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Towards a sustainable European energy system: Linking optimization models with multi-regional input-output analysis

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ABSTRACT

The European Union set ambitious goals regarding renewable energy and greenhouse gas (GHG) emissions. This study uses two models to analyze the implications of these goals on the European energy system and on the rest of the world, based on several scenarios for the mid and long term. First, using a linear programming optimization model for capacity expansion and unit commitment, we obtain the optimal design of the European power system in 2030 and 2050. Results for Germany are then used as input in a Multi-Regional Input-Output Analysis with the objective of analyzing the environmental and socioeconomic effects derived from the new energy system. The linking of both models in each scenario is at the core of this study. Results show the capabilities of this method in terms of GHG emissions, cumulative energy demand, value added, and job creation.

1. Introduction

The European Union has set a long-term target of reducing greenhouse gas emissions (GHG) in the energy sector by 80–95% by 2050 compared to 1990 levels, in order to make the European economy climate-friendly [1]. Because of its biggest potential for reducing direct GHG emissions through the implementation of efficiency measures and the expansion of clean technologies, the electricity sector deserves special attention.[1] Through the electrification of the heat and transport sectors, it is expected to facilitate the decarbonization of the whole economy. In this sense, the use of electricity system models allows for a better understanding of how the system might evolve in the future, so that the demand is satisfied at the minimum cost and under specific constraints. These constraints can be technical, such as resource availability, but also political, such as nuclear phase-out or renewable energy quotas.

The expansion of clean technologies will contribute to the reduction of direct GHG emissions from the electricity sectors but will require new investments, and therefore, many sectors of the economy will respond to the expansion by extending their production. The increase in the production of goods and services will affect not only Europe but also other economies in the world due to economic interactions of the global market. Moreover, the future new configuration will mean additional indirect energy use and GHG emissions, caused by other non-energy sectors at global level. The change in the electricity portfolio of technologies will also entail that employment in the value chain of fossil technologies will be displaced. Considering that the final objective of the European Union is to achieve a zero emissions economy, it is highly important to account for the indirect effects associated with the new energy scenarios. Besides the potential environmental benefits associated to a new energy system, other benefits could be expected. The stimulation of the economy could bring an increase in the value added as well as the creation of new employment, both directly and indirectly. All these effects can be examined through an extended Input-Output Analysis. This methodology also allows for the identification of the employment lost in some sectors of the economy due to the displacement effect.

In this work we combine two quantitative tools in order to better understand the future developments of the electricity system in Europe as a whole, and in Germany in particular. We link the outputs of an expansion optimization model to an extended Multi-Regional Input-Output model in order to assess the environmental and socioeconomic impacts of the electricity sector. This falls within the broader research topic of linking bottom-up and top-down models. As Glynn et al. explained [2], "[t]he rationale behind linking engineering energy systems models with macroeconomic models is to include the feedback effect between energy cost and energy service demands."

Economic impacts of the transition of the electricity sector as well as the employment consequences can be analyzed using general equilibrium models, macro-econometric models, or system dynamics models

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[1] According to the scenarios of the Energy Roadmap 2050, the electricity sector should be able to cut emissions by 57–65% in 2030 and 96–99% in 2050 compared to 1990 levels [1, p. 7].

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[3]. Some studies have been published in the literature using this approach [4–6]. However, the quantity and quality of data needed for an impact assessment based on a full economic model are very high, and the environmental consequences are usually not considered. Also, using the level of technological detail of bottom-up optimization models in top-down models would lead to a higher computational complexity.

Alternatively, indirect emissions and employment factors for the different electricity technologies could be introduced in the optimization model. This approach has the limitation of the accuracy of the factors used, since differences in the value chain for an electricity technology would generate different factors [7].

In this context, the use of energy optimization models coupled with Input-Output analysis is particularly suited for helping in the policy design process of economy–energy-environment–social (E3S) aspects [8]. Model coupling gives additional insight into some important aspects such as inter-regional competition and trade, delocalization of impacts, and macroeconomic consequences of decarbonizing the energy system as done in [2], environmental consequences of different energy policy scenarios as in [9], or the socioeconomic impacts of different electricity generation scenarios as in [10].

Glynn et al. differentiate between *soft-linking* and *hard-linking* of bottom-up and top-down models, and describe the evolution towards hybrid models [2]. They also focus on the particular case of coupling a computable general equilibrium (CGE) model with a system optimization model. Similar instances of hybrid modeling of long-term decarbonization scenarios were conducted for the UK [11], for South Korea [12], and for Germany [13].

However, not only CGE models have been linked to optimization models. Input–output modeling and energy system optimization have also been combined at least since the mid 1970s [14]. Different variations exist in the method and in the scope [15,16]. In fact, the models can exchange different types of data (energy demands, energy prices, energy mixes, etc.), harmonize their assumptions to different extents, and analyze particular countries or regions [17,18].

