Economic Analysis and Policy 85 (2025) 1065–1078

Contents lists available at ScienceDirect

Economic Analysis and Policy

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

Modelling Economic Policy Issues

Macro-level implications of the energy system transition to net-zero carbon emissions: Identifying quick wins amid short-term constraints

Marko Raseta [a], Andrew G. Ross [a,*], Stefan Vögele [a]

[a] Institute of Climate and Energy Systems – Jülich Systems Analysis, Forschungszentrum Jülich GmbH, Jülich, Germany

ARTICLE INFO

Keywords:
Energy system transformation
Energy security
Economic impacts
Economic analysis
Socio-economic analysis
Energy policy

ABSTRACT

Countries are increasingly committing to achieving net-zero carbon emissions while addressing energy security concerns heightened Russia's war of aggression against Ukraine. A key challenge lies in the long-term nature of these goals, which often conflict with shorter political cycles, necessitating consistent political commitment to transform energy systems and secure public support. Existing research frequently overlooks short-term impacts, focusing instead on long-term effects. However, an analysis centered on the short term can uncover immediate challenges, such as ensuring the security of energy supply, identifying potential bottlenecks and barriers that might hinder the timely implementation of policy interventions, and highlighting immediate benefits, such as job creation from renewable energy investments. These short-term considerations are crucial for fostering public support and facilitating a timely transition toward a sustainable energy future. This paper examines the short-term macroeconomic impacts of energy system transformations by utilizing a dynamic disequilibrium Input-Output model linked to an energy system optimization model. The results indicate potential dividends for both the environment and the economy, along with enhanced energy security. The analysis underscores important policy considerations, including potential crowding-out effects resulting from constrained labor markets and supply chains—elements that are often neglected but are crucial for achieving timely energy security and policy objectives. Given the current economic climate, influenced by the recovery from the COVID-19 pandemic and the ongoing Russo-Ukrainian war, it is essential to take these potentially obstructive factors into account when planning and implementing energy, economic, and environmental policies.

1. Introduction

Countries worldwide have acknowledged the significance of the climate crisis and have pledged to achieve net-zero carbon emissions (IEA, 2023). Simultaneously, the ongoing Russo-Ukrainian war has intensified concerns about energy security, prompting a more detailed consideration of these issues in the transformation of energy systems (Ullah et al., 2024). To successfully align energy policies with energy security goals, a strong long-term commitment from various stakeholders is essential. However, a substantial challenge in reaching these goals is their time frame, which often extends beyond the typical duration of conventional policies or

* Correspondence author at: Forschungszentrum Jülich GmbH, Institute of Climate and Energy Systems – Jülich Systems Analysis, Wilhelm-Johnen-Straße, 52428 Jülich, Germany.

E-mail address: a.ross@fz-juelich.de (A.G. Ross).

https://doi.org/10.1016/j.eap.2025.01.011
Received 10 June 2024; Received in revised form 16 December 2024; Accepted 7 January 2025
Available online 9 January 2025

election cycles. This issue poses difficulties for governments in enacting transformations without producing the immediate benefits that their constituencies typically desire.

To address this, governments must adopt a forward-thinking and comprehensive approach to energy and climate policies, prioritizing long-term sustainability over short-term political gains, and ensuring consistent policy implementation across different administrations (IEA, 2021). Many governments have achieved this by setting clear goals and milestones, with accountability mechanisms in place to track progress and ensure that future administrations continue working towards net-zero carbon emissions—and their related economic, energy (security), and environmental goals (IEA, 2023). Similarly, it is essential to maintain ongoing public support and active participation to promote political commitment and facilitate a shift towards clean energy and corresponding energy security goals. Yet, convincing the public to commit to long-term action can be a major challenge, as it often requires offering short-term incentives (Mercure et al., 2021). A potential strategy to generate public support involves emphasizing the creation of domestic benefits, such as job opportunities and economic growth, within the energy transition (Muttitt and Gass, 2023). Such economic effects can be used to directly showcase to all relevant stakeholders the potential benefits of steering toward a more sustainable path (Steg et al., 2015), thus potentially overcoming the "not in my backyard" attitude.

There is a wealth of research that aims to pinpoint such impacts. Much of this research explores the long-term economic and energy security effects of achieving net-zero emissions (Hanna et al., 2024). However, near-term impacts and potential "quick wins"—as well as potential trade-offs—are often neglected or not explicitly accounted for. Recognition of the importance of these short-term effects is crucial, as they can help sustain support from both the public and private sectors, ultimately facilitating the pursuit of energy policy and energy security goals. Moreover, an analysis focused on the short term can reveal immediate challenges, such as ensuring the reliability of energy sources to maintain security of supply, identifying potential bottlenecks and barriers, and ensuring the timely implementation of policy interventions.

Investing in renewable energy technologies, such as solar panels and wind turbines, can result in immediate improvements in energy security (Wang et al., 2024). However, during periods of low generation, known as wind-solar droughts (or Dunkelflaute), energy security can be compromised. Furthermore, these investments can stimulate local economies by creating jobs and supporting local businesses (Godinho, 2022). It is important to emphasize that the magnitude of these economic effects will depend on the amount of locally produced content in these technologies (Allan et al., 2020), and the balance between imported and domestically produced goods can influence domestic energy security (Zhang et al., 2024). Moreover, it is crucial to evaluate the impacts of transitioning to net-zero at the energy systems level rather than focusing solely on individual technologies (such as solar panels).[1] The transformation of the energy system is, in turn, influenced by broader economic structures. For instance, economies are still recovering from the COVID-19 pandemic and facing various challenges due to the ongoing Russo-Ukrainian war. Unfortunately, these real-world constraints and issues are not adequately reflected in current energy-economic models related to energy system transformation (Cazcarro et al., 2022; McCollum et al., 2020). To truly understand the immediate short-term effects, it requires more than simply extrapolating long-term impacts to the short term; it necessitates models and frameworks that explicitly account for the short-term characteristics of the economy (Pollitt, 2024).

This manuscript contributes to the existing literature by emphasizing the importance of understanding the short-term effects of the energy system transition on domestic job creation across various labor market skill categories and its potential impact on economic growth. It also explores "quick wins" and potential trade-offs. This manuscript also notes that the models frequently used in this field often combine characteristics targeting different time frames. However, these characteristics are typically applied uniformly across all simulation periods, failing to adequately consider the distinctive economic structures of the specific time horizons being studied. The primary contribution of this manuscript is an empirical evaluation of the short-term macroeconomic impacts of transitioning the energy system toward net-zero carbon emissions. This assessment considers potential economic constraints that could hinder the achievement of energy policy and energy security objectives defined within the evaluated transition pathway. To identify these impacts, this manuscript utilizes a dynamic disequilibrium Input-Output (IO) model (DEMACRO), which is soft-linked to an energy system optimization model. This effectively connects detailed bottom-up and top-down approaches. The IO model is specifically designed to analyze short-term effects and is tailored to identify the economic impacts resulting from energy transformation pathways. It simulates the dynamics of various macroeconomic variables across different sectors of the economy by incorporating data derived from an energy system optimization model. In this IO model, industry demand and production decisions are based on simple rules of thumb rather than the optimization typically found in partial or general equilibrium frameworks, which are commonly employed in the existing literature. The energy system transformation pathways assessed in this model shed light on several fundamental factors that are currently of key policy importance. For instance, the analysis highlights the potential consequences of a constrained labor market, which is a common issue in many economies today. This crucial factor is often overlooked in discussions about energy system transformation, yet it represents a considerable and potentially persistent challenge that could impede the timely achievement of energy security and broader energy policy goals.

As this manuscript serves as an initial investigation into the short-term effects of energy system transformation, certain simplifications were necessary, and it is important to outline these from the very beginning. The analysis is based on the capital and operational expenses of an average year within the initial five-year period of the energy system transformation, derived from an energy

[1] Substitution effects, such as the gradual phase-out of coal in favor of renewables, could counterbalance potential gains. This concept also extends to the transport sector's shift toward electric cars within the broader energy system. The discussion in this paper does not consider studies that assess the impacts of individual technologies, such as photovoltaic or wind power. Focusing solely on these individual technologies overlooks the broader implications of energy system transformation, including technology transitions and the overall net effects.

system optimization model. This model calculates these cost data in five-year increments up to 2045. While more detailed short-term data would be preferable, this manuscript provides valuable initial insights into potential effects at the macroeconomic level. It is worth noting that additional detailed data would impact quantitative effects rather than qualitative ones (this point is revisited in a sensitivity analysis). Nonetheless, the uncertainty surrounding exact quantitative effects must be acknowledged. Therefore, this manuscript highlights this data gap and stresses the need for more comprehensive data in this field. Additionally, although the empirical analysis presented here focuses primarily on Germany, the qualitative findings can be extended to other countries and regions striving for a similar energy system transformation toward net-zero carbon emissions.

