 56% | 51% |

| | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|
| Basic chemicals | 21% | 27% | 35% | 26% |
| Non-ferrous metals | 20% | 21% | 21% | 21% |
| Paper and paper products | 20% | 19% | 19% | 18% |

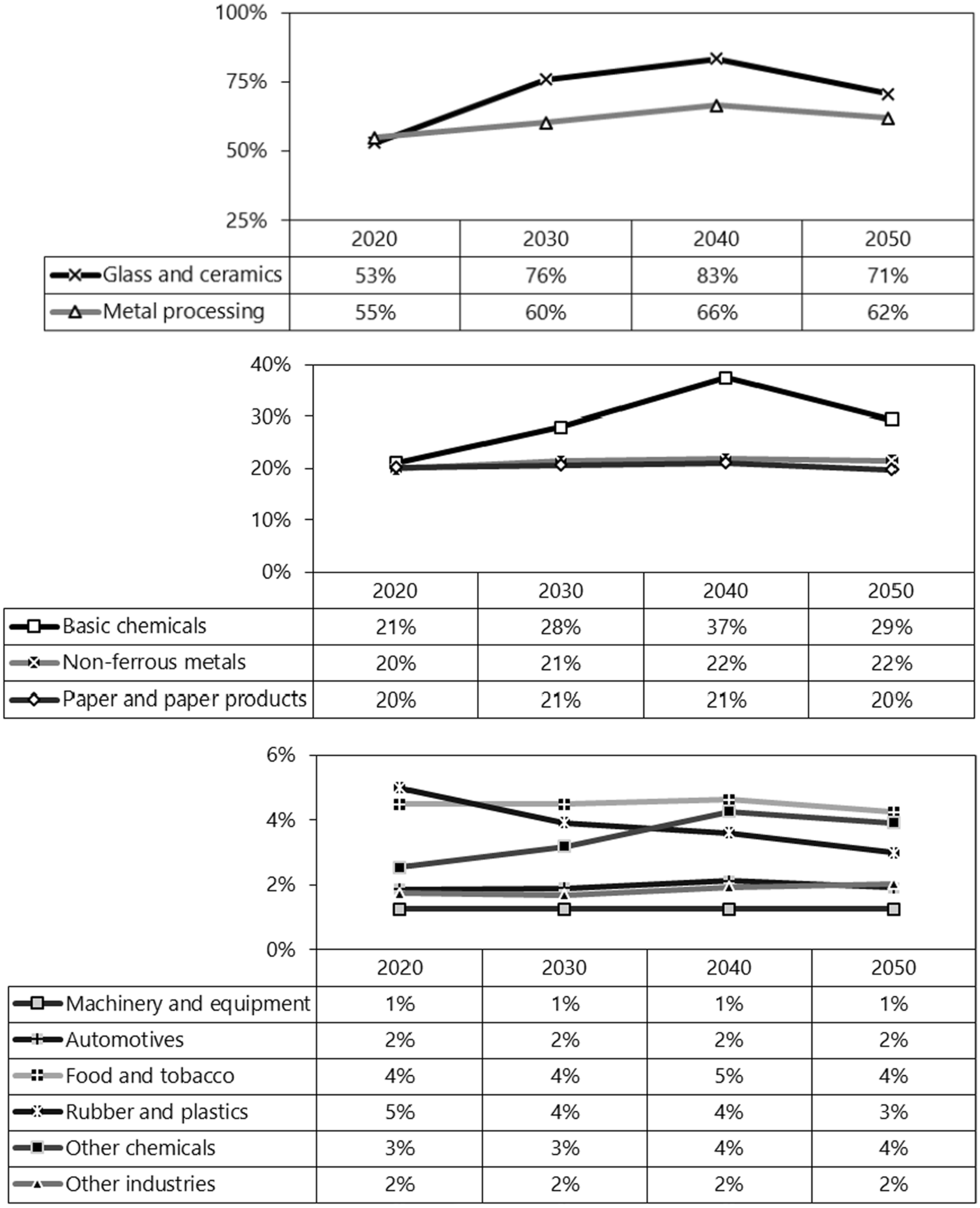
| | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|
| Machinery and equipment | 1% | 1% | 1% | 1% |
| Automotives | 2% | 2% | 2% | 2% |
| Food and tobacco | 4% | 4% | 4% | 3% |
| Rubber and plastics | 5% | 4% | 3% | 3% |
| Other chemicals | 3% | 3% | 4% | 4% |
| Other industries | 2% | 2% | 2% | 2% |

**Fig. 3** Scenario A—stated policies: development of real unit energy costs for different industries—high carbon prices (Source: own calculation)

or less. In the long term, the RUEC of paper and paper products as well as food and tobacco remain constant in scenario B, whereas they decrease in scenario A.

Comparing the results under the high carbon price with the results under the low carbon price reveals that the carbon price adds between less than 1 and 8 percentage points to the RUEC for most industries. However, for glass and ceramic producers, the carbon price increases the RUEC by 26 percentage points and the energy costs for metal processing increase by 8 percentage points in 2030. Thereafter, the effect of the carbon price on energy costs decreases by 2 percentage points. For the producers of basic chemicals, the carbon price raises the RUEC by 6 percentage points in 2030. Its impact on the RUEC declines after 2030 to only 2 percentage points. For the other industries, the carbon price adds one percentage point or less to their RUEC.

The small changes in the machinery and equipment and automotive industries reflect the results given in [55], where authors show that energy constitutes only a



| | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|
| Glass and ceramics | 53% | 76% | 83% | 71% |
| Metal processing | 55% | 60% | 66% | 62% |

| | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|
| Basic chemicals | 21% | 28% | 37% | 29% |
| Non-ferrous metals | 20% | 21% | 22% | 22% |
| Paper and paper products | 20% | 21% | 21% | 20% |

| | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|
| Machinery and equipment | 1% | 1% | 1% | 1% |
| Automotives | 2% | 2% | 2% | 2% |
| Food and tobacco | 4% | 4% | 5% | 4% |
| Rubber and plastics | 5% | 4% | 4% | 3% |
| Other chemicals | 3% | 3% | 4% | 4% |
| Other industries | 2% | 2% | 2% | 2% |

**Fig. 4** Scenario B—additional excise tax: development of real unit energy costs for different industries—high carbon prices (Source: own calculation)

small share of all inputs used in machinery and equipment manufacturing. Moreover, the authors argue that the equipment manufacturing industry has already realised most of its energy efficiency potential and thus minimised the potential effect of changes in SIPC. Therefore, these industries are also less impacted by rising carbon prices.

Figure 5 shows the composition of energy costs for the glass and ceramics manufacturing industry. The glass and ceramics industry also include producers of glass and cement among others. Therefore, this is the industry with the highest final energy consumption in our sample and is likely to be representative of other industries requiring high process heat [56]. Furthermore, this industry is characterised by high initial investment expenditures and has also already achieved substantial energy efficiency gains in the past [57]. This implies that additional energy efficiency measures in the energy transition will be commercially unattractive for the glass and ceramics manufacturing industry. Due to this inflexibility to reduce

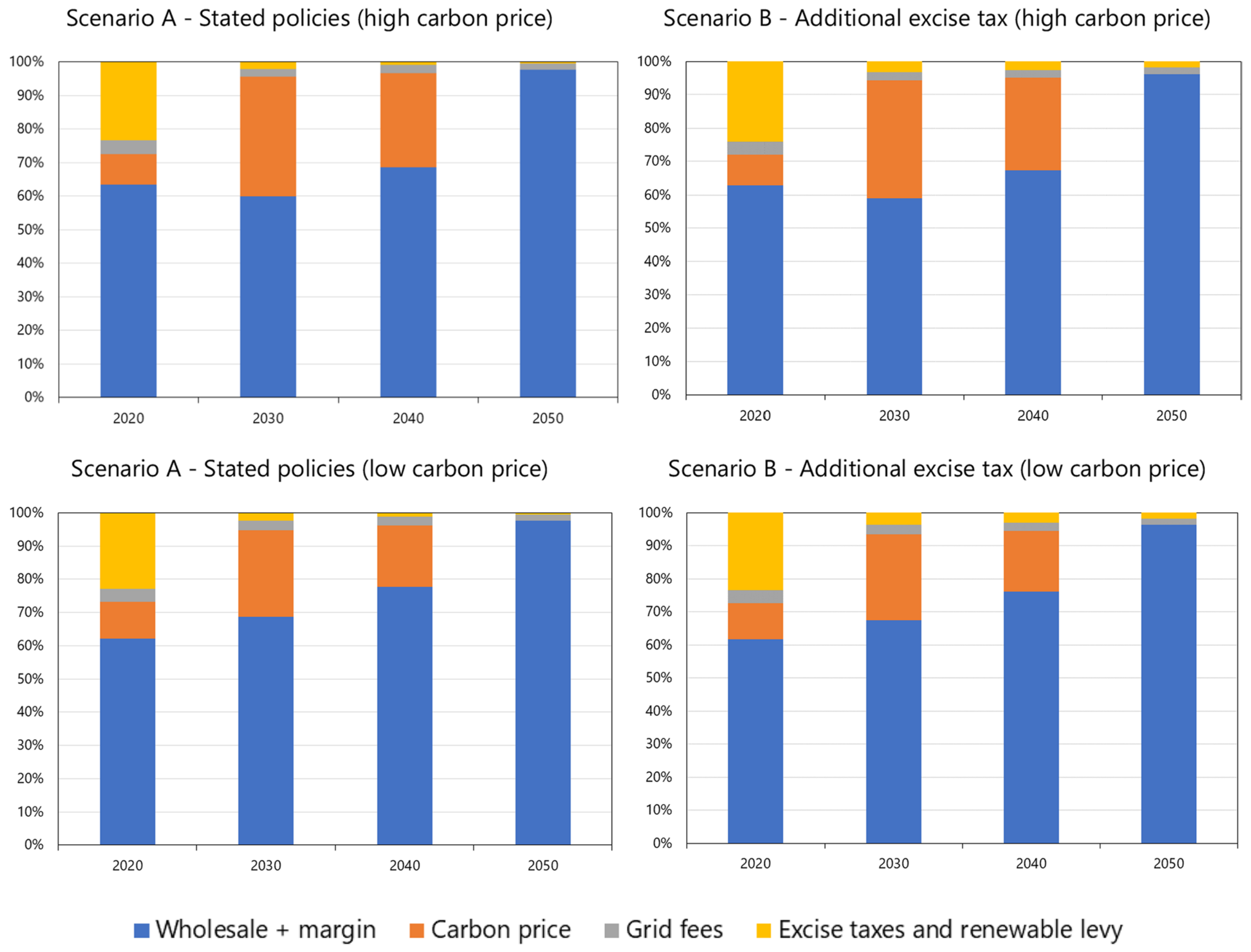


**Fig. 5** Composition of energy costs for the glass and ceramics manufacturing sector. *Note:* Renewable support in 2019 and 2020 is considered as a balanced budget, afterwards financed from the public budget (Source: own calculation)

energy consumption, policymakers should consider other options to alleviate this industry's energy cost burden.