In our case, the energy model outputs are exogenous inputs for the MRIO analysis in terms of costs, quantities and direct CO_2 emissions. Our objective is to combine the strengths of the electricity system model (high technical resolution) with those of the multi-regional input-output analysis (broad geographic and sectoral coverage) to provide different perspectives on the electricity system decarbonization in the mid and long term (2030 and 2050). Compared to the previously mentioned studies, we opted for a soft-linking of the models, with a particular focus on the electricity sector. The novelty lies in the expansion of the MRIO tables by disaggregating the electricity sector into the different technologies used in the optimization model. The geographic scope of the optimization model covers the EU28 minus Cyprus and Malta, in addition to Switzerland and Norway. The latter two countries and Croatia are not included in the MRIO tables, due to the limited granularity of the used database.

Our study is structured in the following way: In section 2, we introduce the models and explain the workflow of the model coupling. In section 3, the results of the models are described. Finally, we discuss the outcomes and their possible policy implications in section 4.

2. Method

This section briefly describes the workflow of the paper with references to the relevant sections for further details.

In the first part of the analysis, we use an expansion planning optimization tool to model the European electricity system in 2015, 2030, and 2050 (blue, left side in Fig. 1). A description of the model is provided in section 2.1. We start by creating the model for 2015, and calibrate assumptions about the fuel costs until we match the historical data for that year. Then, we update the technology costs, and retire the power plants and storage devices that have reached the end of their lifetime by 2030. We run the *urbs* model for 2030 and obtain the cost-optimal configuration of the energy system in 2030, including the necessary investments to be added in the system. We repeat the last steps for 2050 to create the model for that year. The results of the optimization, including the calibration, are given in section 3.1.

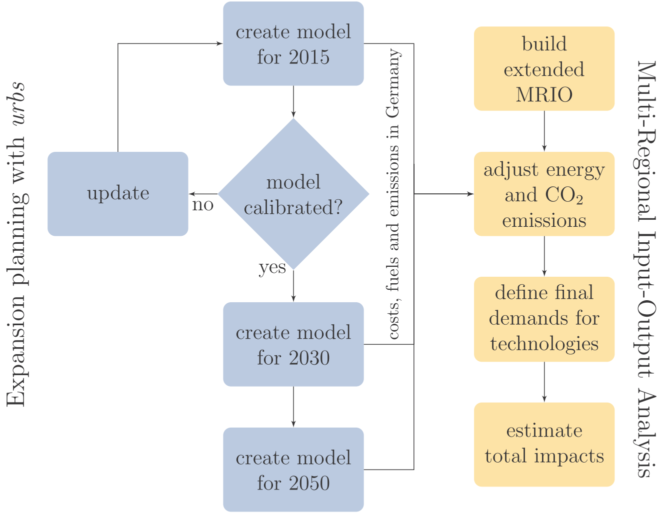

Fig. 1. Workflow of the study.

The different costs, fuels quantities and direct CO_2 emission are then used as an input for the second part, the Multi-Regional Input-Output Analysis (MRIO). Section 2.2 provides a theoretical background in Input-Output Analysis. The core of this study, the linking of the optimization model with MRIO analysis, is explained in section 2.3. In particular, we show how we expanded the MRIO tables to disaggregate the electricity sector. We then feed in the outputs of the optimization model to estimate the total impacts. The results of the analysis for the case of Germany are presented in section 3.2.

2.1. Expansion planning with urbs

We use the open-source model framework *urbs* to generate the models for our analysis. The created models co-optimize capacity expansion, hourly dispatch of generation, transmission, and storage within Europe, using countries as model regions. The optimization goal is to minimize the costs of expanding and operating the European energy system. Major inputs are the hourly time series for the load [19] and the capacity factors of renewable energy sources [20], the existing infrastructure (grid [21], power plants [22,23], storage [23]), and techno-economic parameters such as investment and maintenance costs [24], fuels costs, and specific emissions. Each model solves a linear optimization problem that is written in Python/Pyomo using the gurobi solver. Major outputs include the installed capacities (generation, grid, storage) and the hourly operation of the system. The models also provide the direct emissions, the total costs, and the marginal costs in each region. The source code for *urbs* and an extensive description can be found on GitHub [25].

In this analysis, we do not allow for the expansion of transmission lines. New biomass, hydro power plants and pumped hydroelectric storage units can be built as long as their total installed capacity does not exceed their capacity in 2015. Retrofitting applies also for nuclear power plants, with the exception of countries that do not intend to operate nuclear power plants in the future.[2] Most importantly, we set

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[2] As of 2018, these countries include Austria, Belgium, and Germany. Other countries did not have nuclear power plants in 2015 and are thus *de facto* excluded from having new ones. This assumption might be valid for most cases, but is in contradiction with the policy of some countries such as Poland. We do not think that the exact modeling of all the national policies is necessary for this study, since we focus mostly on Germany.

restrictions on the CO_2 emissions, which should decrease by 50% in 2030 and by 95% in 2050 compared to their level in 2015. The use of 2015 instead of 1990 as a reference year is justified by the general consensus that the electricity sector could play a key role in the decarbonization of the energy sector, hence it should be able to achieve more ambitious targets than the energy sector as a whole [1, p. 7].

