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343
2020
November 2020
(Revised May 2021)

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ifo INSTITUTE
Leibniz Institute for Economic Research
at the University of Munich

Imprint:

ifo Working Papers
Publisher and distributor: ifo Institute – Leibniz Institute for Economic Research at the University of Munich
Poschingerstr. 5, 81679 Munich, Germany
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ifo Working Paper No. 343

Costs and Benefits of Political and Physical Collaboration in the European Power Market*

Abstract

We conduct a hybrid scenario exercise to analyze decarbonization pathways and related distributional effects within the European power market. The cross-impact balance analysis reveals narratives that differ in the level of political (stringency of climate policy) and physical collaboration (expansion of interconnectors). Applying a CGE model and two power market models, we quantify the impact of the two dimensions on CO_2 emissions, abatement cost, and electricity prices. The most collaborative future (176 EUR/t CO_2 in 2050, unrestricted expansion) delivers highest CO_2 emissions cutbacks, lowest abatement costs, and moderate prices. The least collaborative one (44 EUR/t CO_2 in 2050, no expansion) leads to stagnating emissions, highest costs, and lowest prices. In all narratives, countries at the periphery of the European market experience lower prices and abate more, whereas prices are higher and abatement lower in central and Southeast Europe. Price dynamics across narratives vanish when normalizing prices with country-specific GDP per capita, opening interesting insights when evaluating distributional effects of Europe's decarbonization efforts.

JEL code: C61, C68, Q40, Q41

Keywords: Hybrid scenario analysis, CGE modeling, energy system modeling, power market modeling, collaboration, decarbonization, energy transition, distributional effects

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1. Introduction

Imminent climate change due to massive carbon emissions demands for prompt actions. Incumbent firms and new investors need to redirect capital from emission-intensive into cleaner sectors. Policy makers enforce those actions by seeking to internalize the social costs of carbon using carbon taxes, quantity targets such as the European Union emission trading system (EU ETS), direct subsidies for clean technologies, or implicit fostering of renewable expansion through (the subsidization of) transmission grid expansion. However, current policies lag behind the proposed ambitions and estimates suggest that a business-as-usual will not deliver the targeted emission reductions. Moreover, countries even disagree about decarbonization targets and how to achieve them due to diverging national interests with regard to climate change, consumer prices, and the expansion of climate-friendly infrastructure.

Given this context, this paper analyzes decarbonization pathways of the European power market considering different levels of political and physical collaboration. We conduct a hybrid scenario exercise to obtain a better understanding between environmental-energy-related dynamics and social, political, technological, and economical context developments. We further reflect sources of diverging national interest by focusing on distributional impacts, that is, country-specific costs and benefits of the resulting decarbonization pathways.

Scenarios are a formalized way to make statements about possible future development paths using knowledge from the present and insights from the past. Qualitative scenarios are largely based on verbal descriptions of potential futures (e.g., O'Neill et al., 2017). Methods for developing such scenarios allow to consider a range of different social, political, technological, and economical parameters as well as their mutual interdependence. This way, the analysis can include softer and more diffuse concepts such as political stability or environmental awareness (e.g., Rothman et al., 2007).

Quantitative scenarios are computational-based and allow for numerical insight into the system under consideration. Alcamo (2008a) argues that quantitative approaches are more transparent than their qualitative counterparts, because their model assumptions are expressed as mathematical equations. Craig et al. (2002) in turn argue that implicit assumptions are necessary about human innovation and behavior, including social, institutional, and personal interactions.

Nevertheless, qualitative approaches and their combination with qualitative ones have gained momentum in recent years (e.g., Kriegler et al., 2014, O'Neill et al., 2017, Schweizer and O'Neill, 2014). Alcamo (2008a) combines qualitative and quantitative scenario techniques, and argues that such story-and-simulation concepts are best for achieving the goals of a scenario analysis. Raskin et al. (2005) underline this argument by pointing out that the use of qualitative scenarios offers texture, richness, and in-sight, whereas a quantitative analysis offers structure, discipline, and rigor.[1] When it comes to environmental-energy dynamics, model-based (quantitative) scenarios deliver a precise assessment of the implications of related policies for possible future developments and transformation pathways (e.g., Zampara et al., 2016) and are thus still predominant in the field of environmental and energy research (e.g., Zampara et al., 2016, ENTSOE, 2020). However, multiple studies stress the need of new complex scenario techniques allowing the integration of environmental-energy dynamics with social, political, technological, and economical factors in a comprehensive manner (O'Neill et al., 2014, Moss et al., 2010, Kriegler et al., 2014, Trutnevyte, 2016), for example, by means of a macro-economic framework. This can be achieved by linking a landscape of models with a scenario (e.g., Trutnevyte et al., 2014). Alternatively, another option is the soft-linking of energy market with macro-economic models, which allows for an in-depth analysis of effects such as changes in the global trade of energy resources, regional energy demand, or population growth (Martinsen, 2011, Andersen et al., 2019, Lee et al., 2020). However, linking of energy market and macro-economic models is challenging due to their diverging system boundaries and overlaps. Moreover, a number of studies highlight the significance of qualitative aspects that cannot directly be depicted by quantitative modeling frameworks (Schweizer and Kriegler, 2012, Alcamo, 2008b). Yet, many studies tend to disregard such context aspects, like changes in the social dimension (Grubler et al., 2018) that usually are found in the underlying narrative.

There are many methods for generating qualitative scenarios (Börjeson et al., 2006, Bradfield et al., 2005, Bishop et al., 2007), but the cross-impact balance (CIB) analysis (Weimer-Jehle, 2006) is particularly suitable for generating qualitative scenarios with environmental-energy dynamics. The CIB analysis follows an explorative approach (Börjeson et al., 2006), discovering possible future developments without defining specific paths or normative objectives. Weimer-Jehle et al. (2016) demonstrate the ability of the method to deal with a heterogeneous input data set—such as it is the case when it comes to environmental-energy dynamics—to make the context uncertainty of such scenarios tangible. Additionally, Schweizer and Kriegler (2012) show retrospectively, by means of the CIB analysis, that not all underlying scenar-

[1] Neither Alcamo (2008a) nor Raskin et al. (2005) commit themselves to a specific procedure in their observations, but various approaches and terms address this challenge, such as shared socioeconomic pathways (O'Neill et al., 2014), integrated scenarios (O'Mahony, 2014), hybrid scenarios (Hourcade et al., 2006), or narratives to numbers (Kemp-Benedict, 2013).

ios of the IPCC's Special Report on Emissions Scenarios achieve complete internal consistency.

We thus apply the CIB analysis to develop qualitative scenarios for European decarbonization pathways with a focus on power markets considering the social, political, technological, and economical context developments. We find 44 key system elements and consider the most relevant 22 elements (*descriptors*) and their mutual dependencies to generate 16 scenarios that are grouped to analyze three divergent narratives. The macro-economic computational general equilibrium (CGE) model PACE quantifies some of the descriptors (e.g., fuel prices). Those quantified descriptors are used with further descriptors from the narratives to calibrate the two power market models EUREGEN and urbs to assess the development of the European power market until 2050.[2] The coupling of the CGE model with the power market models via the CIB analysis ensures the consistency of the described context and adds one new, research question-tailed way of ensuring comprehensiveness of hybrid scenarios to the literature.

We identify two pivotal differences between the resulting narratives that cover two different dimensions of collaboration. The first dimension is political collaboration in terms of the stringency of the European climate policy. The second dimension is physical collaboration within the European power market in terms of allowed transmission grid expansion between countries. The most collaborative narrative (called "Towards a green revolution", *GREEN*) leads to high CO_2 prices (176 EUR/t in 2050) and unconstrained expansion of transmission lines between countries from 2035 onwards. The least collaborative narrative (called "Return of the nation state", *NATION*) leads to low CO_2 prices (44 EUR/t in 2050) and no transmission grid expansion from 2035 onwards. "Stagnation of the EU" (*EU*) delivers the middle way with 132 EUR/t and transmission grid expansion in line with a 25% interconnectivity target from 2035 onwards.

We then analyze the impact of the two dimensions of collaboration on the resulting technology mix, abatement, related costs, and electricity prices. We thereby focus on differences in costs (e.g., higher system costs) and benefits (e.g., higher CO_2 abatement) between narratives as well as between European countries to identify winners and losers of the aimed transformation and decarbonization pathways.

Section 2 introduces the CIB analysis, used model frameworks, and describes the coupling of CIB analysis and models. Section 3 introduces the narratives and Section 4 describes the translation of CIB outputs into models. Section 5 presents modeling

[2] We decide for the two models due to their fundamental difference in handling investment decisions.

results and Section 6 the synthesis of narratives and modeling results. Section 7 concludes by deriving policy implications.

2. Method

2.1. CIB analysis

The CIB analysis assesses interactions between the defined system under investigation within the defined time horizon and social, political, technological, and economical context developments. The CIB analysis belongs to the family of cross-impact methods, where the probabilities of an event can be influenced by the occurrence of other events. Classical cross-impact methods require experts providing information on conditional probabilities, related probabilities of event pairs, or marginal probabilities (Weimer-Jehle, 2006). Weimer-Jehle (2006) introduced the CIB analysis to overcome the problem that the human mind is ill-equipped to provide such probabilities and that experts are expected to possess insights which rather should be the results of an analysis.

The cross-impact matrix (CIM) at the core of the CIB analysis (Gordon and Hayward, 1968) describes the system under investigation and provides a systematic depiction of relevant descriptors, their possible future developments (*variations*), and their mutual interdependence (*cross-impacts*). The morphological box of descriptors and their possible future states creates a space of thousands to billions of configurations (Weimer-Jehle et al., 2020). In contrast to the original cross-impact methods, the CIB analysis does not rely on assessments about probabilities of cross-impacts described by the CIM. Instead, it uses a rating system that identifies whether a certain development has a promoting or restricting influence on the occurrence of another development.

2.2. Model frameworks

We apply three frameworks to quantify the narratives from the CIB analysis: a CGE modeling framework and two power market models. The time horizon for all frameworks goes in five-year steps from 2015 to 2050 and the geographical resolution comprises 28 countries within the European power market (EU-27 without the island states of Cyprus and Malta, including the United Kingdom, Norway, and Switzerland). The power market models neglect all remaining countries (of the world), but the CGE framework groups all of them into one region and accounts for interactions of that rest-of-the-world region with the respective 28 countries.

The CGE framework. The CGE model PACE is a dynamic-recursive top-down multi-sector and multi-regional model (Böhringer and Löschel, 2006). It features ten economic sectors, including primary and secondary fuels, energy-intensive goods, manufactured goods, and services. Each country or region is depicted by a representative agent. The agent's production function applies the inputs capital, labor, and energy. In the case of intermediate goods, the output is fed back into production. Final output is either consumed by the representative agent, or traded internationally by using Armington elasticities. The model is calibrated for 2014 using the Global Trade Analysis Project (GTAP 10) database. The business-as-usual (BAU) relies on projections for GDP, energy demand, CO_2 emissions, and international fuel prices from the Joint Research Center of the European Union, Institute for Prospective Technological Studies (JRC-IPTS).

The power market frameworks. EUREGEN (Weissbart and Blanford, 2019) and urbs (Dorfner et al., 2018) are two different but representative power market optimization models. Both models optimize dispatch and capacity expansion (generation, storage, transmission) within the European power market. They differ with regard to foresight: EUREGEN optimizes intertemporally, whereas urbs optimizes myopically using a rolling horizon. Within this paper, we harmonize the handling of a joint input database that reflects the quantitative and qualitative descriptors of the developed narratives. We also harmonize the handling of general features that tend to impact results, but we keep specific features that are crucial for the respective modeling framework. The most important ones are the temporal resolution, endogenous decommissioning, and discounting of cashflows. EUREGEN applies an algorithm for choosing and weighting time steps to reduce the temporal complexity, whereas urbs uses 672 heuristically-chosen time steps. Both models scale the time series so that total demand by region and full-load hours of wind, solar, and hydro technologies are consistent with hourly values. Additionally, EUREGEN can decommission capacities endogenously and discount cashflows, which are important features for intertemporal optimizing models.

2.3. Model coupling

A thorough review of relevant literature and an assessment of the market structure give a comprehensive overview of the fundamental elements of the European power market. We identify 44 key system elements at three workshops and via a questionnaire with 24 experts with varying professional backgrounds working in the field of energy economics. Appendix A contains a more detailed description of the process for conducting the CIB analysis. The workshops result in the selection of 22 descriptors that cover four key categories (social, political, technological, economical) and their respective interactions. A detailed characterization of those descriptors is given in Appendix B.

Figure 1 shows the connecting structure between the CIB analysis, the CGE model PACE, and the power market models EUREGEN and urbs. Relevant descriptors for the CGE model, the power market models, as well as context descriptors are shown on the left. The CIB analysis is presented by the CIM that comprises different variations of descriptors and assessment ratings of cross-impacts between them. The results of the evaluation of the CIM are incorporated into scenarios (1), which differ in variations of descriptors. In the scenarios, there are descriptors that are directly placed into PACE (2), others that are directly placed into the power market models (3), and a third group of descriptors that are placed in both frameworks (4). Finally, the data flow (5) describes (quantitative) outcomes from PACE that are used as inputs in the power market models.