In 2020, excise taxes and the renewable levy accounted for 24% of the energy cost share in all scenarios, but this ratio decreases to 2% in Scenario A (4% in Scenario B) by 2030 due to high (low) carbon prices. By 2030, the carbon price accounts for 36% of the total energy costs in Scenario A (26% in Scenario B). The impact of the carbon price then gradually diminishes until it reaches zero by 2050. In 2050, SIPC, consisting of grid fees and excise taxes, make up 2% of the total energy costs in Scenario A and 4% in Scenario B. Consequently, the results indicate that wholesale prices significantly impact the development of energy costs. However, it is important to note that carbon prices are expected to play a crucial role in the transition phase, exerting considerable influence on total energy costs.

### Direct impact on vulnerable households

This section presents the distribution of energy costs among deciles of EDI households. Figure 6 shows the energy costs over the net income of the EDI deciles in the reference year 2019.

The results show that the households' total costs of energy increase with EDI. However, the energy cost share of the net household income increases from 8% to 9% in the first three EDI household deciles and then decreases. It can be seen that especially EDI deciles 3 and 4 faced the highest energy cost shares of 9% in 2019. Those households that have to spend more than 10% of their net income on energy are considered to be experiencing energy poverty.[4] This is especially influenced by the costs of diesel and gasoline, the conventional energy carriers for private transport. The costs for electricity

---

[4] Although there is no official definition of energy poverty in Germany, Schreiner's definition [58] is based on findings from the research on energy poverty in Great Britain (see [59]).

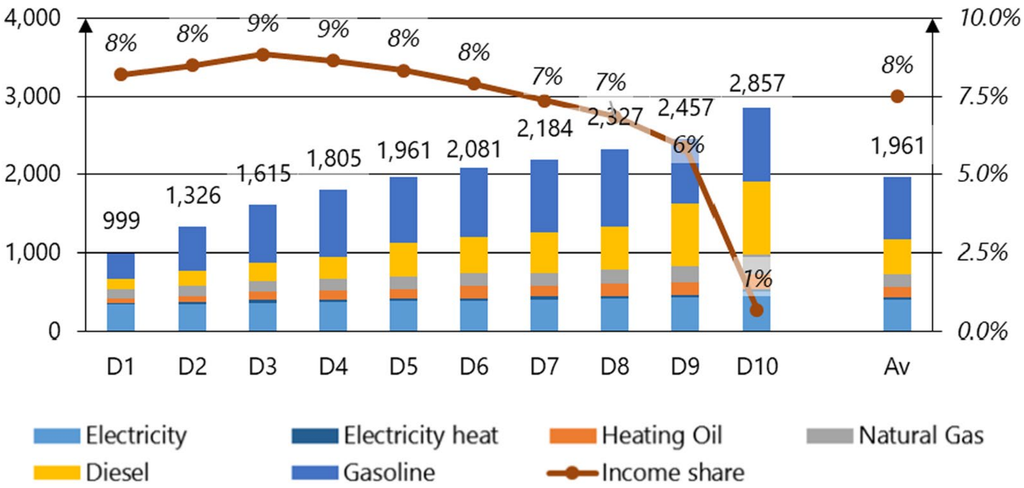


**Fig. 6** Distribution of energy costs in euro per year and share of income by household deciles with equivalent disposable income in 2019. *Note:* Results for the income decile 10 are uncertain, as documentation of the wealthiest households is limited [51] (Source: own calculation)

comprise expenditures for operating household devices, but theoretically also for charging electric vehicles. The share of electric vehicles in the figures presented is close to zero, however, as the market share of electric vehicles was still low. Electricity is also used for heating purposes in directly electrified heating technologies like night storage heaters and heat pumps. Compared to the results from 2012 [60], relative electricity costs had increased by around 3% in 2019.

Figures 7 and 8 present the total energy costs and energy cost shares of net income from 2019 for the first three EDI household deciles for scenario A and scenario B with high carbon prices until 2050. The results for low carbon prices do not differ significantly and are shown in Appendix (Figs. 13 and 14).

In 2020, the share of energy costs in net income comprised 8% for EDI decile 1, and 9% for EDI deciles 2 and 3 in both scenarios. The results show that the energy costs for the equivalent household decreases steadily for all EDI deciles in both scenarios and reach their lowest level in 2050. The strong cost decrease over time is caused by the increasing use of sector coupling technologies, i.e. heat pumps and battery electric vehicles. These directly electrified end-use technologies utilise final energy more efficiently than conventional alternatives. The projected technology diffusion of the scenario study, but also the improved energy efficiency of buildings result in decreasing final energy demand. However, the overall cost decrease is primarily determined by decreases in the costs of fossil final energy carriers for transport, i.e. diesel and gasoline, as these are subject to a higher excise tax than heating fuels.

Consequently, the cost share of electricity increases until 2050. In scenario A, the cost share of electrified appliances in total energy costs is similar to the 2019 level until 2030: 37% for EDI decile 1, 29% EDI decile 2 and 27% EDI decile 3. In scenario B, the energy cost share of electricity increases slightly for all EDI deciles until 2030. In 2040, the cost share of electricity is 57% for EDI decile 1, 47% for EDI decile 2 and 43% for EDI decile 3 in scenario A and 59%, 49% and 45%, respectively, in scenario B.

In 2050, electricity accounts for almost 100% of energy costs in both scenarios, while total energy costs are significantly lower. As a consequence, the energy cost share in EDI income is much smaller. By 2050 compared to 2020, there are energy cost reductions of 65% in EDI decile 1, 73% in EDI decile 2 and 76% in EDI decile 3 in scenario A and 55%, 66% and 69%, respectively, in scenario B. However, it should be noted that the depicted costs only reflect the final energy costs and depreciation of the necessary investments is not included in the results.

## Discussion

Our micro-simulations enable the quantification of the direct impact of state-induced price components (SIPC) on the public budget and the energy costs of industries and low-income households during the German energy transition until 2050. We analyse two scenarios. Scenario A models the current system of levies and taxes. In scenario B, we calculate an additional excise tax on electricity and fossil fuels intended to maintain government revenues at 2019 levels.

Given that SIPC privileges are accorded to certain industrial processes, process-specific data on the development of industrial energy demand are required. Our analysis uses the detailed final energy demand data of the official German long-term scenario “TN Strom”, characterised as the scenario with the lowest costs for a

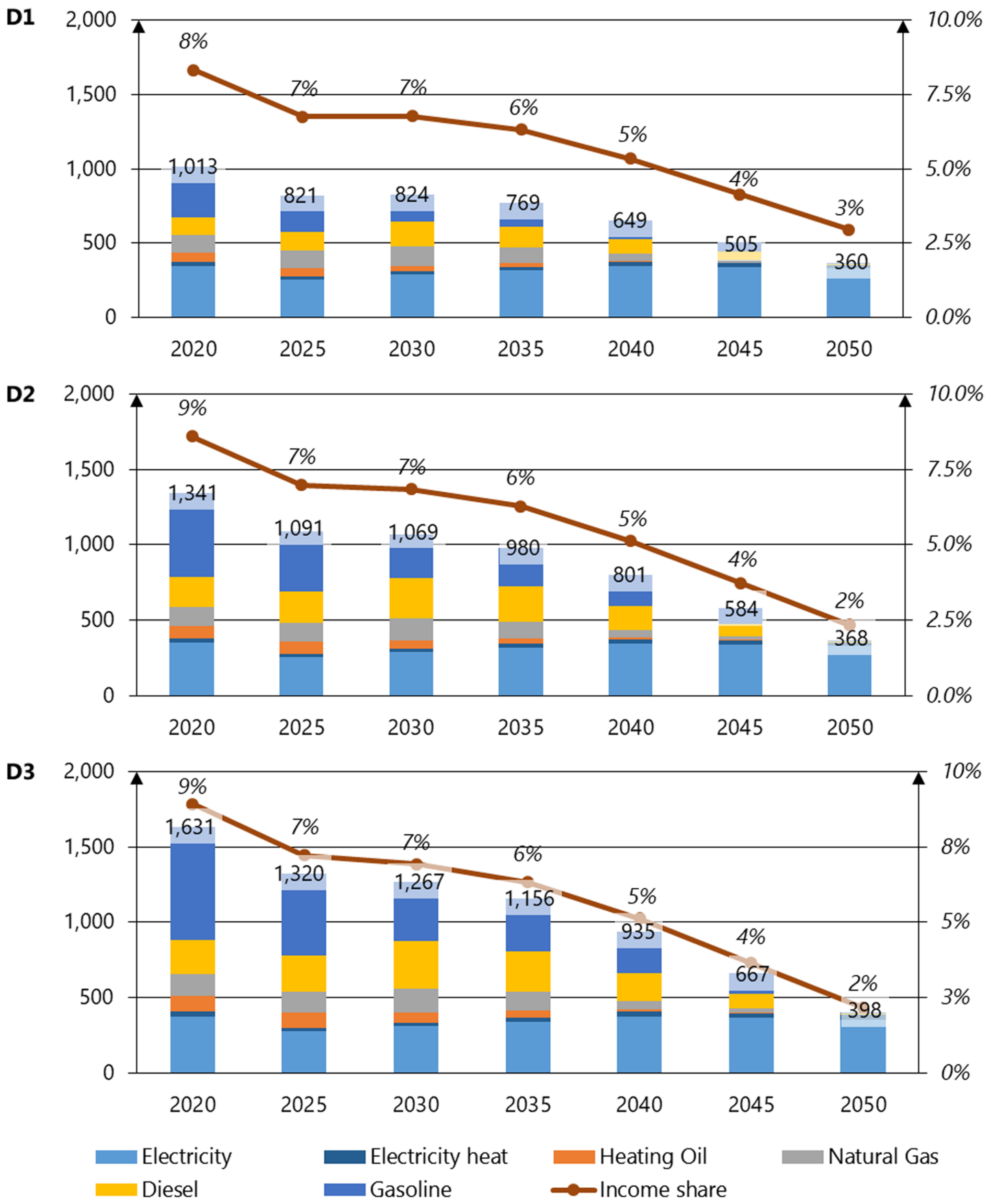


**Fig. 7** Scenario A—development of energy costs in euro per year and share of income for the lowest three household deciles with equivalent disposable income until 2050—high carbon prices (Source: own calculation)

sustainable energy system. This scenario study assumes widespread diffusion of direct electrification in industrial processes and applications, efficiency measures such as building insulation, and the availability of the necessary infrastructures like district heating grids in densely populated areas.