The remaining part of the manuscript is structured as follows: Section 2 provides the theoretical background and literature, emphasizing the importance of models with consistent short-term specifications. Section 3 describes the model and the underlying data, while Section 4 explains the simulation approach. Section 5 outlines the results, and Section 6 presents the discussion and conclusion.

2. Background

To facilitate the subsequent discussion on the different time horizons under consideration in economic analysis, the following basic and simplified intuition is provided. It is important to note that these delineations are not absolute and can vary depending on various factors. The short term refers to a relatively brief timeframe. During this period, it is commonly assumed that prices exhibit rigidity, there are capacity constraints, and the supply of labor is inelastic (Carlin and Soskice, 2014; Layard et al., 2005). The medium term is covered by a relatively longer period, typically spanning a year to a couple of years. During this time, both short-term factors and more persistent changes in the economy can influence prices. Capacity constraints become less binding, and the labor supply becomes more elastic. Finally, the long term encompasses several years or even decades. In the long run, price dynamics are primarily influenced by macroeconomic factors, structural changes, technological advancements, and overall lasting developments on the supply side (Carlin and Soskice, 2014; Layard et al., 2005).

Understanding these timeframes is essential for policymakers and stakeholders navigating the transition to net-zero emissions and to achieving energy security goals (Pollitt, 2024). Short-term analysis can help identify immediate challenges, such as ensuring the reliability of renewable energy sources to maintain energy security and the timely implementation of policy interventions. Medium- and long-term analysis is essential for developing sustainable strategies, considering possible future technological advancements, economic structural changes, and the long-term impacts on growth, demographics, and environmental sustainability, for example. While there is a large body of research focused on the effects in the long term, the question remains: Are we equally well-versed in understanding the potential short-term impacts?

The recent literature analyzing the energy-environment-economy impacts of energy transitions using IO modeling approaches can be segmented into two main groups to shed light on their underlying assumptions regarding specified time horizons, whether implicitly or explicitly.[2] The first group consists of studies that assume fixed technology coefficients and the absence of (endogenous) capacity constraints, with labor supply being infinitely elastic throughout all simulation periods. Examples of this approach can be found in the works of Carvalho et al. (2015), Siala et al. (2019), Solé et al. (2020), Vaccaro and Rocco (2021), and Zhang et al. (2022). While these assumptions are certainly appropriate, they may not hold true for both short- and long-term perspectives. The second group involves studies that incorporate technology coefficients that vary over time (typically determined exogenously) and tend to assume no endogenous capacity constraints, as well as an infinitely elastic labor supply throughout all simulation periods. Examples of such studies can be found in Černý et al. (2021, 2024) and Sievers et al. (2019). Again, these assumptions are relevant but may not align well with both short- and long-term scenarios.

These two main approaches serve to illustrate the utilization of model features and specifications that are most applicable to specific time periods. For instance, utilizing fixed technology coefficients may be suitable for short-term analyses, while assuming unconstrained supply-side labor and capital could be more suitable for longer-term analyses (especially considering current supply-side constraints). Typically, a combination of model features and assumptions is utilized across all simulation periods, rather than being confined solely to their conceptually envisioned timeframe.[3]

Existing literature emphasizes the necessity of carefully considering model specifications, as analyses could overestimate the impacts on employment and output when a growing economy faces capacity or other supply-side constraints in its early stages (McGregor et al., 1996). Thus, it is not advisable to simply extrapolate long-term results and model configurations to the short term, and vice versa. This further emphasizes the need for models that explicitly identify effects within each of these time horizons, in alignment with the fundamental principles of macro and microeconomics. However, these concepts have not been fully integrated into the analysis of the energy system transformation toward net-zero carbon emissions and enhanced domestic energy security goals

[2] Traditionally, IO models have been associated with the short run, where fixed coefficient technologies, the absence of capacity constraints, and an infinitely elastic labor supply are assumed (Miller & Blair, 2009; Oosterhaven, 2022; Raa, 2017). However, IO analysis is more broadly applicable than suggested by this interpretation (McGregor et al., 1996). While there is potential for incorporating endogenous supply-side constraints in IO models, especially in econometric IO models, such methods are not widely utilized in current literature.

[3] It is notable that similar challenges are present in the literature that utilizes Computable General Equilibrium (CGE) models. However, in CGE modeling, it is not uncommon to find models that separate and provide distinct results for the short, medium, and long terms. These models incorporate specific features tailored to each period, allowing for a more detailed analysis of the dynamics and challenges associated with different time horizons (Dixon & Jorgenson, 2012).

(Pollitt, 2024). The next section introduces an empirical model constructed specifically to address this issue, with an emphasis on assessing short-term effects.

3. Model and data

To demonstrate the potential short-term impact of the energy transition on the overall economy (in terms of output and employment by labor market skill category), this manuscript utilizes a dynamic disequilibrium IO model that is soft-linked to an energy system optimization model. Drawing from frameworks established by Hallegatte (2008), Henriet et al. (2012), Inoue and Todo (2019), and specifically Pichler et al. (2022), the IO model incorporates simple heuristics and configurations tailored for short-term analysis.[4] The model implemented in this manuscript aims to identify the immediate economic consequences arising from energy system transformation pathways. It simulates how various macroeconomic variables evolve across different sectors of the economy based on short-term investments and operational expenses associated with transitioning the energy system.

Fig. 1 presents a summary of the general research framework, outlined as follows: Socio-economic and technological scenarios, along with considerations of energy security, are combined to develop pathways for future transformations. This encompasses various economic, social, and environmental factors, along with detailed techno-economic descriptions of the system and the broader policy context, including energy policies and energy security goals such as security of supply. These components are integrated into internally consistent transformation pathways that are evaluated using an energy system optimization model, as discussed in Stolten et al. (2022) and Kullmann et al. (2022). The outputs from this model are subsequently integrated into the disequilibrium IO model used in this manuscript. This integration considers implications of domestic content and other economic factors, including production constraints in industries caused by a lack of critical inputs.

The IO model is based on data for Germany from the year 2020, which is an aggregation of EXIOBASE (Stadler et al., 2018) ,[5] a comprehensive IO database.[6] Moreover, publicly available data are incorporated to determine the essential parameters and other necessary data in the model. A detailed mathematical description of the model is provided in Appendix A (with exact parameter values given in Table A1), while a sensitivity analysis of the exogenous values obtained from the energy system optimization model is presented in Appendix B (Fig. B1). Supplementary Material S1 offers an in-depth discussion of the selection of key parameters.

The following provides a brief description of the IO model, which is closely based on the model developed and validated in Pichler et al. (2022). Throughout the manuscript, model variables in capitals stand for either matrices or tensors (three-dimensional objects explicitly accounting for the temporal component), while those indexed with lowercase symbols stand for vector-valued objects. The basic accounting structure of the economy is given as:

$$\chi_{i,t} = \sum_{j=1}^{N} Z_{ij,t} + c_{i,t} + f_{i,t} \tag{1}$$

where $\chi_{i,t}$ stands for the total output if industry i at time t, and $Z_{ij,t}$ represents the intermediate consumption of good[7] j by industry i. Realized household consumption of good i at time t, is given as $c_{i,t}$. All other realized (non-household) final demands (e.g. government, investment, exports) are denoted by $f_{i,t}$. The profits, $\pi_{i,t}$, of industry i at time t exhibit the following dynamics:

$$\pi_{i,t} = \chi_{i,t} - \sum_{j=1}^{N} Z_{ji,t} - w_{i,t} - e_{i,t} \tag{2}$$

where, $w_{i,t}$ is the labor compensation for the employees in industry i at time t, and $e_{i,t}$ stands for all other expenses (i.e. taxes).

The equations governing the time evolution of both total demand for industry i, denoted by $d_{i,t}$, and intermediate demand, indicated by $O_{ji,t}$ are introduced as:

$$d_{i,t} = \sum_{j=1}^{N} O_{ij,t} + c_{i,t}^{d} + \lambda_{i,t} f_{i,t}^{d} \tag{3}$$

[4] Further adjustments to the technology coefficients, guided by the energy system optimization model, would enable this model to extend its analysis to long-term impacts. This configuration would assumes changes in quantities without any changes in prices over the long run, as imposed, for example, in some CGE models (Lecca et al., 2013).

[5] With latest data being available from: https://zenodo.org/records/5589597

[6] This dataset includes various impact variables, such as water consumption, land use, and employment hours. However, for practical reasons, the results in this paper focus specifically on output and employment. It is important to note that the transformation of the energy system will also affect other crucial variables, including natural capital, human health, fairness and equity, and other distributional issues, which are not covered in this paper. Furthermore, constraints related to natural capital and other resources are not incorporated into the current IO model. The broader system-wide effects of incorporating such constraints are discussed in Ross et al. (2023), for example.