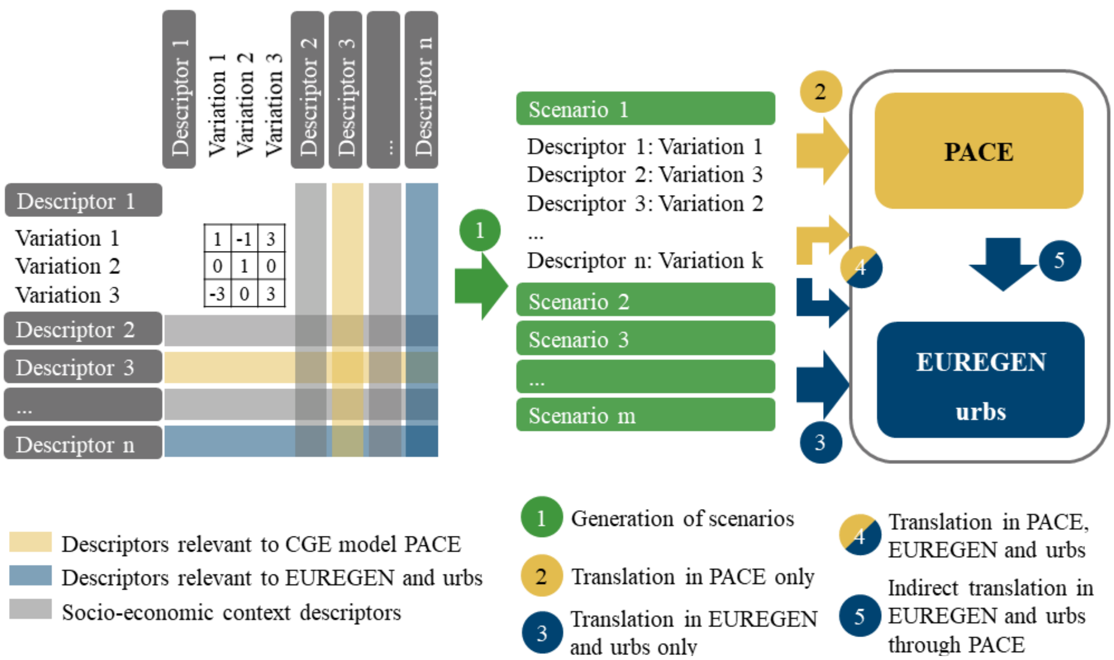


Figure 1: Linking process of CIB and modeling frameworks

3. Narratives

Our CIB analysis yields 16 scenarios that are grouped into four narratives: stagnation of the EU (referred to as *EU*), dash for gas (*GAS*), towards a green revolution (*GREEN*), and return of the nation state (*NATION*). Figure 2 shows the landscape of scenarios and their corresponding narratives with key descriptors in a two-dimensional space. For this, the narratives are interpreted as vectors with the length equal to the total number of descriptors and values corresponding to the effective variation of the descriptor. The figure is the graphical representation of the correspondence analysis (CA) map, which is a statistical technique for representing tabular categorical data graphically and analyzes frequencies formed by categorical data represented in the form of the contingency table (Nenadic and Greenacre, 2007). The position of each point along two dimensions—Dim1 on the x-axis and Dim2 on the y-axis—can be interpreted as a measure of dissimilarity between the plotted points. The percentages indicate the amount of variance explained along each dimension. Distances between the displayed points in the graph do not have a particular interpretation, but the relative position of the points do so. This presentation allows us to see the groups of scenarios that have the common overall message, but are divergent in some descriptors or aspects of the future, respectively. For example, the clusters *GREEN* and *NATION* are quite close regarding Dim2, which explains 33.8% of the data variance. Dim1 in turn presents 63.2% of data variance and thus distinguishes the two contrasting clusters. Conversely, the clusters *GAS* and *EU* are almost the same concerning Dim1 but Dim2 separates them from each other, although they remain quite similar. A complete representation of the scenario landscape with all descriptors and variations is given in Appendix C. In the following, we analyze the narratives *EU*, *GREEN*, and *NATION* in detail. The narrative *GAS* is not discussed further because it delivers very similar results to the narrative *EU* when used in the power system models (observe their proximity in Figure 2).

Scenarios within the identified clusters show only minor deviations, providing ancillary accents to the clustered paths. We give an overview of the most important descriptors of the three narratives under closer investigation in Table 1. Appendix D presents the full lists of descriptors and narratives.

A closer look at the narratives reveals that an essential distinguishing feature lies in two dimensions of collaboration, namely political and physical. Political collaboration also includes aspects of economic collaboration on common European energy and climate policy objectives. The physical dimension of collaboration describes the creation of the infrastructure necessary to achieve these objectives. The descriptor "*Cooperation* in Europe" (D20) has one of the leading active cross-impacts: It determines variations of other descriptors and forces differences in the narratives by the degree of political and physical collaboration between the countries. The three analyzed narratives can be characterized as follows:

Stagnation of the EU. European cooperation in both the political and physical dimension is stagnating due to institutional and bureaucratic hurdles. This develop-

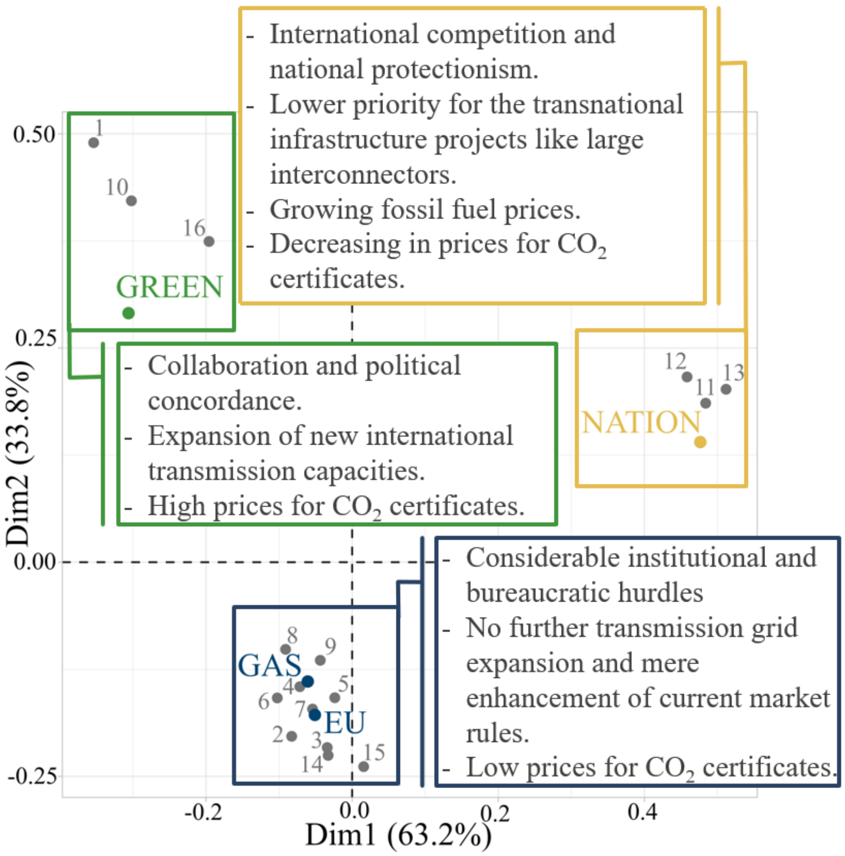


Figure 2: Landscape of scenarios (1–16, in gray) and key differences. The percentages for each dimension Dim1 (63.2%) and Dim1 (33.8%) indicate what proportion of the variance in the data is explained along each axis. Overall, 97% of the variance is explained by the two dimensions.

ment leads to an unfavorable environment for large European-wide infrastructure investments in the energy sector.

Towards a green revolution. International relations are characterized by a collaborative effort to jointly solve the challenges of a transformation towards a carbon-neutral power system. Therefore, strategies at the European level to achieve climate targets are preferred to those at the country level.

Return of the nation state. There is a substantial shift away from the idea of the EU as a super-ordinate body for jointly addressing existing challenges. Strategies for decarbonization of the power sector are preferably sought at the country level, and national energy self-sufficiency is preferred to international strategies.

Table 1: Selected descriptors in the three narratives

No	Descriptor	Stagnation of the EU	Green revolution	Return of the nation state
D1	Specific investment costs (generation and CCS)	Moderate decrease -0.57	Moderate decrease -0.57	Weak decrease -0.21
D2	Grid infrastructure	Moderate transmission grid expansion	Further grid expansion	No further transmission grid expansion
D3	Incentives for RES	Weak policy incentives for RES	Weak policy incentives for RES	Strong policy incentives for RES
D4	Consumer behavior	Raising the level of individual consumption	Raising the level of individual consumption	Sharing economy becomes popular in Europe
D5	CO_2 prices	Low increase in CO_2 prices	High to a significant increase in CO_2 prices	Diminishing trend or low prices from 2017 prevail until 2040
D14	Global economic cohesion	Trend for bilateral/supranational cooperation	Trend for bilateral/supranational cooperation	Trend towards national protectionism and international competition
D15	Natural gas prices	Natural gas independent on oil: low prices	Natural gas independent on oil: low prices	Natural gas dependent on oil: high prices
D16	Coal prices	Stable prices (+0%/year)	The trend towards low prices	High coal price (+2.5%/year)
D20	Cooperation in Europe and political culture	Non-regulatory approach (autarky)	Full harmonization approach	Non-regulatory approach (autarky)
D21	Agriculture for the power sector	The growth of bioenergy production is maintained	Lower growth of bioenergy production	The growth of bioenergy production is maintained

4. Translation of descriptors into models

Addressing the specific calibration process of CGE models, PACE is set up to a business-as-usual (BAU) scenario that covers all EU climate policies as currently implemented and all major macroeconomic developments as projected by JRC-IPTS. In BAU, PACE estimates a CO_2 price of 88 EUR/t in 2050. For the implementation of the CIB narratives, CO_2 prices are treated as exogenous input parameters. Some other relevant factors (e.g., changes in GDP development or changes in electricity demand) are not directly implemented into PACE, because they strongly deviate from the *BAU* as described in JRC-IPTS future trends. Table 2 provides an overview of the descriptors which are translated into PACE and the corresponding way of implementation.

Table 2: Translation of descriptors in PACE

No	Descriptor	Implementation
D2	Grid infrastructure	Increase or decrease of Armington elasticities between domestic and imported electricity
D3	Incentives for RES	Adjustment of capital subsidies for electricity generation from RES
D5	CO_2 prices	Direct implementation of CO_2 price variations
D9	The focus of R&D	Changes in autonomous energy efficiency index for respective technologies
D14	Global economic cohesion	Variation of import tariffs in relation to *BAU*
D19	Energy sources and available reserves	Adjustment of national endowments of natural gas and coal in comparison to *BAU*

For each narrative, PACE gives a consistent collection of region-specific fuel prices, trade flows of energy resources, and sector-specific energy demand. However, PACE does not have a comprehensive bottom-up representation of the power sector. EUREGEN and urbs close that gap in a second step. The results from PACE are used as input for the power market models, which quantify descriptors characterizing different market regulation regimes, technology-specific investment costs, and, in particular, interconnectivity targets that cannot be directly considered in PACE. Table 3 summarizes descriptors that are directly translated into EUREGEN and urbs.

We apply different translation approaches due to the diverging model structures, that is, bottom-up (power market models) vs. top-down (CGE model), technological aggregation, and varying system boundaries. As can be seen from Tables 2 and 3, there are overlaps of descriptors which are translated into PACE as well as into the power market models EUREGEN and urbs (D2, D5). We translate the development of the European power grid structure (D2) only implicitly in PACE by adjusting the respective Armington elasticity. The power market models in turn consider installed and planned transmission capacities between countries as exogenous inputs and upper values that leave space for each model to optimize trade capacities. The outcome from the CIB analysis regarding CO_2 prices (D5) shows fundamental devi-

Table 3: Translation of descriptors in power market models

No	Descriptor	Implementation
D1	Specific investment costs	Direct implementation
D2	Grid infrastructure	Upper- and lower bounds for the model endogenous expansion of NTCs
D5	CO_2 prices	Direct implementation
D6	Perception of nuclear power	Adjustments of risk premiums for the expansion of nuclear power
D12	Perception of CCS	Adaptation of the available CCS potential
D17	Land use policy	Adaptation of the available potentials for renewable energy sources
D21	Agriculture for the power sector	Changes in bioenergy potential

ations from the *BAU* scenario price calculated by PACE (88 EUR/t in 2050). We therefore translate the variations from the CIB analysis as relative changes, so that 2050 prices are twice as high in *GREEN*, 50% higher in *EU*, and 50% lower in *NATION*. The resulting PACE prices in turn are implemented as exogenous inputs in EUREGEN or urbs, respectively.

Next, the adjustment of energy sources and available reserves (D19) in PACE leads to consistent gas and coal prices (D15, D16). Those consistent prices are directly implemented in the power market models. Moreover, PACE is not able to consider technology-specific investment costs of the respective technologies (D1). We thus connect PACE and D1 via descriptor D9 ("The focus of R&D"), that is, decreasing costs follow from higher focus on R&D. The power market models implement the investment costs directly but neither EUREGEN nor urbs are able to reflect the focus of R&D. This dual implementation strategy ensures that the modeling results of the two different frameworks remain as congruent as possible within the analyzed narratives.

Finally, the CIB outcome considers climate change impacts on general welfare and distributional effects within the population. In contrast, the PACE utility function neither accounts for climate damages from carbon emissions nor disutility arising from inequality. As a consequence, the CIB analysis predicts lowest welfare for *NATION*. The implementation of low CO_2 prices in that narrative in turn overrules other modeled aspects, so that the PACE model calculates highest GDP in a returning *NATION* state. Low CO_2 prices and resulting higher emissions do not hamper productive capital or come with a damage (as it is the case in integrated assessment models with climate modules). Additionally, welfare is mainly driven by (electricity) demand (in our field of investigation). Thus, high welfare implies high electricity demand in the CGE model, which contrast the results from the qualitative scenarios resulting from the CIB analysis. To make CIB and PACE outcomes comparable, we therefore aim for equalizing GDP across narratives in PACE, also resulting in quite similar electricity demand. Higher carbon emissions must then be interpreted as lower welfare (higher carbon damages) and lower ones as higher welfare. Such interpretation of results and translation strategies ensure consistency between CIB outcome and PACE modeling results.

5. Modeling results

This section provides an overview of the implications of the narratives for the future development of the European power market, followed by the implications of cooperation at the level of individual countries. We will first look at the development of aggregated carbon emissions, overall installed generation capacity, and international electricity transfers in Subsection 5.1 as well as abatement costs at European level in Subsection 5.2. The following Subsections 5.3 and 5.4 analyze CO_2 abatement and electricity prices at regional level, respectively. To complete the picture and to avoid distortions caused by different GDP levels within Europe, we present GDP-adjusted electricity prices in Subsection 5.5.

