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The effects of energy efficiency on GDP and GHG emissions in Germany

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Non-technical summary

Research Question

Energy efficiency improvements are considered as a key factor for curbing greenhouse gas emissions. However, little is known about the dynamic general equilibrium effects of energy efficiency improvements over the short and medium term and how they influence the macroeconomic impact of a rising emissions price.

Contribution

This paper uses the Environmental Multi-Sector Model EMuSe to analyses the macroeconomic and environmental effects of energy efficiency improvements. Energy efficiency in the model corresponds to firms' level of energy saving technology (EST). We identify the sector-specific development of EST in Germany between 1991 and 2019, using the production function approach by Hassler et al. (2021). Based on simulations with the EMuSe model, we examine under which emission price path the emission reduction goal of the German Federal Climate Change Act is achievable if energy efficiency improves as in the last three decades.

Results

We show that energy efficiency in Germany improved on a broad sectoral basis since 1991. Weighted across the economic sectors, energy efficiency increased by roughly 3 percent per year. According to the model, taking into account a sustained exogenous increase in energy efficiency as in the past three decades reduces emissions while at the same time it increases output. Thereby, energy efficiency improvements attenuate the model-implied negative co-movement between emissions and output caused by an increasing emission price. If, however, the emission price increases in line with the path under the national and European ETS, energy efficiency improvements as during the last three decades are insufficient to meet the German emission goal by 2030. Assuming that energy efficiency in each sector grows at its historical rate, the emissions price path must be almost twice as high as the current path in order to achieve the emissions goal by 2030.

Nichttechnische Zusammenfassung

Fragestellung

Energieeffizienzsteigerungen werden als ein Schlüsselfaktor für die Verringerung der Treibhausgasemissionen angesehen. Es ist jedoch bisher wenig bekannt über die dynamischen allgemeinen Gleichgewichtseffekte von Energieeffizienzsteigerungen über die kurze und mittlere Frist und darüber, wie sie die makroökonomischen Auswirkungen eines steigenden Emissionspreises beeinflussen.

Beitrag

Um die ökologischen und makroökonomischen Auswirkungen von Verbesserungen der Energieeffizienz zu analysieren verwendet das vorliegende Papier das Umwelt-Multisektor-Modell EMuSe. Die Energieeffizienz entspricht im Modell dem Niveau der energiesparenden Technologie (EST) der Unternehmen. Wir identifizieren die sektorspezifische Entwicklung der EST in Deutschland zwischen 1991 und 2019, indem wir den Produktionsfunktionsansatz von Hassler et al. (2021) verwenden. Anhand von Simulationen mit dem EMuSe-Modell untersuchen wir, unter welchem Emissionspreispfad das Emissionsminderungsziel des deutschen Klimaschutzgesetzes erreichbar ist, wenn sich die Energieeffizienz wie in den letzten drei Jahrzehnten beobachtet entwickelt.

Ergebnisse

Wir zeigen, dass sich die Energieeffizienz in Deutschland seit 1991 auf breiter sektoraler Basis verbessert hat. Über die Wirtschaftssektoren gewichtet stieg die Energieeffizienz im Durchschnitt um etwa 3 Prozent pro Jahr. Das Modell zeigt, dass eine nachhaltige exogene Energieeffizienzsteigerung, wie sie in den letzten drei Jahrzehnten stattfand, die Emissionen reduziert und gleichzeitig die Produktion erhöht. Dadurch schwächen Energieeffizienzsteigerungen die vom Modell unterstellte negative Korrelation zwischen Emissionen und Produktion ab, die durch einen steigenden Emissionspreis verursacht wird. Steigt der Emissionspreis jedoch entsprechend dem Pfad im Rahmen des nationalen und europäischen EHS, reichen die in den letzten drei Jahrzehnten beobachteten Energieeffizienzsteigerungen nicht aus, um das deutsche Emissionsziel bis 2030 zu erreichen. Wenn man davon ausgeht, dass die Energieeffizienz in jedem Sektor mit der historischen Rate zunimmt, müsste der Emissionspreispfad fast doppelt so hoch liegen wie der derzeitige Pfad, um das Emissionsziel bis 2030 zu erreichen.

The Effects of Energy Efficiency on GDP and GHG Emissions in Germany[*]

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Abstract

Energy efficiency improvements are a key component on the road towards a carbon-neutral economy. We identify the development of energy efficiency in the data and show that in recent decades it has increased at the aggregate level. At the sectoral level, however, the development in energy efficiency was highly heterogenous. We, then, analyse the effects of exogenous improvements in energy saving technology by means of Environmental Multi-Sector Model EMuSe. According to the model, sustained exogenous gains in energy saving technology increase output while, at the same time, reduce emissions energy use and energy intensity. Thereby, they attenuate the model-implied negative co-movement of output and emissions that results from the introduction or an intensified increase of an emission price schedule. However, if energy efficiency evolves as during the last decades and the emission price follows the currently intended schedule in the national and EU-wide emissions trading system, the model predicts that the emissions reduction by 2030 set by the German Federal Climate Change Act cannot be met. It additionally requires a higher emission price or larger (exogenous) energy efficiency gains.

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1 Introduction

According to the German federal climate change act, greenhouse gas emissions have to be reduced in 2030 by roughly 35% relative to 2023.[1] This target lies above the emission reduction goal for the European Union set by the European Commission.[2] There are various ways to achieve this goal. Among others, taxing carbon emissions via an emission price or investment in renewable energy sources and low-carbon technologies are important instruments. In particular, the emission price is a meaningful measure to combat rising carbon emissions. It directly rises the costs of fossil energy usage in production. In the short run, this can potentially lead to moderate output losses, but the transition to a carbon neutral economy promises higher aggregate production compared to a case, where no climate action is taken and economic damages from climate change kick in in the long-run.[3,4]

Another important factor for curbing down greenhouse gas emissions is rising energy efficiency. Generally, the notion of energy efficiency is associated with smaller energy demand to produce a given amount of output (Metcalf 2008) and a reduction in energy consumption eventually leads to a drop in greenhouse gas emissions. Empirical and theoretical research confirm the important role of energy efficiency for lowering emissions.[5] Increasing energy efficiency is also frequently mentioned in international and national strategies to combat climate change by reducing energy consumption and greenhouse gas emissions (IPCC 2022; IEA 2023). More recently, the UN Climate Change Conference in Dubai, COP28, formulated a resolution regarding energy efficiency improvements. Energy efficiency, measured as the level of GDP per unit of energy consumed in production, is supposed to increase globally at a rate of 4% per year by 2030 instead of the current average growth rate of 2%. According to several studies for Germany, reaching the German climate goals also requires a significant decline in energy demand via energy efficiency improvements (Deutsche Energieagentur 2019; KfW 2018). However, little is

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[1] The emission reduction formulated in the German federal climate change act states that emissions should fall by 65% in 2030 relative to 1990. Until 2023, around 46% of emissions have been already reduced.

[2] The European Commission aims an emission reduction of 55% until 2030 relative to 1990 in the EU on average. How strict climate goals are for the individual countries depends on their economic strength.

[3] Empirical literature examining the effects of higher emission prices on production is ambiguous. While Metcalf and Stock (2023) find low real effects of an emission price, the analysis of Känzig (2023) indicates negative effects on economic activity.

[4] For more references, see Acemoglu et al. (2012) and NGFS (2023).

[5] Studies for the US show that changes in energy efficiency are an important driver of the evolution of emissions (Jo and Karnizova 2021; Nordhaus 2013). Improvements in energy efficiency might decrease the economic costs of standard climate change policies. In particular, they might help avoiding losses in output associated with a drop in energy consumption (Bönke et al. 2023; Deutsche Bundesbank 2024; Kriegler et al. 2014).

known about the dynamic general equilibrium effects of energy efficiency improvements over the short and medium term and how they influence the macroeconomic impact of a rising emissions price.[6]

This paper analyses the effects of energy efficiency improvements on economic activity and greenhouse gas emissions in Germany. In particular, we investigate transition paths of emissions and output after sustained exogenous energy saving technological progress over time. We, further, examine how energy saving technological gains interact with an emissions price and which combination of these two factors achieves the emission reduction goal of the German Federal Climate Change Act. To this end, we first give a short overview on the definition of energy efficiency and its measurement. In the next step, we then compute the development of energy efficiency on the sectoral level over time based on a production function approach by Hassler et al. (2021). We use the estimation results to analyse the effects of sector-specific improvements in energy efficiency on emission reductions and GDP in Germany. In particular, we investigate transition paths of emissions and output following sustained sectoral energy efficiency increases over time. For the simulations, we use the **E**nvironmental **Mu**lti-**Se**ctor DSGE model EMuSe developed by the Bundesbank (Hinterlang et al. (2023)) calibrated to Germany. The model features several sectors that are interconneced via input-output linkages. Within an environmental block, each sector generates emissions during the production process, adding to the stock of pollution in the spirit of Heutel (2012). In addition, this model version follows Hinterlang et al. (2022) assuming that sectoral emissions intensity positively depends on the fossil energy use in production. Moreover, it distinguishes between energy and non-energy intermediate inputs, which allows to stress the special role of energy in the production process and introduce efficiency gains which are energy-specific. Finally, we examine how well energy efficiency improvements and an emission price perform in achieving the emission reduction goal of the German Federal Climate Change Act and simulate which adjustments of either the emission price path or energy efficiency gains are necessary so that the desired emission reduction could be achieved.