It is important to point out that our analysis has certain limitations based on this development of final energy demand. We rely on static demand, meaning that the decarbonisation pathway does not alter, even when faced with increased SIPC rates like higher carbon prices or additional excise taxes (scenario B). To address this limitation, we integrated a sensitivity analysis considering price elasticities. However, a thorough examination considering industrial relocations and job effects due to SIPC changes would require equally detailed global data forecasting industrial processes until 2050. Consequently, we leave the analysis of such dynamic effects to future

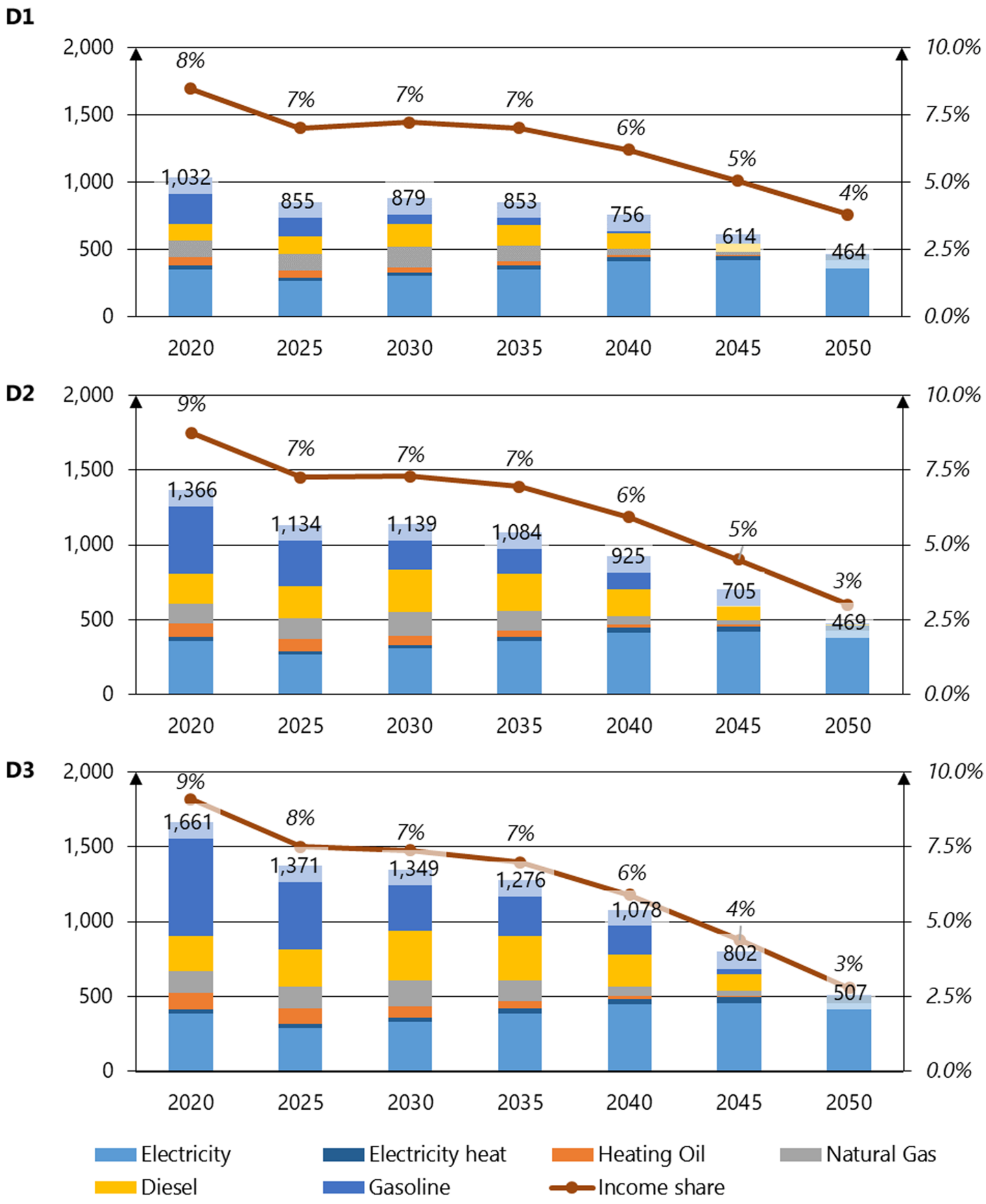


**Fig. 8** Scenario B—development of energy costs in euro per year and share of income for the lowest three household deciles with equivalent disposable income until 2050—high carbon prices (Source: own calculation)

research. Nevertheless, our approach is able to explore the direct consequences of an alternative tax regime that maintains constant excise tax revenues during the energy transition.

The results of the micro-simulation in scenario A show that the cost-effective decarbonisation pathway leads to greatly reduced government revenues from SIPC on final energy prices from 2040 onwards. Although, net contributions to the public budget from SIPC remain constant at 2019 levels from 2030 to 2035 under high carbon prices (€130/t in 2030 and €225/t in 2035), they decrease when applying lower carbon prices (€97/t in 2030 and €140/t in 2035).

The decline in government revenues from SIPC especially after 2040 triggers the search for additional income streams. One option analysed in scenario B is the introduction of an additional excise tax on fossil fuels and electricity. Alternative tax reforms could also encompass climate-neutral energy carriers such as biofuels, hydrogen or electricity-based synthetic fuels. The analysis of scenario B shows that revenues from excise taxes can be maintained at 2019 levels during the energy transition if annual and asymmetric excise tax adjustments are applied.

It should be noted that this finding is based on the assumption that there are no changes in energy demand as a result of increasing the SIPC. However, estimations of changes in government revenues resulting from demand response are marginal (see Appendix). Furthermore, the additional excise tax on electricity could incentivise the expansion of self-consumption, which is exempt from excise tax (§9 Electricity Tax Act). More self-consumed electricity generation reduces the power drawn from the public grid and consequently the revenues from excise tax, electricity grid fees and if applicable value added tax.

Other results of our analysis concern the sectoral distribution of SIPC payments. Whereas in 2019 households account for the highest share of SIPC, in 2050, the SIPC-based fiscal payments are spread more evenly across the sectors of industry, CTS, households and transport in both scenarios. Whereas scenario A shows considerable decreases in SIPC contributions in all sectors, scenario B indicates increases in industry and more or less constant SIPC payments in the transport sector until 2050. Although the additional excise taxes take the privileges of current policies into account, the simulations show a shift of the financial burden from households to industry. Although the validity of these results may be limited by the assumptions made for the allocation of energy demand to privileged categories of SIPC, they do indicate that an additional excise tax on final energy under current SIPC policies would represent a disproportional burden on the industrial sector.

The impact on industry is further analysed in microsimulations of the real unit energy costs (RUEC) of various industrial sectors. The results show that current SIPC policies (scenario A) cause heterogeneous impacts on RUEC among industries. The RUEC of the glass and ceramics industry, which includes the production of cement, and basic chemicals, increase significantly with higher carbon prices in 2030 and 2040. RUEC increases in other industries remain moderate at about 1 to 2 percentage points as long as they decarbonise their processes as the “TN Strom” scenario suggests. The non-ferrous metal and the paper industries may even experience decreasing RUEC and are, therefore, better off provided they decarbonise their production processes. However, most industries experience only slight changes in the RUEC in scenario A regardless of whether the carbon price is high or low.

In scenario B, on the other hand, we observe that RUEC increase moderately for all industries due to a higher excise tax on electricity in the long term under the given assumptions. Despite the moderate increase, the additional SIPC generated make a substantial contribution to the public budget. We find that industries have higher energy costs mainly due to increasing wholesale prices, which decline after 2040. The abolishment of the renewable support levy and shifting renewable support to the public budget reduce the SIPC payments of the industrial sector in 2030 compared to 2019. However, the carbon price increase means additional payments from industries and offsets the energy cost reductions due to abolishing the renewable support levy.

Our analysis reveals that the energy cost burden of decarbonisation varies by industry, based on current SIPC policies and privileges. Therefore, policymakers need to carefully consider implementing support policies for specific industries.

The energy cost development for EDI deciles 1, 2, and 3 shows that the adoption of sector coupling technologies and energy efficiency measures in the transition to an integrated energy system generally leads to lower energy costs for vulnerable households in all scenarios. However, these results are based on ambitious assumptions regarding the development of final energy demand in the scenario study “TN Strom”, which may not be realistic. Successfully implementing this scenario necessitates substantial investments across all energy system sectors, complemented by changes in consumer behaviour.

Our cost analysis does not account for the required investments and their economic impact. Therefore, while energy costs may decrease on average, the financial relief for vulnerable households could be limited due to investment allocations (compare the study on tenant heating [61]). Further research should also account for the necessary investments when analysing the cost impact of the energy transition on vulnerable households.

Especially low-income households may need help accessing and affording these technologies, resulting in delayed transitions and potentially higher expenses due to rising carbon prices. This effect leads to regressive distributional effects [62], similar to the additional excise taxes on final energy carriers. Perceived disparities in cost distribution during the energy transition may significantly affect public acceptance of it and potentially hinder the implementation of essential measures.

**Table 4** Percentage of electricity used in processes by industry

| Industrial subsector | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|
| Metal processing | 1 | 3 | 6 | 12 | 17 | 24 | 32 |
| Paper and paper products | – | – | – | – | – | – | – |
| Non-ferrous metals | 10 | 13 | 15 | 19 | 22 | 31 | 43 |
| Machinery and equipment | – | – | – | – | – | – | – |
| Chemicals | 19 | 20 | 24 | 30 | 50 | 50 | 50 |
| Glass and ceramics | 12 | 14 | 25 | 62 | 78 | 88 | 93 |
| Basic metal | 42 | 53 | 65 | 75 | 82 | 88 | 92 |
| Weighted average[a] | 13 | 15 | 19 | 25 | 36 | 40 | 40 |

[a] The weighted average is calculated by dividing the sum of the entire electricity used in the processes by the total electricity demand in the industry sector. Therefore, the weighted average does not refer to the weighted average of the seven industries shown in our paper but to the average of the total industry sector

Source: Own calculations based on [33] and §9a Electricity Tax Act

## Conclusions

Three conclusions can be drawn from the analysis conducted in this paper: first, the government can expect the revenues from SIPC to decrease with increasing decarbonisation in the long term. Second, the energy-intensive industries are adversely affected by decarbonisation. Glass and ceramics, basic chemicals and other chemicals are likely to experience increases in RUEC in 2030 and 2040 and RUEC remain high until 2050. Significant increases in RUEC in other manufacturing industries are not expected. Industries relying heavily on electricity for decarbonisation, such as metal processing, would be disproportionately burdened by the imposition of an additional excise tax intended to retain current government revenues under current SIPC policies. For energy-intensive industries such as glass and ceramics, subsidies on the electricity wholesale price seem to be an adequate and effective policy tool to reduce energy costs. Since this analysis is constrained by assuming static energy demand, further research of alternative SIPC policies should consider responsive demand and direct as well as indirect impacts.

Third, energy costs for low-income households are expected to decrease continuously with further direct electrification of building heat and transport. As these household segments are likely to have limited financial resources to undertake these investments, further subsidies might be required. Further research may address potential investment constraints within the different income segments.

As the transition from an energy system based on fossil fuels to one based on renewable electricity progresses, government revenues from SIPC are expected to decrease while the need for subsidies increases. Thus, systemic reforms or financing outside the energy system might become necessary for policymakers to balance the books.

## Appendix

### Allocation of income streams

We allocate the historical final energy demand to the income streams $I_i$ in the sectors $s$ for 2019 and 2020 according to official statistics [39]. The historical national energy volumes of each privileged category are published in the official statistics for fiscal income categories of excise tax on fossil final energy [41, 43] and excise tax on electricity [40, 42] for 2019 and 2020.

To allocate the historical and future national income of each privileged tax category $\rho$ and fiscal income category $f$ among the sectors considered, we assume the following: tax reductions for processes are assigned to the industry sector for all energy carriers. Reduced tax rates for manufacturing industries are divided between industry and the CTS sector based on the shares of their historical energy demand. Tax reductions for public transport are assigned to the transport sector. The shares of synthetic fuels are allocated among the sectors relative to the final energy demand in each sector.