5.1. European decarbonization pathways

Figure 3 shows the development of CO_2 prices (dotted lines, left axis), and CO_2 emissions (solid lines, right axis) for PACE (on the left) and the two power market models (on the right). Observe that PACE delivers similar CO_2 emissions for *BAU* (gray) and the respective narratives *EU* (blue), *GREEN* (green), and *NATION* (yellow), although prices differ by a factor of four between *NATION* and *GREEN* (44 EUR/t vs. 176 EUR/t in 2050). EUREGEN and urbs, both of which depict electricity generation, storage, and transmission technologies in more detail, are more sensitive to CO_2 prices.

We first start by analyzing the power market outcomes in the *GREEN* narrative. In contrast to PACE outcomes, where emissions decrease continuously, emissions go up from 2020 to 2025 and then drop to a level slightly below the PACE values in 2050. EUREGEN decarbonizes a bit slower than urbs, but the 2050 values are very close. In the *EU* narrative, emissions also increase first, then drop until 2050 with similar values for EUREGEN and urbs. Here again, urbs decarbonizes a bit faster. The developments in the *NATION* narrative contrast completely with results

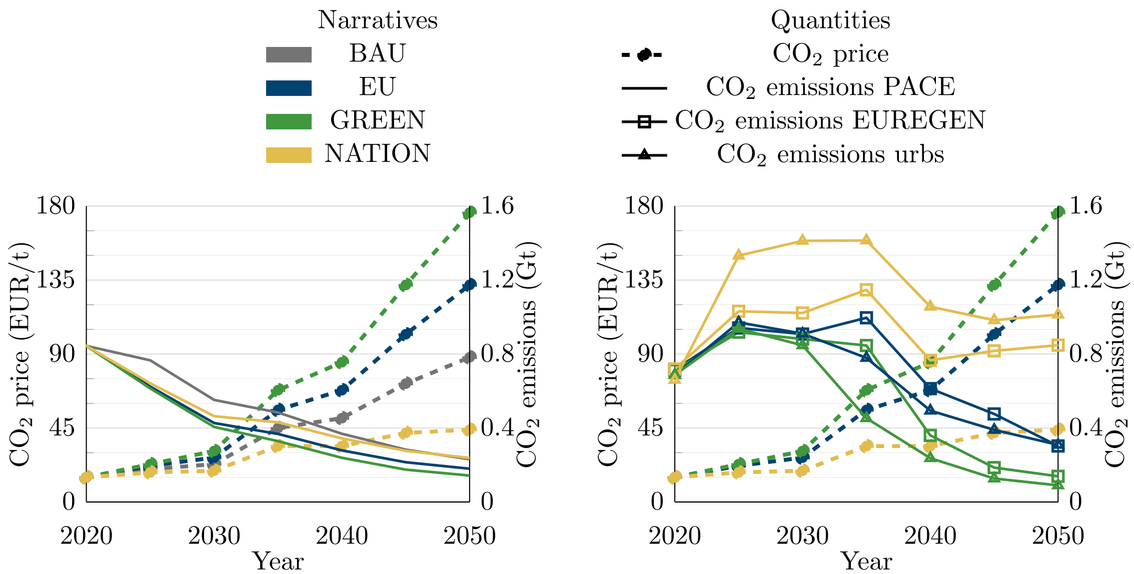


Figure 3: Price for CO_2 emissions and resulting CO_2 emissions in the European power sector for narratives *EU*, *GREEN*, and *NATION* according to PACE (solid lines without markers), EUREGEN (square markers), and urbs (triangle markers)

from the CGE model. Emissions increase until 2035, then slightly drop due to the introduction of higher wind turbines in 2040, to finally settle at a level higher than in 2020. Interestingly, EUREGEN decarbonizes more than urbs in this case. However, the discrepancies between the models can be traced back to differences in the model horizon (myopic vs. intertemporal, see Siala et al. (2020) for more detail).

The different decarbonization pathways reflect variations in the underlying power systems, particularly with regard to the shares of renewable energy technologies. Figure 4 compares the development of generation capacities of EUREGEN and urbs. Overall, the evolution patterns are similar across models. The total amount of installed generation capacities in Europe increases considerably with rising demand. A high price for CO_2 emissions, coupled with a decrease in specific investment costs for renewable energy sources, result in a sharp growth of solar and wind power in *GREEN*, substituting gas power in the system compared to the *EU* narrative. *NATION* shows a higher share of conventional and less of renewable capacities. Less ambitious climate protection targets hinder the expansion of CCS plants in *NATION* completely. In the other narratives, the expansion of CCS plants is small. Despite the ability of bioenergy CCS to “remove” CO_2 from the atmosphere, its expansion is constrained by strict bioenergy limits. Nevertheless, minor differences between the models exist. In *GREEN* and *EU* narratives, urbs installs more wind onshore and solar power, leading to lower carbon emissions. In *NATION*, urbs remains committed to the use of coal power, while EUREGEN phases it out entirely by 2035.

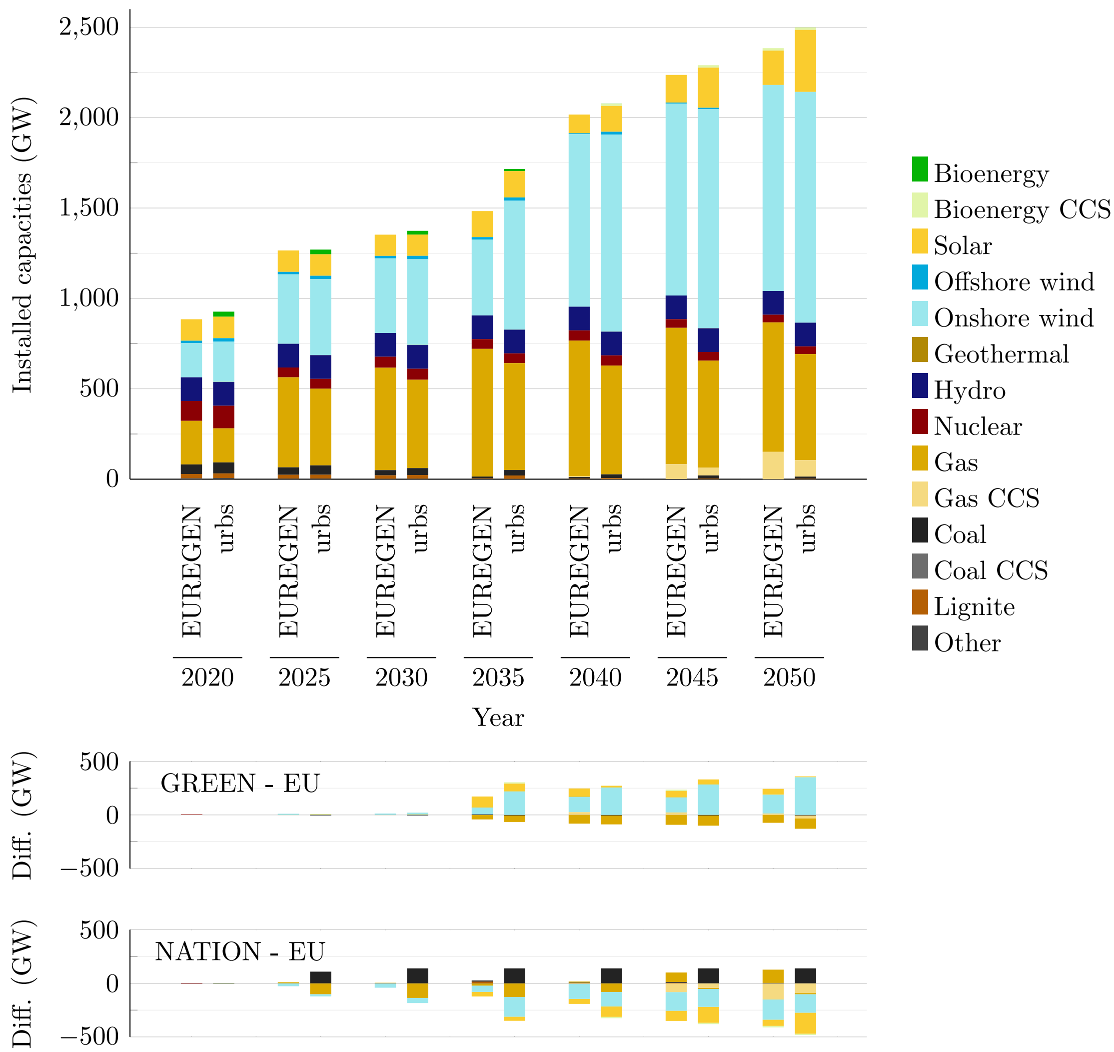


Figure 4: Installed capacity in *EU* (top), *GREEN* (middle), and *NATION* (bottom). Data for *GREEN* and *NATION* is shown as difference to *EU*

The two narratives *GREEN* and *EU* show a considerably higher expansion of generation capacities, particularly for renewable technologies, than *NATION*. Cross-country transmission lines foster the integration of wind and solar power by balancing the demand of one country with power supply from its neighbors which are endowed with better wind and solar resource potentials. Hence, it is interesting to compare the energy transfers between countries by narrative and model, as shown in Figure 5. Although the models have strikingly different absolute values of energy transfers, their qualitative development over time is similar. For all three narratives, transfers are the same until 2030, following the common 10-year network development plan (TYNDP). From 2035 onwards, a higher level of physical collaboration in *EU* and *GREEN* allows for the expansion of transmission lines. However, the 25% interconnectivity target in the *EU* narrative just leads to slightly higher transfers (in urbs) compared to *NATION*, where this target does not apply. The *GREEN* narrative allows for unconstrained transmission expansion, leading to a sharp rise in transfers from 2035 onwards. Thus, the models choose to harness solar and wind resources in the best locations in Europe and to rely on the high level of physical collaboration to transfer energy to the demand centers.

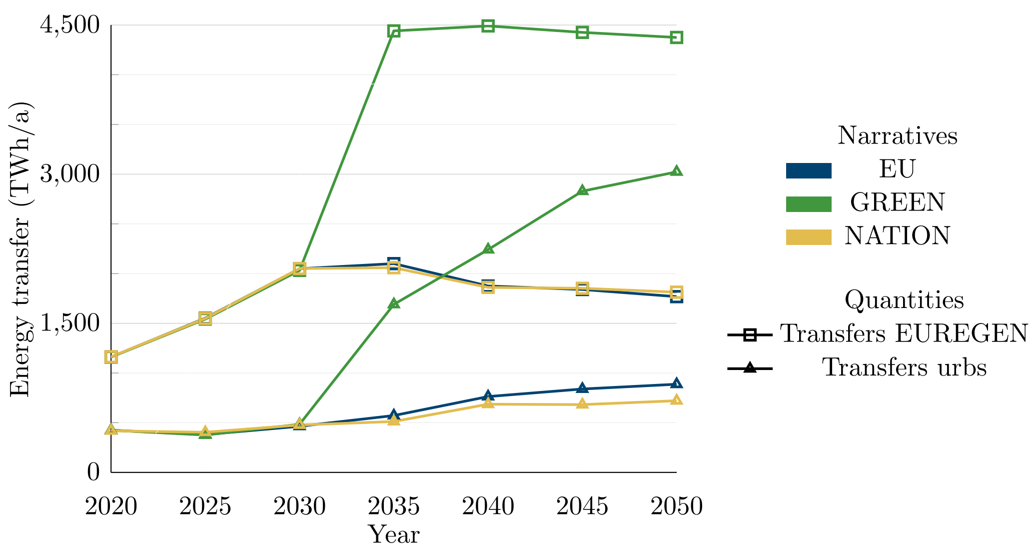


Figure 5: Total interregional energy transfers in the European power sector for narratives *EU*, *GREEN*, and *NATION* according to EUREGEN and urbs

5.2. Abatement cost

The overall level of CO_2 emissions and the underlying power system configurations in terms of technology mix and transmission connections are just one dimension of evaluating different possible futures of the European power market. We now turn our focus to the resulting cost by applying the abatement cost metric (equation (F.12)) from Appendix F.

The baseline CO_2 emissions in 2015, from the *BAU* scenario in PACE, amount to 994 Mt. Until 2050, urbs (EUREGEN) reduces that amount to 309 Mt (303 Mt) in the *EU* narrative, to 90 Mt (139 Mt) in *GREEN*, and even increases emissions to 1013 Mt (decreases to 848 Mt) in *NATION*. Using the abatement cost metric, we obtain the values as specified in Table 4. By design, this metric contains accumulated system cost as well as accumulated abatement over the entire model horizon (2015 to 2050), because CO_2 emissions impact climate change as stock. Thus, annual values provide only a snapshot of the transformation and are inadequate for reflecting the impacts of long-term investments.