Note that conceptually, there are interactions between emissions pricing and energy efficiency that are not straightforward to capture in this modeling framework. As a higher carbon price tends to make energy use more expensive, firms, who face rising carbon prices, have a greater interest in developing and deploying energy-saving technologies more rapidly. The effect of carbon pricing on emission reductions might increase via

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[6] The theoretical literature that analyses energy efficiency improvements mainly focus on the long-run effects on the aggregate economy (Casey 2024; Hassler et al. 2021). Further studies analyse the implications of energy efficiency improvements in the energy transformation sector (Bosetti et al. 2006; Popp 2004). The present paper, in turn, focuses on macroeconomic effects of exogenous energy efficiency improvements within the production sector over the short and medium term.

this channel. However, the empirical evidence on the degree to which carbon pricing affects energy efficiency improvements is scarce.[7] The following analysis uses a model framework in which energy efficiency gains are exogenous. In the model, they are not directly influenced by macroeconomic developments or economic policy measures such as a carbon price. Instead, assumption-based scenarios are defined, setting out different pathways for energy efficiency and emissions pricing. This depicts the two driving forces of emission reduction more clearly in isolation, but disregards presumably important interactions for now.

Our analysis generates several findings. First, we identify exogenous sector-specific variations in energy efficiency in Germany between 1991 and 2019. We rely on the approach proposed by Hassler et al. (2021) and identify these sectoral variations in energy efficiency based on the sectoral production function embedded in the EMuSe model. We show that energy efficiency improved on a broad sectoral basis since 1991. Weighted across the economic sectors, energy efficiency increased by roughly 3 percent per year, on average. At the same time, energy intensity declined by roughly two percent per year between 1991 and 2019.[8] However, the change in energy efficiency displays a pronounced heterogeneity across sectors. The average rate of change in energy efficiency varied between a half and five percent in the period from 1991 to 2019.[9]

Second, simulations with EMuSe suggest that the currently planned emission price path without considering sustained energy efficiency improvements reduces emissions effectively, but this policy misses the emission reduction required by the German federal climate change law. Moreover, the model predicts a slight drop in output due to an increase in marginal costs of the production input energy.

Third, considering a sustained exogenous increase in energy efficiency as in the past three decades in addition to the planned emission price path, however, mitigates this negative output effect. In this scenario, emissions are further reduced through a drop in energy consumption, while the technological progress in using energy in the production process raises production.

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[7] There is microeconomic evidence that variations in energy prices affect the direction of research and development (Aghion et al. 2016; Popp 2002). Further, Karmaker et al. (2021) show that environmental taxes stimulate technological innovation in high and middle-income nations. Based on these empirical studies, however, it is difficult to estimate the incentive effects of carbon pricing for innovations in energy-saving technologies.

[8] Energy intensity is defined as the primary energy use in relation to GDP and corresponds to the International Energy Agency preferred measure of energy efficiency (IEA 2023).

[9] Economic sectors with above-average rates are the agricultural industry, water supply, service providers (excluding trade and transport and storage) and the non-fossil energy sector. Sectors in which rate of change in energy-saving technology was below-average are part of the manufacturing industry not covered by the EU Emissions Trading Scheme, the fossil energy sector and the transport and storage sector. Moreover, the fossil energy sector even experiences a decline in energy efficiency between 2012 and 2019.

Fourth, although considering both factors, energy efficiency improvements and the emission price path, achieves a substantially larger emission reduction than the emission price only, it still misses the emission reduction goals set in the German federal climate change law.

Fifth, we also determine the increase of the emission price that is required from the viewpoint of the model to meet the emission reduction targets in Germany. Assuming that energy efficiency in each sector grows at its historical rate, the emissions price path must be almost twice as high as the current path in order to achieve the emissions goal by 2030. Despite initial small output losses, in 2030 an output level slightly larger than 2023 can be reached.[10] Hypothetically, energy efficiency gains could be larger in the future than they have been in the past three decades. This would lead to a larger emission drop and output gains than in the scenario in which energy efficiency grows as observed during the last three decades. Such a higher growth rate would require a smaller emission price increase over the entire time span.

Finally, assuming that the emission prices follows the intended path until 2030, the required annual growth rate in energy efficiency would have to more than double in every sector by 2030 in order to achieve the climate targets. These rates over such a time horizon have been observed historically only sporadically in individual sectors and not on the aggregate. Recalling that outside the model, the emission price surely incentivizes investment in energy efficiency, solely this incentive effect would have to be very strong to generate these high growth rates of energy efficiency in the near future.

The rest of the paper is organized as follows. Section 2 describes the role of energy efficiency in the light of climate policy. It shows where energy efficiency changes take place in the production process and how these energy-specific innovations can be identified in the data. Further, it continues with a description of how energy efficiency evolved over time across different sectors and elaborates on the connection between energy efficiency in the production process and the aggregate energy intensity of the economy. Section 3 gives a short presentation of the model EMuSe and describes all scenario simulations. Finally, Section 4 concludes.

2 Energy Efficiency in EMuSe and in the data

In order to reduce the emissions of greenhouse gas, fossil energy consumption has to drop. Energy efficiency improvements, ceteris paribus, lower the energy consumption required

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[10] Model simulations do not make any further assumptions about economic developments up to 2030. It should be stressed that this is not an economic projection. The simulations focus exclusively on the contribution of the two components: energy efficiency improvements and carbon pricing.

for a given level of production. From the angle of *production theory*, the term energy efficiency improvements refers to energy-saving technological (EST) progress. This form of technology feeds into firms' production technology, but is linked to the energy input. In this sense, energy efficiency measures how effectively energy is used in production. Examples of improvements in energy saving technology are new machines that deliver the same performance but require less power, or recycling the heat generated when burning fossil fuels for use in production processes.[11]

From a *macroeconomic perspective*, energy efficiency often refers to energy intensity, which is the ratio of aggregate energy consumption to GDP.[12] In this case, an increase in energy efficiency means a lower energy intensity. Consequently, it is not solely about how effectively energy can be used, but more generally about reducing energy consumption relative to output. The source of this shift is not relevant for determining energy intensity. Therefore, this is not a technological variable, but an observable measure of energy efficiency. As shown below, reductions in aggregate energy intensity do not necessarily reflect progress in energy saving technology.

Energy-saving technological progress is a major driving force of aggregate savings in energy use. The level of energy-saving technology indicates how efficient energy can be used in the production process. This type of technology is not an observed variable and has to be estimated as a consequence. The identification of the sector-specific energy efficiency shocks relies on the production function approach of Hassler et al. (2021).[13] We make use of the sector specific production function embedded in the Environmental Multi-Sector DSGE Model EMuSe. This production function combines capital, labor and the intermediate good bundle to produce final output. In order to identify energy-specific innovations, we rely on a version of the model, which distinguishes between non-energy and energy intermediate inputs as in Hinterlang et al. (2022). This approach allows identifying model-consistent sectoral energy efficiency changes in the data. In the following, we describe the production structure of EMuSe as well as the identification of energy saving technology.

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[11] A decline in energy efficiency can come about, for example, as a result of organizational changes within enterprises that lower the efficiency of energy input in production.

[12] In particular, the COP28 decisions on energy efficiency are based on energy intensity.

[13] Gemeinschaftsdiagnose (2022) compute the energy-saving technology also with a similar approach but based on a one-sector model. The energy-saving technological progress is computed similarly to the Solow residual. In addition, demand functions for factor inputs from the optimization process are needed.

2.1 Sectoral Production

There are S production sectors, each containing a perfectly competitive representative firm. Let the set of sectors be denoted by $\mathcal{S} = \left\{1, \ldots, S^{NE}, \ldots, S\right\}$, where S^{NE} denotes the number of sectors producing non-energy goods. The remaining $S - S^{NE}$ sectors produce energy goods. Each sector $s \in \mathcal{S}$ produces sectoral output $y_{s,t}$ by combining capital $K_{s,t-1}$, labour $N_{s,t}$ and a bundle of intermediate inputs $H_{s,t}$. Sectoral output $y_{s,t}$ is sold to households, investors and to intermediate good retailers (described in detail below) at price $P_{s,t}$. The representative firm in sector s produces $y_{s,t}$ according to the constant returns to scale production technology:

$$y_{s,t} = \left(K_{s,t-1}^{1-\alpha_{N,s}} N_{s,t}^{\alpha_{N,s}}\right)^{1-\alpha_{H,s}} H_{s,t}^{\alpha_{H,s}} \ , \tag{1}$$

with $\alpha_{N,s} \in (0,1)$ and $\alpha_{H,s} \in (0,1)$. The cost minimisation problem of firms is given by:

$$\min_{N_{s,t}, K_{s,t-1}, H_{s,t}} w_{s,t} N_{s,t} + r^k_{s,t} K_{s,t-1} + P^H_{s,t} H_{s,t}$$

subject to equation (1). Here, $w_{s,t}$ denotes the sectoral wage, $r^k_{s,t}$ the sector specific return on capital and $P^H_{s,t}$ denotes the sector-specific price for the intermediate good bundle. The first-order necessary conditions of the cost minimisation problem read:

$$w_{s,t} = mc_{s,t} \alpha_{N,s} \frac{y_{s,t}}{N_{s,t}} \alpha_{H,s} \tag{2}$$

$$r^k_{s,t} = mc_{s,t} (1 - \alpha_{N,s}) \frac{y_{s,t}}{K_{s,t-1}} \alpha_{H,s} \tag{3}$$

$$P^H_{s,t} = mc_{s,t} (1 - \alpha_{H,s}) \frac{y_{s,t}}{H_{s,t}} \tag{4}$$

Here, $mc_{s,t}$ are the real marginal production costs in sector s. Under perfect competition, $mc_{s,t} = P_{s,t}$.[14]