The historical shares of fossil final energy demand in each income category and sector are kept constant in our simulation. With respect to sector coupling, the following assumptions are made to consider fuel switching in processes from fossil final energy to electricity. In "TN Strom", the scenario chosen for the future energy demand from [33], hydrogen is only utilised in the industry sector. The share of electricity used in processes in the industry sector is derived from [33] and considered as presented in Tables 4 and 5.

To determine the final energy used by households for private transport, we derive the shares of private demand from national final energy demand for diesel and gasoline based in historical statistics. The demand for gasoline and diesel at national level is derived from [63] and for households from [64]. The resulting shares

**Table 5** Percentage of electricity demand receiving a reduced excise tax rate for privileged industries

| Industrial subsector | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|
| Metal processing | 19 | 17 | 13 | 7 | 2 | 0 | 0 |
| Paper and paper products | 27 | 25 | 16 | 1 | 0 | 0 | 0 |
| Non-ferrous metals | 18 | 16 | 13 | 10 | 6 | 0 | 0 |
| Machinery and equipment | 23 | 24 | 26 | 32 | 38 | 46 | 52 |
| Chemicals | 10 | 9 | 5 | 0.1 | 0 | 0 | 0 |
| Glass and glass products | 14 | 12 | 1 | 0 | 0 | 0 | 0 |
| Basic metal | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Weighted average[a] | 79 | 76 | 71 | 61 | 49 | 43 | 39 |

[a] The weighted average is calculated by dividing the sum of the entire electricity used in the processes by the total electricity demand in the industry sector. Therefore, the weighted average does not refer to the weighted average of the seven industries shown in our paper but to the average of the total industry sector

Source: Own calculations based on [33] and §9b Electricity Tax Act

**Table 6** Assumed development of wholesale prices

| [€/MWh] | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|
| Coal | 6.3 | 7 | 6.9 | 6.7 |
| Fuel oil | 45.5 | 63.4 | 63.9 | 64.5 |
| Gas | 12.6 | 24.4 | 23.8 | 23.2 |
| Syngas | 310.1 | 290.1 | 270.2 | 258.9 |
| Heat | 7.5 | 7.5 | 7.5 | 7.5 |
| Hydrogen | 351.6 | 156.4 | 143.4 | 134.9 |
| Electricity | 50 | 69 | 69 | 66 |

Sources: electricity price from scenario "TN Strom" [33]; natural gas price is a mean of the "stated policy" scenario and the "net zero" scenario of the IEA market projections of the World Energy Outlook [65]; gasoline, diesel and fuel oil: extrapolated the historical average price from 2019 [66] with the change rate for crude oil for the same scenarios of the World Energy Outlook as natural gas

**Table 7** Development of grid fees for electricity for different consumer types

| [€ct/kWh] | | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|
| Highest voltage | Priv. §19 2 2 NEV | 0.14 | 0.13 | 0.15 | 0.12 |
| High voltage | Priv. §19 2 2 NEV | 0.20 | 0.24 | 0.27 | 0.30 |
| Medium voltage | Medium full load hours | 3.45 | 4.05 | 4.37 | 5.08 |
| Household | | 7.41 | 8.51 | 10.96 | 12.19 |
| Household heat | | 2.78 | 3.19 | 4.11 | 4.57 |

Source: grid fees for industry from [33, 68]; grid fees for households in 2020 from [68], extrapolation with the development of total grid cost to total electricity demand ratio from "TN Strom" scenario of [33]

**Table 8** Development of grid fees for natural gas for different consumer types

| [€ct/kWh] | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|
| Energy-intensive industries | 1.5 | 1.0 | 3.0 | 4.6 |
| Other industries | 3.7 | 4.8 | 9.1 | 17.3 |

Source: [67]

**Table 9** Development of financing volume for renewable support

| [€ bn] | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|
| Renewable support | 24.23 | 22.50 | 11.80 | 4.39 |

Source: [31]

of final energy demand, which we allocate to the household sector, are 64% for gasoline and 58% for diesel, which we keep constant for future energy allocation. The electricity demand for electrified road transport assigned to households is derived from the average of diesel and gasoline shares, resulting in 60%.

### Development of market prices and price components

We derive the ranges of wholesale market price developments from various long-term studies. The price assumptions are depicted in Table 6.

The development of grid fees for electricity and natural gas is based on cost developments for system grid costs and final energy demand from [33] and follows the methodology from [67]. The results for the electricity grid are presented in Table 7, and those for the natural gas grid are presented in Table 8.

The development of the required financing volume for renewable support and the renewable levy until 2026 is derived from the mid-term forecast of the German transmission grid operators [30]. The long-term development until 2040 is derived from the calculation tool of Agora Energiewende [31] with adjustments regarding the diffusion of renewables according to the "TN Strom" scenario of the official long-term scenarios [33]. The estimated financing volumes are presented in Table 9.

The development of the renewable levy is derived considering the respective share of electricity in each income stream. The resulting values are presented in Table 10.

**Table 10** Development of renewable support levy

| [€ct/kWh] | 2019 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|
| Regular rate | 6.41 | 6.76 | 5.26 | 2.77 | 0.99 |
| 80% | 1.28 | 1.35 | 1.05 | 0.55 | 0.20 |
| 60% | 2.33 | 2.55 | 1.98 | 1.04 | 0.37 |
| BSAR 95% | 0.42 | 0.44 | 0.34 | 0.18 | 0.06 |

Source: [31]

### Derivation of SIPC burden for industries

To calculate the SIPC paid by each industry, we must derive the proportional privileged energy demand $\alpha e_{\varepsilon}^{k}(f,\rho)$ for each energy carrier associated with the relevant fiscal income stream and SIPC privilege. SIPC privileges play an important role in the industrial sector and can reduce expenses by 80% of the electricity and 60% of the energy tax [69, 70]. Under German law, the two most important privileges for industries are granted for the energy used in processes and the energy used in operations in manufacturing industries. Fortunately, the model in [33] is built on energy demand estimations by usage type for each industry. We use their data to derive the share of energy used for processes and operations. We follow the German law as closely as possible by defining energy demand in processes as the energy used for the production of steam and hot water, and the energy used in furnaces and cooling processes. Energy demand related to operations compromises the former plus energy used in cross-cutting technologies, such as ventilation, machinery, engines, pumps and compressors. However, the energy demand in operations does not include the energy used for lighting, heating or cooling of the interior. Though not yet explicitly stated in the current legislation, we also assume that the energy used in carbon-capture technologies will be declared as an energy used in operations and, hence, receive a tax privilege. For better understanding, Eq. (13), (14), (15) and (16) show the calculations of the proportional SIPC privileges on the excise taxes and renewable energy levy:

$$C_{\varepsilon}^{k}=\sum_{\varepsilon}E_{\varepsilon}^{k}*(p_{\varepsilon}^{w}+p_{\varepsilon}^{g}+p_{\varepsilon}^{o}+\sum_{f}\sum_{\rho}\alpha e_{\varepsilon}^{k}(f,\rho)*p_{\varepsilon}^{s}(f,\rho), \tag{13}$$

$$\alpha e_{\varepsilon}^{k}(n\mathrm{ETS},\rho)=0.9, \tag{15}$$

$$\alpha e_{\mathrm{electricity}}^{k}(\mathrm{res},\rho)=\begin{cases}\dfrac{E_{\mathrm{electricity}}^{k}(\text{self - consumed renewable})}{E_{\varepsilon}^{k}}\\ 0.5\text{ for }\rho=BesAR\\ 0.4\text{ for }\rho=60\%\\ 0.1\text{ for }\rho=80\%\end{cases}. \tag{16}$$

While we can derive the proportional SIPC privileges for the energy and electricity excise taxes from the data, there are no data available to calculate the proportional SIPC privileges for the peak demand of electricity excise tax, the BesAR of renewable support, the 80% and 60% privilege of the renewable levy for the self-produced electricity. We assume that 70% of an industry's electricity demand is privileged under the electricity excise tax for peak demand and similarly high values for all other privilege schemes. Imposing such high values is reasonable because we focus on industries that benefit from considerable privileges in order to avoid employment losses and reduced competitiveness [71].

We need to distinguish the derivation of $\alpha e_{\epsilon}^{k}(extax,peak)$ for different industries because machinery and equipment manufacturers as well as the producers of paper and paper products do not receive tax exemptions for energy that falls under production processes. Therefore, we have industries in group A that have tax privileges for energy in processes and industries in group B that do not have tax privileges for energy used in processes, i.e.

$$\alpha e_{\epsilon}^{k}(\mathrm{extax},\mathrm{process})=\frac{E_{\varepsilon}^{k}(\mathrm{extax},\rho)}{E_{\epsilon}^{k}}=0\quad\text{for }k\in B. \tag{17}$$

To prevent the total proportional privileged energy demand exceeding unity for any energy carrier, the proportional privileged energy demand related to the peak demand privilege is the minimum of 70% and the share of electricity consumption which does not receive any privileges for being used in operations and processes. For those industries where the privilege

$$\alpha e_{\varepsilon}^{k}(\mathrm{extax},\rho)=\begin{cases}\frac{E_{\varepsilon}^{k}(extax,processes)}{E_{\varepsilon}^{k}}\\ \mathrm{MAX}\left(\frac{E_{\varepsilon}^{k}(\mathrm{extax,operations})}{E_{\varepsilon}^{k}}-\alpha e_{\varepsilon}^{k}(\mathrm{extax},\mathrm{processes})-\alpha e_{\varepsilon}^{k}(\mathrm{extax},\mathrm{peak});0\right)\quad\text{for }\rho=\text{producing industries}\\ \mathrm{MIN}\left(1-\alpha e_{\varepsilon}^{k}(\mathrm{extax},\mathrm{processes})-\alpha e_{\varepsilon}^{k}(\mathrm{extax},\text{producing industries}),70\%\right),\quad\text{for }k\in A\text{ and }\rho=\text{peak}\\ \mathrm{MIN}\left(1-\frac{E_{\varepsilon}^{k}(\mathrm{extax,operations})}{E_{\varepsilon}^{k}};70\%\right),\quad\text{for }k\in B\text{ and }\rho=\text{peak},\end{cases} \tag{14}$$

**Table 11** Annual equivalent of final energy demand for income deciles in Germany for the reference year

| [kWh/eHH/a] | Decile 1 | Decile 2 | Decile 3 | Decile 4 | Decile 5 | Decile 6 | Decile 7 | Decile 8 | Decile 9 | Decile 10 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Electricity | 1089 | 1102 | 1178 | 1201 | 1266 | 1256 | 1323 | 1341 | 1383 | 1630 | 1277 |
| Electricity heat | 119 | 118 | 142 | 120 | 141 | 137 | 153 | 126 | 143 | 121 | 132 |
| Heating oil | 875 | 1260 | 1574 | 1841 | 1763 | 2470 | 2100 | 2496 | 2445 | 3009 | 1983 |
| Natural gas | 1850 | 1988 | 2202 | 2432 | 2538 | 2609 | 2548 | 2812 | 3203 | 3996 | 2618 |
| Diesel | 950 | 1545 | 1790 | 2075 | 3260 | 3447 | 3941 | 4216 | 6217 | 7140 | 3458 |
| Gasoline | 1974 | 3212 | 4343 | 5032 | 4898 | 5177 | 5429 | 5810 | 4840 | 5554 | 4626 |

Sources: values, according to [47], with deviants to individual household mobility as no occupancy rate was taken into account in the calculation of the energy demand. The resulting demand corresponds to the values from the mobility in Germany study [74]. Electricity used for heating is shown separately from the electricity demand for household devices and transport

**Table 12** Annual net income of equivalent households

| [€/eHH/a] | Decile 1 | Decile 2 | Decile 3 | Decile 4 | Decile 5 | Decile 6 | Decile 7 | Decile 8 | Decile 9 | Decile 10 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Annual net income | 12,174 | 15,612 | 18,271 | 20,881 | 23,515 | 26,313 | 29,625 | 33,976 | 41,874 | 423,727 | 26,105 |

Sources: [51]

for energy used in processes does not apply, the proportional privileged energy demand due to the peak demand privilege is the minimum of 70% and the share of electricity consumption which does not receive any other privileges.