[7] For simplicity, the text does not differentiate between goods, commodities, and services; however, these categories are explicitly included and distinguished in the underlying data.

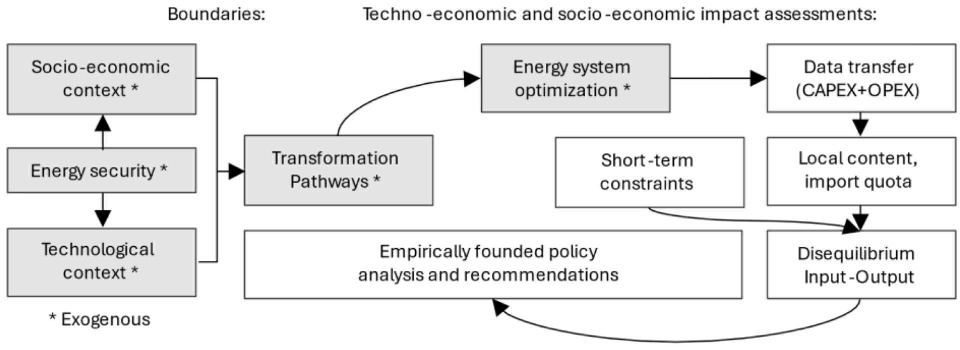

Fig. 1. Research framework. Socio-economic and technological scenarios are integrated along with energy security aspects to formulate transformation pathways. These pathways are assessed using an energy system optimization model. The results are subsequently linked to a disequilibrium Input-Output (IO) model, which considers domestic content and production constraints. This approach aims to support evidence-based policymaking.

$$O_{ji,t} = A_{ji,t}\, d_{i,t-1} + \frac{1}{\tau}\left(n_i Z_{ji,0} - S_{ji,t-1}\right) \tag{4}$$

In the above, $\lambda_{i,t}$ is the exogenous shock parameter, $c^d_{i,t}$ stands for the demand of household consumption of good i at time t while $f^d_{i,t}$ stands for all other (non-household) final demands of good i at time t. $S_{ji,t}$ denotes the stock of input j held in i's inventory at time t, τ represents the speed of inventory adjustment while n_i represents the number of days for which the production is ensured for industry i, A stands for the technical coefficient matrix and N signifies the number of sectors in the economy. The exact functional form for $c^d_{i,t}$ is specified in Appendix A. The difference between quantities f and c with and without the superscript d must be highlighted; namely in the absence of this superscript the quantity refers to the realized values, while its presence indicates that the quantity represents the required/demanded values which may not necessarily be fully realized. The exact relationship is specified in Appendix A. Note that the intermediate demand $O_{ji,t}$ is modeled as sum of two quantities where the first summand represents the assumption that the demand will not change on a daily basis while the second component represents the notion that the industry needs to maintain a certain amount of inventory to produce goods for another n_i days while adjusting its demand based on the inventory gap at speed τ.

Assuming that all workers in the same industry earn the same wage, employment in industry i at time t is denoted by $l_{i,t}$. The time evolution of labor demand by industry i at time t is represented by $l^d_{i,t}$ and is governed by:

$$l^d_{i,t} = l_{i,t} + \Delta l_{i,t} \tag{5}$$

$$\Delta l_{i,t} = \frac{l_{i,0}}{\chi_{i,0}}\left[\min\left\{\chi^{inp}_{i,t},\ d_{i,t}\right\} - \chi^{cap}_{i,t}\right] \tag{6}$$

$$l_{i,t} = \begin{cases} l_{i,t} + \gamma_H\, \Delta l_{i,t}\ \mathit{if}\ \Delta l_{i,t} \geq 0 \\ l_{i,t} + \gamma_F\, \Delta l_{i,t}\ \mathit{if}\ \Delta l_{i,t} < 0 \end{cases} \tag{7}$$

$$\frac{l_{i,t}}{l_{i,0}} \leq lab_{max} \tag{8}$$

$$lab_{max} \in \{1.032,\ +\infty\} \tag{9}$$

where hiring and firing rates are denoted by γ_H and γ_F, respectively. Note that $\chi^{cap}_{i,t}$ and $\chi^{inp}_{i,t}$ stand for the productive capacity of industry i at time t and intermediate input-based production capacities, respectively. Specifically, $\chi^{inp}_{i,t}$ is given as a Leontief production function. The intuition behind Eq. (6) is as follows: if $\min\left\{\chi^{inp}_{i,t},\ d_{i,t}\right\} < \chi^{cap}_{i,t}$ the firm has more capacity than it needs (this being the minimum of input and demand) and whence it is optimal for the firm to fire workers until this inequality holds true. If, on the other hand, $\min\left\{\chi^{inp}_{i,t},\ d_{i,t}\right\} \geq \chi^{cap}_{i,t}$ this means that the firm does not have enough workers to meet its demand and whence it is optimal to hire workers so long as this inequality is valid. The above in turn determines the sign of $\Delta l_{i,t}$, in case this is non-negative, the firms will hire and will otherwise fire workers. These relationships are mathematically formalized in Eq. (5) and Eq. (7). Furthermore, Eq. (8) imposes the upper bound on the availability of labor, namely that at any one time, the labor force cannot be larger than a specified multiple lab_{max} of its baseline value $l_{i,o}$. The lab_{max} in Eq. (9) value of 1.032 corresponds to the current unemployment rate of Germany (DESTATIS, 2024) while infinity corresponds to the assumption that the labor force is essentially unrestricted, and if needed, any number of qualified workers required are indeed available for the corresponding position. The model assumes prices remain constant. Demand does not necessarily match actual transactions, allowing for potential market inefficiencies. Additional behavioral responses are not considered.[8]

Previous literature (Alleman et al., 2023; Pichler et al., 2022) has prioritized selecting values for inventory adjustments that maximize the overall model's goodness of fit or predictive performance, rather than estimating them separately through empirical, computational, or analytical inference. Similar approaches have also been taken for hiring and firing rates. However, simulations (or projections) are typically based on point estimates of the underlying model parameters. Thus, it is fundamentally important to ensure a strong scientific rationale behind the choice of parameter values to ensure viability and increase confidence in the inferences provided by the model simulation (or prediction). This manuscript employs several mathematical techniques, primarily from the domain of probability theory, to determine reasonable values for multiple parameters, including those mentioned above, which are subsequently used to parameterize the applied model. Detailed information on these techniques is provided in Supplementary Material S1. It is also important to note that legal constraints related to hiring and firing, which have not received explicit attention in previous literature, are now addressed in greater depth. The parameter estimation presented, therefore, utilizes realistic real-world constraints and rigorous mathematical reasoning to yield reliable estimates of the parameters guiding the time evolution of the economic model.

4. Scenario specification

The scenario analysis in the upcoming results section draws upon data from Stolten et al. (2022) and Kullmann et al. (2022). These authors use an energy system optimization model (ETHOS.NESTOR) to evaluate strategies for transitioning the energy system to achieve net-zero emissions through a mixed-integer linear optimization approach.[9] Their assessments of transformation pathways quantify the capital (CAPEX) and operational (OPEX) expenses necessary for technically retrofitting the energy system to reach greenhouse gas neutrality. Their analysis focuses on strategies aligned with the Bundes-Klimaschutzgesetz (KSG), which establishes, among other targets, emission reduction goals for Germany until 2045. For an in-depth discussion, see Stolten et al. (2022).

This manuscript analyzes the short-term effects of energy system transformation costs incurred within a one-year timeframe. For this, the daily averages are derived from the initial five years of the energy system transformation (Kullmann et al., 2022; Stolten et al., 2022), and are subsequently allocated and linked to the relevant IO sectors.[10] Appendix B presents a sensitivity analysis of the exogenous values obtained from the energy system optimization model.

The simulations presented in the following section illustrate the overall net effects of the KSG scenario in comparison to a business-as-usual (BAU) scenario. In the analysis, the total capital expenditures for the year amount to 25 billion EUR, whereas operating expenses have a combined negative value of 3 billion EUR (Kullmann et al., 2022), corresponding to approximately 26.4 billion USD and 3.1 billion USD at the time of writing. It is important to note that although the overall CAPEX is positive, certain sectors, such as the manufacture of conventional motor vehicles, are experiencing disinvestments due to a shift towards e-cars. Similarly, while the overall OPEX is negative, with the manufacture of conventional motor vehicles showing the largest decline in OPEX costs, there are sectors, such as the electricity transmission sector, that have positive OPEX costs. The subsequent net effects of these changes are revealed in the results section. The system incorporates the investment and operational expenditures of a single year through the exogenous shock parameter, $\lambda_{i,t}$, in Eq. (3). The model runs for two years to account for any legacy effects of these expenditures. Without the exogenous shock, the model would simply replicate the base year data each period.