Table 4: Abatement cost by narrative and model in EUR/t CO_2

Model	EU	GREEN	NATION
EUREGEN	313	271	378
urbs	296	245	559

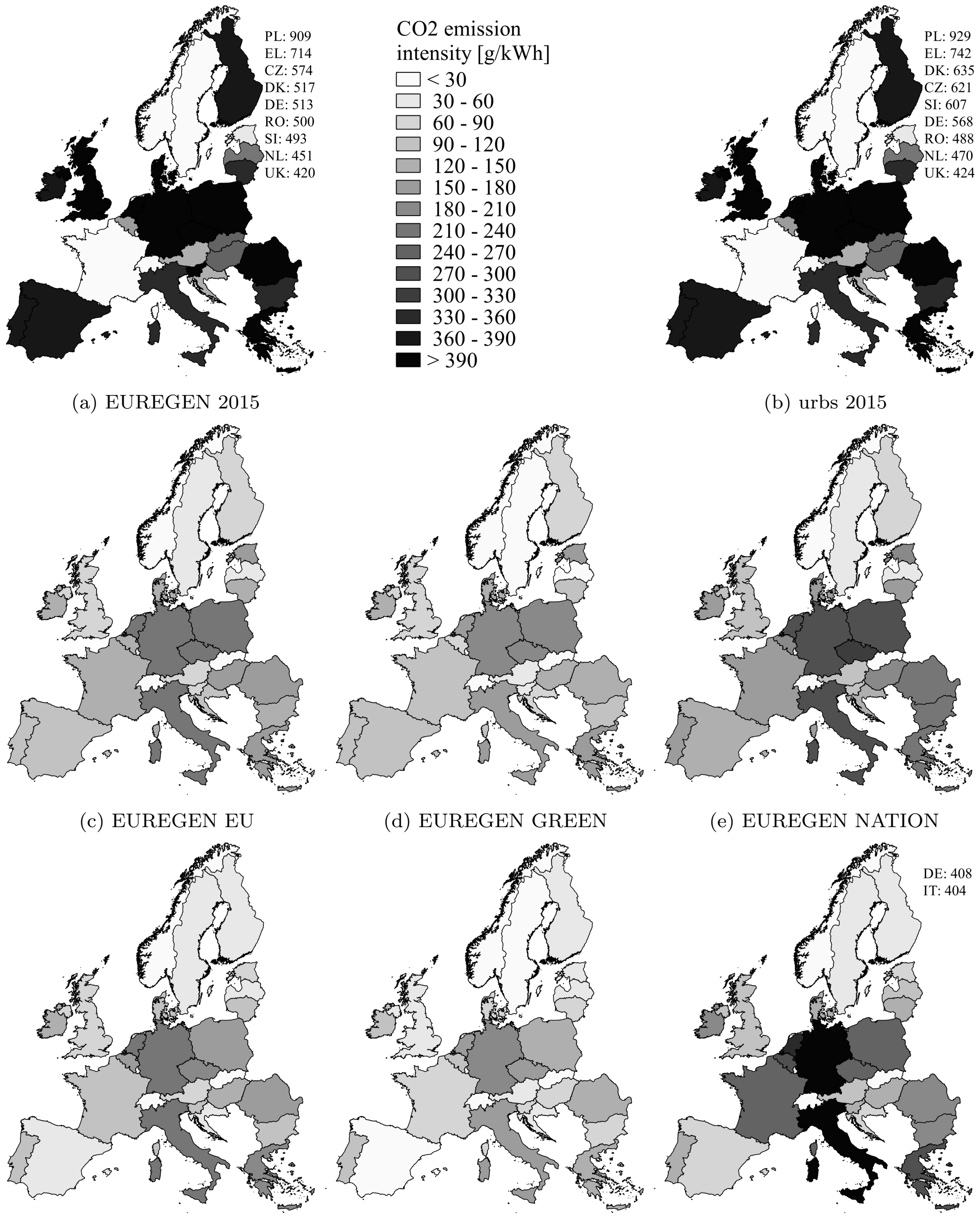
The cost of decarbonization in urbs is lower in *GREEN* and *EU*, but higher than EUREGEN in *NATION*, reflecting the evolution of CO_2 emissions. Despite the differences in *NATION*, both power market models predict similar results. The discrepancies are largely due to the different optimization approaches and the underlying time series of EUREGEN and urbs. In a recent paper, Siala et al. (2020) analyze the impact of myopic and intertemporal models under different CO_2 price trajectories by using the same calibration as here. They find that the myopic and intertemporal models are quite close under a price trajectory as depicted by the *EU* narrative because this trajectory does not change the profitability of wind and solar power resources, whereas it does when CO_2 prices are closer to the *NATION* trajectory. In particular, *NATION* leads to the expansion of coal power in some countries (see Figure 4).

Observe that the values reflect EUR/t CO_2 emissions abated, that is, how much the entire system spends to abate a certain amount of CO_2 emissions. Taking *EU* as the benchmark of medium collaboration in political and physical terms the differences to the other narratives indicate resulting costs and benefits of political and physical collaboration. The benefits from collaborating (*GREEN* narrative) are thus between 42 (EUREGEN) and 51 EUR/t CO_2 (urbs). The costs from not collaborating (*NATION* narrative) are much higher than the potential costs, i.e., between 65 (EUREGEN) and 263 EUR/t CO_2 (urbs). Results underline that the prospect of *NATION* states must be considered as more threatening than the possible benefits of a *GREEN* revolution in absolute terms, forcing participating countries into collaboration again.

5.3. Regional abatement

The European decarbonization pathways and related abatement cost just depict the uppermost level. An analysis at country-level shows who is actually bearing the burden of decarbonization. Figure 6 depicts CO_2 emission intensity at country-level (see equation (F.4) in Appendix F). The first line (two maps) presents 2015 values from EUREGEN and urbs. The middle line (three maps) presents outcomes for the three narratives in 2050 for EUREGEN and the lower line (again three maps) the same for urbs. Note that emission intensities above 390 g/kWh are shown separately to allow for a better contrast in the 2050 maps. Starting with 2015 values, Europe is mainly divided into two groups of countries with high (black) and low (white) emission intensities. For example, Poland is the most emission-intensive country in Europe in 2015, whereas Norway, Sweden, France, and Switzerland have almost zero CO_2 emissions from power generation. The emission-intensive countries rely heavily on coal, lignite, and natural gas to meet electricity demand. The countries with clean power systems have either high hydro potential (e.g., Norway), rely heavily on nuclear power (e.g., France), or do both (e.g., Switzerland). However, the business model of nuclear power is under stress in the future according to the three narratives. Most countries consider nuclear power as not economically viable anymore, leading to a reduced usage of it until 2050. As a consequence, France experiences an increase of its emissions in all three narratives.

Aside from the countries with clean power systems in 2015, which either stay clean or increase their emissions slightly, almost all other countries have a lower emission intensity by 2050 in all three narratives, even in *NATION*. In *EU* and *GREEN*, the countries at the periphery of the European market show the lowest emission intensities, whereas central Europe (e.g., Germany, Czech Republic, Poland) emits the most CO_2 per unit of energy. However, we cannot conclude that the well performing countries (those that reduce their emission intensity or keep it low) carry per se a higher burden of abatement than the low performing countries (those that increase their emission intensity (France) or keep it high). Sometimes, it might be in the interest of the country itself to decarbonize because of high quality wind and solar sites. We thus analyze how decarbonization pathways impact electricity prices in the next subsection to allow for a country-specific evaluation of costs and benefits.



(a) EUREGEN 2015 (b) urbs 2015

(c) EUREGEN EU (d) EUREGEN GREEN (e) EUREGEN NATION

(f) urbs EU (g) urbs GREEN (h) urbs NATION

Figure 6: CO_2 emission intensity for European countries over the period 2015–2050 across the three narratives *EU*, *GREEN*, and *NATION* according to EUREGEN and urbs

5.4. Electricity prices

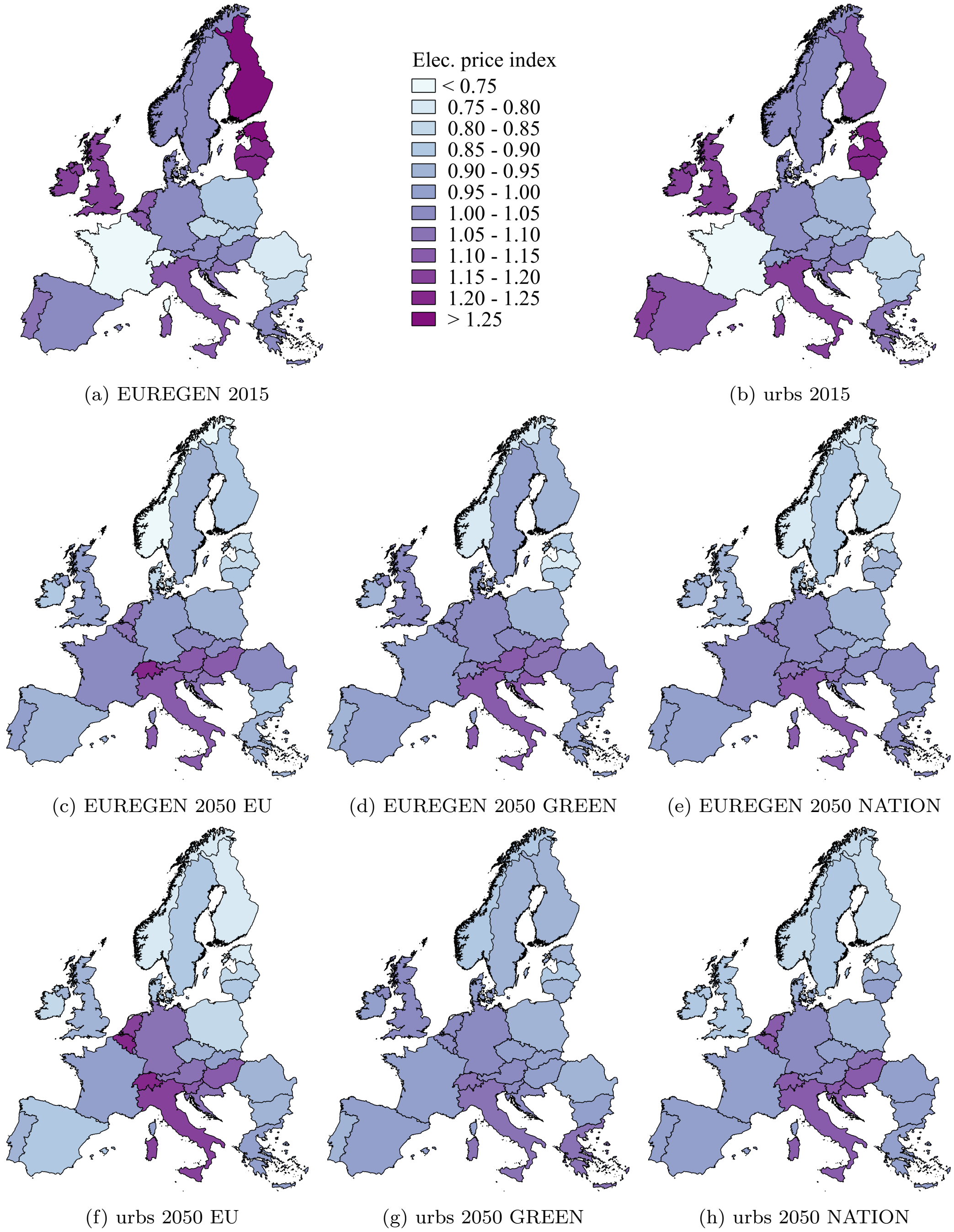
Electricity prices differ within Europe across narratives. Table 5 presents differences between narratives over time by showing the weighted-average of European electricity prices from 2015 to 2050 for the two power market models EUREGEN and urbs (see Subsection F.6 in Appendix F for the underlying metrics to calculate prices). Observe that prices are slightly higher in EUREGEN than in urbs (6% in 2015, 14 to 21% in 2050).

Table 5: European electricity prices by model and narrative in EUR/MWh

	EUREGEN			urbs		
Year	*EU*	*GREEN*	*NATION*	*EU*	*GREEN*	*NATION*
2015	37	37	37	35	35	35
2020	53	53	53	39	39	39
2025	60	60	59	46	46	45
2030	58	60	56	47	48	44
2035	70	75	63	55	57	49
2040	65	66	56	50	50	44
2045	68	66	60	56	53	46
2050	68	67	57	59	56	47

Differences between models can be traced back to model-specific features and the underlying temporal resolution. For example, EUREGEN allows for endogenous decommissioning of capacities, which increases prices in 2020 already. The differences decrease over time (for all three narratives) but remain substantial due to the selection of hours to represent the whole year. The hour choice and weighting algorithm of EUREGEN selects 112 representative hours to reflect the extremes of wind, solar, and load in each country of Europe, and weights them to reduce the error to the hourly time series. urbs selects 672 hours heuristically and weights them equally. As a consequence, the representation of hours in EUREGEN leads to higher prices than the specific selection of hours in urbs. Thus, we apply electricity price indices (referring to the respective European average of each model) in the following to compare regional differences of the models across narratives.

Figure 7 compares electricity prices within Europe in 2015 (maps in the first line) and their development in the three different narratives *EU* (left), *GREEN* (middle), and *NATION* (right) for the two power market models EUREGEN (second line) and urbs (third line). Prices are shown as index as described by equation (F.18) in Appendix F, that is, an index value of 1 means that a country has exactly the European average price.



(a) EUREGEN 2015 (b) urbs 2015

(c) EUREGEN 2050 EU (d) EUREGEN 2050 GREEN (e) EUREGEN 2050 NATION

(f) urbs 2050 EU (g) urbs 2050 GREEN (h) urbs 2050 NATION

Figure 7: Electricity price index for European countries in 2015 and 2050 across the three narratives *EU*, *GREEN*, and *NATION* according to EUREGEN and urbs

Start with analyzing 2015 values of urbs (first line, right). Observe that countries at the periphery of the European market experience high prices, Eastern Europe low prices, and France the lowest prices in 2015. Ireland, the United Kingdom, Portugal, Italy, and the Baltic region have prices that are more than 20% higher than the European average. The Benelux region, Spain, and Finland are also expensive with prices more than 15% higher. Also Greece and Croatia are more expensive than neighbouring countries. EUREGEN (first line, left) match the general findings that electricity in countries at the periphery of the market is more expensive, cheaper in Eastern Europe, and the cheapest in France. However, note that France is an outlier due to its initial endowment with nuclear capacity whose past investment cost are not reflected in prices.

Now turn to 2050 values in the *EU* narrative (second and third line, left). Both models now deliver even closer values. Interestingly, the pattern of electricity prices is flipped. Electricity in Norway, Finland, and Estonia is now the cheapest. Belgium and Switzerland (which has similarly cheap electricity as France in 2015 in EUREGEN) become the most expensive countries. France now reaches the European average, as do Portugal and the United Kingdom. Electricity in Italy is already quite expensive in 2015 and remains so in the future.

The maps in the middle show results for the *GREEN* narrative (highest CO_2 prices, unconstrained transmission expansion from 2035 onwards). The expansion of transmission lines in general reduces price differences between countries. No region experiences prices that are 25% above or below the European average. Central Europe, Italy, and the United Kingdom still experience the highest prices. Switzerland, Austria, and Norway play an interesting role because those countries have the highest (pumped) hydroelectric potentials in Europe. Better interconnectivity increases prices for Norway but decreases those of Switzerland and Austria. However, the tendency that central Europe, Eastern Europe, and Italy experience the highest prices holds true in this narrative.