2.2. *Multi-regional input-output analysis*

The second tool presented in this paper is based on the Input-Output Analysis (IOA), developed by Wassile Leontief [26]. It measures how the different economic activity sectors respond to a change in the final demand of goods and services within a national economy. The core of the IOA are the Input-Output Tables, which describe the trading relationships among the different economic sectors and with the final demand users in monetary units. Based on the National Accounts, these tables have two main components: the *inter-industry flows*, also known as *transaction matrix*, and the *final demand*.

The transaction matrix describes the production process by industry or activity in columns, and the use of goods and services in rows. In the transaction matrix, the goods and services being interchanged correspond to intermediate goods, which will be further processed by other activity sectors [27]. Thus, the units included in the final demand component refer only to goods and services already processed.

The Input-Output Tables can be represented using the technical coefficients, which describe the normalized cost requirements by sector and are denoted by:

$$a_{ij} = z_{ij}/x_j \tag{1}$$

where a_{ij} is the technical coefficient, z_{ij} is the amount of goods and services from sector i consumed by sector j, and x_j is the total output or production of sector j.

All the productions by sector x_{ij} can be expressed as a whole in a matrix equation:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \tag{2}$$

where $(\mathbf{I} - \mathbf{A})^{-1}$ is the Leontief inverse matrix, or the multiplier matrix, that expresses the direct and indirect requirements by sector per unit of final demand. Using this analysis, it is possible to estimate the potential economic impacts of new infrastructure projects or policies, in terms of total gross production and value added.

The IOA was initially applied in national or regional economies. However, the current global situation cannot be analyzed from a domestic perspective only, because the supply chains have been fragmented in the last decades across countries, modifying the domestic economies and the international trade structure. These changes have affected not only the economic structure, but also other aspects such as pollution or job creation, due to the differences among the countries in terms of environmental legislation, industrial automation and employment structures. The Multi-Regional Input-Output Analysis gets beyond this limitation by including the interregional and intraregional transactions [28].

Besides the economic impacts, it is possible to estimate other effects by expanding the Input-Output tables with other relevant sectorial information such as environmental aspect, which leads to an Environmentally Extended Input-Output Analysis [29–31]. To do that, an additional matrix or vector shall be included in equation (2), which defines how much energy for instance is used by each activity sector to produce one unit of its output [32,33].

The new equation is the following:

$$\mathbf{e} = \lambda \cdot (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \tag{3}$$

where λ describes the direct impact coefficients, such as energy used per unit of output, and **e** is the total impact (total energy used), direct and indirect, associated to the total output that satisfies the new final demand.

2.3. *Linking the optimization model with MRIO*

In this study, we use the World Input-Output Database (WIOD) to build the multi-regional model. The database was developed under the 7th Framework Program, and it contains Input-Output Tables for 41 regions of the world [34]. Additionally, the project also produced satellite accounts containing environmental and social data, which allow us to develop an extended multi-regional model.

The use of economic models relies on many assumptions and simplifications. For instance, input-output models describe the economy in a particular year, in which the relation between inputs (in terms of required goods and services) and outputs of sectors remains constant. Difficulties in data collection and subsequent compilation of input-output tables prevent the development of tables on a yearly basis. Therefore, the national statistic institutions usually produce one input-output table every ten years. Thus, technological changes that happen in a shorter time frame are difficult to trace. There are several methods to update the input-output tables so that changes in time can be captured [35]. One of the most used methods is the RAS method developed by Richard Stone [36]. However, this method is not feasible for the development of future tables in a multi-regional context, because of the large amount of information required.

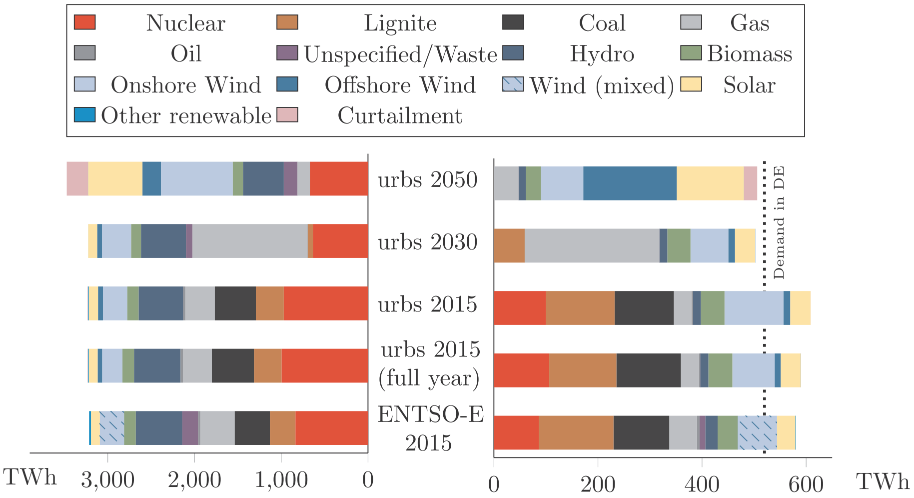
The assumption of constant technical coefficients becomes stronger in the case of the environmental performance of each sector. If the emissions in one sector changed in the short term, the IOA would not be able to capture this new situation. When dealing with future scenarios, this becomes a limiting factor, even more when the electricity sector is involved. By using the current static information, any intermediate production of the electricity sector in the future scenarios would result in CO_2 emissions higher than what would correspond to that sector. Many researchers have already dealt with this challenge and different approaches have been used [37–39]. In cases where the approach is consumption-based and not production-based, information from additional climate-economic model is used [40].