5. Simulation results

To highlight the potential short-term effects of an economy facing constraints, two versions of the dynamic disequilibrium IO model are utilized. The first constrained version is configured so that inventory adjustments are not instantaneous, such that $\tau = 47/4$, and a propensity to consume, m, in Eq (A12) set to 0.8. Moreover, the hiring and firing constraints are defined by setting γ_H to 0.0144 and γ_F to 0.0141, respectively, in accordance with labor market regulations, which means that hiring and firing are not immediate. This version of the model, however, assumes an infinitely elastic supply of labor, with lab_{max} set to $+\infty$ in Eq. (9). In the second model version, which is our preferred model specification, all the settings noted above are retained, but lab_{max} is set to 1.032 to reflect a realistic and currently observed constraint on the availability of labor. To illustrate how the two constrained versions of the model diverge from the current literature, commonly employed Type I and Type II IO multipliers models (Emonts-Holley et al., 2021) are also employed.[11] It is important to note that the results for the Type I and Type II approaches are considered entirely unconstrained,

[8] It is important to note that this approach is highly stylized, and a general equilibrium setting that includes behavioral responses would be necessary for a more detailed assessment. For example, McGregor et al. (2021) explore a similar issue in a CGE model and suggest that public spending on environmental improvement could gain support, along with the establishment of an "environmental social wage," where workers accept lower pay in return for environmental improvements.

[9] Incorporating non-linear methods could improve our understanding of nonconvexities, provide a more realistic representation of system constraints, and enhance our grasp of market dynamics, potentially leading to different technology selections, investment levels, or operational strategies that might align more closely with real-world conditions (Kotzur et al., 2021). While including these considerations might alter the results presented in this paper by offering alternative pathways, the general modeling approach would remain unchanged.

[10] As commonly employed in the literature (Siala et al., 2019; Solé et al., 2020; Vaccaro & Rocco, 2021).

[11] These are described in detail in the literature (Emonts-Holley et al., 2021; Miller & Blair, 2009) and are not further elaborated upon in this manuscript.

aligning with prevailing practice.

Fig. 2 and Table 1 illustrate the key results from the constrained dynamic models and compare them with the outcomes from the Type I and Type II multiplier models. Fig. 2 displays the changes in daily output, while Table 1 presents the aggregate impacts on output and employment for all models across all simulation periods, taking legacy effects into consideration. The term "direct" refers to CAPEX and OPEX expenditures derived from the energy system optimization model, which can be viewed as the exogenous shock to the IO system. It is important to reiterate that energy security considerations are explicitly detailed within the energy transformation pathways assessed in the energy system optimization model, which is, in turn, linked to the disequilibrium IO model used here.

The general transmission mechanisms for the Type I and Type II models can be summarized as follows: Initial CAPEX and OPEX expenditures, referred to as the direct effects, trigger additional ripple effects through inter-industry demand linkages—known as the indirect effects. The sum of these direct and indirect effects is termed the Type I effect. Increased sectoral demands, in turn, lead to higher household income from labor earnings, which is subsequently spent, yielding a further boost to sectoral demand. This is known as the induced effect. The direct, indirect, and induced effects are all encompassed within the Type II model. Consequently, the impact order is typically Type II > Type *I* > Direct. The disequilibrium IO model operates through a more complex transmission mechanism, which is outlined in more detail below.

To provide context for the absolute values, the results of the Type II model (representing the most optimistic model specification) indicate that output increases by 58 billion EUR (approximately 61 billion USD at the time of writing), corresponding to a 0.8 % rise in overall output. Similarly, the 427 thousand jobs created are modest in relative terms, representing a 0.9 % increase in total employment. The Type I and Type II multipliers do not incorporate any crowding-out effects, portraying the most optimistic scenario possible. Despite these overly positive projections regarding potential macro-level effects, empirical ex-post evidence does not support them (Godinho, 2022), although they remain widely used.

Unlike the Type I and Type II IO models, the dynamic disequilibrium IO model includes nonlinear adjustments that can accommodate nonoptimal outcomes. This model introduces constraints and crowding-out effects that limit some of the potential output that could otherwise be achieved. As a result, it implicitly hinders the timely achievement of energy security and broader energy policy goals, as specified in the energy system transformation pathways. In this model, industry demand and production decisions are made using simple rules of thumb, as opposed to the optimization approaches typically used in partial or general equilibrium setups. Specifically, the model executes a set of steps on a daily frequency: firms hire and fire workers based on previous production, households determine consumption demand, industries place orders for intermediate goods, industries produce to satisfy demand, distribution is conducted pro rata if production is insufficient, and inventory is updated while labor compensation is allocated. These steps are repeated with daily time resolution to simulate economic activity and track fluctuations in production, employment, consumption, and inventory levels (see Pichler et al. (2022) for a detailed overview of the algorithm). It is important to note that negative shocks in this disequilibrium IO model have a more immediate impact than positive shocks, resulting in negative aggregate effects before positive impacts can materialize. This corresponds to the dip in output observed in Fig. 2. Specifically, sectors like the conventional motor vehicle manufacturing industry experience a decrease in CAPEX and OPEX, leading to a negative shock. This negative shock takes effect before sectors that receive positive CAPEX and/or OPEX can respond.

As a result of model dynamics, the impacts on output and employment in the disequilibrium IO constrained models, while positive, are notably lower than those estimated by the commonly used Type I and Type II multipliers. The version of the disequilibrium model that incorporates real-world limitations—such as gradual inventory adjustments, constraints on consumption propensity, and legal hiring and firing restrictions (though with an infinitely elastic labor supply)—aligns most closely with the results of the Type I model. These findings are illustrated in Fig. 2b and data row 4 of Table 1. However, even in this scenario, the effects fall short of those indicated by the Type I and Type II multipliers. Additional constraints, such as limitations on labor availability, further diminish economic impacts and lead to considerable crowding-out effects, resulting in minimal impacts beyond the direct effects.

While the employment effects by labor market skill category are detailed in Table 1, it is important to interpret the data with caution, as the modeling does not account for potential changes in the labor force due to migration and does not consider the possibility of workers transitioning between skill groups through avenues such as education or training. Nevertheless, since the analysis focuses on the short term, this simplified and widely used approach may be appropriate. The results indicate that low-skilled workers have the potential to benefit from the energy system transformation, implying that policies in this area could create opportunities for the entire workforce and help prevent worker marginalization.

The overall qualitative effects, along with the modest increases in economic growth and employment, are consistent with findings from existing literature, such as Meyer and Sommer (2016), O'Sullivan and Edler (2020), Sievers et al. (2019), and Ulrich et al. (2022). However, the potential short-term crowding-out effects have not been thoroughly examined using current state-of-the-art IO models. The results outlined here provide evidence that the real-world dynamics faced by economies in the short run can lead to the crowding-out of potential macro-level effects. These crowding-out effects can, in turn, hinder the timely achievement of energy security goals. Relying on models that do not account for such economic constraints can result in misguided policy choices.

Fig. 3 summarizes the sectoral output effects by illustrating the distribution of output as a percentage of total output. It presents values for direct costs, along with the Type I and Type II IO models, as well as two versions of the dynamic disequilibrium IO model. The figure employs a "running total" approach, where the shares of total output per sector are cumulatively added, ultimately reaching 100 % in the bottom right corner. A selection of the 148 sectors is provided.[12]

[12] The full description of each sector is given in Stadler et al. (2018), specifically: https://onlinelibrary.wiley.com/action/downloadSupplement?doi=10.1111%2Fjiec.12715&file=jiec12715-sup-0009-SuppMat-9.xlsx

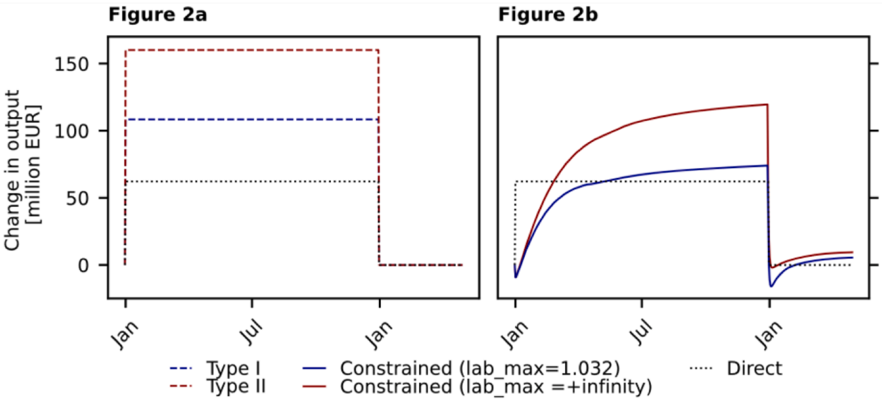

Fig. 2. Aggregate results for the impact on output (the change in output from base year values in million EUR) are presented, resulting from CAPEX and OPEX expenditures in an average year during the initial years of the KSG energy system transformation scenario. Fig. 2a displays the direct, indirect, and induced effects utilizing the standard Type I and Type II IO models, while Fig. 2b showcases the results for the direct effects and the two constrained versions of the dynamic disequilibrium IO model. Considerable crowding-out effects are evident in the constrained models, leading to outcomes that fall short of those projected by the Type I and Type II multipliers.