2.2 Energy Saving Technology

We assume that the intermediate good used in the production process of sector s is produced by a perfectly competitive intermediate good retailer. The retailer produces the intermediate good bundle $H_{s,t}$ by combining a non-energy intermediate good bundle $NE_{s,t}$ and an energy intermediate good bundle $E_{s,t}$. The intermediate good bundle $H_{s,t}$ is then sold to the firm in sector s at price $P^H_{s,t}$ and is produced according to the following

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[14] Note that, by assumption, in the steady state, there is no emission price. Then, firms' marginal cost correspond to the price of their product.

production technology:

$$H_{s,t} = \left[\alpha_{NE,s}^{1-\sigma_H} \left(NE_{s,t}\right)^{\sigma_H} + \left(1-\alpha_{NE,s}\right)^{1-\sigma_H} \left(\epsilon_{s,t} E_{s,t}\right)^{\sigma_H}\right]^{\frac{1}{\sigma_H}} \tag{5}$$

Here, $\epsilon_{s,t}$ denotes the energy saving technology, which we refer to as the sector specific energy efficiency. Profit maximisation of the intermediate good retailer yields the following first-order necessary condition for the energy intermediate good bundle:

$$E_{s,t} = \left(1-\alpha_{NE,s}\right) \left(\frac{P^H_{s,t}}{P^E_{s,t}}\right)^{\frac{1}{1-\sigma_H}} H_{s,t} \left(\epsilon_{s,t}\right)^{\frac{\sigma_H}{1-\sigma_H}} \quad , \tag{6}$$

where $P^E_{s,t}$ denotes the price that the representative firm in sector s pays for the energy intermediate good bundle.[15] Using equation (4) and the fact that $mc_{s,t} = P_{s,t}$ to replace the intermediate good price $P^H_{s,t}$ in equation (6), the level of the EST is determined as a residual:

$$\epsilon_{s,t} = \frac{H_{s,t}}{E_{s,t}} \left[\frac{1}{\gamma_s} \frac{P^E_{s,t} E_{s,t}}{P_{s,t} y_{s,t}}\right]^{\frac{1}{\sigma_H}} \tag{7}$$

Intuitively, for each sector s, an increase in EST is associated with (a) a lower growth of the energy input, $E_{s,t}$, relative to the one of total intermediate inputs $H_{s,t}$, or (b) with a reduction in sector s's total energy costs relative to its production value. The parameter $\gamma_s \equiv (1-\alpha_{NE,s})^{1-\sigma_H}(1-\alpha_{H,s})$ is a composite of the sector's production technology parameters and is a mere shifter of the sector-specific time series that does not play a major role for our quantitative analysis.

2.3 Empirical Results

Data on gross output and intermediate inputs come from National Accounts provided by Destatis. The share of energy costs in total costs for intermediate inputs is calculated based on data from the input-output tables of Destatis. Data on energy consumption come from the Environmental Economic Accounting of Destatis. The value for the elasticity of substitution between non-energy and energy inputs bundles is set according to the calibration in EMuSe. The factor intensity for intermediate goods $(1-\alpha_{H,s})$ is calculated as the mean of the ratio of intermediate goods to gross output over the whole sample period. The weight of non-energy inputs in total intermediate goods $\alpha_{NE,s}$ is

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[15] As in Hinterlang et al. (2022), the non-energy and the energy intermediate good bundle are produced according to a CES function that combines the final output of non-energy and energy sectors, respectively.

calculated as one minus the mean of the energy costs share over the whole sample period. We distinguish the following sectors in the estimation based on the NACE classification: agriculture (A), water supply (E), construction (F), retail trade (G), transportation and storage (H), other services (I-N, R, S), fossil energy (B, C19) and non-fossil energy (D35). Further, we split the manufacturing sector into an energy-intensive manufacturing sector (C17, C20, C23, C24), which underlies the EU-ETS, and a non-energy-intensive manufacturing sector (C without C19).

According to calculations using aggregate data for the total economy, energy efficiency increased by 120 percent between 1991 and 2019. On the aggregate, energy efficiency increased around 2.8% per year. However, Figure 1 shows that there was substantial heterogeneity with respect to sectoral developments. On balance, the largest improvement in energy efficiency occurred in the water supply sector, while the smallest improvement occurred in the transport and storage sector. Moreover, the fossil energy sector even experienced a sizable regress in energy efficiency since 2012. Finally, the ranking of energy efficiency changed over time. While the transportation sector featured much stronger energy efficiency gains in the late 1990s compared to manufacturing or services, the latter two sectors saw a much steeper progress and overtook in 2013.

Finally, the link between energy efficiency in the sense of energy saving technology and energy intensity is visible in Figure 2. It shows the development of aggregate energy saving technological progress and aggregate energy productivity, which corresponds to the reciprocal of energy intensity. Hence, an increase energy productivity is equivalent to a reduction in energy intensity.

By comparing the development of both measures, we see that changes in energy efficiency in the sense of technological progress are closely linked to energy productivity. However, they do not necessarily reflect changes in energy efficiency in the sense of technological progress. For example, sectoral shifts may lead to a reduction in aggregate energy intensity without efficiency gains in the use of energy being generated within production processes. This occurs, for instance, when the weight of the services sector increases relative to more energy-intensive economic sectors. Another factor that can lead to a reduction in energy intensity through lower energy use is the substitution of energy for other goods in the production process.[16] Even so, we can conclude that energy efficiency in the sense of energy-saving technology is closely linked to energy intensity. Energy-saving technological progress means less energy being used for the same level of production. Energy intensity therefore decreases. Thus, energy-saving technological progress can lead

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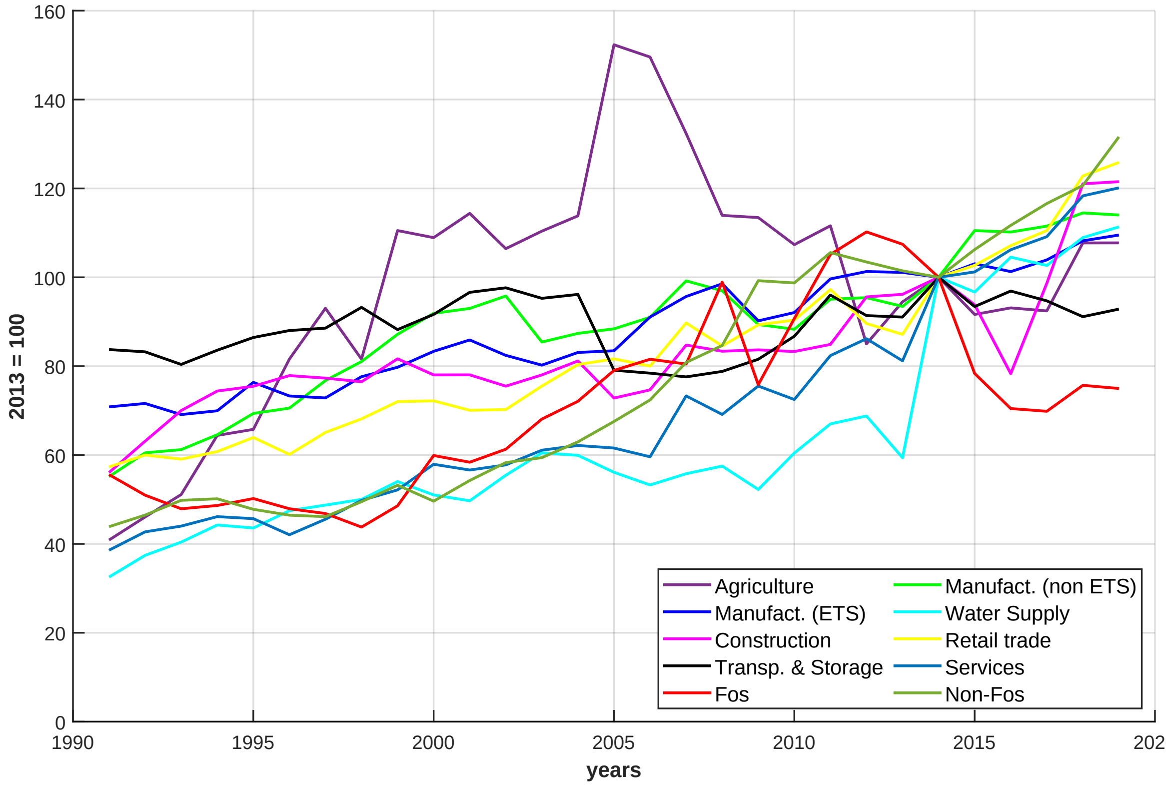
[16] There are multiple viewpoints in the academic debate about how well energy can be substituted with other factors of production within production processes. Essentially, though, energy plays a special role in the production process and its degree of substitutability is limited, at least in the short term (Stern 2019).