In this paper, we solve the problem in two steps. First, we focus on the environmental performance. Then, we tackle the constraint related to constant technical coefficients.

As said before, we have generated new emission and primary energy use factors for the German electricity sector described in the input-output table for each future scenario, which converts the model into a hybrid model. The new figures were obtained from the optimization results from the *urbs* model, which provides the direct CO_2 emissions and direct energy use associated to the German electric energy mix at each scenario. This ensures that whenever another sector requires electricity as input in its production function, the embodied impacts associated to this electricity are properly described.

Concerning the technical coefficients, input-output models rely on aggregated sector data, which might not represent a particular good or service precisely. This means that the model is not able to distinguish between the different energy technologies within the electricity sector. Based on this, producing 1€ of electricity from solar energy requires the same amount and structure of goods and services as any other technology, and additionally, it results in the same emissions or value added as producing it from natural gas, as an example. To overcome this constraint, the most appropriate approach would be to break down the current electricity sector by technology, readjusting the supply and use tables, and then generating new technical coefficients for each technology. However, the large amount of assumptions and data required, under a multirregional framework, make this solution impractical.

As Zafrilla et al. have done [41], instead of disaggregating or creating a new sector for each technology, we have defined new final demand vectors for them, so that the output from each technology will be treated as an exogenous demand. Each final demand vector represents the cost function of the technology, which is linked to the activity sector in the input-output table which will supply the required good or service. Once the final demand vector is defined by each



(a) Europe

(b) Germany

Fig. 2. Electric energy supply in TWh according to the *urbs* model and to ENTSO-E statistics of 2015. The model *urbs 2015 (full year)* is the one using 8760 time steps for calibration. The three other models (2015, 2030 and 2050) use only four weeks in hourly resolution.

technology, we calculate the total amount of goods and services required by technology and scenario. To do that, we use the results obtained from the electricity system model. In fact, *urbs* provides the investment, fix, variable, and fuel costs by technology, all of which are necessary so that the demand of electricity is fulfilled in a cost-optimal way. Hence, *urbs* outputs are the exogenous final demands for the MRIO analysis. This way, only the electricity sector describes future performance, while any other economic sector within the matrix remains constant. A similar approach has been followed by Blazejczak et al. [42].

Although *urbs* is used to model the European electricity system, the analysis will focus on the German context. Therefore, only the environmental and socioeconomic impacts associated to the German electricity system are estimated, although the effects will be located not only in Germany but in the 40 remaining regions included in the WIOD.

3. Results

In this section, the results of the electricity system optimization are discussed first, followed by an overview of the results that are obtained by linking the optimization model to the MRIO.

3.1. Energy mixes of Europe and Germany

As stated in section 2.1, the optimization model delivers several outputs including the new capacities to be added, the hourly dispatch of power plants, and the costs and emissions caused directly by the operation of the electricity system. We aggregate the hourly dispatch of the power plants to obtain the energy mixes of Europe and Germany, which are shown in Fig. 2. Germany is chosen as a case study because it has the highest electricity demand in Europe, while its electricity mix is diverse and carbon-intensive. Hence, the energy transition of Germany is particularly challenging and would have important repercussions on the different aspects considered in this study.

The full-year *urbs* model of Europe for 2015 does not allow any new capacities to be built. It is solely used for calibration[3] in order to match the energy mix according to ENTSO-E statistics [19]. The result shows that the model overestimates the share of nuclear power in the energy mix, but underestimates the shares of coal, gas, and other mixed fuels, so that the ratio between conventional and renewable generation is the same. In terms of CO_2 emissions, the energy mix of the *urbs* model leads to slightly lower emissions.