Finally, the maps on the right show electricity prices from the *NATION* narrative (lowest CO_2 prices, no NTC expansion after 2030). Observe that in this narrative—which is the complete opposite to the *GREEN* narrative—price differences also converge over time and remaining differences are quite similar to the *GREEN* narrative. There are slightly higher prices in some countries at the periphery such as Portugal, but prices tend to be similar or even lower. Differences are also smaller because less stringent decarbonization requirements (CO_2 prices are just 44 EUR/t in 2050) allow countries to optimize systems similarly, so that there is less reliance on the existing resource potentials.

Regional differences can be traced back to country-specific resource potentials (wind, solar, hydro, pumped hydro), the initial endowment with generation capacities (mainly coal and nuclear power plants), and the location within the European power market. The location is particularly important because cross-country transmission capacity is restricted physically.

5.5. GDP-adjusted electricity prices

Comparing absolute values does not reflect the reality in Europe because countries differ in their GDP per capita (see Tables E.2 and E.3 in Appendix E for current estimates and projections until 2050 from the PACE calibration). Figure 8 thus resembles Figure 7, but the index now refers to prices that are normalized as described in equation (F.21) in Appendix F, that is, countries with higher GDP per capita (e.g., Norway) experience lower prices in general, whereas poorer countries (e.g., Romania) have higher prices. Observe that this adjustment takes away the original pattern (of more expensive electricity prices at the periphery of the European market) and shifts the most expensive locations to Eastern Europe, where the poorest countries (in terms of GDP per capita) are located. The general pattern only changes marginally after 2015 in all three narratives. Hence, we relinquish to show the corresponding maps here (they are available in Appendix G instead). In a nutshell, poor countries stay poor and experience the highest normalized prices, whereas rich countries stay rich. This finding has fundamental implications when trying to evaluate diverging national interests with regard to decarbonization and consumer prices, and is thus discussed with other policy relevant issues in the concluding section.

(a) EUREGEN 2015　　(b) urbs 2015

Figure 8: GDP-normalized electricity price index for European countries in 2015 according to EUREGEN and urbs. The indices vary marginally in the future across all narratives

6. Synthesis of narratives and modeling results

We now relate the descriptor variations of the respective CIB outcome (see Section 3) to the modeling results from the previous section. In this way, we extend the qualitative character from the CIB analysis with quantitative aspects from the modeling exercise and simultaneously ensure the consistency of narratives.

Stagnation of the EU. National power markets continue to integrate towards a common European market in accordance with the regulations and institutions already in place. However, limited willingness to engage in far-reaching political and physical cooperation leads to moderate carbon prices (132 EUR/t in 2050) and an unfavorable environment for investments in European-wide infrastructure projects. Limited physical collaboration affects the expansion of interconnectors, so that energy transfers across countries increase only slightly from 2020 to 2030 and stagnate from 2030 onwards. Moreover, the average electricity prices in Europe and price differences across countries are highest in this narrative. The prevalent CO_2 price does not provide a sufficient incentive to push ahead with a comprehensive transition of the power system, but—induced by intense R&D and steep learning—renewables gain further traction, particularly from 2035 onwards. As a result, the growing demand for flexibility opens a larger niche for various storage technologies and flexible generators. Coal power loses its importance and CCS technologies (for natural gas, coal, and biomass) remain a niche technology. The electricity generation mix is predominantly composed of renewable energies and natural gas-fired power plants. As a consequence, carbon emissions increase slightly from 2020 to 2025 but then drop considerably until 2050 so that CO_2 abatement costs are between those of the other two narratives *GREEN* and *NATION*. However, the abatement burden is unequally shared across Europe. Centrally located countries abate relatively less compared to countries at the periphery of the European power market. Moreover, centrally located countries experience high electricity prices, whereas countries at the periphery of the European market benefit from high potentials of wind and solar power.

Towards a green revolution. A common vision of a low-carbon power system prevails within Europe. Collaboration and political concordance characterize international relations and the society exhibits a very positive attitude towards sustainability. Sustainable behavior becomes the predominant lifestyle, which drives a transformation in all economic sectors. The general public prefers an energy system based on renewables, fossil fuels are perceived as environmentally harmful, and CCS technologies lacks public acceptance. In contrast to *EU*, expansion of wind power substitutes parts of the natural gas-fired power plants. Overall, the power sector achieves tremendous carbon emission cutbacks so that a carbon-free power generation seems reachable. Collective decision-making processes on the European level prevail over national policy measures with regard to energy and climate policy. Efforts towards a unified climate and energy policy manifest themselves in a strengthening of the EU ETS and result in high carbon prices (176 EUR/t in 2050). Great importance is attached to the expansion of net transfer capacities to link the European power market more closely together. This expansion leads to a sharp increase in electricity transfers between 2030 and 2050. Compared to the *EU*, electricity prices in Europe decrease and converge across countries. In addition, the strong interconnection of the markets leads to a further convergence of the national power markets. The achievement of climate protection targets is seen as a joint effort, in which regional differences and potentials are exploited to their best possible extent for the common goal of climate change mitigation. This is also reflected in lowest CO_2 abatement costs.

Return of the nation state. The *NATION* narrative is in sharp contrast to *GREEN*. Prevailing international competition and national protectionism lead to a renunciation of transnational trade agreements. A trend is emerging that places greater emphasis on issues of national decision-making. The integration within the European power market is not a priority of national policy, so that transnational infrastructure projects like large interconnectors experience low priority. Similar to *EU*, this development is reflected in higher differences in national electricity prices. National policy measures towards climate and environmental protection are preferred to international institutions. As a result, the EU ETS becomes less important, leading to diminishing CO_2 prices of 44 EUR/t in 2050. This development is contrasted by lowest electricity prices (due to the lack of pricing the social costs of carbon). Additional policy incentives are introduced to stimulate investment in renewables as a means for a higher level of energy autarky. The regional potential of renewables can only be utilized to the extent that it is used for national power supply. Whereas some countries with favorable conditions—mainly those at at Western periphery with high quality wind power resources—realize a considerable reduction in carbon emissions through the national expansion of renewable technologies, others—e.g., Germany, Poland, and Italy—achieve only slight decarbonization due to the continuous use of fossil fuels. The focus on the national expansion of renewables instead of a European-wide strategy compromises the economic efficiency of CO_2 abatement, so that carbon emissions even increase temporarily and no substantial cutbacks happen in the long-run. Consequently, abatement cost are fundamentally higher than in the other two narratives.

In all narratives, the pattern of electricity price benefits vanishes when accounting for inequality between countries with regard to substantial differences in GDP per capita. Now, the poorest countries and, in particular, the poor countries at the periphery of the European power market carry the burden of abatement and of relatively high electricity prices.

7. Conclusion

We link results from a CIB analysis with a CGE and two power market models. The CIB analysis delivers consistent narratives that describe possible futures with a focus on the European power market. The CGE model PACE translates some descriptors for the usage in the two power market models that finally quantify the impact on the European power market.

The main difference between the narratives are the levels of political collaboration (stringency of the European climate policy) and physical collaboration (possible transmission grid expansion between countries). The most collaborative narrative, "Towards a Green Revolution" (*GREEN*), leads to highest CO_2 prices (176 EUR/t in 2050) and unconstrained expansion of transmission lines between countries from 2035 onwards. The least collaborative narrative, "Return of the Nation State" (*NATION*), leads to lowest CO_2 prices (44 EUR/t in 2050) and no transmission grid expansion from 2035 onwards. "Stagnation of the EU" (*EU*) delivers the middle way with 132 EUR/t and transmission grid expansion in line with a 25% interconnectivity target from 2035 onwards.

This paper contributes threefold to the literature. First, it shows a manageable way of combining qualitative scenarios and models (hybrid scenarios) for depicting environmental-energy dynamics in a comprehensive manner, that is, within a macroeconomic context. We thereby depict power markets in great detail by using two quite different power market models. Second, it shows decarbonization pathways of the European power market under different futures containing social, political, technological, and economical context developments. Third, it contributes to the understanding of distributional effects between countries arising from decarbonization pathways and helping to explain national interest when bargaining about targets and how to achieve them.

7.1. Creation of hybrid scenarios

Let us start with the hybrid scenario exercise, conducted by using the CIB analysis, the CGE model PACE, and the two power market models EUREGEN and urbs. The qualitative scenarios resulting from the CIB analysis are consistent given their cross-impacts. The clustered narratives are also consistent given their quantification by the PACE model, but the quantification procedure already reveals difficulties in translating qualitative scenario outputs into the CGE model. Moreover, the further quantification by the power market models and the calculation of some overlapping outputs with the PACE model show inconsistencies that are not further tangible by soft-linking.[3] For example, the CO_2 emission levels from PACE and the two power market models differ fundamentally. For *GREEN* revolution, absolute levels (of all three models) are close together, but for a stagnating *EU* the values of the power market models are almost twice as high as those from PACE. The difference in *NATION* is even more pronounced, i.e., emissions increase from 2020 to 2050 in EUREGEN and urbs but the drop in PACE is similar to the one in the other two narratives. Additionally, even the power market models with their same calibration (but different ways of optimizing investment decisions) differ, in particular, for the *NATION* scenario.

7.2. Decarbonization pathways

In the *EU* narrative, we calculate a drop of CO_2 emissions from 994 Mt in 2015 to 303 Mt (EUREGEN) or 309 Mt (urbs) in 2050, respectively. The drop is more pronounced in *GREEN* (139 Mt in EUREGEN and 90 Mt in urbs). *NATION* even leads to 848 Mt (EUREGEN) or 1013 Mt (urbs), respectively. The efforts to reduce carbon emissions are reflected in the expansion of renewable energy technologies, which is highest for *GREEN* and lowest for *NATION*. A large expansion of renewable technologies goes hand in hand with transmission grid expansion and fosters energy transfers between countries. In fact, transfers more than double in the most collaborative future (*GREEN*) in comparison to the other two narratives. Abatement costs are highest in *NATION* (378 EUR/t for EUREGEN, 559 EUR/t for urbs) and lowest in *GREEN* (271 EUR/t or 245 EUR/t, respectively). The difference to a stagnating *EU*, the narrative with medium collaboration, could be considered as costs or benefits of collaboration, respectively. Given abatement costs of 313 EUR/t (EUREGEN) or 296 EUR/t (urbs) in *EU*, the costs of a non-collaborative future are strikingly higher than the possible benefits from collaboration. However, abatement costs only reflect the system cost perspective and the gain from abating CO_2 emissions. Electricity prices are far more interesting from the consumer perspective. In *EU*, prices increase from 37 (35) EUR/MWh in 2015 to 68 (59) EUR/MWh in 2050 in EUREGEN (urbs). Higher collaboration (in *GREEN*) decreases those prices only slightly to 67 (56) EUR/MWh. *NATION* in turn leads to lowest electricity prices (57

[3] Possibilities to overcome this problem is to integrate power market models within a CGE framework (Böhringer, 1998, Böhringer and Rutherford, 2008, Wing, 2006, 2008) or to decompose as done by Böhringer and Rutherford (2009) and Abrell and Rausch (2016).

or 47 EUR/MWh, respectively, for EUREGEN and urbs) due to lower (internalized) costs from CO_2 emissions. Those facts underline free-riding problems of providing a public good (or not providing a public bad). It is cheaper for Europe to not enforce high CO_2 prices when not considering rebounds of a potential tipped climate and costs for other countries.

7.3. Distributional effects

The burden of carbon abatement is unequally shared across Europe. Countries with high quality renewable energy potentials, such as Spain, Ireland, the United Kingdom, and Finland, carry the major burden of abatement in all three narratives, i.e., independent of whether there is a collaborative future. Greece, also equipped with high quality solar potentials, uses its potential far less under a returning *NATION* state. In tendency, countries at the periphery of the European market decarbonize more than countries in the middle, such as Germany, Poland, or the Czech Republic. Moreover, the role of Germany, Czech Republic, Poland, and Italy differs by narratives. Those countries keep on having the highest emission intensities but are closer to other European countries in *GREEN* and more far away when there is a returning *NATION* state. Consequently, convergence of CO_2 emission intensities is greatest under a *GREEN* revolution. High CO_2 prices force each European country to decarbonize its power generation. Emission intensities converge also under a returning *Nation* state, but only the countries with quite good resource potential realize substantial carbon emission cutbacks.

When contrasting this development with those of electricity prices, convergence is highest in *GREEN*, *NATION* is the middle way of convergence, and *EU* shows highest differences in prices in 2050. We discover that some countries with very different initial endowments and resource potentials benefit from a returning *Nation* state, despite lower absolute prices in *Nation* due to low carbon prices. For example, Switzerland clearly benefits from a *Nation* state, whereas Spain bears additional costs (higher electricity prices). However, Switzerland (Spain) also benefits (loses) from a *GREEN* revolution, hinting, together with the (non-)convergence of prices across Europe to interesting non-linear dynamics when evaluating costs and benefits from collaboration on a regional level. Countries at the periphery of the European market tend to experience higher prices in the two contrasting narratives *GREEN* and *NATION*. However, the unequal development of prices vanishes when looking at the GDP per capita-normalized electricity prices. In all narratives, it is the poor countries, Eastern Europe and Portugal, that experience the highest electricity prices per unit of GDP per capita. The additional abatement burden (costs) in turn is delivered mostly by poor countries at the periphery of the European market with good renewable energy potentials, such as Portugal and Greece.

7.4. Policy implications

Our findings with regard to hybrid scenario exercises add fundamental complexity for policy makers when it comes to the interpretation of scientific results and final decision-making. Qualitative scenarios come with more complexity in terms of social and political context developments, which are difficult to incorporate in technological-economical-rich models. However, neglecting social and political context when making political decisions with fundamental social impacts is not an advisable option either. So, policy makers need to interpret results carefully and should always take into account the respective framework. Already quite similar power market models deliver considerable differences in quantitative results, although their qualitative messages are similar. When interpreting our results, one also needs to consider that the chosen CGE framework, PACE, deviates from other CGE frameworks, for example, with regard to spatial resolution (28 European countries plus on rest-of-the-world region).