Figure 1: Sector Specific Development in Energy Saving Technology



Notes. Energy saving technology variable for ten sectors classified according to NACE2 estimated based on the production function approach of Hassler et al. (2021) by using the production function in EMuSe relative to the year 2013. We distinguish the following sectors: agriculture (A), manufacturing (C without C19), water supply (E), construction (F), retail trade (G), transportation and storage (H), services (I-N, R, S), fossil energy (B, C19) and non-fossil energy (D35).

to lower energy intensity, but a reduction in energy intensity does not necessarily require an increase in energy-saving technology. Overall growth in energy productivity between 1991 and 2019 was lower than energy-saving technological progress. One reason for this is probably rebound effects.[17]

2.4 Relation to other Identification Approaches

An alternative approach to identify variations in energy efficiency is to use structural vector autoregressions (SVAR), which has been done for example by Bruns et al. (2021) and in the empirical part of Jo and Karnizova (2021). These approaches have the advantage

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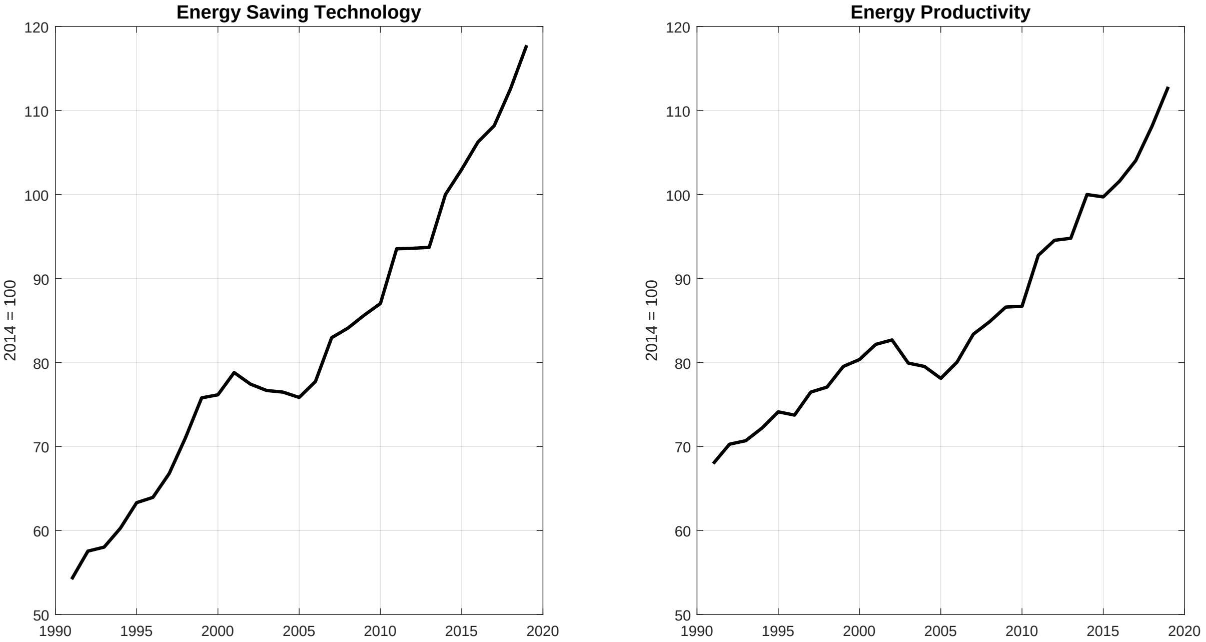
[17] Rebound effects may weaken the reduction in energy intensity compared with energy efficiency improvements, meaning that not all energy savings that would be technically possible are actually implemented. Once energy can be used more efficiently, production costs can be cut because energy consumption and the price of energy drop. These cost savings make it possible to increase production. As a result, demand for energy goes up again somewhat relative to other factors of production, and energy intensity falls somewhat less than it does immediately after the increase in energy efficiency.

Figure 2: Aggregate Energy Efficiency in Germany



Notes. Energy Productivity corresponds to GDP relative to energy consumption. Energy saving technology identified using the production theory approach by Hassler et al. (2021) based on the production function from the EMuSe model developed at Bundesbank.

that no assumptions regarding a specific production structure has to be made. However, drawing any conclusions about macroeconomic effects of energy efficiency improvements still requires other types of assumptions. Specifically, these assumptions mostly concern the relationship between underlying driving forces, which sometimes predetermines the economic forces behind the results, like the identification of structural shocks.

The production function approach, in turn, is useful because the production function can be included within dynamic stochastic general equilibrium models (DSGE models), which are are well-suited structural alternatives for the type of research question we are interested in this paper. The major advantage of this class of models compared to econometric estimation methods is their detailed micro-founded structure, which allows to shed light on different impact channels and driving forces that explain the results. Regarding this particular research question, they are an adequate tool to consider trend developments and take into account many special features such as sectoral heterogeneity, interdependencies in production or emissions.[18] In addition, they allow to take into account new sorts of mechanisms and policies that were weak or absent. This is partic-

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[18] The importance of sectoral interdependencies for macroeconomic effects, especially in the case of the introduction of an emission price, was explained in Deutsche Bundesbank (2022).

ularly important for the effects of the emission price, which has increased significantly since 2021.

3 The role of energy efficiency from the perspective of the EMuSe model

3.1 The EMuSe Model

The following simulations are carried out with the model EMuSe, which was developed at the Bundesbank. It is an environmental multi-sector DSGE model, which is specifically designed to analyze macroeconomic implications of climate policy adaptation processes and its interactions (Hinterlang et al. 2023). The model can be flexibly adjusted in many dimensions to fit the needs of the analyzed question. Moreover, the model is able to provide transition dynamics within a time period, which is also relevant to monetary policy decisions. This is typically much shorter than time periods covered by conventional climate impact models with macroeconomic variables, such as Integrated Assessment Models (IAM).

EMuSe is based on a prototypical DSGE model, but it features several advantages and combines different specifics of other macroeconomic models. First, it rigorously encompasses intersectoral linkages across different economic sectors. Besides capital and labor, firms also use intermediate goods as inputs in their production technology. These intermediate goods stem from all sectors, which are described in the model. Their composition also varies across sectors. This modeling choice creates a production network with many interdependencies. This, in turn, implies that any changes due to external shocks or policies in one sector, as for example technological innovations or the introduction of an emission price, have immediate repercussions to other sectors. The reason is that other sectors use the goods from the affected ones as intermediate inputs in their production. Hence, changes in policy measures or productivity affect the relative price of intermediate inputs and hence, production decisions in the entire economy.

Moreover, the substitutability across these intermediate inputs is limited, so that more expensive inputs cannot be fully replaced with other intermediates in case of relative price increases. Within EMuSe, it is also possible to distinguish energy and non-energy intermediate inputs as in Hinterlang et al. (2022). This distinction allows to account for the reduced substitutability of energy with other intermediate inputs in production.[19]

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[19] There is a wide literature strand on substitutability between energy and other production inputs (often capital). The general consensus is that at least in the short and medium term, energy is weakly substitutable with other production inputs, but its substitutability improves over time. The simulation

Moreover, the distinction of purely energy-related intermediate goods allows to identify energy-specific technology progress and to better distinguish between emission intensive and low emission energy sectors.

Second, EMuSe also features a climate module, within which emissions from production and the usage of fossil energy can be modeled. Following Hinterlang et al. (2022), we specify the sectoral carbon intensity as a function of the sectoral fossil energy use. In contrast to this paper, however, we do not consider the carbon intensity as a linear but a log-linear function of the sector specific fossil energy use, which writes as follows:

$$\log\left(\frac{\kappa_{s,t}}{\kappa_s}\right) = \chi_1 \log\left(\frac{E_{s,F,t}}{E_{s,F}}\right), \tag{8}$$

where $\kappa_{s,t}$ denotes the sectoral carbon intensity in production and $E_{s,F,t}$ denotes the fossil energy use in sector s. Variables without a time subscript t denote their steady state value. The parameter χ_1 denotes the elasticity of the sectoral carbon intensity with respect to the fossil energy use.

As described in section 2, we extend the production structure of EMuSe with an exogenous input-specific technological innovation: the energy-saving technological progress.[20] At this point it is important to stress that the energy-saving technological progress, which we refer to as energy efficiency improvements, is exogenous to the model. This means that energy efficiency improvements cannot be influenced by R&D activities or relative price changes originating from climate policy measures. Hence, climate policies in the model as for example the emission price, have no feedback effect on energy efficiency by increasing the incentives to invest in more energy efficient technologies. Since energy efficiency improvements are exogenous, they do not incur any economic costs. Hence, in the model, energy efficiency improvements come as "manna from heaven" (Hulten 2001), even though in reality, any type of R&D activities or modernizing production processes incurs some costs. This simplified approach facilitates the distinction between the macroeconomic effects of an increased emission price or energy efficiency improvements. Moreover, the respective transmission channels of these two exogenous model changes can be better delimited and explained.

Other policy measures, as for example the intensified development of renewable energies and the renewable energy sector are also not covered in the model. We also abstract from the modeling of transfers generated by the emission price to climate-friendly invest-

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horizon of the following analysis is quite short, compared to longer term analyses until the end of this century, for example with IAM models. Hence, the assumption of weak substitutability of energy is in line with findings in the literature.

[20] All other assumptions follow Hinterlang et al. (2022, 2023). The equilibrium equations are summarized in Appendix A.

ments as for example Andrés et al. (2024). We also neglect the implications of international linkages, as for example spill-over effects of energy-saving technological progress or implications on prices and trade after an increase of the emission price.

Finally, we also refrain from modeling economic damage from a high concentration of emissions/green house gases in this analysis. Although EMuSe is able to account for the feedback mechanism from emissions to economic damage via reducing the total factor productivity of all firms, in our model set-up, accounting for this feature would probably overestimate economic effects of an emission reduction. Since the model is a closed economy model modeling the case of Germany and does not account for emissions from the rest of the world, reducing (or increasing) emissions is not expected to cause a substantial effect on the concentration of green house gases in the atmosphere and hence, damages to economic activity in the short time period observed here. According to Deutsche Bundesbank (2022), physical risks from gradual climate warming have been neglectable in Germany at least until 2020. Still, other effects, such as risks stemming from extreme weather events have not been analyzed.