In order to speed up the optimization, we run all the models for four weeks (4 × 7 × 24 time steps) instead of a full year. In 2015, we only observe slight discrepancies due to an overestimation of the wind generation in Europe as a whole and in Germany in particular. Despite the differences between the reduced *urbs* model for 2015 and the ENTSO-E statistics, we can use the 2015 model as a basis to build the models of 2030 and 2050, as long as we conduct an analysis based on qualitative trends and relative quantitative changes. The current level of precision is sufficient to demonstrate the method, but higher accuracy is necessary for a more detailed discussion of the policy implications.

When comparing the results for 2015 with the models for 2030 and 2050, we observe that the decarbonization of the electricity system occurs in two steps. In the mid-term, assuming a 50% reduction in CO_2 emissions, all coal power plants and most lignite power plants are phased out in Europe. They are mainly replaced by gas-fired power plants, and, to a lesser extent, by wind farms. In Germany, due to the lack of baseload nuclear capacity by 2030, lignite power plants still contribute to the electricity mix, even though their share shrinks to less than half what it used to be in 2015. According to the model, wind generation also decreases. The reason is that some wind parks would have reached the end of their lifetime by 2030, so they are decommissioned and replaced with gas-fired plants. This development is due to two limitations of the model. First, power plant retrofitting at lower costs than the costs of new installations is not implemented in the model. Second, the wind generation profile that is used in the model is an aggregate that does not reflect the diversity of the regions within Germany, which includes many profitable, cost-competitive onshore wind locations.

Furthermore, based on the model results, Germany becomes a net electricity importer in 2030, and the trend intensifies in 2050. The void left by the nuclear shutdown will be filled by new capacities in Germany and by more imports from other countries, which will increase considerably. The main reason is the higher capacity factors for onshore wind in neighboring countries, particularly in the Netherlands and Denmark. Germany is also connected to many countries with high

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[3] For the calibration, we use the full-year model with 8760 time steps, scale down the hourly capacity factors for solar and wind power to match the yearly generation in Europe, and vary the prices of fuels within a certain range while preserving the merit-order of power plants. All the other models use four weeks (one for each season), while preserving the assumptions regarding fuel prices.

shares of cost-competitive hydro power (Austria, Switzerland, Norway). Another possible explanation lies in the cost assumptions of the different technologies. Based on [24], the investment costs of nuclear power plants are roughly 3.1 times higher than onshore wind in 2030, and 3.4 times higher in 2050. By taking into account the availability of the technologies and the variability of wind, nuclear power could be in some cases a cost-competitive option for CO_2-free electricity generation. Hence, other countries in Europe which still use nuclear power plants would be able to generate electricity in a more cost-competitive way than Germany.

The second step of the decarbonization occurs in the long-term and is characterized by a large-scale deployment of renewable power plants. Together, solar, onshore wind and offshore wind power plants may provide half of the power demand in Europe. In Germany, their share could exceed 75%. Lignite is completely phased out of the system, and gas-fired power plants are the only technology that emits CO_2 directly during operation. However, the renewable power plants are not completely integrated into the system. Despite the investment in battery storage and pumped hydroelectric storage, a considerable amount of the power generated in Europe (equivalent to 47.5% of the electricity demand in Germany) is curtailed.

Uncertainty affects all parameters in the energy system models, notably the cost parameters, the time series, and the choice of the time steps. For the latter, it is possible to run the optimization for the full year and/or with different time series for the load and the renewable energy sources. Regarding the costs, we run a sensitivity analysis with two cases for 2050. In the first one, denoted by “PV-30%“, we reduced the investment costs of PV modules and batteries by 30%. In the second one, “Wind-30%“, onshore and offshore wind power plants are 30% cheaper than in the base case. We noticed that cheaper PV modules and batteries would lead to an increase in the share of solar in the energy mixes of Europe and Germany, but also to more onshore wind, less offshore wind, and more curtailment. In the case of “Wind-30%“, no big variations are noticeable. Thus, the model results are robust regarding the costs of wind power plants, but would vary if PV modules and batteries become cheaper than expected in 2050.

3.2. Results of the model coupling

As stated in section 2.3, the costs of investing in and operating the power system are delivered by the *urbs* models and used by the MRIO analysis to measure the spreading effect on the economy, which must satisfy the goods and services required by each energy technology within the system. The direct CO_2 emissions, as well as the direct energy in terms of consumption of fuels in the operation phase are also provided by the *urbs* models, since the MRIO will only determine the indirect effects. In this section, we restrict the scope of the study to the case of Germany and discuss the socioeconomic and environmental impacts of its electricity sector on a national and global scale. Major results are displayed in Figs. 3 and 4.

Looking at the annualized system costs in Fig. 3a, and assuming that investments prior to 2015 are already paid off, we observe that the system costs almost stagnate between 2015 and 2030, before doubling in 2050. The stagnation of the absolute costs in 2030 coincides with a decline in the total electricity generation, which leads to higher specific costs per unit of electricity generated. The costs are driven by investments, with fuel and variable costs declining in the future. However, if we do not neglect the share of the investments that have not been paid off by 2015, the system costs in 2030 would actually be lower than in 2015. This could be explained by the decommissioning of many conventional power plants (most coal and lignite power plants, and several nuclear power plants), whose fix costs are not considered anymore, and the switch to gas power plants, which are more efficient. Up until 2030, all the renewable power plants made less than 30% of the system costs. In 2050, offshore wind plants are responsible for almost half the costs, even though they cover only one third of the total electricity demand.