Table 1
Aggregate results for the total impact on output (in billion EUR) and employment by skill category (in thousands of jobs) resulting from CAPEX and OPEX expenditures in an average year during the initial years of the KSG energy system transformation scenario.

	Output (billion EUR)	Employment (thousands of jobs)			
		Low skilled	Medium skilled	High skilled	Total
Direct	23	18	64	66	148
Type I	40	33	127	127	287
Type II	58	46	191	190	427
Constrained model ($lab_{max} = +\infty$) [*]	37	31	121	123	275
Constrained model ($lab_{max} = 1.032$) [*]	23	24	80	91	195

[*] along with: $\tau = 47/4$, $\gamma_H = 0.0144$, $\gamma_F = 0.0141$, and $m = 0.8$.

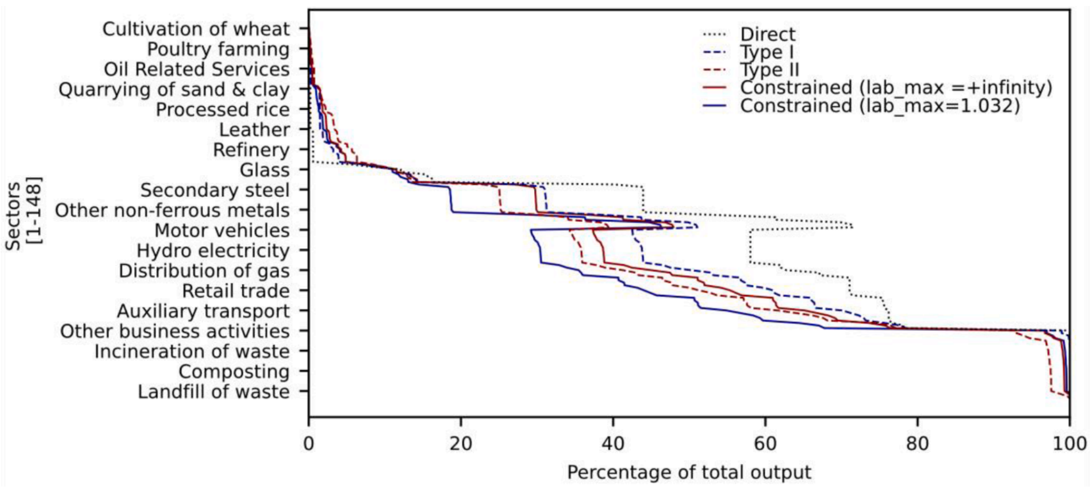

Fig. 3. The output effects by sector are illustrated as a percentage of total output for direct costs, as well as for the Type I and Type II multipliers, and two versions of the disequilibrium IO model. The figure utilizes a "running total" approach, where the shares of total output for each sector are cumulatively summed, ending in 100 % in the bottom right corner. A subset of the 148 sectors is explicitly labeled on the y-axis.

The figure shows that the direct costs of the energy system transformation are distributed across 29 of the 148 sectors. A substantial portion of these costs arises in other business activities and in numerous manufacturing sectors (located toward the middle of the y-axis), such as the production of machinery and electrical equipment, and construction related sectors. One sector experiencing a decline in direct investment, as well as in operation and maintenance expenditures, is the motor vehicle production sector, which is witnessing a decrease in the production of conventional motor vehicles. The production of electric vehicles is distributed across various sectors, with only a portion of the costs being directly attributed to the motor vehicle sector.

While direct costs affect only a limited number of sectors, the Type I and Type II multipliers, along with the dynamic disequilibrium IO models, demonstrate that all sectors are impacted, albeit to varying extents, when industry interlinkages are considered. This is especially true for manufacturing-related sectors, but service sectors such as real estate, retail and trade, and finance are also positively impacted. As a result, all sectors—excluding those involved in the production of traditional motor vehicles and conventional energy—may find growth opportunities. Each model produces a distinct distribution of impacts, shaped by its underlying model assumptions, particularly regarding labor constraints and turnover rates. Nevertheless, the direct costs resulting from the energy system optimization model, provided exogenously, establish the foundational structure of these distributions. Consequently, sectors such as other business activities and manufacturing activities continue to account for substantial proportions of total output. Domestic opportunities are, of course, dependent on maintaining strong domestic production capacities that can compete in the international market, as well as addressing the persistent economic constraints.

Importantly, the findings indicate that relying on commonly used models that overlook short-term economic constraints can lead to markedly different impacts across sectors and on the aggregate economy as compared to models that do consider such constraints. Entirely unconstrained models may create expectations for outcomes that do not materialize in the short term, which could ultimately obstruct the effective implementation of energy policies and hinder the achievement of energy security goals. Clearly, the key issue pertains to the duration for which economic constraints may persist. For example, Germany has been grappling with availability of labor (Arbeitskräftemangel)[13] for an extended period, suggesting that the model could be applied to assess the longer-term impacts of the energy system transformation.

6. Discussion and conclusion

Countries worldwide are striving to achieve net-zero carbon emissions while enhancing domestic energy security; however, they face the challenge of balancing long-term sustainability goals with short-term political interests. A consistent political commitment is essential for driving changes in energy systems. While research often overlooks short-term impacts, identifying "quick wins"—such as job creation from investments in renewable energy technologies—can help sustain public support and further incentivize policymakers to pursue long-term objectives. By emphasizing the immediate economic effects of the energy transition, policymakers can create a favorable environment for sustained investment and progress toward both net-zero emissions and energy security.

Existing analyses often do not adequately consider the unique economic structures of different time frames, resulting in (overly) optimistic projections that lack empirical support. To address this gap, this manuscript investigates the short-term economic effects of transitioning to net-zero carbon emissions using a dynamic disequilibrium Input-Output model that incorporates investment and operational expenses derived from an energy system optimization model. The transformation pathway assessed in the empirical modeling factors in various aspects of energy policy and energy security, including critical elements such as the security of supply. By prioritizing the identification of short-term effects, the analysis presented in this paper aims to mitigate the risks associated with suboptimal policy decisions and recommendations, which could result in sunk costs or the neglect of viable policy options.

The results indicate that modest positive impacts on output and job creation (across a range of labor market skill categories and industries) may be realized, offering reassurance to policymakers that pursuing net-zero carbon emissions and domestic energy security can foster both economic growth and job opportunities. This potential double dividend benefits both the economy and the environment and should encourage greater commitment from stakeholders toward these policy goals. However, the extent of these economic effects is substantially influenced by existing constraints within the economy.

The analysis highlights potential crowding-out effects that may arise from gradual inventory adjustments due to constrained supply chains, as well as from labor supply constraints—factors that are often overlooked in current analyses. Recognizing these real-world economic dynamics is crucial for accurately assessing the impacts of energy transformation pathways and their ability to achieve energy security and policy objectives, as they can significantly affect the duration and scale of impacts, thereby increasing the risk of suboptimal or ineffective policy actions.

At the sector level, the analysis indicates that various service sectors, along with manufacturing industries such as electrical equipment and those associated with the production of electric vehicles, are poised to gain considerably from the energy system transformation. However, the realization of these benefits hinges on the ability to maintain a competitive advantage in domestic production within these sectors. Failing to adapt to the changing landscape could result in a greater dependence on imported goods, which could, in turn, negatively impact energy security aspects. Conversely, industries related to fossil fuels, including traditional motor vehicle manufacturing, are likely to experience considerable declines (unless they adapt and retool their business models to

[13] "Arbeitskräftemangel" refers to labor shortages or a lack of available workers within the German context. This term encapsulates the challenges faced by sectors where there is a disparity between the demand for labor and the supply of the workforce (Garnitz et al., 2023). To conduct a comprehensive analysis of this issue, a more detailed modeling approach is needed that considers the interactions of demand, supply, and prices. One possible methodology for assessing this in detail is described in Ross et al. (2024).

seize the opportunities created by the energy transition).