3.2 Calibration

Regarding the calibration, EMuSe features three sets of parameters: those that mostly concern the aggregate economy and are taken from existing literature, sector specific parameters, which describe the production linkages, and climate parameters setting the link between economic activity and emissions. For the first two types of parameters, we refer to former literature and to the calibration toolkit published within Hinterlang et al. (2023). For the calibration of the energy sector, we follow Hinterlang et al. (2022). Regarding the link between fossil energy consumption and emissions, we estimate χ_1 with pooled OLS based on sectoral data for the carbon intensity. χ_1 is obtained from the WIOD database and sectoral data for fossil energy use obtained from the European Commission. The estimated value for is χ_1 is 0.3569 and is statistically significant at the 5 % level. All parameter values are summarized in Appendix B.

3.3 Simulations with EMuSe

3.3.1 Transition paths without Energy Efficiency Improvements

The staring point of our analysis is a hypothetical scenario, in which improvements in energy saving technology are not taken into account and the only exogenous change in the model origins in the increase of the emission price path. This means that energy efficiency does not change until 2030. This scenario allows to account for the implications and contributions on GDP and emissions of the emission price only and delimit the effects from other factors as energy efficiency gains. The emission price path in this scenario mimics the evolution of the emission price path which is known until now. The emission price in the model concerns the sectors "transportation and storage", the "fossil energy" sector and the energy-intensive branches of the "manufacturing" sector. This choice tries to mimic the coverage of sectors, which are exposed to an emission price in reality as close as possible. Emission prices are charged either through the national emission trading system (nETS) or the European emission trading system (EU ETS). When we refer to the emission price path below, we mean the combination of the national price path and the path of the EU ETS price.

The initial emission price in the model is set such that it mimics the initial price increase in common fossil fuels following the introduction of the national emission price in Germany. We use these absolute price increases and compare them to the average price of common fossil fuels (as gasoline or diesel) in 2019 as reported by the ADAC (2024).[21] Since 2024 corresponds to the first year of the simulation, we compute the average price increase of gasoline and Diesel in 2024 relative to their respective values in 2019. The resulting price increase for the main fossil fuels amounts to 10.15%. We set the emission price in the model such that in the first period after its introduction, the fossil energy price rises by 10.15%. Further, the emission price in the model grows at the same rate as the officially decided national emission price until 2026. Since the national emission price path beyond 2026 is unknown, we assume that the price converges to the EU-ETS price. We assume that from 2027, the emission price will increase at an annual rate of 7.8% until 2030 in order to reach the projected value of around €88. The latter value corresponds to the average price for emission in the EU-ETS in 2023.[22]

Figure 3 shows that, in the model, an increasing emission price without accounting

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[21] We use 2019 as a reference year since it was the last year before the introduction of the emission price in Germany without pandemic effects on energy prices (as in 2020). From a theoretical perspective, a better way to calculate the initial price increase would be to compare the average price of common fossil fules in 2024 with the price resulting from a hypothetical scenario without carbon pricing in the same year. Data for such a hypothetical scenario is missing, however. While other steps for calculating the initial price are conceivable, the method chosen here is based on a counterpart in the data that can be observed directly.

[22] This value is roughly in line with market expectations on the price for EU ETS futures. Futures markets currently trade permits for the early 2030s at over €80 per ton (see ICE Endex EUA Futures). In a recent survey, Pahle et al. (2022) show that expectations based on leading forecasting models about the EU ETS price range from €80 to €80 in 2030 (Pahle et al. 2022). The projections result from different forecasting models from seven organizations that operate carbon market models. However, these estimates are surrounded by high uncertainty due to model uncertainty and depend on model assumptions, e.g. whether agents have perfect or limited foresight. In consequence, our projection for the emission price in 2030 relies on the average price from 2023 and market expectations from EU ETS futures markets. In this sense, our projection corresponds to a naive forecast that cor-responds to the best prediction under the assumption that the EU ETS price follows a random walk.

for energy saving technology improvements causes a drop in output, emissions and energy intensity.[23] Producers in sectors where the emission price hits, reduce their output because they are exposed to higher marginal costs. In general equilibrium, the output reduction increases the price for their good. Due to intersectoral linkages, a higher price increases the costs for intermediate inputs also in those sectors that are not directly exposed to the higher emission price. These firms also reduce their production so that the price of their goods increases as well. Still, the dampening effects of an emission price on output are rather small. Until 2030, economic activity falls by certis paribus only 1% on the entire horizon. Concerning energy demand and emissions, lower equilibrium production makes firms reduce their energy demand as well, which in turn lowers their emissions. In order to avoid higher emission costs, they try to substitute fossil energy by non-fossil one, which does not produce emissions. Still, the substitution capacities are not sufficient to make up for the increased production costs and to use enough energy and increase output. On the aggregate, the model predicts a drop in emissions by roughly 16% relative to 2023, which is not sufficient to meet the emission reduction goals set by the German Federal Climate Change Act. According to this act, the emission reduction predicted by the model should more than double.

In addition, energy and output fall in a similar pace, which does not reduce energy intensity significantly. Hence, the COP 28 resolution on the reduction of energy intensity by 2% per year until 2030 is not met in this scenario. These findings still do not speak against the introduction of an emission price. According to the model, it is a simple and effective policy measure to reduce emissions.[24]

On the sectoral level, all sectors reduce their output due to higher energy prices on the market, except the non-fossil energy sector, which experiences a sharp increase in output (Appendix Figure 4). Moreover, emissions in the non-fossil sector increase through the strongly positive output effect. Using non-fossil energy does not produce emissions, however, the production of non-fossil energy does. Due to the increased demand of non-fossil energy, emissions also rise. This strengthening of the non-fossil energy sector is not sufficient to slow down the negative effects from other sectors on the aggregate output. Hence, without any additional climate policy measures or accounting for energy-saving

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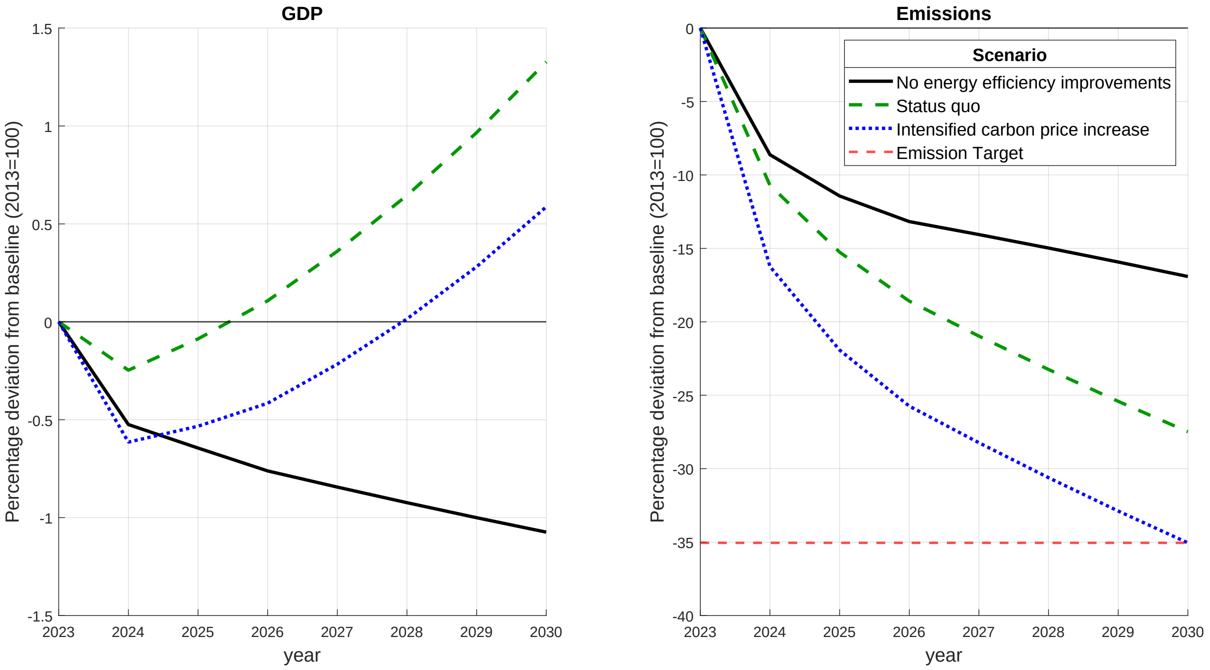
[23] Further contributions from literature which predict a drop of production after the introduction of an emission price are for example Bönke et al. (2023) and Hinterlang et al. (2022).

[24] The emission price has several advantages in the implementation and its impact compared to other measures. It is easy to implement and acts as a tax on emissions, which raises the price of fossil energy. This immediately incentivizes producers to reduce their demand for fossil fuels and consequently, emissions. No investment or other support programs are needed and the effects of the emission price materialize almost immediately after its introduction (Brand et al. 2023). Furthermore, the emission price can be easily adjusted depending on the strength of the effects it triggers. In general, it should also have a positive incentive scheme on investment in less emission-intensive technologies.

Figure 3: Impact of carbon pricing on GDP and emissions - The role of energy efficiency improvements



Notes. Transition paths of GDP and emissions under different paths for the CO2 price and energy efficiency. Solid black line: transition paths under the baseline CO2 emission price path. Dashed green line: transition paths under the baseline CO2 emission price and energy efficiency improvements at the previous average. Dotted blue line: transition paths under an intensified carbon price increase and energy efficiency improvements at the previous average.

technology gains the model predicts that the emission price always induces a hard trade-off between emissions and output.