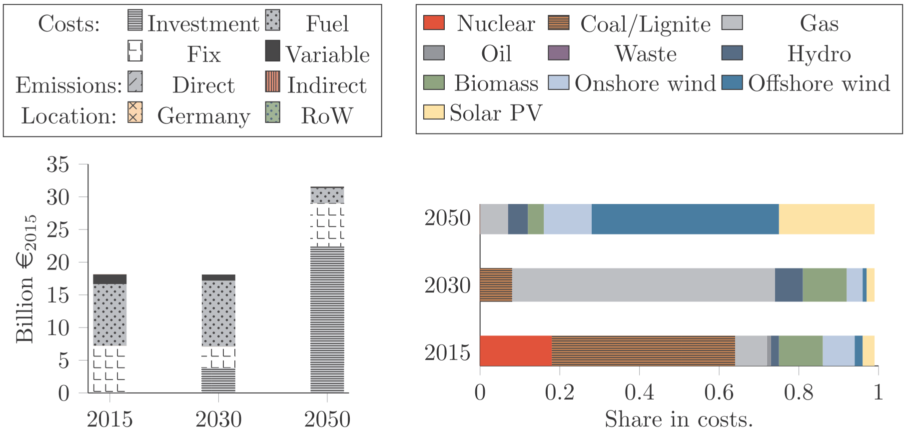
CO_2 emissions form the main constraints of the *urbs* models. However, the constraints only affect the direct emissions caused by the combustion of fuels. Other CO_2 emissions due to the increased economic activity, which was stimulated by the electricity system, are obtained from the input-output model. Both direct and indirect emissions are displayed in Fig. 3c. According to both models, the total emissions in Germany decrease from 253 megatons in 2015 to 136 in 2030, and to 20 in 2050. In 2015 and 2030, the indirect emissions are negligible compared to the direct emissions, yet in 2050 they actually reach one third of the total emissions. Most of the indirect emissions can be traced back to the investment in offshore wind power plants and solar modules. In fact, when comparing the shares in indirect emissions to the shares in the electricity mix in 2050, it emerges that offshore wind plants cause the most indirect CO_2 emissions per unit of electricity produced, followed closely by solar PV, then by onshore wind.

Additionally, we compare the total primary energy use associated to each scenario. In 2015, primary energy use, both directly and indirectly, amounts to almost 4 EJ. The total energy use decreases with stricter CO_2 constraints on direct emissions, but its decline is slower, with a decrease of 44% by 2030 (direct CO_2 emissions: 50%) and only 88% in 2050 (−95% for direct CO_2 emissions). The location where the energy is used varies considerably, since most of it will happen outside of Germany by 2050. According to Fig. 3f, the total primary energy use in 2050 will mainly be related to gas-fired power plants (sectors in Germany) and to offshore wind and solar power plants (from sectors located in the rest of the world).

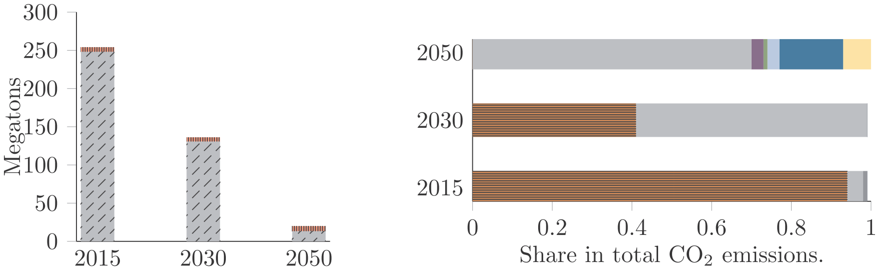
There is an obvious correlation between the evolution of the system costs on one side, and the total value added on the other side, which is visible in Fig. 3a and g. However, it is interesting to see *where* the value added is created. Whereas the share of value added that is created outside Germany lies between 20% and 22% until 2030, it increases to 25% by 2050. Thus, the doubling of the value added, which is stimulated by the German electricity sector, will be more beneficial to other economies. The shares of the different technologies in the value added are similar to their shares in the costs.

The evolution of the number of jobs created, displayed in Fig. 3i, follows a similar trend. In fact, we observe that the share of jobs created within Germany would decrease from 72% in 2015 to 69% in 2050. Interestingly, the highest share of jobs created within Germany occurs in 2030 (74%), and even though the absolute number of jobs remains stable between 2015 and 2030, the specific jobs created per unit of power generated are higher in 2030. Consequently, these findings highlight the fact that it might possible to decarbonize the German electricity sector in the midterm while preserving jobs and increasing the efficiency of the system. In terms of the shares in job creation for each technology, Fig. 3j shows that biomass and PV feature among the most job-intensive technologies, especially if we consider their specific job creation per unit of power generated.