Notably, the model used in this study does not impose strict constraints; instead, it reflects the current economic landscape, where various economic challenges are presenting substantial headwinds. Therefore, the results provide a rather balanced view of the current implications. To fully realize the potential benefits of investing in energy system transformation, policymakers must thereby address and alleviate existing roadblocks or economic constraints that could hinder progress. Germany's Federal Cabinet has adopted a draft budget for the present year (2025), outlining an initiative for growth aimed at enhancing security and stability during turbulent times (Bundesregierung, 2024). This growth initiative encompasses measures to strengthen competitiveness, promote electric mobility, reduce bureaucracy, improve supply chains, and enhance labor market access, among many other priorities. As highlighted in this paper, these measures are valid and crucial for overcoming existing roadblocks. However, the proclamation of these actions is only the first step; effective implementation is now essential.

Funding

This work was supported in part by the Helmholtz Association under the program "Energy System Design" and the project "Helmholtz platform for the design of robust energy systems and raw material supply" (RESUR). Open Access is funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) (491,111,487).

CRediT authorship contribution statement

Marko Raseta: Writing – review & editing, Writing – original draft, Software. **Andrew G. Ross:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Funding acquisition. **Stefan Vögele:** Writing – review & editing, Funding acquisition.

Declaration of competing interest

During the preparation of this work, the authors used ChatGPT for language editing and grammar checking. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Acknowledgements

We would like to express our sincere gratitude to Felix Kullmann for sharing his invaluable insights from the energy system optimization model ETHOS.NESTOR. We also extend our thanks to Johannes Kremers for his feedback on earlier versions of this paper. We also extend our gratitude to Guest Editor Rabindra Nepal and the two anonymous referees for their valuable and constructive feedback, which has greatly enhanced the quality of our work.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.eap.2025.01.011.

Appendices

Appendix A: Mathematical description of the model

Production

$$\chi_{i,t} = \sum_{j=1}^{N} Z_{ij,t} + c_{i,t} + f_{i,t} \tag{A1}$$

$$\pi_{i,t} = \chi_{i,t} - \sum_{j=1}^{N} Z_{ij,t} - w_{i,t} - e_{i,t} \tag{A2}$$

$$d_{i,t} = \sum_{j=1}^{N} O_{ij,t} + c^d_{i,t} + \lambda_{i,t} f^d_{i,t} \tag{A3}$$

$$f_{i,t} = f^d_{i,t} \frac{\chi_{i,t}}{d_{i,t}} \tag{A4}$$

$$\chi_{i,t}^{cap} = \frac{l_{i,t}}{l_{i,0}} \chi_{i,0}^{cap} \text{(capacity bounds)} \tag{A5}$$

$$\chi_{i,t}^{inp} = \underset{(j:A_{ji>0})}{min} \left(\frac{S_{ji,t}}{A_{ji}} \right) \text{(Leontief production function)} \tag{A6}$$

$$\chi_{i,t} = \min \left(\chi_{i,t}^{cap},\ \chi_{i,t}^{inp},\ d_{i,t} \right) \text{(realized production)} \tag{A7}$$

$$Z_{ji,t} = O_{ji,t} \frac{\chi_{i,t}}{d_{i,t}} \text{(final delivery from industry } j \text{ to industry } i\text{)} \tag{A8}$$

$$S_{ji,t+1} = \max \left(S_{ji,t} + Z_{ji,t} - A_{ji}\chi_{i,t},\ 0 \right) \text{(inventory update)} \tag{A9}$$

Consumption

$$O_{ji,t} = A_{ji,t}\ d_{i,t-1} + \frac{1}{\tau} \left(n_i Z_{ji,0} - S_{ji,t-1} \right) \tag{A10}$$

$$c_{i,t}^{d} = \theta_{i,t} \widetilde{c}_t^{\,d} \text{(consumption demand)} \tag{A11}$$

$$\widetilde{c}_t^{\,d} = \exp\left(\rho \log \widetilde{c}_{t-1}^{\,d} + (1-\rho)\log(m\widetilde{w}_t) \right) \text{(total required consumption demand)} \tag{A12}$$

Labor market

$$l_{i,t}^{d} = l_{i,t} + \Delta l_{i,t} \tag{A13}$$

$$\Delta l_{i,t} = \frac{l_{i,0}}{\chi_{i,0}} \left[\min\left(\chi_{i,t}^{inp},\ d_{i,t} \right) - \chi_{i,t}^{cap} \right] \tag{A14}$$

$$l_{i,t} = \begin{cases} l_{i,t} + \gamma_H\ \Delta l_{i,t}\ if\ \Delta l_{i,t} \geq 0 \\ l_{i,t} + \gamma_F\ \Delta l_{i,t}\ if\ \Delta l_{i,t} < 0 \end{cases} \tag{A15}$$

$$\frac{l_{i,t}}{l_{i,0}} \leq lab_{max} \text{(constraint on the labor force)} \tag{A16}$$

Table A1
Parameters and data sources.

Symbol	Name	Value / Source
i	Industry	
t	Time at daily intervals	
N	Number of industries	148
$\chi_{i,t}$	Total output of industry i at time t	
A_{ij}	ij^{th} element of the technical coefficient matrix A	
$\chi_{i,t}^{cap}$	Production capacity of industry i based on available labor at time t	
$\chi_{i,t}^{inp}$	Production capacity of industry i based on available inputs other than labor at time t	
$d_{i,t}$	Total demand for industry i at time t	
$Z_{ij,t}$	Intermediate consumption of good i by industry j	
m	Propensity to consume	0.8024
ρ	Consumption adjustment	0.99 Pichler et al. (2022)
$O_{ij,t}$	Intermediate demand from industry j to industry i at time t	
$S_{ij,t-1}$	Stock of input j held in inventory of industry i at time t	Pichler et al. (2022)
$c_{i,t}^{d}$	Demand of household consumption of good i at time t	
$\widetilde{c}_t^{\,d}$	Total required consumption demand at time t	
$\theta_{i,t}$	Preference coefficient giving the share of goods from industry i out of total consumption demand $\widetilde{c}_t^{\,d}$	
$c_{i,t}$	Realized household consumption of good i at time t	
$f_{i,t}$	All other realized (non-household) final demands for good i at time t	
$f_{i,t}^{d}$	All other (non-household) final demands of good i at time t	
$\lambda_{i,t}$	Exogenous shock parameter	ETHOS.NESTOR (Kullmann et al., 2022; Stolten et al., 2022)
$l_{i,t}$	Employment in industry i at time t	
$w_{i,t}$	Labor compensation in industry i at time t	

(continued on next page)

Table A1 (*continued*)

Symbol	Name	Value / Source
$\widetilde{w_t}$	Total labor compensation at time t	
$l^d_{i,t}$	Labor demand by industry i at time t	
τ	Inventory adjustment (in days)	$\in$(1,47/4) Supplementary Material S1
γ_H	Hiring rate	$\in$(1,0.0144) Supplementary Material S1
γ_F	Firing rate	$\in$(1,0.0141) Supplementary Material S1
lab_{max}	Upper bound on the availability of labor	$\in$(1.032,+∞) DESTATIS (2024)

Note: All data, unless explicitly denoted or calculated in the model, are sourced from EXIOBASE (Stadler et al., 2018).

Appendix B: Sensitivity analysis

The results presented in the main body of this paper are based on the average costs incurred during the initial years of the energy system transformation, as determined by an energy system optimization model (Kullmann et al., 2022; Stolten et al., 2022). However, significant cost variations are expected in subsequent years as sectoral investments and operational costs are adjusted to meet emission reduction targets. Additionally, technology substitutions will influence both the overall results and those specific to individual sectors. For example, as traditional motor vehicles are phased out, electric cars are anticipated to become more prevalent. Therefore, this appendix examines the sectoral effects over additional years of model simulations, focusing on the years 2025, 2030, 2035, 2040, and 2045. Fig. B1 summarizes the key results at the sector level.