3.3.2 Transition paths under the Status-quo

In a second scenario, which we refer to as status-quo scenario in the following, the model economy takes into account energy efficiency gains besides the previously presented emission price path. This means that all emission and output effects in the following are caused by the exogenous changes of these two components. Energy efficiency improvements, which are introduced for these model simulations correspond to the average annual growth rate of energy efficiency in each of the sectors between 1991 and 2019 presented in Section 2.3.[25] Since energy efficiency gains are exogenous, they are also cost-neutral

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[25] Note that the energy saving technology in the model simulations concerns only the production sectors and not the household. Energy efficiency of household, especially in consuming energy-related consumption goods, does not change by assumption. It is way more involved to determine this type of energy efficiency from the data. Hence, the value of the aggregate energy-saving technology in the

and do not cause any frictions in their implementation.

Dotted lines in Figure 3 display transition paths for the same variables when the three sectors are exposed to the emission price and at the same time energy efficiency improvements. After the first period, when the emission price hits and efficiency improvements are still small, output first stagnates, but it increases again for the rest of the time horizon. Output in 2030 reaches an almost 1.5% higher level than in 2023 without an emission price and energy efficiency gains. Production increases but emissions fall since energy demand decreases due to energy efficiency gains. Still, energy efficiency gains are one type of technological progress, which boosts production. Hence, the transition to a low-carbon economy can boost economic activity, as long as energy efficiency improvements take place.

In terms of emissions, this scenario delivers much larger reductions of around 25% compared to the scenario, when only an emission price is considered.[26] However, this reduction is still not sufficient to reach the climate goals. Energy intensity also drops sharply. The average increase in energy efficiency, measured as energy productivity, amounts to 2%, which does not fulfill the COP28 resolutions. Those require a reduction in energy intensity of 4%. On the sectoral level, (Appendix Figure 5) output increases for all sectors except the fossil energy sector. Some sectors take time to increase their production significantly, but the energy efficiency gains eventually materialize. The non-fossil energy sector takes off quite importantly. Hence, energy efficiency gains mitigate the hard trade-off between emissions and output and allow reducing emissions and energy use more effectively while at same time increasing output.

3.3.3 Transition paths under Intensified Carbon Price Increase

Model simulations imply that reaching the emission goals of the German federal climate change act requires either an increase in the emission price or further technological advances in the energy-saving technology. Dashed lines in Figure 3 show the transition paths under the intensified carbon price increase. Even though the emission price is a very effective instrument to reduce emissions, the emission price path must increase significantly according to the model to reach the desired emission reduction of 34.9% relative to 2023. Accompanied by the increases in energy efficiency at the same pace as in

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model is rather a lower bound. In general, energy efficiency gains in the household sector could also lead to a reduction in the aggregate energy demand and hence, also energy intensity.

[26] However, the scenario simulations neglect other technological innovations as for example factor-neutral technological progress. This type of technological innovations could potentially increase the demand for energy overall and hence, also fossil energy. Consequently, emissions could start to increase. As long as firms do not incur any efficiency gains in the usage of energy in the production process, emission reduction in the status-quo scenario would end up lower and require even more other climate related measures.

the last three decades, the emission price must almost double on the entire time horizon according to model simulations. Although this strong increase of the expected emission price path produces small output losses at its introduction, once energy efficiency gains kick in and increase over time, output reductions can be compensated and end up at a level in 2030 which is slightly higher compared to the case without an emission price or energy efficiency improvements. Increasing energy-saving technological progress reduces the relative price of energy and hence, also marginal costs of production. This counteracts the negative effect on energy demand caused by the emission price.

In this scenario, the aggregate energy efficiency is almost unchanged compared with the status-quo scenario. In these simulations, the origin of energy efficiency gains is the process of energy-saving technology as in the status-quo case. The higher emission price reduces energy demand and production in the same way and hence, does not alter the share of energy used in production. Consequently, the same conclusion concerning the COP28 resolution applies as in the status-quo scenario and the reduction of energy intensity by 4% cannot be achieved.

Note that taking into account other technological changes, such as standard neutral technology progress, might require more stringent climate action. All type of technological improvement which increase the productivity of all production inputs in the same way, also increase energy demand. Without additional input-specific energy-saving technological gains, this would, all else equal, result in higher emissions. Consequently, the emission price schedule has to rise even stronger the keep aiming at the climate goals.

3.3.4 Transition paths under Intensified Energy Efficiency Improvements

A last thought experiment on how to reach the emission reduction goals concerns higher growth rates of energy-saving technology. Hypothetically, technological progress could also turn out to be larger in the imminent future compared to the last three decades. According to model simulations, the energy-saving technological progress would have to increase very strongly to reach the climate goals, when the emission price path remains at the level currently expected until 2030. In this case, the rate of change in the energy-saving technology must more than double in each sector to achieve the desired reduction in emissions. Growth rates of energy efficiency of this size in the last three decades have been observed only sporadically in individual sectors and not as an aggregate pattern.

4 Conclusion

It follows from our empirical analysis that energy efficiency in Germany, based on the production function in EMuSe, experienced an increasing trend in the last three decades. However, energy efficiency gains are quite heterogeneous across sectors both in size and sign. Some sectors outpace initially more efficient ones, while others experience periods of declining energy efficiency, such as the fossil energy sector since 2012.

Based on simulations with EMuSe, energy efficiency gains are a crucial factor to reach emission reduction goals without generating losses in production. Unlike standard technological progress, energy-saving technology gains reduce energy consumption and hence, emissions. At the same time, they boost economic activity by increasing production. This leads to a substantial decrease in aggregate energy intensity.

Based on the expected emission price path in Germany, we find that energy efficiency improvements are an important factor - albeit one that cannot be directly controlled for - in mitigating potential adverse macroeconomic effects caused by other climate policy measures. Surely, there is also an additional relationship between energy efficiency and stricter climate policy, especially a higher emission price than currently planned, where higher emission pricing incentivizes producers to extend their energy-saving technology. Still, this is disregarded here, meaning that historical developments might tend to represent a lower bound for the potential of efficiency gains.

From the model simulations it follows that a combination of increased energy efficiency and strict climate action is more effective in achieving the emission targets than emission pricing or energy efficiency taken in isolation. Absent any incentivising effect of increasing carbon prices for innovation that boosts energy saving technological progress, the latter needs to more than double to achieve the planned reduction in emissions without other accompanying climate policy measures. Based on historical findings, however, it seems questionable if these growth rates can be achieved. It is also unclear, whether the currently planned emission price path could potentially create enough incentives to achieve these large energy-saving technological advances. This question cannot be answered within this model set-up and is left for future analysis. According to the model, absent any effect of the carbon price on energy saving technological progress, meeting the climate targets requires a significant increase in the planned CO2 price path.

The analysis, further, shows that a even higher carbon price, accompanied by greater energy saving technological advances, could result in larger output levels over the course of time. Energy efficiency improvements could also be stimulated by undertaking higher efforts to promote research and development in this field. Alongside efficiency gains, other factors, such as the expansion of renewable energy sources, networks and storage facilities, are also key for achieving the emission targets.

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A System of equations

This Appendix lists the equilibrium equations of the model used to generate the results in the main text. For a detailed description of the variables and the underlying model see Hinterlang et al. (2022, 2023).

Climate Block:

- Aggregate Stock of Emissions:

$$M_t = (1 - \rho^M)M_{t-1} + Z_t \tag{A.1}$$

- Aggregate flow emissions:

$$Z_t = \sum_{s \in \mathcal{S}} Z_{s,t} \tag{A.2}$$

- Sectoral emissions:

$$Z_{s,t} = \kappa_{s,t} y_{s,t} \tag{A.3}$$

- Sectoral carbon intensity:

$$\kappa_{s,t} = \kappa_s \left(\frac{E_{s,\mathcal{F},t}}{E_{s,\mathcal{F}}} \right)^{\chi_1} \tag{A.4}$$

Household Block:

- Law of motion aggregate capital:

$$K_t = (1 - \delta)K_{t-1} + I_t \tag{A.5}$$

- Household first order condition - bonds:

$$1 = \beta \mathbb{E}_t \left(\left(\frac{C_{t+1}}{C_t} \right)^{-\sigma} \frac{R_t}{\Pi_{t+1}^{CPI}} \right) \tag{A.6}$$

- Household first order condition - capital:

$$1 = \beta \mathbb{E}_t \left(\left(\frac{C_{t+1}}{C_t} \right)^{-\sigma} \frac{R_{t+1}^k + (1 - \delta)P_{t+1}^I}{P_t^I} \right) \tag{A.7}$$

- Household first order condition - labour:

$$w_t = \kappa_N N_t^{\psi} C_t^{\sigma} \tag{A.8}$$

Bundlers (consumption, labour and capital):

- Price index derived from opt. problem of consumption bundler:

$$1 = \left(\psi_C \left(P_t^{C,NE}\right)^{-\frac{\sigma_C}{1-\sigma_C}} + (1-\psi_C)\left(P_t^{C,E}\right)^{-\frac{\sigma_C}{1-\sigma_C}}\right)^{-\frac{1-\sigma_C}{\sigma_C}} \tag{A.9}$$

- Demand for non-energy consumption bundle:

$$C_t^{NE} = \psi_C \left(P_t^{C,NE}\right)^{-\frac{1}{1-\sigma_C}} C_t \tag{A.10}$$