Furthermore, electricity generated from renewable energy sources by the companies themselves is exempt from the renewable levy. This privilege is indicated by allowing for $\rho =$ self-consumption. Self-produced renewable electricity is not included in the calculations by the TU Berlin [33], but the German federal statistical office reports data on self-produced renewable electricity for all the industries analysed here. The data come with the caveat that for many industries, the time-series is incomplete and has many missing values. We therefore took averages of the proportion of self-produced renewable electricity for the years for which data are available. If data are only available for one year, the proportional tax privilege due to the share of self-produced electricity is represented by that particular year [72]. To extend the data to the year 2050, we assumed that the self-produced renewable electricity increases and never decreases because we consider the technologies used for generating renewable electricity to have a long payback time [73].

#### The final energy demand of equivalent income households

The final energy demand of each equivalent household for the reference year is depicted in Table 11, and the corresponding net income taken from [51] is shown in Table 12.

#### Elasticities of final energy demand

To estimate the potential change in government revenues from SIPC due to demand-responsive energy consumers, we conducted a sensitivity analysis based on empirical elasticities $\eta_\varepsilon$. Thus, the potential energy demand with elasticities $\widehat{E}_\varepsilon(t)$ for energy carrier $\varepsilon$ is given by Eq. 18.

$$\hat{E}_{\varepsilon,\rho}(t) = \left(1 + \eta_\varepsilon \frac{p_{\varepsilon,\rho}^{\text{Scenario}B}(t)}{p_{\varepsilon,\rho}^{\text{Scenario}A}(t)}\right) * E_{\varepsilon,\rho}(t). \tag{18}$$

Subsequently, the potential energy demand with elasticities for fossil fuels and electricity is multiplied by the respective SIPC components to estimate the government revenue with demand-responsive consumers. The elasticities of industrial consumers and the service sector for fossil fuels and electricity are based on the gas price and electricity elasticity estimated by [75]. The price elasticities of fossil fuels, electricity, and transport for households are taken from [76]. Finally, we obtained the results by calculating the difference in government revenues with and without elasticities.

See Figs. 9, 10, 11, 12, 13, 14).

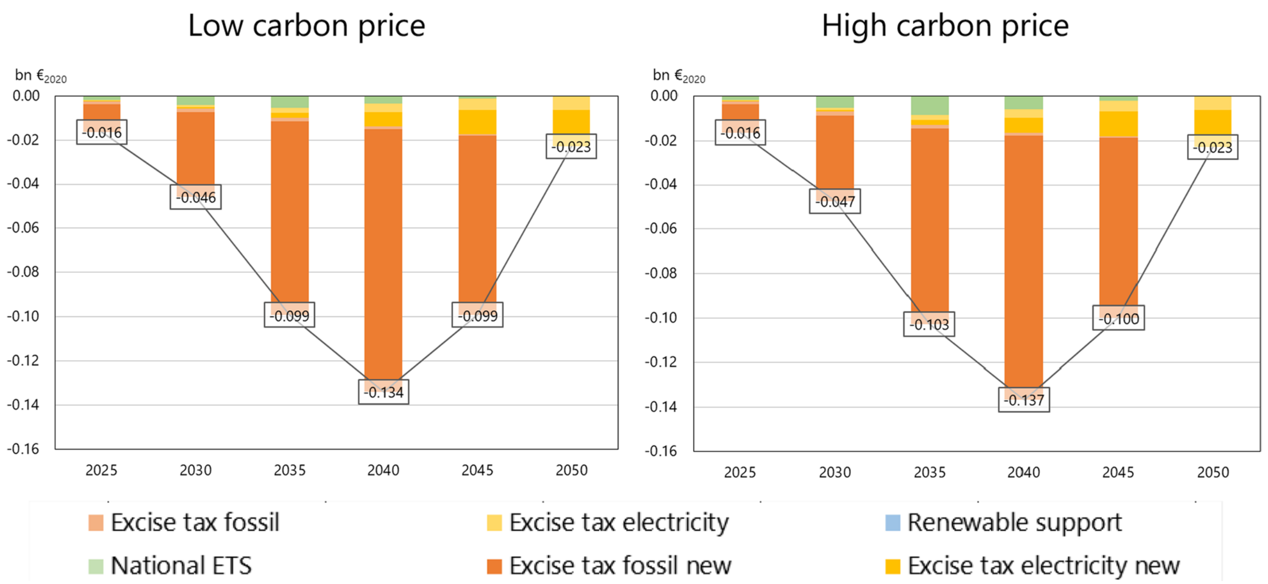


**Fig. 9** Change in government revenues in the sensitivity analysis considering demand elasticities (Source: own calculations)

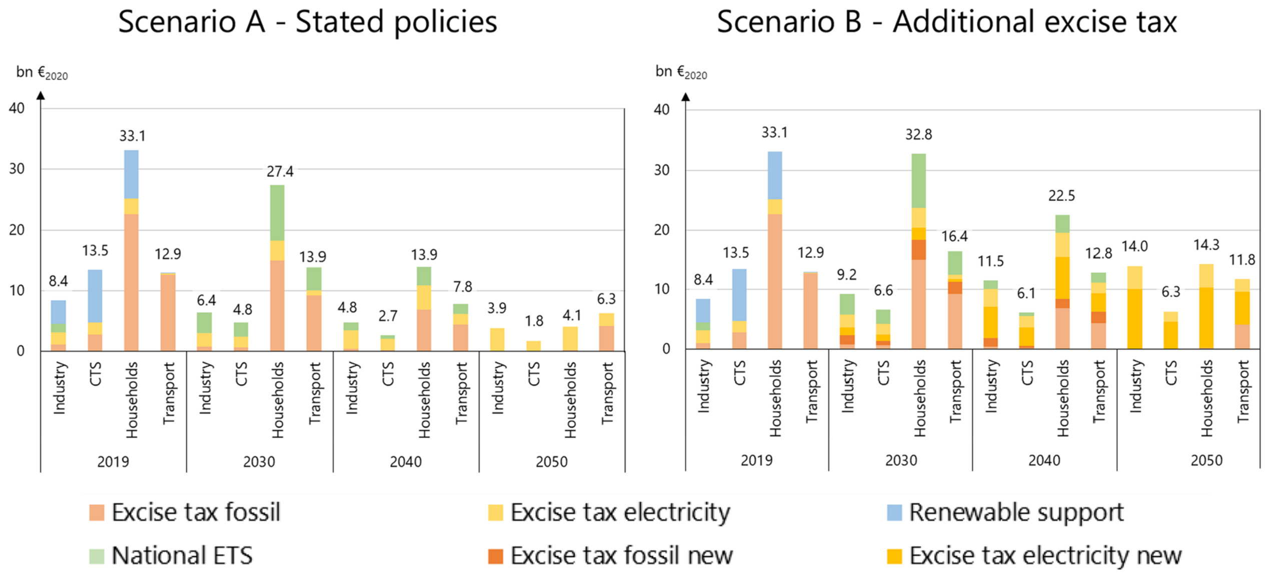
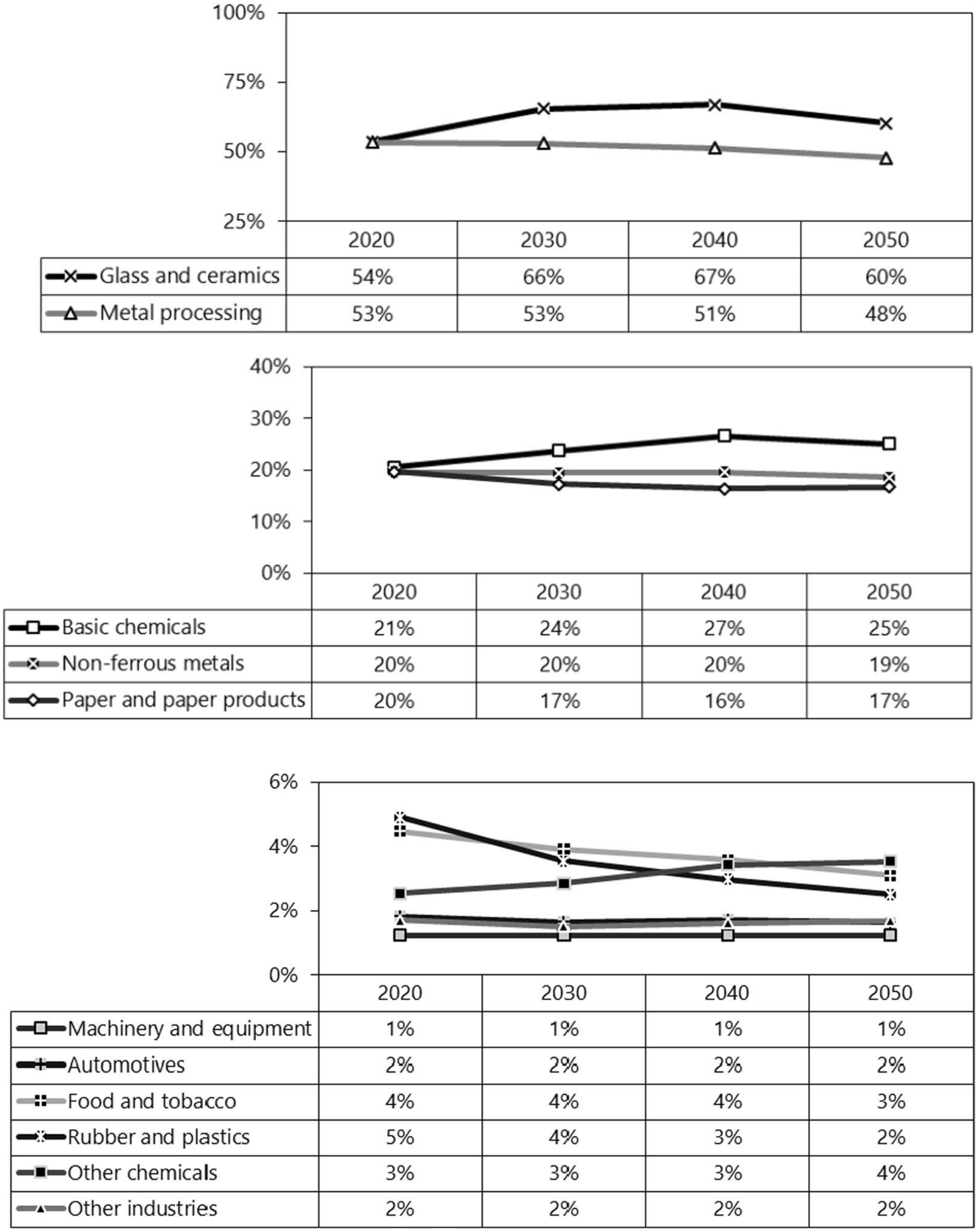