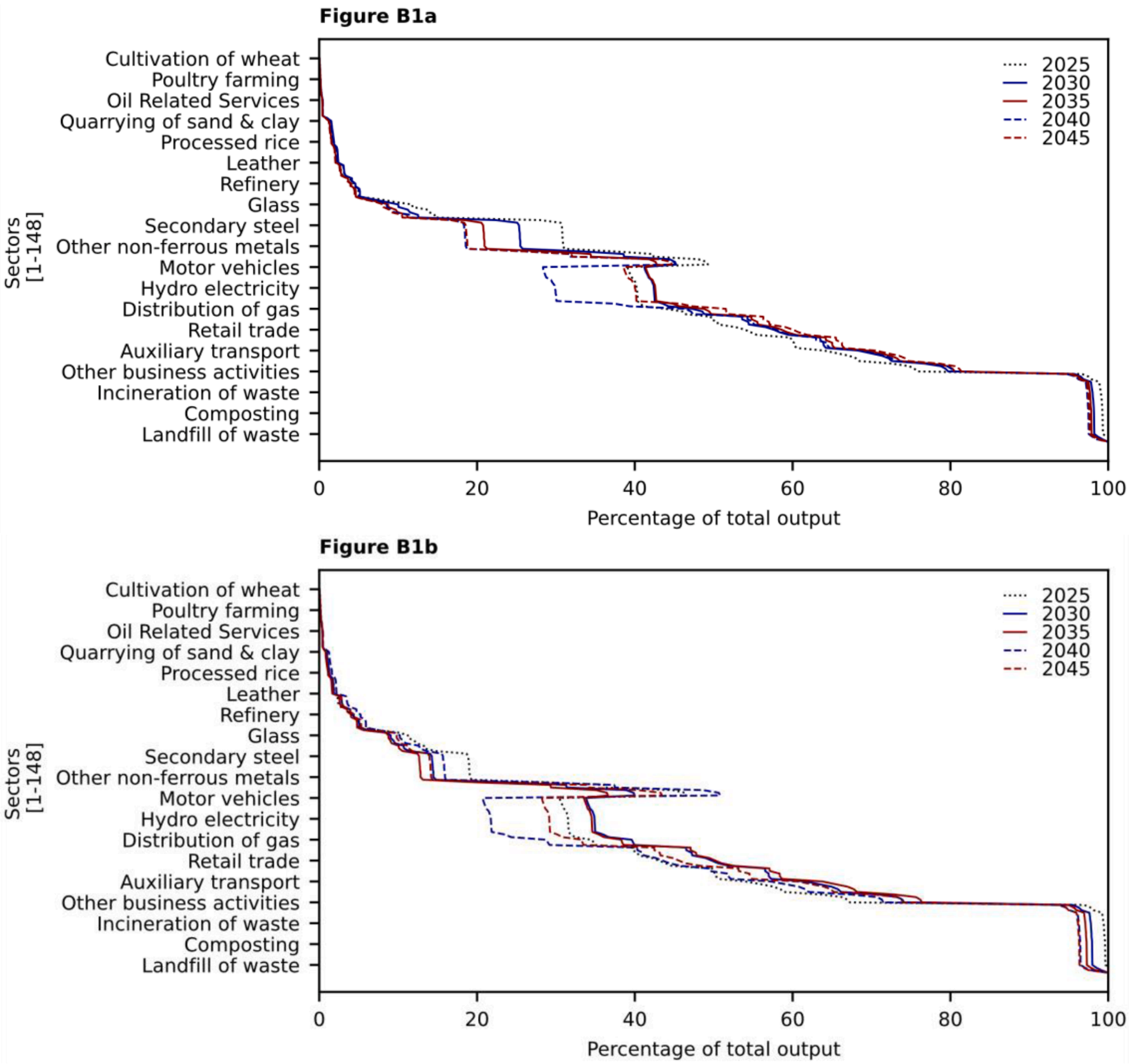

Fig. B1. The output effects by sector are illustrated as a percentage of total output for the two versions of the disequilibrium IO model. The figure utilizes a "running total" approach, where the shares of total output for each sector are cumulatively summed, ending in 100 % in the bottom right corner. Fig. B1a presents the results for the model with lab_{max} set to $+\infty$, while Fig. B1b shows the results for the model with lab_{max} set to 1.032 – with both models also assuming: $\tau = 47/4$, $\gamma_H = 0.0144$, $\gamma_F = 0.0141$, and $m = 0.8$. A subset of the 148 sectors is explicitly labeled on the y-axis.

Figures B1a—b can be interpreted similarly to Fig. 3 in the results section of this paper; however, these figures specifically compare the sectoral distribution of output across different years of the energy system transformation. The results indicate, as anticipated, that differences between the constrained version of the disequilibrium IO model persist, but now exhibit more pronounced variations due to the different years of the energy transition. For example, the decline in the production of conventional motor vehicles is most pronounced in 2040, although a phase-out occurs in all years. While there is some variation within the other business activity sector across different years, strong increases are consistently observed. Similarly, the manufacturing sectors (located toward the middle of the y-axis) are expected to benefit significantly from the energy system transformation throughout all time periods. However, the extent of these benefits depends on maintaining competitive domestic production capacities in the future and addressing the economic constraints as outlined in the main section of this paper.

References

Allan, G., Comerford, D., Connolly, K., McGregor, P., Ross, A.G., 2020. The economic and environmental impacts of UK offshore wind development: the importance of local content. Energy 199, 117436. https://doi.org/10.1016/j.energy.2020.117436.

Alleman, T.W., Schoors, K., & Baetens, J.M. (2023). Validating a dynamic input-output model for the propagation of supply and demand shocks during the COVID-19 pandemic in Belgium. *arXiv preprint* arXiv:2305.16377. https://doi.org/10.48550/arXiv.2305.16377.

Bundesregierung. (2024). *Haushaltsentwurf 2025 setzt klare Prioritäten* https://www.bundesregierung.de/breg-de/aktuelles/haushalt-2025-2299130.

Carlin, W., Soskice, D.W., 2014. Macroeconomics: Institutions, Instability, And The Financial System. Oxford University Press.

Carvalho, A.L.d., Antunes, C.H., Freire, F., Henriques, C.O., 2015. A hybrid input–output multi-objective model to assess economic–energy–environment trade-offs in Brazil. Energy 82, 769–785. https://doi.org/10.1016/j.energy.2015.01.089.

Cazcarro, I., García-Gusano, D., Iribarren, D., Linares, P., Romero, J.C., Arocena, P., Arto, I., Banacloche, S., Lechón, Y., Miguel, L.J., Zafrilla, J., López, L.-A., Langarita, R., Cadarso, M.-Á., 2022. Energy-socio-economic-environmental modelling for the EU energy and post-COVID-19 transitions. Sci. Total Environ. 805, 150329. https://doi.org/10.1016/j.scitotenv.2021.150329.

Černý, M., Bruckner, M., Weinzettel, J., Wiebe, K., Kimmich, C., Kerschner, C., Hubacek, K., 2021. Employment Effects of the Renewable Energy Transition in the Electricity sector: An input-Output Approach. ETUI Research Paper-Working Paper.

Černý, M., Bruckner, M., Weinzettel, J., Wiebe, K., Kimmich, C., Kerschner, C., Hubacek, K., 2024. Global employment and skill level requirements for 'Post-Carbon Europe. Ecolog. Econom. 216, 108014. https://doi.org/10.1016/j.ecolecon.2023.108014.

DESTATIS. (2024). *German federal statistical office national accounts*. Retrieved 11.04.2024 from https://www.destatis.de/EN/Themes/Labour/Labour-Market/Unemployment/_node.html.

Dixon, P.B., & Jorgenson, D. (2012). *Handbook of Computable General Equilibrium Modeling* (Vol. 1). Newnes.

Emonts-Holley, T., Ross, A., Swales, K., 2021. Estimating induced effects in IO impact analysis: variation in the methods for calculating the Type II Leontief multipliers. Econom. Syst. Res. 33 (4), 429–445. https://doi.org/10.1080/09535314.2020.1837741.

Garnitz, J., Sauer, S., Schaller, D., 2023. Arbeitskräftemangel belastet die deutsche Wirtschaft. ifo Schnelldienst 76 (09), 60–64.

Godinho, C., 2022. What do we know about the employment impacts of climate policies? A review of the ex post literature. WIREs Climate Change 13 (6), e794. https://doi.org/10.1002/wcc.794.

Hallegatte, S., 2008. An adaptive regional input-output model and its application to the assessment of the economic cost of katrina. Risk Anal. 28 (3), 779–799. https://doi.org/10.1111/j.1539-6924.2008.01046.x.

Hanna, R., Heptonstall, P., Gross, R., 2024. Job creation in a low carbon transition to renewables and energy efficiency: a review of international evidence. Sustain. Sci. 19 (1), 125–150. https://doi.org/10.1007/s11625-023-01440-y.

Henriet, F., Hallegatte, S., Tabourier, L., 2012. Firm-network characteristics and economic robustness to natural disasters. J. Econom. Dyn. Control 36 (1), 150–167. https://doi.org/10.1016/j.jedc.2011.10.001.

IEA. (2021). *Net Zero by 2050: a roadmap for the global energy sector* https://www.iea.org/reports/net-zero-by-2050.

IEA. (2023). *Net zero roadmap: a global pathway to keep the 1.5 °C goal in Reach.* https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach.