The decarbonization of the European power market is cheap and ubiquitous when fostered by collaboration. Non-collaborative actions, e.g., no stringent climate policy, hamper investment into clean technologies and technologies that facilitate the integration of intermittent renewables. However, stringent climate policy comes at costs of internalizing carbon prices so that electricity prices increase. This fact makes it definitely difficult for policy makers to sell a stringent climate policy, in particular, when costs connected to carbon emissions are mostly dedicated to future generations to be born after 2050 and also to other world regions. However, recent obvious tragic developments (e.g., structural occurrence of heavy droughts) in European climate might increase acceptance for high carbon prices (and thus a sufficient internalization of costs from carbon emissions), maintaining the probability of a stagnating *EU* but increasing the likeliness of a *GREEN* revolution.

When bargaining about the future of the European climate policy, distributional effects should be taken into account. Unequal costs and benefits across European countries create political dynamics that might increase the likeliness of a returning *NATION* state. Countries that are already quite clean and experience increasing prices, might withdrawal from current agreements to avoid higher domestic prices. Additionally, poorer countries might realize that they will not (or never) catch up economically with richer ones, placing relatively higher burden on them. Additional transfers for fostering their energy transition towards low-carbon technologies might increase political and physical collaboration, necessary to reduce carbon emissions fundamentally.

7.5. Outlook

The strength of our analysis relies in the ability to assess a mix of technical outputs within a socio-economic context, which power market models are usually not able to do. However, it comes with some caveats. We analyze three narratives that are consistent given their cross-impacts but also given their quantification by the PACE model. We therefore refrain from conducting extensive sensitivity analysis or running multiple scenarios as often done by studies that apply quantitative scenarios (e.g., (Sasse and Trutnevyte, 2020)). We also refrain from using additional data (e.g., results in other sectors) from the CGE model because the two power market models and the CGE model do not have a similar equilibrium with respect to the decarbonization pathway. Addressing the last point would be an interesting topic for future work. Finally, the CIB analysis and the related elicitation process took place in 2015 so that narrative outcomes with regard to politically agreed decarbonization targets are a bit outdated. Current policies in place hint towards a stagnating *EU*, whereas declared targets are more in line with the *GREEN* narrative.

Declaration of interests. The authors declare that they have no known competing conflict of interest or financial interests that could have appeared to influence the work reported in this paper.

Contributions and Acknowledgements. This work was funded by the Federal Ministry for Economic Affairs and Energy of Germany (BMWi) within the project *Research Network for the Development of New Methods in Energy System Modeling (4NEMO)* under grant number 0324008A. The authors would like to thank Wolfgang Habla, Sebastian Voigt, and Paul Kunz for their contributions in developing and providing the used narratives. The contribution of Christoph Weissbart, Wolfgang Habla, Georgios Savvidis, Frieder Borggrefe, Lukas Schmidt, and Siamak Sheykhha in collecting information and building the input database is gratefully acknowledged.

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Appendix A. Process of narrative construction

24 experts were involved. The experts were selected with a high degree of heterogeneity in terms of their scientific expertise. In addition to economists (microeconomics, macroeconomics, environmental economics, and resource economics), also physicists, scientists from the engineering field, CGE and power market modelers were involved. The team responsible for creating the scenarios consisted of four economists. Furthermore, we regularly consulted experts in the field of scenario construction in the energy, environment, and climate domains. The process took place in three stages, with each stage concluded by a two-day workshop.

At stage 1, we developed a list of potential descriptors necessary for describing future developments of the European electricity market. The list consisted of 44 elements. We then asked ten experts via a questionnaire about the importance (0 means not important at all and 5 very important) of the respective descriptor for describing the future development of the European power system. In addition, the experts were able to add descriptors which were not included yet. This resulted in a list of 51 elements. We then invited these experts to the first workshop to discuss and evaluate the 51 descriptors and their respective importance. As a result, we ended up with 22 descriptors that were most significant for describing the future of the European power system.

Stage 2 identified the cross-impacts. Again, we asked ten experts to determine potential impacts between descriptors. Together with the experts, we assessed these interactions against the descriptor variations during the second workshop. We considered both the direction of the effect—i.e., promoting or inhibiting effect of a variation of a descriptor on the variation of another descriptor—and the strength of the effect (within a scale of 0 to 5). This process resulted in a cross-impact matrix that is the underlying element of the CIB analysis and is used to generate the set of consistent scenarios.

In stage 3, we evaluated the cross-impact matrix using the CIB algorithm. The resulting set of scenarios was presented to ten experts at the third and final CIB workshop. At this point, the experts were able to evaluate the scenario landscape to identify any potential inconsistencies. Finally, we clustered the scenarios (to narratives) to facilitate the transfer of the scenarios into the quantitative model frameworks.

Appendix B. Descriptors and variations

No	Descriptor	Interpretation	Variations	Remarks
D1	Specific investment costs (generation and CCS)	Development of specific investment costs of energy generation units. For comprehensiveness, typical technologies are aggregated (e.g., RES, coal, gas, nuclear, CCS) and absolute values converted to annual average growth rates.	**V1:** Weak decrease. Only RES will achieve little improvements (Schröder et al., 2013). **V2:** Moderate decrease, especially for RES and nuclear power. Coal and gas technologies experience a small decrease (IEA, 2016). **V3:** Strong decrease, especially for RES and CCS but also slight decrease for coal, gas, and nuclear (IEA, 2016).	The descriptor variations are implemented as cited.
D2	Grid infrastructure	Trans-border transmission grid expansion. In accordance with EU regulation and grid-development targets, ENTSOE's ten-year network development plan (TYNDP) proposes a set of planned transmission grid expansion projects (ENTSOE, 2020).	**V1:** No further expansion (beyond the existing TYNDP plan). **V2:** Moderate expansion (beyond the existing TYNDP plan) to reach 20% interconnectivity by 2050.[4] **V3:** Further grid expansion (beyond the existing TYNDP plan), reaching an interconnectivity of 25% by 2050 (with regard to the respective generation capacity of each state).	**V1:** Grid expansion as specified by TYNDP but not beyond. **V2:** Upper bound of 25% interconnectivity when TYNDP is not already on a higher level. **V3:** Lower bound of 25% interconnectivity or TYNDP, respectively, and no upper bound.

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[4] Interconnectivity is defined as the ratio of net transfer capacity and the generation capacity of a country.

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No	Descriptor	Interpretation	Variations	Remarks
D3	Incentives for RES	Incentives are regulative measures which support RES beyond the usual market mechanisms. Incentives considered can be monetary subsidies (e.g., feed-in tariffs), indirect subsidies (e.g., tax benefits), regulative benefits, and information campaigns. Public R&D and CO_2 prices are not included.	**V1:** Strong incentives: Additional incentives for renewables capacities in terms of monetary and indirect subsidies prevail within Europe. **V2:** Moderate incentives: Additional incentives in terms of monetary and indirect subsidies for small power stations and emerging technologies only. **V3:** Weak incentives: Monetary and indirect subsidies abolished.	Not implemented because CO_2 prices serve as dominating (incentive) policy.
D4	Consumer behaviour	Consumer behavior reflects two dimensions of behavioral change. "Sufficiency" describes a balance between increasing the level of individual consumption of socially and ecologically responsible products and the willingness to renounce consumption of energy and energy services. "Sharing economy" promotes a willingness to share goods and invest in communities. This descriptor expresses the willingness to shift focus from ownership of goods to the consumption of products or services without acquiring ownership, e.g., in the form of neighborhood investments as small-scale utilities.	**V1:** Increasing level of individual consumption: Rising GDP per capita indicates growth of prosperity and welfare. **V2:** The level of fulfilled desires stays stable, but consumption decreases. Emerging long-term commitment to share goods within the community (sufficiency is constant but sharing economy improves). **V3:** Sharing economy becomes popular in Europe. The customers can fulfill their needs and cooperate. The overall demand for goods and services decreases (sufficiency increases and sharing economy improves).	Context descriptor that is not implemented directly.

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No	Descriptor	Interpretation	Variations	Remarks
D5	CO_2 prices	Development of EU emission allowance prices (EU ETS). The CO_2 price depends on the reduction targets set on the national or international level, respectively, the allocation of the CO_2 allowances, and the cost of mitigation options.	**V1:** High to significant increase: 2020 20 \$/t CO_2, 2030 100 \$/t CO_2, 2040 140 \$/t CO_2 (Capros et al., 2016). **V2:** High increase: 2020 20 \$/t CO_2, 2030 37 \$/t CO_2, 2040 50 \$/t CO_2, 2050 90 \$/t CO_2 (IEA, 2016). **V3:** Diminishing trend or low prices from 2017 prevail until 2040.	**V1:** 2050 price is twice as high (176 EUR/t) as the price from the BAU scenario from the CGE model PACE. **V2:** 2050 price is 50% higher. **V3:** 2050 price is 50% lower.
D6	Perception of nuclear power	Political willingness to use nuclear power on the European level. No distinction is made between public and political attitudes toward nuclear power because political decisions are made on the basis of public opinion (Burstein, 2003).	**V1:** Nuclear Power is a way to lower CO_2 emissions and a resilient as well as save power system. The use or development of nuclear power plants is not restricted by policy intervention. **V2:** Nuclear power is a high-risk technology. Higher security requirements and taxes decrease the profitability of nuclear power.	In PACE, implemented either as upper bound on supplied nuclear energy or higher variable costs. In EUREGEN and urbs, implemented as risk premiums on top of specific investment costs.

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No	Descriptor	Interpretation	Variations	Remarks
D7	Support for environmental sustainability	Public and corporate attitude towards the sustainability of the (energy) system. Environmental sustainability is the capacity for continuance of environmental functions. Environmental functions are the capacity of natural processes and components to provide goods and services that satisfy human needs, i.e., the continuing ability of the environment to provide the necessary inputs to the economy to enable it to maintain economic welfare (Ekins et al., 2000).	**V1:** The public attitude towards sustainability is highly positive and the majority of European companies is involved in corporate social responsibility practices (CSR) that become a common indicator for credit or investment decisions. **V2:** The attitude towards sustainability is still positive, but people do not want to individually change their personal routines or actively influence their surroundings. Mainly big companies with a solid financial background get involved in CSR. **V3:** Low requirements for sustainability. Political regulations regarding social or environmental topics are controversial. Companies mainly focus on legal compliance and environmental regulation.	Context descriptor that is not implemented directly.
D8	Urbanization	Share of population living in urban areas. The current European urbanization rate is 74.8% (+0.24%/year) (minimal in Slovenia 49% with -0.05%/year, maximal in Belgium 97% with +0.06%/year).	**V1:** Rate increases (+0.3 to +0.5%/year), especially in highly urbanized countries. **V2:** Rate is stable (+0.2%/year). **V3:** Rate decreases (-0.2%/year).	Implemented as cited in PACE only.

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No	Descriptor	Interpretation	Variations	Remarks
D9	Focus of R&D	Public and private spending in R&D in the energy sector. To evaluate the effect of R&D on the future power system, this descriptor considers the general focal point of R&D activities. The focus can either lie on the field of a low carbon power system or on further development of system based on conventional technologies burning fossil fuels.	**V1:** Focus towards a low carbon system. Nuclear power is categorized as low carbon power. **V2:** Focus towards a fossil system. Fossil fuel power plants using CCS technologies are categorized as fossil power.	Implemented in PACE to reflect drop in specific investment costs. Implemented in EUREGEN and urbs as altered timeseries that depict higher availability of variable RES over time.
D10	Realization of the demand side management (DSM) potential	Changes in the European technical DSM potential. Gils (2014) estimates 61 GW of load reduction and 68 GW of load increases (per hour), which roughly corresponds to 9% of annual peak load of 620 GW.	**V1:** Potential is extensively utilized (more than 50%). **V2:** Potential is moderately utilized (between 20% and 50%). **V3:** Slight increase in the utilization of the DSM potential (between 10% and 20%).	Potential implementation either as generic load profile for DSM potential or direct modeling of DSM technology with technological and cost parameters. Not implemented in used model specifications.

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No	Descriptor	Interpretation	Variations	Remarks
D11	Demand for flexibility on the power market	Technical demand for flexibility in the power system. Demand for flexibility focuses on short-term services for power regulation (minutes reserves) to balance fluctuations in frequency and voltage, and unit commitment services (minutes to days), which are used to manage errors and uncertainties in predicted wind and solar output.	**V1:** Strongly increase. Enhanced procurement rules at the balancing markets increase opportunities for small (decentralized) resources, renewables, DSM, and battery storage. **V2:** Moderately increase. **V3:** Additional demand does not require large investments in increasing flexibility.	Context descriptor that is not implemented directly. Indirect effects are considered via D2 and D10.
D12	CCS accepted storage potential	In addition to high costs of the technology, acceptance constitutes another main obstacle to CCS. The European geographic storage potential of CO_2 is assessed by Neele et al. (2009) at 360 Gt. Storage capacity can be limited by public acceptance problems and unresolved technological issues. Examples are the fierce controversies in Germany and Poland concerning the implementation of the CCS Directive on geological storage of CO_2 (2009/31/CE Directive) in national law.	**V1:** CCS lacks public acceptance. **V2:** CCS is a climate mitigation option, but considered as local pollution. CCS potential is partly accessible. **V3:** CCS is a climate mitigation option and not considered as local pollution. CCS potential is fully accessible.	Direct implementation of the restricted potential of CCS in the models.

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No	Descriptor	Interpretation	Variations	Remarks
D13	Overall welfare and equality	The overall welfare is expressed by the Human Development Index (HDI) that includes gross national product, life expectancy, and the level of education. The level of equality is described by the adjusted HDI and describes equality regarding the distribution of these three factors. In Europe, the HDI is 0.748 with an average growth rate of 0.058%/year.	**V1:** Welfare and equality increase. **V2:** Welfare increases and equality decreases. **V3:** Welfare stagnates or increases very slowly and equality increases. **V4:** Welfare increases slowly and equality decreases.	Validated in PACE (GDP as proxy). Final implementation of similar GDP levels across narratives.
D14	Global economic cohesion	Degree of economic cooperation in the world. The degree can be expressed by an increase or decline in international trade barriers. It displays the global level of collaboration. The geographical area of European countries is regarded as one uniform unit within the global political landscape. The relationship between European countries is not covered by this descriptor.	**V1:** Trend towards national protectionism and international competition. **V2:** Trend towards open economies and cooperation. **V3:** Trend for bilateral/supranational cooperation (including trade zones, trade agreements).	Implementation possible in PACE only.