**Fig. 10** Sectoral distribution of SIPC payments—low carbon prices (Source: own calculations)

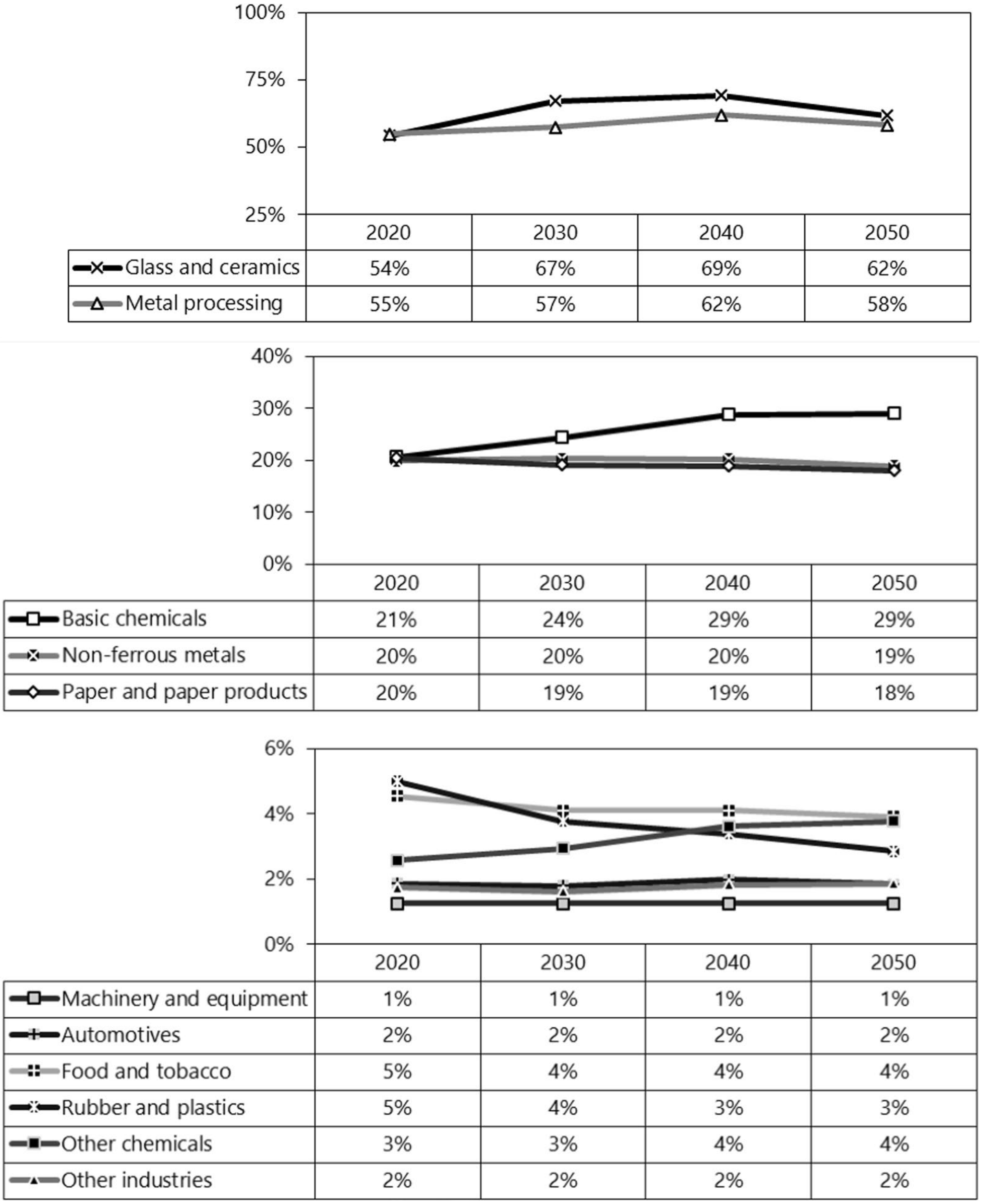


| | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|
| Glass and ceramics | 54% | 66% | 67% | 60% |
| Metal processing | 53% | 53% | 51% | 48% |

| | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|
| Basic chemicals | 21% | 24% | 27% | 25% |
| Non-ferrous metals | 20% | 20% | 20% | 19% |
| Paper and paper products | 20% | 17% | 16% | 17% |

| | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|
| Machinery and equipment | 1% | 1% | 1% | 1% |
| Automotives | 2% | 2% | 2% | 2% |
| Food and tobacco | 4% | 4% | 4% | 3% |
| Rubber and plastics | 5% | 4% | 3% | 2% |
| Other chemicals | 3% | 3% | 3% | 4% |
| Other industries | 2% | 2% | 2% | 2% |

**Fig. 11** Scenario A—stated policies: development of real unit energy costs for different industries—low carbon prices (Source: own calculation)



| | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|
| Glass and ceramics | 54% | 67% | 69% | 62% |
| Metal processing | 55% | 57% | 62% | 58% |

| | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|
| Basic chemicals | 21% | 24% | 29% | 29% |
| Non-ferrous metals | 20% | 20% | 20% | 19% |
| Paper and paper products | 20% | 19% | 19% | 18% |

| | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|
| Machinery and equipment | 1% | 1% | 1% | 1% |
| Automotives | 2% | 2% | 2% | 2% |
| Food and tobacco | 5% | 4% | 4% | 4% |
| Rubber and plastics | 5% | 4% | 3% | 3% |
| Other chemicals | 3% | 3% | 4% | 4% |
| Other industries | 2% | 2% | 2% | 2% |

**Fig. 12** Scenario B—stated policies: development of real unit energy costs for different industries—low carbon prices (Source: own calculation)

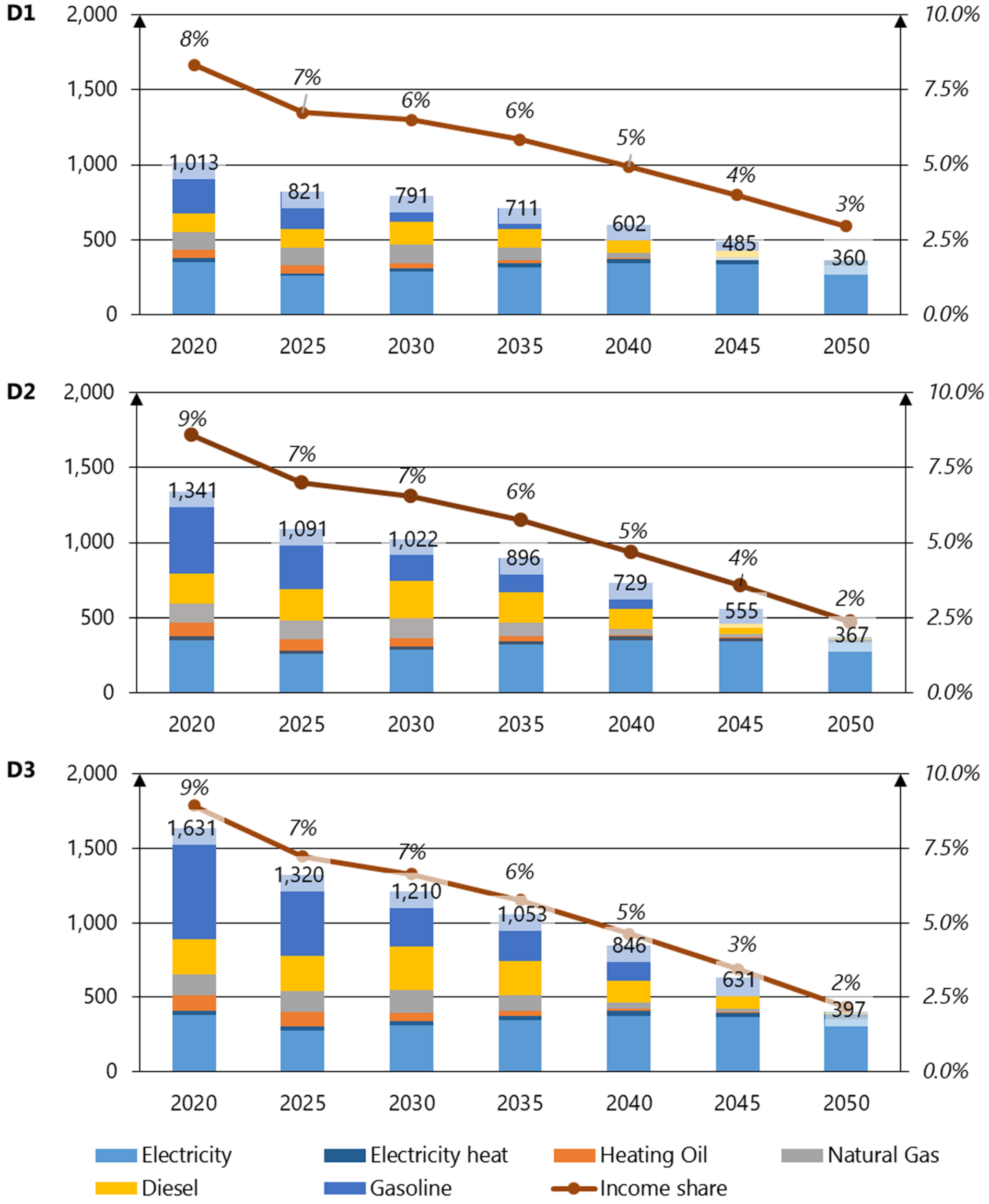


**Fig. 13** Scenario A—development of energy costs in euro per year and share of income for the lowest three household deciles with equivalent disposable income until 2050—low carbon prices (Source: own calculation)