- Demand for energy consumption bundle:

$$C_t^{E} = (1-\psi_C) \left(P_t^{C,E}\right)^{-\frac{1}{1-\sigma_C}} C_t \tag{A.11}$$

- Price index for non-energy/energy consumption:

$$P_t^{C,i} = \left(\sum_{s\in\mathcal{S}^i} \psi_{C^i,s} P_{s,t}^{-\frac{\sigma_{C^i}}{1-\sigma_{C^i}}}\right)^{-\frac{1-\sigma_{C^i}}{\sigma_{C^i}}} \qquad \text{for } i \in \{E, NE\} \tag{A.12}$$

- Demand functions non-energy/energy consumption bundler in sector s:

$$C_{s,t}^i = \psi_{C^i,s} \left(\frac{P_{s,t}}{P_t^{C,i}}\right)^{-\frac{1}{1-\sigma_C^i}} C_t^i \qquad \text{for } i \in \{E, NE\} \tag{A.13}$$

- Price indicex investment, investment bundler:

$$P_t^I = \left(\sum_{s\in\mathcal{S}} \psi_{I,s} P_{s,t}^{-\frac{\sigma_I}{1-\sigma_I}}\right)^{-\frac{1-\sigma_I}{\sigma_I}} \tag{A.14}$$

- Wage index, labor bundler:

$$w_t = \left(\sum_{s\in\mathcal{S}} \omega_{N,s} w_{s,t}^{-\frac{\nu_N}{1-\nu_N}}\right)^{-\frac{1-\nu_N}{\nu_N}} \tag{A.15}$$

- Capital return index, capital bundler:

$$r_t^k = \left(\sum_{s \in \mathcal{S}} \omega_{K,s} (r_{s,t}^k)^{-\frac{\nu_K}{1-\nu_K}} \right)^{-\frac{1-\nu_K}{\nu_K}} \tag{A.16}$$

- Demand for investment good from sector s:

$$I_{s,t} = \psi_{I,s} \left(\frac{P_t^I}{P_{s,t}} \right)^{\frac{1}{1-\sigma_I}} I_t \tag{A.17}$$

- Labour demand - sector s:

$$N_{s,t} = \omega_{N,s} \left(\frac{w_t}{w_{s,t}} \right)^{\frac{1}{1-\nu_N}} N_t \tag{A.18}$$

- Capital demand - sector s:

$$K_{s,t} = \omega_{K,s} \left(\frac{r_t^k}{r_{s,t}^k} \right)^{\frac{1}{1-\nu_K}} K_t \tag{A.19}$$

Intermediate good bundler:

- Price-index of intermediate good - sector s:

$$P_{s,t}^H = \left[\alpha_{NE,s} \left(P_{s,t}^{NE} \right)^{-\frac{\sigma_H}{1-\sigma_H}} + (1-\alpha_{NE,s}) \epsilon_{s,t}^{\frac{\sigma_H}{1-\sigma_H}} \left(P_{s,t}^E \right)^{-\frac{\sigma_H}{1-\sigma_H}} \right]^{-\frac{1-\sigma_H}{\sigma_H}} \tag{A.20}$$

- Non-Energy demand for intermediate good bundle H_s - sector s:

$$NE_{s,t} = \alpha_{NE,s} \left(\frac{P_{s,t}^H}{P_{s,t}^{NE}} \right)^{\frac{1}{1-\sigma_H}} H_{s,t} \tag{A.21}$$

- Energy demand for intermediate good bundle H_s - sector s:

$$E_{s,t} = (1-\alpha_{NE,s}) \left(\frac{P_{s,t}^H}{P_{s,t}^E} \right)^{\frac{1}{1-\sigma_H}} H_{s,t} \epsilon_{s,t}^{\frac{\sigma_H}{1-\sigma_H}} \tag{A.22}$$

- Price index of non-energy/energy goods - sector s:

$$P^i_{s,t} = \left[\sum_{j \in \mathcal{S}^i} \psi_{i,s,j} P_{j,t}^{-\frac{\sigma_i}{1-\sigma_i}} \right]^{-\frac{1-\sigma_i}{\sigma_i}} \qquad \text{for } i \in \{E, NE\} \tag{A.23}$$

- Demand for non-energy/energy inputs of sector s from sector j:

$$i_{s,j,t} = \psi_{i,s,j} \left(\frac{P^i_{s,t}}{P_{j,t}} \right)^{\frac{1}{1-\sigma_i}} i_{s,t} \qquad \text{for } i \in \{E, NE\} \tag{A.24}$$

Sectoral producers:[27]

- Production function - sector s:

$$y_{s,t} = [1 - D(M_t)] \left(K_{s,t-1}^{1-\alpha_{N,s}} N_{s,t}^{\alpha_{N,s}} \right)^{1-\alpha_{H,s}} H_{s,t}^{\alpha_{H,s}} \tag{A.25}$$

- Price of sectoral good - sector s:

$$\begin{aligned} 0 = &\frac{\kappa^P_s}{\theta^P_s} \left(\Pi^{PPI}_{s,t} - 1 \right) \Pi^{PPI}_{s,t} - \left(\frac{\widetilde{mc}_{s,t}}{P_{s,t}} - \frac{\theta^P_s - 1}{\theta^P_s} \right) \\ &- \frac{\kappa^P_s}{\theta^P_s} \beta \mathbb{E}_t \left[\left(\frac{C_{t+1}}{C_t} \right)^{-\sigma} \frac{y_{s,t+1}}{y_{s,t}} \frac{\Pi^{PPI}_{s,t+1}}{\Pi^{CPI}_{t+1}} \left(\Pi^{PPI}_{s,t+1} - 1 \right) \Pi^{PPI}_{s,t+1} \right] \end{aligned} \tag{A.26}$$

- Total marginal cost - sector s:

$$\widetilde{mc}_{t,s} = mc_{s,t} + P^{em}_t \kappa_{s,t} \tag{A.27}$$

- Labour-FOC cost minimization - sector s:

$$w_{s,t} = (1 - \alpha_{H,s}) \alpha_{N,s} mc_{s,t} \frac{y_{s,t}}{N_{s,t}} \tag{A.28}$$

- Capital-FOC cost minimization - sector s:

$$r^k_{s,t} = (1 - \alpha_{H,s})(1 - \alpha_{N,s}) mc_{s,t} \frac{y_{s,t}}{K_{s,t-1}} \tag{A.29}$$

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[27] Note that if $\theta^P_s \to \infty$ and $\kappa^P_s = 0$, then we are in the flexible price economy. Then, $P_{s,t} = \widetilde{mc}_{s,t}$. In this case, real and nominal variables are determined independently.

- Int. good-FOC cost minimization - sector s:

$$P^H_{s,t} = \alpha_{H,s} mc_{t,s} \frac{y_{s,t}}{H_{s,t}} \tag{A.30}$$

- Sectoral market clearing condition for non-energy/energy goods:

$$y_{s,t} = C^i_{s,t} + I_{s,t} + \sum_{j \in \mathcal{S}^i} i_{j,s,t} + \frac{\kappa^P_s}{2} \left(\Pi^{PPI}_{s,t} - 1\right)^2 y_{s,t} \tag{A.31}$$

Market clearing condition

$$\mathcal{Y}_t = C_t + P^I_t I_t \tag{A.32}$$

where $\mathcal{Y}_t = \sum_{s \in \mathcal{S}} y^v_{s,t}$ and

$$y^v_{s,t} = P_{s,t} y_{s,t} - P^H_{s,t} H_{s,t} - 0.5 \kappa^P_s \left(\Pi^{PPI}_{s,t} - 1\right)^2 P_{s,t} y_{s,t}$$

Economic Policy:

- Government budget constraint:

$$T_t = P^{em}_t Z_t \tag{A.33}$$

- Monetary Policy Rule:

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{\varphi_R} \left(\frac{\Pi^{CPI}_t}{\Pi^{CPI}}\right)^{\varphi_\pi (1-\varphi_R)} \tag{A.34}$$

Definitions:

- Sectoral producer price inflation:

$$\Pi^{PPI}_{s,t} = \Pi^{PPI}_{1,t} \frac{P_{s,t}}{P_{s,t-1}} \frac{P_{1,t-1}}{P_{1,t}} \tag{A.35}$$

- Consumer price inflation:

$$\Pi^{CPI}_t = \frac{P^C_t}{P^C_{t-1}} \tag{A.36}$$

B Calibrated Parameters

Table 1: Calibration of general parameters

Description	*Parameter*	*Value*
General parameters:		
Discount factor	β	0.970
Elasticity of intertemporal substitution	σ	2.000
Inverse of Frisch elasticity of lab. supply	ζ	0.500
Labor disutility scaling	κ_N	32.732
Capital depreciation rate	δ^k	0.100
Share of non-energy consumption	ϕ_C	0.940
Parameters setting the EOS between:		
NE & E consumption bundles	σ_C	-9.000
NE consumption goods	$\sigma_{C^{NE}}$	-0.100
E consumption goods	σ_{C^E}	0.600
investment goods	σ_I	-0.331
labor across sectors	υ_N	2.000
capital across sectors	υ_K	2.000
NE & E intermediate input bundles $\forall s$	$\sigma_{H,s}$	-9.000
NE intermediate inputs $\forall s$	$\sigma_{NE,s}$	-2.330
E intermediate inputs $\forall s$	$\sigma_{E,s}$	0.6.00

The table shows calibrated values for the parameters determining the elasticity of substitution (EOS) as described in the main text. NE and E refer to non-energy and energy, respectively. The corresponding EOS can be computes as $1 - \frac{1}{\sigma}$, where $\sigma \in \{\sigma_C, \sigma_{C^N E}, \sigma_{C^E}, \sigma_I, \varphi_N, \varphi_K, \sigma_{H,s}, \sigma_{NE,s}, \sigma_{E,s}\}$

Table 2: Environmental parameters

Description	*Parameter*	*Value*
Aggregate environmental parameters:		
Pollution decay	$1-\rho^{EM}$	0.992
Slope carbon intensity	χ_1	0.3569
Carbon intensity in sector s:	κ_s	
1) Agriculture		0.137
2) Manufacturing - non ETS		0.073
3) Manufacturing - ETS		0.088
4) Water supply		0.201
5) Construction		0.026
6) Retail trade		0.032
7) Transport and warehousing		0.202
8) Other service activities		0.007
9) Fossil energy		3.610
10) Non-fossil energy		0.010

This table reports the calibrated environmental parameters of the model, described in the main text. Carbon intensities were computed by the authors based on the World Input Output Database and environmental accounts and refer to 2014.