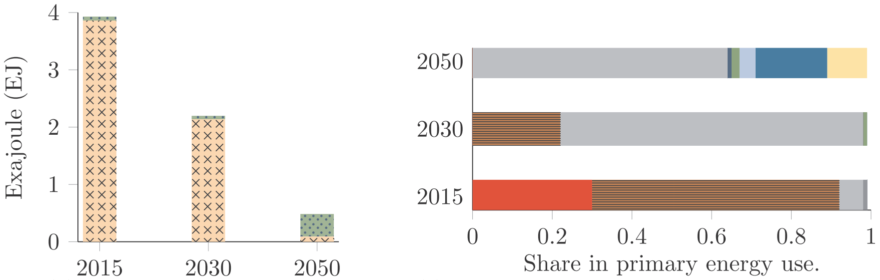
One of the strengths of a multi-regional analysis is the ability to identify the regions that will be stimulated or that will contribute the most to certain impacts. For instance, we could analyze in more depth the socioeconomic and environmental impacts derived from the energy system in 2030. As previously shown, Germany would keep 80% of the value added and 74% of the employment. 65% of the indirect CO_2 emissions associated to the new configuration of the energy system would occur in Germany. Europe, excluding Germany, would also benefit from the new energy system by keeping 12% of the value added generated and 9% of the job creation. Around 13% of the emissions would be located along other European regions. The case of other regions and countries, such China, deserves also some attention. China is nowadays one of the main primary suppliers, and a multi-regional model should be able to track its relevance. As we could expect, any increase in the final demand of goods and services in Europe might have some consequences in China, and this is also the case for the energy system in 2030. Around 8% of the total employment generated will be located in China. However, the value added remaining in the country is



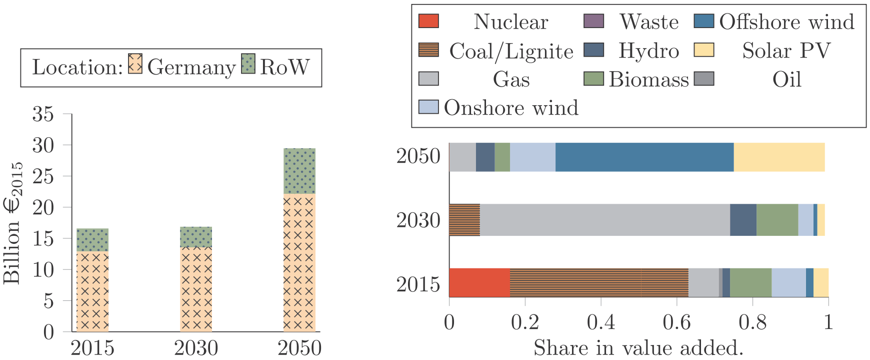
(a) Annualized system costs. (b) Share in costs for each technology.



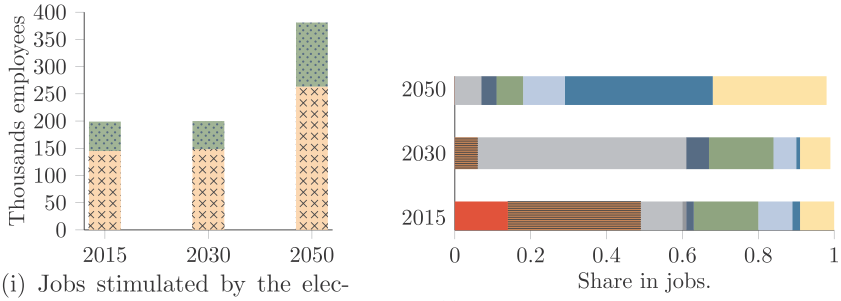
(c) Total CO$_2$ emissions. (d) Share in emissions for each technology.



(e) Primary energy use. (f) Share in energy use for each technology.



(g) Total value added. (h) Share in value added for each technology.



(i) Jobs stimulated by the electricity sector. (j) Share in jobs for each technology.

Fig. 3. Results of the *urbs* models and the MRIO analysis for Germany.