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No	Descriptor	Interpretation	Variations	Remarks
D15	Natural gas prices	This descriptor discusses the European oil and gas price developments. European gas prices reveal correlated with oil prices in the long-term (more than 1 year) and with a delay of 3 to 5 months (Albrecht et al., 2014). Although oil indexation of gas prices remains applicable in many regions, it is slightly weakening and following the trend towards greater flexibility of contract terms, shorter contract duration, and a greater share of gas available on a spot basis (IEA, 2016). Due to the fact that there is no joint natural gas price on a global level, we assume European prices for natural gas, taking into account effects that come from the oil market. We also assume the possibility of eased market conditions, a higher share of LNG and spot traded gas, and as a result lower correlation between gas and oil prices.	**V1:** Natural gas becomes a globally traded good with prices independent from oil. We observe developments over the scenario horizon leading to low natural gas (+3.5%/year; 10 $/MBtu) prices in 2040. **V2:** Natural gas becomes a globally traded good with prices independent from oil. We observe developments over the scenario horizon leading to high natural gas (+5%/year; 13 $/MBtu) prices in 2040. **V3:** Natural gas prices will further follow the oil price. We observe high oil prices (+7.5%/year; 150 $/Brl) and high gas prices (+5%/year; 13 $/MBtu) in 2040). **V4:** The price for oil stays low over the scenario horizon. The gas price follows the oil price and is also low (no growth; 50 $/Brl and +3.5%year; 10 $/MBtu) in 2040.	Final natural gas prices as outcome from PACE via adjustments of D19. Direct implementation of PACE prices in EUREGEN and urbs.
D16	Coal prices	The price of coal often differs for lignite and hard coal. However, the global coal market is composed of regional sub-markets where prices vary significantly. Lignite is barely traded at international markets and its prices are driven by exploitation costs (Hermann et al., 2017). We assume an average coal price for Europe based on the mixture of hard coal price and domestic lignite price.	**V1:** Trend towards high coal prices (+2.5%/year). **V2:** Stable prices (+0%/year). **V3:** Trend towards low prices (40$/t in 2040, -1%/year).	Final coal prices as outcome from PACE via adjustments of D19. Direct implementation of PACE prices in EUREGEN and urbs.

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No	Descriptor	Interpretation	Variations	Remarks
D17	Land use policy	Trend in future policy toward preferential use of land. Policy differentiates between nature conservation, industrial forestry, sealed land, and agriculture. We assume that there is a common trend for land use policy within European countries. The land-use trend will be described with 4 main indicators/types. These indicators can refer to the potential of energy technologies.	**V1:** Policy targets towards an increase of land use for forestry. As well for industrial forestry (industrial forestry can expand the bioenergy potential and those areas are also available for wind power). **V2:** Policy targets towards a higher share of land for agriculture and pasture, with sealed land for infrastructure and living (sealed land is mainly not available for wind power, but we assume the possibility of rooftop PV installations). **V3:** Land use policies are pushing for a higher percentage of sealed land. Arable and pasture land is available for agricultural purposes, limiting the availability for wind power, bioenergy production, and reducing the potential for large-scale PV installations. **V4:** Policy targets for a higher share of natural preservation are in place. In areas under natural preservation no power generation facilities are allowed and grid construction is subject to major regulatory restrictions.	Implemented in EUREGEN and urbs via bioenergy price (lowest for *NATION*).
D18	Regulation of the European power market	Regulatory framework of the European power market with a particular focus on price formation on the retail market. It is assumed that European policy follows the roadmap stated in the EU Winter Package from 2016. In particular, this includes a continuation of subsidies for renewables beyond 2020 where necessary to ensure profitability (yet in a cost-effective way), causing minimal market distortions.	**V1:** Liberalized power market (initially on-regulatory approach). Limited policy intervention, liberalization of power market advances, market-based price formation. **V2:** Enhancement of current market rules. Current policies are basically continued. European authorities take regulatory action to increase the flexibility of the system. **V3:** Fully integrated approach. The institutional framework is restructured in a more centralized manner and enforces a common energy policy in Europe.	Context descriptor that is not implemented directly, but indirectly via D2 and D5.

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No	Descriptor	Interpretation	Variations	Remarks
D19	Energy sources and available reserves	Identifies the global availability of reserves of two main energy sources relevant for electricity production: natural gas and coal. We identify reserves as proven volumes of energy resources economically exploitable at today's prices and today's technology.	**V1:** Available reserves of coal and gas grow more compared to the current trend. **V2:** Available reserves of coal grow more compared to the current trend. Available reserves of gas grow less compared to the current trend. **V3:** Available reserves of coal and gas grow less compared to the current trend. **V4:** Available reserves of gas grow more compared to the current trend. Available reserves of coal grow less compared to the current trend.	Implemented as changes in the national endowment of energy resources within PACE, resulting in coal and natural gas prices (covers D15 and D16) suitable for direct implementation in EUREGEN and urbs.
D20	Cooperation in Europe and political culture	This descriptor discusses the European cooperation in a common power market and perception and participation by the population. The cooperation character between European countries affects the development of the power market on multiple levels. Most notably, it influences investment decisions in generation capacity, which should satisfy the requirement of resource adequacy (the ability of the electricity system to serve demand at all times).	**V1:** Non-regulatory approach (autarky). Unity by difference with no enhanced cooperation within European nations. No cooperation in planning, operation, and optimization of power systems. **V2:** Common minimum European rules on cooperation, facilitated by the bilateral cooperation. Common set of supranational rules targeting crisis situations and blackout prevention. New financial measures (e.g., grid or service tariffs). **V3:** Full harmonization approach. All decisions on the national level must receive the approval of a supra-ordinate body. Common rules for security standards, load shedding, grid development, and strategically planning regarding the power sector.	Context descriptor that is not implemented directly, but indirectly via D2 and D5.

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No	Descriptor	Interpretation	Variations	Remarks
D21	Agriculture for the power sector	Focus on the bioenergy used for electricity generation, heating, and cooling services. EEA (2013) estimates the overall European bioenergy potential.	**V1:** Lower growth of bioenergy production in the limits of the determined bioenergy potential. **V2:** Growth of bioenergy production is maintained in the limits of the determined bioenergy potential.	Directly implemented as changes in the potential for bioenergy (bioenergy and renewable waste) and indirectly via D17 and changing bioenergy prices.
D22	Population growth	Projection of the total population growth within Europe including migration.	**V1:** The population growth in Europe follows an increasing trend (+0.12%/year) until 2050. **V2:** The European population stagnates. **V3:** The European population follows a decreasing trend (-0.12%/year) until 2050.	Validation in PACE via the scaling of labor intensity in production but finally not implemented as variations to aim for similar electricity demand (and welfare) across narratives.

Appendix C. Descriptors, variatins, scenarios, and narrative clusters

<table>
<tr><th></th><th></th><th colspan="6">Stagnation of the EU</th><th colspan="4">Dash for gas</th><th colspan="3">Green revolution</th><th colspan="3">Return of the nation state</th></tr>
<tr><th>No</th><th>Descriptor / Scenario</th><th>2</th><th>3</th><th>4</th><th>5</th><th>14</th><th>15</th><th>6</th><th>7</th><th>8</th><th>9</th><th>1</th><th>10</th><th>16</th><th>11</th><th>12</th><th>13</th></tr>
<tr><td>D1</td><td>Specific investment costs (generation and CCS)</td><td colspan="6">V2</td><td colspan="4">V2</td><td colspan="3">V2</td><td colspan="3">V1</td></tr>
<tr><td>D2</td><td>Grid infrastructure</td><td colspan="6">V2</td><td colspan="4">V1</td><td colspan="3">V3</td><td colspan="3">V1</td></tr>
<tr><td>D3</td><td>Incentives for RES</td><td colspan="6">V3</td><td colspan="4">V3</td><td colspan="3">V3</td><td colspan="3">V1</td></tr>
<tr><td>D4</td><td>Consumer behaviour</td><td colspan="6">V1</td><td colspan="4">V1</td><td colspan="3">V1</td><td colspan="3">V3</td></tr>
<tr><td>D5</td><td>CO_2 prices</td><td colspan="6">V2</td><td colspan="4">V2</td><td colspan="3">V1</td><td colspan="3">V3</td></tr>
<tr><td>D6</td><td>Perception of nuclear power</td><td colspan="16">V2</td></tr>
<tr><td>D7</td><td>Support for environmental sustainability</td><td colspan="6">V2</td><td colspan="4">V2</td><td colspan="3">V1</td><td colspan="3">V1</td></tr>
<tr><td>D8</td><td>Urbanization</td><td colspan="16">V2</td></tr>
<tr><td>D9</td><td>The focus of R&D</td><td>V1</td><td>V2</td><td>V1</td><td>V2</td><td>V1</td><td>V2</td><td>V1</td><td>V2</td><td>V1</td><td>V2</td><td colspan="3">V1</td><td>V2</td><td>V1</td><td>V2</td></tr>
<tr><td>D10</td><td>Realization of DSM potential</td><td colspan="16">V2</td></tr>
<tr><td>D11</td><td>Demand for flexibility on the power market</td><td colspan="2">V1</td><td colspan="2">V2</td><td colspan="2">V1</td><td colspan="2">V1</td><td colspan="2">V2</td><td colspan="3">V2</td><td colspan="3">V2</td></tr>
<tr><td>D12</td><td>CCS accepted storage potential</td><td colspan="16">V1</td></tr>
<tr><td>D13</td><td>Overall welfare and equality</td><td colspan="6">V2</td><td colspan="4">V2</td><td colspan="3">V1</td><td colspan="3">V3</td></tr>
<tr><td>D14</td><td>Global economic cohesion</td><td colspan="6">V3</td><td colspan="4">V3</td><td colspan="3">V3</td><td colspan="3">V1</td></tr>
<tr><td>D15</td><td>Natural gas prices</td><td colspan="6">V1</td><td colspan="4">V1</td><td colspan="3">V1</td><td>V1</td><td colspan="2">V3</td></tr>
<tr><td>D16</td><td>Coal prices</td><td colspan="6">V2</td><td colspan="4">V2</td><td colspan="3">V3</td><td colspan="3">V1</td></tr>
<tr><td>D17</td><td>Land use policy</td><td colspan="6">V1</td><td colspan="4">V4</td><td colspan="2">V4</td><td>V1</td><td colspan="3">V1</td></tr>
<tr><td>D18</td><td>Regulation of the European power market</td><td colspan="6">V1</td><td colspan="4">V1</td><td colspan="3">V3</td><td colspan="3">V1</td></tr>
<tr><td>D19</td><td>Energy sources and available reserves</td><td colspan="6">V4</td><td colspan="4">V4</td><td colspan="3">V3</td><td colspan="3">V4</td></tr>
<tr><td>D20</td><td>Cooperation in Europe and political culture</td><td colspan="6">V1</td><td colspan="4">V1</td><td colspan="3">V3</td><td colspan="3">V1</td></tr>
<tr><td>D21</td><td>Agriculture for the power sector</td><td colspan="4">V1</td><td colspan="2">V2</td><td colspan="4">V1</td><td colspan="2">V1</td><td>V2</td><td colspan="3">V2</td></tr>
<tr><td>D22</td><td>Population growth</td><td colspan="6">V2</td><td colspan="4">V2</td><td>V1</td><td colspan="2">V2</td><td colspan="3">V2</td></tr>
</table>

Appendix D. Descriptors and narratives

No	Descriptor	Stagnation of the EU	Dash for gas	Green revolution	Return of the nation state
D1	Specific investment costs (generation and CCS)	Moderate decrease -0.57	Moderate decrease -0.57	Moderate decrease -0.57	Weak decrease -0.21
D2	Grid infrastructure	Moderate transmission grid expansion	No further transmission grid expansion	Further grid expansion	No further transmission grid expansion
D3	Incentives for RES	Weak policy incentives for RES	Weak policy incentives for RES	Weak policy incentives for RES	Strong policy incentives for RES
D4	Consumer behavior	Raising the level of individual consumption	Raising the level of individual consumption	Raising the level of individual consumption	Sharing economy becomes popular in Europe
D5	CO_2 prices	Low increase in CO_2 prices	Low increase in CO_2 prices	High to a significant increase in CO_2 prices	Diminishing trend or low prices referring to 2017 until 2040
D6	Perception of nuclear power	Nuclear power is perceived as a high-risk technology	Nuclear power is perceived as a high-risk technology	Nuclear power is perceived as a high-risk technology	Nuclear power is perceived as a high-risk technology
D7	Support for environmental sustainability	Support for sustainability is high on all levels (weak corporate social responsibility, CSR)	Support for sustainability is high on all levels (weak CSR)	Support for sustainability is high on all levels (CSR)	Support for sustainability is high on all levels (CSR)
D8	Urbanization	Urbanization rate is stable	Urbanization rate is stable	Urbanization rate is stable	Urbanization rate is stable
D9	The focus of research and development	Towards a low carbon power system	Towards a fossil fuel power system	Towards a low carbon power system	Towards a fossil fuel power system
D10	Realization of the demand side management potential	EU potential is moderately utilized	EU potential is moderately utilized	EU potential is moderately utilized	EU potential is moderately utilized
D11	Demand for flexibility on the electricity market	Strongly increasing demand for flexibility	Moderately increasing demand for flexibility	Moderately increasing demand for flexibility	Moderately increasing demand for flexibility