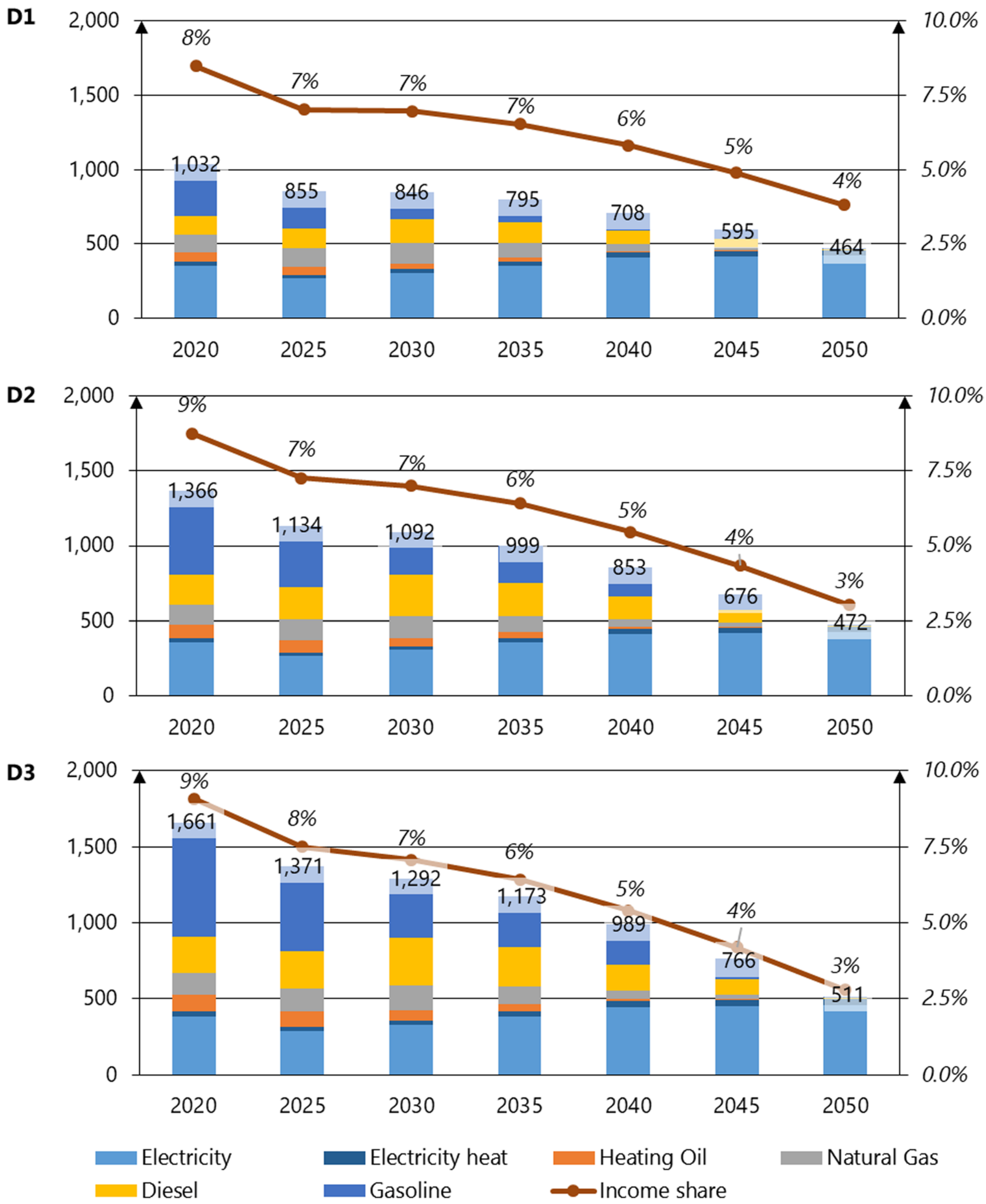


**Fig. 14** Scenario B—development of energy costs in euro per year and share of income for the lowest three household deciles with equivalent disposable income until 2050—low carbon prices (Source: own calculation)

## Abbreviations

| | |
|---|---|
| EDI | Equivalent disposable income |
| ETS | Emission trading system |
| RUEC | Real unit energy costs |
| SIPC | State-induced price components |

## Acknowledgements

The authors are grateful to the anonymous reviewers for their valuable comments. Furthermore, they thank Barbara Koch, Chair of Remote Sensing and Landscape Information Systems at the University of Freiburg, for her advice and support. Responsibility for the article's content lies with the authors alone.

## Author contributions

JFG: conceptualisation, methodology, software, formal analysis, investigation, writing—original draft, writing—review and editing, visualisation. AM: conceptualisation, methodology, software, formal analysis, investigation, writing—original draft, writing—review and editing, visualisation. AH: conceptualisation, methodology, writing—review and editing, supervision, project administration. JW: conceptualisation, writing—review and editing, supervision. AB: conceptualisation; data curation; investigation, project administration. MR: writing—review and editing, supervision, project administration.

**Funding**
Open Access funding enabled and organized by Projekt DEAL. Funding from the Kopernikus-Projekt Ariadne (FKZ 03SFK5D0) by the German Federal Ministry of Education and Research is gratefully acknowledged.

**Availability of data and materials**
The data sets used and/or analysed in this study are available from the corresponding author on reasonable request.

## Declarations

**Ethics approval and consent to participate**
Not relevant.

**Consent for publication**
Not relevant.

**Competing interests**
The authors declare no competing interests.

**Author details**
[1]Fraunhofer Institute for Systems and Innovation Research ISI, Breslauer Straße 48, 76139 Karlsruhe, Germany. [2]Faculty of Environment and Natural Resources, University of Freiburg, Tennenbacher Str. 4, 79106 Freiburg, Germany. [3]Faculty VII Economics and Management, Chair of Economics and Infrastructure Policy, Technische Universität Berlin, Straße Des 17. Juni 135, 10623 Berlin, Germany. [4]Fraunhofer Research Institution for Energy Infrastructures and Geothermal Systems IEG, Gulbener Straße 23, 03046 Cottbus, Germany. [5]Brandenburg University of Technology Cottbus-Senftenberg BTU CS, Platz Der Deutschen Einheit 1, 03046 Cottbus, Germany.

Received: 27 July 2023 Accepted: 5 April 2024

**References**

1. IPCC (2022) Synthesis report of the IPCC sixth assessment report (AR6). https://report.ipcc.ch/ar6syr/pdf/IPCC_AR6_SYR_LongerReport.pdf.
2. Hainsch K, Löffler K, Burandt T, Auer H, Del Crespo GP, Pisciella P et al (2022) Energy transition scenarios: What policies, societal attitudes, and technology developments will realize the EU Green Deal? Energy 239:122067. https://doi.org/10.1016/j.energy.2021.122067
3. Tsiropoulus I, Tarvydas D, Lebedeva N (2018) Li-ion batteries for mobility and stationary storage applications: Scenario for costs and market growth. https://doi.org/10.2760/87175
4. Markard J (2018) The next phase of the energy transition and its implications for research and policy. Nat Energy 3(8):628–633. https://doi.org/10.1038/s41560-018-0171-7
5. Trutnevyte E, Hirt LF, Bauer N, Cherp A, Hawkes A, Edelenbosch OY et al (2019) Societal transformations in models for energy and climate policy: the ambitious next step. One Earth. https://doi.org/10.1016/j.oneear.2019.12.002
6. Karapin R (2020) Household costs and resistance to Germany's energy transition. Rev Policy Res 37(3):313–341. https://doi.org/10.1111/ropr.12371
7. Branger F, Quirion P (2014) Would border carbon adjustments prevent carbon leakage and heavy industry competitiveness losses? Insights from a meta-analysis of recent economic studies. Ecol Econ 99:29–39. https://doi.org/10.1016/j.ecolecon.2013.12.010
8. Kalt T (2021) Jobs vs. climate justice? Contentious narratives of labor and climate movements in the coal transition in Germany. Environ Polit 30(7):1135–1154. https://doi.org/10.1080/09644016.2021.1892979
9. Branger F, Quirion P, Chevallier J (2016) Carbon leakage and competitiveness of cement and steel industries under the EU ETS: much ado about nothing. Energ J. https://doi.org/10.5547/01956574.37.3.fbra
10. Dechezleprêtre A, Sato M (2017) The impacts of environmental regulations on competitiveness. Rev Env Econ Policy 11(2):183–206. https://doi.org/10.1093/reep/rex013
11. Freire-González J, Puig-Ventosa I (2019) Reformulating taxes for an energy transition. Energ Econ 78:312–323. https://doi.org/10.1016/j.eneco.2018.11.027
12. OECD and International Transport Forum Tax Revenue Implications Of Decarbonising Road Transport: Scenarios for Slovenia: OECD; 2019.
13. World Bank (2021) State and trends of carbon pricing 2021. World Bank. https://doi.org/10.1596/978-1-4648-1728-1
14. Steenkamp LA (2021) A classification framework for carbon tax revenue use. Clim Policy 21(7):897–911. https://doi.org/10.1080/14693062.2021.1946381
15. DeCarolis J, Daly H, Dodds P, Keppo I, Li F, McDowall W et al (2017) Formalizing best practice for energy system optimization modelling. Appl Energ. https://doi.org/10.1016/j.apenergy.2017.03.001
16. Faehn T, Bachner G, Beach R, Chateau J, Fujimori S, Ghosh M et al (2020) Capturing key energy and emission trends in cge models: assessment of status and remaining challenges. www.RePEc.org.
17. Berntsen PB, Trutnevyte E (2017) Ensuring diversity of national energy scenarios: bottom-up energy system model with modeling to generate alternatives. Energy 126:886–898. https://doi.org/10.1016/j.energy.2017.03.043
18. German Federal Statistical Agency (destatis) (2023) Industrial sector in Germany remains stronger than in many other EU Member States. https://www.destatis.de/Europa/EN/Topic/Industry-trade-services/Industry_GVA.html. Accessed 15 Apr 2023.
19. German Federal Statistical Agency (destatis) (2022) Statistics on tax revenue 2018–2020. https://www-genesis.destatis.de/genesis/online.
20. Ekins P (2011) Speck S Environmental tax reform (ETR): a policy for green growth. University Press, Oxford, New York
21. Gawel E, Purkus A (2015) Die Rolle von Energie- und Strombesteuerung im Kontext der Energiewende. Z Energiewirtsch 39(2):77–103. https://doi.org/10.1007/s12398-015-0150-7
22. Agnolucci P (2009) The effect of the German and British environmental taxation reforms: A simple assessment. Energ Policy 37(8):3043–3051. https://doi.org/10.1016/j.enpol.2009.03.052
23. Flues F, Lutz J (2015) Competitiveness impacts of the German electricity tax. OECD Environment Policy Papers 88:1–25. https://doi.org/10.1787/5js0752mkzmv-en
24. Rosenberg A, Schopp A, Neuhoff K, Vasa A (2011) Impact of reductions and exemptions in energy taxes and levies on German industry. CPI Brief, Climate Policy Initiative. http://hdl.handle.net/10419/65904.
25. Bardt H, Kempermann H (2014) The German Energiewende: is the manufacturing sector at risk? J Energy Markets 7(4):3–15
26. Lutz C, Meyer B (2010) Environmental tax reform in the European Union: impact on CO2 emissions and the economy. Z Energiewirtsch 34(1):1–10. https://doi.org/10.1007/s12398-010-0009-x
27. Großmann A (2017) Lutz C Economic effects of reforming energy tax exemptions for the industry in Germany. In: Weishaar SE, Kreiser L, Milne JE, Ashiabor H, Mehling M (eds) The green market transition: carbon taxes, energy subsidies and smart instrument mixes. Edward Elgar Publishing, pp 128–142
28. Többen J (2017) Regional net impacts and social distribution effects of promoting renewable energies in Germany. Ecol Econ 135:195–208. https://doi.org/10.1016/j.ecolecon.2017.01.010
29. German Federal Ministry of Economic Affairs and Climate Protection (BMWK) (2021) EEG levy 2022: facts & background. https://www.bmwi.de/Redaktion/DE/Downloads/E/zahlen-und-fakten-zur-eeg-umlage-2022.pdf?__blob=publicationFile&v=4.
30. German Transmission System Operators (2021) Mid-term forecast 2022–2026. https://www.netztransparenz.de/EEG/Mittelfristprognosen/Mittelfristprognose-2022-2026. Accessed 28 Feb 2022.
31. Agora Energiewende (2021) EEG calculator for Excel: Calculation and scenario model for determining the EEG surcharge until 2035. https://www.agora-energiewende.de/veroeffentlichungen/eeg-rechner-fuer-excel/. Accessed 28 Feb 2022.
32. Matthes FC, Schumacher K, Blanck R, Cludius J, Hermann H, Kreye K et al. (2021) CO2 pricing and the reform of taxes and levies on electricity: the refinancing of the levy under the Renewable Energy Act. https://www.stiftung-klima.de/app/uploads/2021/06/2021-06-03-Oeko-Institut-CO2-Bepreisung-und-die-Reform-der-Steuern.pdf. Accessed 28 Feb 2022.