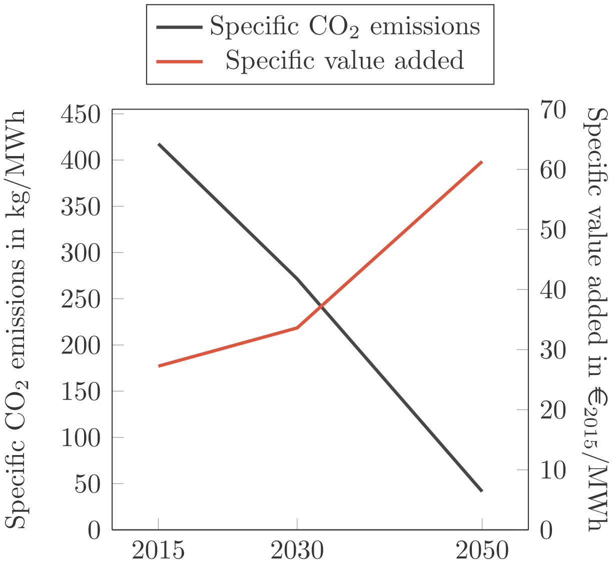


Fig. 4. Evolution of the specific CO_2 emissions and the specific value added per unit of power generated between 2015 and 2050.

very low (only 2%). This gives an idea about the economic structure of the country, meaning that the sectors being more stimulated have low productivity. In terms of CO_2 emissions, 7% of the indirect emissions would be located in China. This effect is known as *carbon leakage*.

The effects of decarbonization can be analyzed by comparing the specific CO_2 emissions and the specific value added, even if we include carbon leakage. Decoupling economy growth and CO_2 emissions seems to be feasible through an economically optimal energy system. Results suggests that a reduction of CO_2 emissions might not slow down the growth of the economy, by creating new opportunities that contribute to the generation of value added and employment, as can be seen in Fig. 4. It is necessary to remark that our analysis focuses on the effects derived only by one sector. A rippling effect would be expected along the whole economy, so that an analysis for the whole German economy should also go in a similar direction. Nevertheless, other aspects, such as rebound effects and substitution effects might also play an important role and should be further investigated.

4. Conclusions and discussion

This study has two main achievements: the first on the methodological level, and the second on the application level. Regarding the methodology, we successfully linked the outputs of an optimization model of the electricity system of Europe to an extended Multi-Regional Input-Output model. The combination takes advantage of the strengths of both models (high technical resolution for the optimization model, and geographic and sectoral coverage for the MRIO) to provide different perspectives on the electricity system of Germany in the mid and long term. The results go beyond the technical aspects to also address environmental and economic repercussions on other sectors, whether in Germany or in other countries. The method is faster and less data-intensive than detailed computable general equilibrium models with high technical and temporal resolutions, and complements the techno-economic optimizations with the environmental and socioeconomic dimensions. It is also flexible, because the list of modeled technologies can be easily adapted to the region of interest. Even though the MRIO analysis has been only carried out for the electricity sector in Germany, the method is reproducible and can be applied to all the European countries which are modeled.

There are at least three limitations when applying this method. First, the model linking is only valid if the electricity system optimization is conducted on an almost autarkic system, i.e. if the electricity trade with other regions is considerably lower than the energy generated locally. This is because electricity imports are not included in the final demand in MRIO. Second, one major limitation from the side of the MRIO is related to the staticity of the database. In this study, we alleviated this problem by adjusting the specific CO_2 emissions and energy use for each year. However, other parts of the global economy were not changed, even though they will not remain constant until 2050. Limitations also arise from the fact that the linking is conducted as an *ex-post* analysis, where the results of the optimization cannot be altered anymore. If a feedback effect is desired, where the MRIO analysis adjusts the optimization targets and is affected by it, we obtain a multi-objective analysis that relies on a hard-linking of the models. This type of analysis was out of the scope of the study due to its higher complexity and might be tested in the future.

The second achievement concerns the outcomes of the analysis of the German electricity system. The study provides a detailed impact assessment of the mid and long-term decarbonization targets. Hence, the contribution of each technology to the energy mix, system costs, total CO_2 emissions, primary energy use, job creation, and value added are assessed to obtain a more holistic and nuanced view. The obtained results validate the idea of decoupling the economy growth from CO_2 emissions through the deployment of an optimized energy system. The results also show that, especially in the mid-term, the decarbonization can be achieved by phasing out coal and lignite power plants and replacing them with gas-fired power plants, without a dramatic increase of system costs and without net job losses. We believe that this analysis can support policy-makers in assessing the consequences of their policies from a national, regional and global perspective, and it can provide substantiated arguments for them when they reach out to a wider audience.

Since the focus of the study was the implementation of the method and displaying its capabilities, the future scenarios were defined in a simple way by only taking into account the direct CO_2 emissions constraints. However, there is a lot of uncertainty regarding the future electricity demand, which may increase significantly due to sector-coupling. Nevertheless, the method can be applied on other scenarios to conduct a thorough analysis of a future electricity system characterized by a high degree of sector-coupling. Uncertainty affects also the parameters in the energy system models, and as the sensitivity analysis on the cost assumptions for wind, solar and batteries has shown, the results are sensitive to the costs of PV and batteries. The changes will be reflected in the results of the MRIO according to the shares of the technologies. For future applications where the quantitative impacts of the decarbonization need to be determined more accurately, we recommend using scenarios that vary different parameters for which the energy system models are sensitive.

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