Table 3: Calibration of sector specific parameters

	$\alpha_{N,s}$	$\alpha_{H,s}$	$\alpha_{NE,s}$	$\psi_{E,s,9}$	$\omega_{\tilde{N},s}$	$\omega_{\tilde{K},s}$	$\frac{\psi^{NE,s}}{\psi_C}$ or $\frac{\psi^{E,s}}{(1-\psi_C)}$	ψ_I
1) Agriculture	0.788	0.339	0.930	0.877	0.016	0.017	0.006	0.002
2) Manufacturing - non ETS	0.646	0.382	0.956	0.846	0.132	0.058	0.018	0.003
3) Manufacturing - ETS	0.616	0.283	0.973	0.708	0.025	0.015	0.006	0.434
4) Water supply	0.561	0.105	0.942	0.992	0.002	0.002	0.040	0.002
5) Construction	0.777	0.437	0.951	0.946	0.060	0.005	0.161	0.040
6) Retail trade	0.768	0.573	0.972	0.791	0.144	0.023	0.156	0.251
7) Transport and warehousing	0.585	0.410	0.876	0.955	0.051	0.044	0.016	0.022
8) Other service activities	0.589	0.630	0.971	0.648	0.554	0.788	0.599	0.230
9) Fossil energy	0.374	0.401	0.719	0.625	0.007	0.021	0.830	0.001
10) Non-fossil energy	0.365	0.270	0.656	0.019	0.009	0.028	0.170	0.016

The table shows calibrated values for sector-specific parameters computed with the calibration tool provided by **Hinterlang et al. (2023)**. The values were computed based on the World Input-Output Database, based on 2014 data, on the Energy Use Statistics and on the World Energy Balance Dataset (2021).

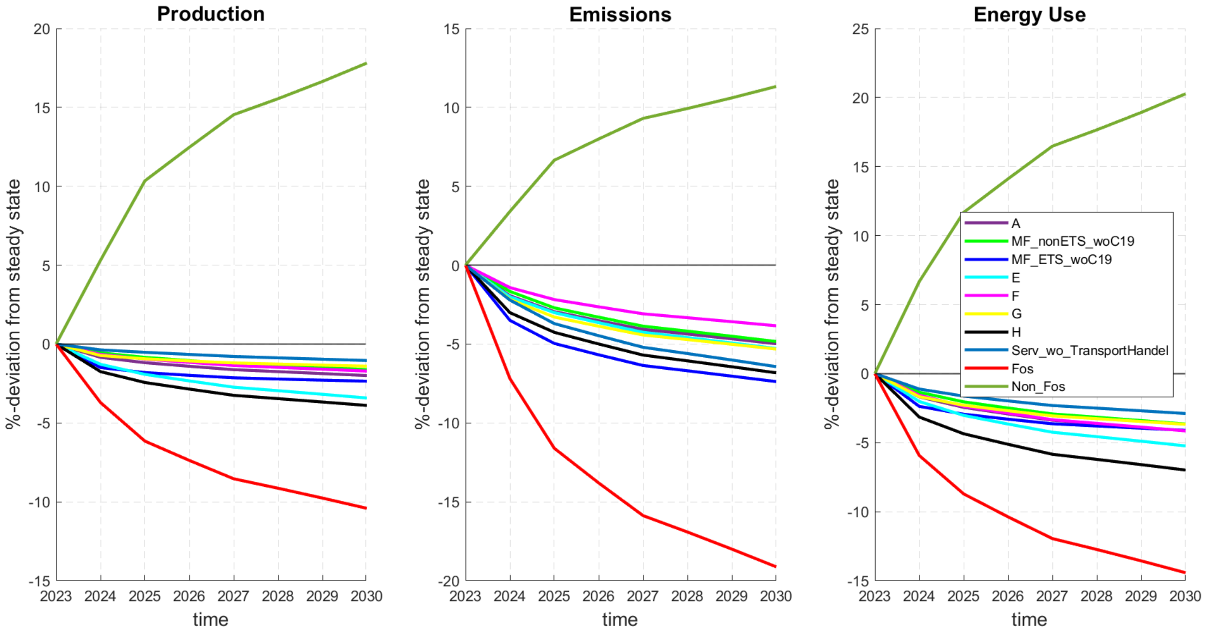
Table 4: Input-Output matrix: Non-energy inputs $\psi_{NE,s,j}$

Consumer s Producer j	1)	2)	3)	4)	5)	6)	7)	8)	9)	10)
1)	11.827	0.028	0.101	0.015	0.126	5.150	0.203	0.219	0.192	0.037
2)	3.661	21.503	0.394	0.242	0.743	1.421	4.822	0.998	1.597	1.131
3)	3.539	11.137	14.610	2.425	1.827	1.210	2.343	7.369	3.503	8.219
4)	2.182	2.498	1.746	61.131	33.920	6.423	10.067	3.571	20.858	12.533
5)	19.624	8.294	14.141	5.375	8.149	13.163	9.266	5.052	14.239	5.712
6)	20.314	7.633	22.976	5.584	7.027	40.568	13.171	6.955	12.895	17.067
7)	4.262	1.453	13.043	0.573	1.675	8.248	33.885	0.895	8.836	3.250
8)	34.591	47.453	32.988	24.654	46.533	23.819	26.243	74.940	37.881	52.051

This table reports the share of total non-energy intermediates (in expenditure terms and %) used by the consuming sector that comes from the producing sector. (For example, 3.6% of the total intermediates used by the first sector stem from the second sector.) The shares were computed using the calibration toll in Hinterlang et al. (2023) based on 2014 data of the World Input-Output Database.

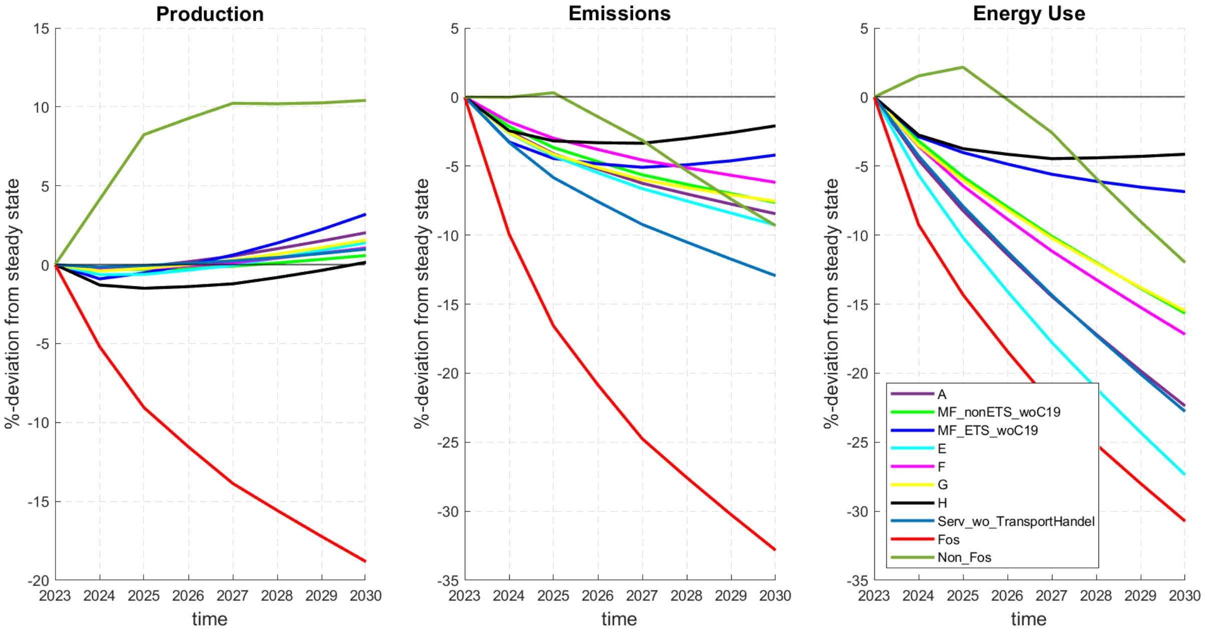
C Sector-Specific Transition Paths

Figure 4: Sector specific transition paths without energy saving technological improvements



Notes. Transition paths of output, emissions and energy intensity in each sector after the introduction of an emission price. All variables are expressed as percentage deviations from their respective steady state value.

Figure 5: Sector specific transition paths with energy saving technological improvements



Notes. Transition paths of production, emissions and energy use in each sector after the introduction of an emission price and sectoral energy efficiency shocks following their respective historical trend. All variables are expressed as percentage deviations from their respective steady state value.