33. Fraunhofer ISI, Consentec, TU Berlin, ifeu (2022) Langfristszenarien für die Transformation des Energiesystems in Deutschland. https://www.langfristszenarien.de/enertile-explorer-de/dokumente/.
34. Prognos, Öko-Institut, Wuppertal-Institut (2021) Klimaneutrales Deutschland 2045: Wie Deutschland seine Klimaziele schon vor 2050 erreichen kann. Langfassung im Auftrag von Stiftung Klimaneutralität Agora Energiewende und Agora Verkehrswende. https://www.agora-energiewende.de/veroeffentlichungen/klimaneutrales-deutschland-2045-vollversion/.
35. Kopernikus-Projekt Ariadne (2021) Ariadne-Report: Deutschland auf dem Weg zur Klimaneutralität 2045 - Szenarien und Pfade im Modellvergleich. https://doi.org/10.48485/pik.2021.006.
36. Deutsche Energie-Agentur (dena) (2021) dena-Leitstudie Aufbruch Klimaneutralität. https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2021/Abschlussbericht_dena-Leitstudie_Aufbruch_Klimaneutralitaet.pdf.
37. BCG (2021) Klimapfade 2.0: Ein Wirtschaftsprogramm für Klima und Zukunft. Gesamtstudie im Auftrag von BDI. https://www.bcg.com/klimapfade.
38. Deutsche Energie-Agentur (dena) (2022) Vergleich der "Big 5" Klimaneutralitätsszenarien. https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2022/Vergleich_der_Big_5_Klimaneutralitaetsszenarien.pdf.
39. German Federal Ministry of Economic Affairs and Climate Protection (2021) Facts and figures: Energy data. http://www.bmwi.de/Navigation/DE/Themen/energiedaten.html. Accessed 24 Feb 2022.
40. German Federal Statistical Agency (destatis) (2020) Electricity taxation statistics 2019. https://www.destatis.de/DE/Themen/Staat/Steuern/Verbrauchsteuern/Publikationen/Downloads-Verbrauchsteuern/stromsteuer-2140970197004.html. Accessed 15 Aug 2022.
41. German Federal Statistical Agency (destatis) (2020) Energy taxation statistics 2019. https://www.destatis.de/DE/Themen/Staat/Steuern/Verbrauchsteuern/Publikationen/Downloads-Verbrauchsteuern/energiesteuer-2140930207004.html. Accessed 15 Aug 2022.
42. German Federal Statistical Agency (destatis) (2021) Electricity taxation statistics 2020. https://www.destatis.de/DE/Themen/Staat/Steuern/Verbrauchsteuern/Publikationen/Downloads-Verbrauchsteuern/stromsteuer-2140970207004.html. Accessed 15 Aug 2022.
43. German Federal Statistical Agency (destatis) (2021) Energy taxation statistics 2020. https://www.destatis.de/DE/Themen/Staat/Steuern/Verbrauchsteuern/Publikationen/Downloads-Verbrauchsteuern/energiesteuer-2140930207004.html. Accessed 15 Aug 2022.
44. Grave K, Breitschopf B, Ordonez J, Wachsmuth J, Boeve S, Smith M et al. (2022) Prices and costs of EU energy. Final Report. https://www.isi.fraunhofer.de/content/dam/isi/dokumente/ccx/2016/report_ecofys2016.pdf. Accessed 28 Feb 2022.
45. Kaltenegger O, Löschel A, Baikowski M, Lingens J (2017) Energy costs in Germany and Europe: An assessment based on a (total real unit) energy cost accounting framework. Energ Policy 104:419–430. https://doi.org/10.1016/j.enpol.2016.11.039
46. Bach S, Harnisch M, Isaak N (2018) Verteilungswirkungen der Energiepolitik – Personelle Einkommensverteilung. https://www.bmwk.de/Redaktion/DE/Publikationen/Studien/verteilungswirkungen-der-energiepolitiken.pdf?__blob=publicationFile&v=8.
47. Held B Auswirkungen der Internalisierung externer Kosten des Konsums - Eine empirische Analyse der sozialen Verteilungswirkungen; 2018.
48. Neuhoff K, Bach S, Diekmann J, Beznoska M, El-Laboudy T (2013) Distributional effects of energy transition: impacts of renewable electricity support in Germany. EEEP. https://doi.org/10.5547/2160-5890.2.1.3
49. Flues F, Alastair T (2023) The distributional effects of energy taxes, 23. https://doi.org/10.1787/5js1qwkqqrbv-en. Accessed 15 Apr 2023.
50. Atkinson AB (1970) On the measurement of inequality. J Econ Theory 2(3):244–263. https://doi.org/10.1016/0022-0531(70)90039-6
51. German Federal Statistical Agency (destatis) (2019) Living in Europe (EU-SILC): Income and living conditions in Germany and the European Union. https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Einkommen-Konsum-Lebensbedingungen/Lebensbedingungen-Armutsgefaehrdung/Publikationen/Downloads-Lebensbedingungen/einkommen-lebensbedingungen-2150300197004.pdf?__blob=publicationFile. Accessed 28 Feb 2022.
52. German Federal Environmental Agency (UBA) (2023) Framework data for the 2023 projection report. https://www.umweltbundesamt.de/publikationen/rahmendaten-fuer-den-projektionsbericht-2023. Accessed 15 Apr 2023.
53. Intercontinental Exchange (ICE) (2023) EUA Futures. https://www.theice.com/products/197/EUA-Futures/data?marketId=5474737. Accessed 15 June 2023.
54. Martin LW, Vanberg G (2013) Multiparty Government, Fiscal Institutions, and Public Spending. J Polit 75(4):953–967. https://doi.org/10.1017/S0022381613000947
55. Lutz BJ, Massier P, Sommerfeld K, Löschel A (2018) Drivers of energy efficiency in German manufacturing: a firm-level stochastic frontier analysis. SSRN Electr J. https://doi.org/10.2139/ssrn.3091570
56. Castro Oliveira M, Iten M, Cruz PL, Monteiro H (2020) Review on energy efficiency progresses, technologies and strategies in the ceramic sector focusing on waste heat recovery. Energies 13(22):6096. https://doi.org/10.3390/en13226096
57. Gerres T, Chaves Ávila JP, Llamas PL, San Román TG (2019) A review of cross-sector decarbonisation potentials in the European energy intensive industry. J Clean Prod 210:585–601. https://doi.org/10.1016/j.jclepro.2018.11.036
58. Schreiner N (2015) Auf der Suche nach Energiearmut: Eine Potentialanalyse des Low-Income-High-Costs Indikators für Deutschland. http://hdl.handle.net/10419/129734. Accessed 28 Feb 2022.
59. Boardman B (1991) Fuel poverty: from cold homes to affordable warmth. Pinter Pub Limited
60. Neuhoff K, Bach S, Diekmann J, Beznoska M, El-Laboudy T (2013) Distributional effects of energy transition: impacts of renewable electricity support in Germany. Econ Energy Env Pol 2(2):41–54
61. George JF, Werner S, Preuß S, Winkler J, Held A, Ragwitz M (2023) The landlord–tenant dilemma: distributional effects of carbon prices, redistribution and building modernisation policies in the German heating transition. Appl Energ 339:120783. https://doi.org/10.1016/j.apenergy.2023.120783
62. Edenhofer O, Kalkuhl M, Roolfs C (2021) Carbon pricing and revenue recycling: an overview of vertical and horizontal equity effects for Germany. CESifo Forum 5:10–14
63. German Federal Ministry of Transport and Digital Infrastructure (BMVi) (2021) Traffic in numbers 2021/2022. https://www.bmvi.de/SharedDocs/DE/Publikationen/G/verkehr-in-zahlen-2020-pdf.pdf?__blob=publicationFile. Accessed 28 Feb 2022.
64. German Federal Statistical Agency (destatis) (2019) Mileage and fuel consumption of private households with passenger cars. https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Umwelt/Materialfluesse-Energiefluesse/Tabellen/fahrleistungen-haushalte.html;jsessionid=6E95B91886FEE08DB125C730D7AE6B24.live741#fussnote-1-133564. Accessed 28 Feb 2022.
65. International Energy Agency (IEA) (2021) World Energy Outlook 2021. https://www.iea.org/reports/world-energy-outlook-2021. Accessed 18 Oct 2021.
66. en2X - Fuels and Energy Business Association e. V. (en2X) (2022) Statistics—prices for premium petrol, diesel fuel and light heating oil. https://en2x.de/service/statistiken/. Accessed 28 Feb 2022.
67. George JF, Müller VP, Winkler J, Ragwitz M (2022) Is blue hydrogen a bridging technology?—the limits of a $CO_2$ price and the role of state induced price components for green hydrogen production in Germany. Energ Policy. https://doi.org/10.1016/j.enpol.2022.113072
68. German Federal Cartel Office (BKartA), German Federal Network Agency (BNetzA) (2021) Monitoring Report 2020. https://www.bundesnetzagentur.de/EN/Areas/Energy/Companies/DataCollection_Monitoring/start.html. Accessed 10 Spet 2021.
69. Flues F, Thomas A (2015) The distributional effects of energy taxes. https://doi.org/10.1787/5js1qwkqqrbv-en.
70. Speck S, Jilkova J (2009) Design of environmental tax reforms in Europe. In: Andersen MS, Ekins P (eds) Carbon-energy taxation. Oxford University Press, Oxford, pp 24–52
71. Andersen MS, Ekins P (2009) carbon-energy taxation: lessons from Europe. OUP Oxford, Oxford
72. German Federal Statistical Agency (destatis) (2022) Stromerzeugung, Strombezug, Stromabgabe, Stromverbrauch: Deutschland, Jahre, Wirtschaftszweige. https://www-genesis.destatis.de/genesis//online?operation=table&code=43531-0002&bypass=true&levelindex=0&levelid=1661867927200. Accessed 28 Feb 2022.

73. Weißbach D, Ruprecht G, Huke A, Czerski K, Gottlieb S, Hussein A (2013) Energy intensities, EROIs (energy returned on invested), and energy payback times of electricity generating power plants. Energy 52:210–221. https://doi.org/10.1016/j.energy.2013.01.029
74. Infas, DLR, IVT und infas 360 (2017) Mobilität in Deutschland (MiD)—final report: on behalf of the German federal ministry of transport and digital infrastructure. http://www.mobilitaet-in-deutschland.de/pdf/MiD2017_Ergebnisbericht.pdf. Accessed 28 Feb 2022.
75. Andersen TB, Nilsen OB, Tveteras R (2011) How is demand for natural gas determined across European industrial sectors? Energ Policy 39(9):5499–5508. https://doi.org/10.1016/j.enpol.2011.05.012
76. Schulte I, Heindl P (2017) Price and income elasticities of residential energy demand in Germany. Energ Policy 102:512–528. https://doi.org/10.1016/j.enpol.2016.12.055

## Publisher's Note