Inoue, H., Todo, Y., 2019. Firm-level propagation of shocks through supply-chain networks. Nat. Sustain. 2 (9), 841–847. https://doi.org/10.1038/s41893-019-0351-x.

Kotzur, L., Nolting, L., Hoffmann, M., Groß, T., Smolenko, A., Priesmann, J., Büsing, H., Beer, R., Kullmann, F., Singh, B., Praktiknjo, A., Stolten, D., Robinius, M., 2021. A modeler's guide to handle complexity in energy systems optimization. Adv. Appl. Energy 4, 100063. https://doi.org/10.1016/j.adapen.2021.100063.

Kullmann, F., Markewitz, P., Kotzur, L., Stolten, D., 2022. The value of recycling for low-carbon energy systems - A case study of Germany's energy transition. Energy 256, 124660. https://doi.org/10.1016/j.energy.2022.124660.

Layard, P.R.G., Layard, R., Nickell, S.J., Jackman, R., 2005. Unemployment: Macroeconomic Performance and the Labour Market. Oxford University Press on Demand. https://doi.org/10.1093/acprof:oso/9780199279166.001.0001.

Lecca, P., McGregor, P.G., Swales, J.K., 2013. Forward-looking and myopic regional Computable general equilibrium models: how significant is the distinction? Econ. Model. 31, 160–176. https://doi.org/10.1016/j.econmod.2012.11.010.

McCollum, D.L., Gambhir, A., Rogelj, J., Wilson, C., 2020. Energy modellers should explore extremes more systematically in scenarios. Nat. Energy 5 (2), 104–107. https://doi.org/10.1038/s41560-020-0555-3.

McGregor, P.G., Ross, A.G., Swales, J.K., 2021. How fiscal policies affect energy systems: the importance of an 'environmental social wage. Reg. Stud. 55 (8), 1354–1364. https://doi.org/10.1080/00343404.2021.1893895.

McGregor, P.G., Swales, J.K., Yin, Y.P., 1996. A long-run interpretation of regional input-output analysis. J. Reg. Sci. 36 (3), 479–501. https://doi.org/10.1111/j.1467-9787.1996.tb01113.x.

Mercure, J.F., Salas, P., Vercoulen, P., Semieniuk, G., Lam, A., Pollitt, H., Holden, P.B., Vakilifard, N., Chewpreecha, U., Edwards, N.R., Vinuales, J.E., 2021. Reframing incentives for climate policy action. Nat. Energy 6 (12), 1133–1143. https://doi.org/10.1038/s41560-021-00934-2.

Meyer, I., Sommer, M.W., 2016. Employment effects of renewable energy deployment - a review. Int. J. Sustain. Develop. 19 (3), 217–245. https://doi.org/10.1504/IJSD.2016.078274.

Miller, R.E., Blair, P.D., 2009. Input-Output Analysis: Foundations and Extensions, 2 ed. Cambridge University Press. https://doi.org/10.1017/CBO9780511626982.

Muttitt, G., Gass, P., 2023. How energy transition affects jobs. Nat. Clim. Chang. 13 (11), 1162–1163. https://doi.org/10.1038/s41558-023-01830-1.

O'Sullivan, M., Edler, D., 2020. Gross employment effects in the renewable energy industry in germany—an input–output analysis from 2000 to 2018. Sustainability. (15), 12.
Oosterhaven, J. (2022). *Rethinking input-output analysis: a spatial perspective*. https://doi.org/10.1007/978-3-031-05087-9.
Pichler, A., Pangallo, M., del Rio-Chanona, R.M., Lafond, F., Farmer, J.D., 2022. Forecasting the propagation of pandemic shocks with a dynamic input-output model. J. Econom. Dyn. Control 144, 104527. https://doi.org/10.1016/j.jedc.2022.104527.
Pollitt, H., 2024. Integrating multiple timescales in the economic modelling of the low-carbon transition. In: Booß-Bavnbek, B., Hesselbjerg Christensen, J., Richardson, K., Vallès Codina, O. (Eds.), Multiplicity of Time Scales in Complex Systems: Challenges for Sciences and Communication I. Springer International Publishing, pp. 297–325. https://doi.org/10.1007/16618_2023_65.
Raa, T.t., 2017. Handbook of Input-Output Analysis. Edward Elgar.
Ross, A.G., Connolly, K., Rhoden, I., Vögele, S., 2023. Resource-use intensity and the labour market: more for less? Environ. Impact. Assess. Rev. 102, 107173. https://doi.org/10.1016/j.eiar.2023.107173.
Ross, A.G., McGregor, P.G., Swales, J.K., 2024. Labour market dynamics in the era of technological advancements: the system-wide impacts of labour augmenting technological change. Technol. Soc. 77, 102539. https://doi.org/10.1016/j.techsoc.2024.102539.
Siala, K., de la Rúa, C., Lechón, Y., Hamacher, T., 2019. Towards a sustainable European energy system: linking optimization models with multi-regional input-output analysis. Energy Strat. Rev. 26, 100391. https://doi.org/10.1016/j.esr.2019.100391.
Sievers, L., Breitschopf, B., Pfaff, M., Schaffer, A., 2019. Macroeconomic impact of the German energy transition and its distribution by sectors and regions. Ecolog. Econom. 160, 191–204. https://doi.org/10.1016/j.ecolecon.2019.02.017.
Solé, J., Samsó, R., García-Ladona, E., García-Olivares, A., Ballabrera-Poy, J., Madurell, T., Turiel, A., Osychenko, O., Álvarez, D., Bardi, U., Baumann, M., Buchmann, K., Capellán-Pérez, Í., Černý, M., Carpintero, Ó., De Blas, I., De Castro, C., De Lathouwer, J.D., Duce, C., Theofilidi, M., 2020. Modelling the renewable transition: scenarios and pathways for a decarbonized future using pymedeas, a new open-source energy systems model. Renew. Sustain. Energy Rev. 132, 110105. https://doi.org/10.1016/j.rser.2020.110105.
Stadler, K., Wood, R., Bulavskaya, T., Södersten, C.-J., Simas, M., Schmidt, S., Usubiaga, A., Acosta-Fernández, J., Kuenen, J., Bruckner, M., Giljum, S., Lutter, S., Merciai, S., Schmidt, J.H., Theurl, M.C., Plutzar, C., Kastner, T., Eisenmenger, N., Erb, K.-H., Tukker, A., 2018. EXIOBASE 3: developing a time series of detailed environmentally extended multi-regional input-output tables. J. Ind. Ecol. 22 (3), 502–515. https://doi.org/10.1111/jiec.12715.
Steg, L., Perlaviciute, G., van der Werff, E., 2015. Understanding the human dimensions of a sustainable energy transition [Review]. Front. Psychol. 6. https://doi.org/10.3389/fpsyg.2015.00805.
Stolten, D., Markewitz, P., Kraus, S., Franzmann, D., Schöb, T., Grube, T., Heinrichs, H., Gillessen, B., Linssen, J., Pflugradt, N., 2022. Neue Ziele auf alten Wegen? Strategien für eine treibhausgasneutrale Energieversorgung bis zum Jahr 2045, 3958066275.
Ullah, S., Gozgor, G., Lu, Z., 2024. How do conflicts affect energy security risk? Evidence from major energy-consuming economies. Econ. Anal. Policy. 82, 175–187. https://doi.org/10.1016/j.eap.2024.02.039.
Ulrich, P., Naegler, T., Becker, L., Lehr, U., Simon, S., Sutardhio, C., Weidlich, A., 2022. Comparison of macroeconomic developments in ten scenarios of energy system transformation in Germany: national and regional results. Energy Sustain. Soc. 12 (1), 35. https://doi.org/10.1186/s13705-022-00361-5.
Vaccaro, R., Rocco, M.V., 2021. Quantifying the impact of low carbon transition scenarios at regional level through soft-linked energy and economy models: the case of South-Tyrol Province in Italy. Energy 220, 119742. https://doi.org/10.1016/j.energy.2020.119742.
Wang, B., Dong, K., Zhong, W., Zhao, C., 2024. Can high-quality energy development and energy security achieve a win-win situation? The case of China. Econ. Anal. Policy. 83, 17–28. https://doi.org/10.1016/j.eap.2024.06.004.
Zhang, J., Liu, L., Xie, Y., Zhang, Y., Guo, H., 2022. An integrated optimization and multi-scale input–output model for interaction mechanism analysis of energy–economic–environmental policy in a typical fossil-energy-dependent region. Energy Strat. Rev. 44, 100947. https://doi.org/10.1016/j.esr.2022.100947.
Zhang, X., Meng, X., Su, C.W., 2024. The security of energy import: do economic policy uncertainty and geopolitical risk really matter? Econ. Anal. Policy. 82, 377–388. https://doi.org/10.1016/j.eap.2024.03.014.