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No	Descriptor	Stagnation of the EU	Dash for gas	Green revolution	Return of the nation state
D12	CCS accepted storage potential	Storage potential is lacking public acceptance	Storage potential is lacking public acceptance	Storage potential is lacking public acceptance	Storage potential is lacking public acceptance
D13	Overall welfare and equality	Welfare increase and equality decreases	The welfare increase and equality decreases	Welfare and equality increase	Welfare growth stagnates and equality increases
D14	Global economic cohesion	Trend for bilateral/supranational cooperation	Trend for bilateral/supranational cooperation	Trend for bilateral/supranational cooperation	Trend towards national protectionism and international competition
D15	Natural gas prices	Natural gas independent from oil: low prices	Natural gas independent from oil: low prices	Natural gas independent from oil: low prices	Natural gas dependent on oil: high prices
D16	Coal prices	Stable prices (+0%/year)	Stable prices (+0%/year)	The trend towards low prices	High coal price (+2.5%/year)
D17	Land use policy	Policy targets towards an increase in land use for forestry	Policy targets for a higher share of natural preservation	Policy targets for a higher share of natural preservation	Policy targets towards an increase in land use for forestry
D18	Regulation of the European power market	Liberalized power market	Liberalized power market	Fully integrated approach	Liberalized power market
D19	Energy sources and available reserves	Available reserves of gas grow higher than the current trend. Available reserves of coal grow lower than the current trend	Available reserves of gas grow more compared to the current trend. Available reserves of coal grow less compared to the current trend	Available reserves of coal and gas grow less compared to the current trend	Available reserves of gas grow more compared to the current trend. Available reserves of coal grow less compared to the current trend
D20	Cooperation in Europe and political culture	Non-regulatory approach (autarky)	Non-regulatory approach (autarky)	Full harmonization approach	Non-regulatory approach (autarky)
D21	Agriculture for the power sector	The growth of bioenergy production is maintained	Lower growth of bioenergy production	Lower growth of bioenergy production	The growth of bioenergy production is maintained
D22	Population growth	No population growth	No population growth	Population increases (+0.12%/year)	No population growth

Appendix E. Narrative results from PACE

Table E.1: Average commodity prices by narrative

Commodity	Narrative	2015	2020	2025	2030	2035	2040	2045	2050
Oil	EU	40.26	41.02	41.34	41.68	42.22	42.72	43.34	43.86
	GREEN	40.26	41.02	41.53	42.09	42.89	43.65	44.55	45.48
	NATION	40.26	41.02	41.39	41.79	42.37	42.90	43.50	44.09
Coal	EU	8.35	8.26	8.16	8.05	7.95	7.86	7.79	7.72
	GREEN	8.35	8.26	8.16	8.04	7.94	7.85	7.77	7.70
	NATION	8.35	8.26	8.18	8.07	7.99	7.92	7.85	7.80
Gas	EU	20.65	20.43	20.20	19.91	19.66	19.46	19.28	19.10
	GREEN	20.65	20.43	20.19	19.89	19.63	19.42	19.22	19.05
	NATION	20.65	20.43	20.24	19.97	19.76	19.59	19.43	19.29
Lignite	EU	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00
	GREEN	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00
	NATION	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00
Bioenergy	EU	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00
	GREEN	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00
	NATION	12.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
CO_2	EU	7.75	15.00	22.00	27.00	56.00	68.00	102.00	132.00
	GREEN	7.75	15.00	23.00	31.00	68.00	85.00	132.00	176.00
	NATION	7.75	15.00	18.00	19.00	34.00	34.00	42.00	44.00

Table E.2: GDP per capita by narrative

Narrative	2015	2020	2025	2030	2035	2040	2045	2050
EU	37,374	40,349	43,258	46,206	49,648	53,604	57,586	61,881
GREEN	37,374	40,349	43,205	46,109	49,476	53,368	57,284	61,486
NATION	37,374	40,349	43,248	46,198	49,648	53,600	57,614	61,899

Table E.3: GDP per capita by country for the EU narrative

Reg.	2015	2020	2025	2030	2035	2040	2045	2050
AT	48,412	52,585	56,760	60,769	65,692	70,956	76,246	81,477
BE	45,552	48,871	52,408	56,523	62,319	69,077	76,080	83,444
BG	8,061	8,987	9,754	10,363	10,959	11,635	12,219	12,740
CH	80,914	89,671	99,293	109,909	122,130	135,824	150,674	166,149
CZ	19,063	20,785	22,281	24,282	26,126	28,043	30,132	32,130
DE	45,955	48,822	51,704	53,672	55,542	58,161	61,064	63,976
DK	59,739	66,921	74,038	80,101	86,358	93,842	102,354	111,765
EE	19,900	21,847	23,501	25,142	26,765	28,432	29,842	31,240
EL	22,429	23,145	23,636	24,621	26,560	28,559	29,715	30,845
ES	29,435	32,306	35,366	38,415	41,509	44,233	45,988	48,692
FI	48,983	51,706	54,729	58,411	63,369	69,097	74,861	80,738
FR	43,524	46,972	50,144	53,511	57,770	62,890	68,193	74,181
HR	13,834	15,042	15,933	16,868	18,340	20,156	21,694	23,137
HU	14,206	15,366	17,112	18,777	20,302	21,632	22,821	24,292
IE	50,672	57,119	62,007	67,484	73,633	79,731	85,319	92,456
IT	35,258	37,586	39,913	42,371	45,417	48,911	52,336	56,422
LT	17,441	19,797	21,010	21,338	21,843	23,229	24,735	26,407
LU	103,411	117,421	133,629	151,363	172,890	197,008	221,510	246,477
LV	16,494	18,804	20,728	22,124	23,408	25,174	26,603	27,917
NL	51,120	54,740	57,734	60,258	63,628	67,830	72,444	77,645
NO	93,440	102,406	111,181	121,193	132,837	146,008	160,223	174,662
PL	14,320	16,425	18,468	20,406	21,956	23,458	24,538	25,302
PT	22,406	24,000	26,097	27,637	29,088	30,407	31,473	32,608
RO	10,313	11,534	12,669	13,608	14,464	15,501	16,539	17,641
SE	56,403	62,367	69,036	75,965	84,150	93,308	103,308	113,412
SI	23,699	25,631	27,871	29,684	31,609	33,618	35,603	37,730
SK	18,146	20,815	23,477	26,568	28,794	30,371	31,332	32,268
UK	43,958	46,960	49,616	53,257	58,270	64,279	70,603	77,062

Appendix F. Evaluation metrics

F.1. Notation

Let $j \in J$ denote a generation or storage technology and $r \in R$ a country within the European power market. EUREGEN and urbs use the installed capacity Q across the vintages $v = 1960, 1965, ..., 2050$ to generate or store power Y in hour h and period $t = 2015, 2020, ..., 2050$ in order to meet demand D. The models are capable of expanding the capacities Q starting from $t = 2020$ within the scenario constraints.

In the following equations, j and r are used as subscripts, whereas h, v, and t are shown in parentheses. For example, $Y_{jr}(h, v, t)$ is the production in hour h and period t of capacity $Q_{jr}(v)$ that is installed in v.

Let $k \in K$ denote a transmission technology and (r, r') a country pair that is eligible for transmission exchange. The amount of exports from r to r', $Y_{k,r\to r'}$, is restricted by the transmission capacity $Q_{k,r\to r'}$, i.e.,

$$0 \leq Y_{k,r\to r'}(h,t) \leq Q_{k,r\to r'}(h,t).$$

The amount of trade between the two regions, $Y_{k,r-r'} = Y_{k,r'\to r} - Y_{k,r\to r'}$, is positive if r imports more from r' than it exports to it.

F.2. Underlying optimization problem

EUREGEN minimizes cost C over the entire time horizon (2015 to 2050) applying discounting ($\delta(t)$ is the discount factor), i.e.,

$$Z^{\text{EUREGEN}} = \min_{\mathbf{Q},\mathbf{Y}} \sum_t \delta(t) \sum_r C_r(t), \tag{F.1}$$

where Z^{EUREGEN} is the cost function for EUREGEN, and $\mathbf{Q}$ and $\mathbf{Y}$ are the vectors of capacity and production decisions for all generation, storage, and transmission technologies.

urbs minimizes cost in a specific period t only, i.e.,

$$Z^{\text{urbs}}(t) = \min_{\mathbf{Q},\mathbf{Y}} \sum_r C_r(t). \tag{F.2}$$

urbs takes the optimized values from t as given in $t + 1$ (rolling horizon). Such a myopic approach allows to neglect discounting completely.

F.3. Emission intensity

Let $E_r(t)$ be the CO_2 emissions on a country-level from the respective power market model. The emission intensity per unit of energy then follows from

$$e_r(t) = \frac{E_r(t)}{\sum_h D_r(h,t)}. \tag{F.3}$$

We use the accumulated emission intensity to compare the abatement on a country level, i.e.,

$$\xi_r = \frac{\sum_t E_r(t)}{\sum_{t,h} D_r(h,t)}. \tag{F.4}$$

The 2015 values, i.e., $e_r(2015) = \dfrac{E_r(2015)}{\sum_h D_r(h,2015)}$, serve as benchmark to evaluate changes.

F.4. System cost

System cost consists of capital cost from investment IC into generation, storage, and transmission capacity c^{cap}, fixed cost FC (fixed operational and maintenance cost c^{fom}) for holding capacity, and variable cost VC (dispatch cost including variable operational and maintenance cost c^{vom}, fuel cost c^{fuel}, and cost of buying CO_2 certificates c^{CO_2}).

We take into account whether an investment is still under depreciation. Let Λ be a binary parameter that takes the value 1 when the investment is still under depreciation and 0 else, i.e.,

$$\Lambda_l(v,t) = \begin{cases} 1 & \text{if } t \leq v + t_{l,depr}(v), \\ 0 & \text{if } t > v + t_{l,depr}(v), \end{cases} \tag{F.5}$$

where $t_{l,depr}(v)$ is the depreciation time of an investment for all $l \in J \cup K$. We assume that an investment is financed by lended capital only. The annuity factor a_l reflects a constant stream of interests (i is the interest rate) and repayment, i.e.,

$$a_l(v) = \frac{i(1+i)^{t_{l,depr}(v)}}{(1+i)} - 1. \tag{F.6}$$

We further exclude investments that are under construction or planned already. For example, the 10-year development plan foresees the construction of transmission lines until 2030. We therefore exclude those cost because they are not optimized values. The same applies to renewable and nuclear projects which are planned to get commissioned in 2020, 2025, or even later. However, we do not exclude fixed and variable cost from those investment. Denoting those *pipeline* investment by superscript *pipe*, we calculate cost (in country r and period t) from

$$
\begin{aligned}
IC_r(t) \; &= \; \sum_{v\leq t}\sum_{j} c^{\text{cap}}_{j,r}(v)\left(Q_{j,r}(v) - Q^{\text{pipe}}_{j,r}(v)\right)\Lambda_j(v,t)\,a_j(v) + \\
&\quad \sum_{v\leq t}\sum_{k,r'} \frac{1}{2} c^{\text{cap}}_{k,r\to r'}\left(Q_{k,r\to r'}(v) - Q^{\text{pipe}}_{k,r\to r'}(v)\right)\Lambda_k(v,t)\,a_k(v) + \\
&\quad \sum_{v\leq t}\sum_{k,r'} \frac{1}{2} c^{\text{cap}}_{k,r'\to r}\left(Q_{k,r'\to r}(v) - Q^{\text{pipe}}_{k,r'\to r}(v)\right)\Lambda_k(v,t)\,a_k(v), \qquad \text{(F.7)} \\
FC_r(t) \; &= \; \sum_{v\leq t}\Bigg[\sum_{j} c^{\text{fom}}_{j,r}(v,t)\,Q_{j,r}(v,t) + \\
&\quad \frac{1}{2}\sum_{k,r'}\left(c^{\text{fom}}_{k,r\to r'}(v,t)\,Q_{k,r\to r'}(v) + c^{\text{fom}}_{k,r'\to r}(v,t)\,Q_{k,r'\to r}(v)\right)\Bigg], \qquad \text{(F.8)} \\
VC_r(t) \; &= \; \sum_{v\leq t}\sum_{j}\left(c^{\text{vom}}_{j,r}(v,t) + c^{\text{fuel}}_{j,r}(v,t) + c^{\text{CO}_2}_{j,r}(v,t)\right)Y_{j,r}(h,v,t). \qquad \text{(F.9)}
\end{aligned}
$$

Equation (F.7) calculates the investment cost. The first line shows cost from generation and storage technologies and the second and third lines are cost from transmission technologies. Observe that $v \leq t$ indicates the current cost from all capacity investments that are already installed. Equation (F.8) corresponds to fixed cost, and equation (F.9) to variable cost.

F.5. Abatement and abatement cost

We consider the 2015 emissions from PACE from the business-as-usual (BAU) scenario as benchmark to calculate the abatement of the power market models. Let $E^{\text{PACE}}(2015)$ be the emissions from PACE in 2015. Assuming a constant emission intensity, we can extrapolate the benchmark emissions in period t as follows:

$$\widetilde{E}^{\text{PACE}}(t) = E^{\text{PACE}}(2015) \cdot \sum_{r,h} \frac{D_r(h,t)}{D_r(h,2015)}, \qquad \text{(F.10)}$$

where $D_r(h, 2015)$ indicates electricity demand in 2015. Hence, the accumulated abatement takes into account the rising electricity demand and is calculated according to

$$\zeta = \sum_t \left(E(t) - \widetilde{E}^{\mathrm{PACE}}(t) \right) \tag{F.11}$$

From the system cost equations ((F.7), (F.8), and (F.9)) and the accumulated abatement equation (F.11), we calculate abatement cost κ as

$$\kappa = \frac{\sum_{t,r} \left(IC_r(t) + VC_r(t) + FC_r(t) \right)}{\sum_t \left(E(t) - \widetilde{E}^{\mathrm{PACE}}(t) \right)}. \tag{F.12}$$

F.6. Electricity price index

EUREGEN and urbs optimize the power system subject to multiple constraints. The ones that are relevant for the calculation of electricity prices are:

$$D_r(h,t) = \sum_j Y_{jr}(h,t) + \sum_k \sum_{r'} Y_{k,r-r'}(h,t), \tag{F.13}$$

$$D_r(h_{r,peak},t) \leq \sum_j \beta_j Q_{jr}(t) + \sum_k \sum_{r'} \gamma_k Q_{k,r-r'}(v,t). \tag{F.14}$$

Equation (F.13) is the demand-equals-supply constraint. The total amount produced (right side of the equation) must exactly match demand (left side of the equation). Equation (F.14) is the resource adequacy constraint. Secured capacity (right side of the equation) must always be sufficient to meet demand in the country-specific peak hour $h_{r,peak}$. We use capacity credits β_j and γ_k to determine the secured capacity. For example, $\beta = 0.898$ for coal power plants and $\gamma = 0.1$ for all transmission technologies. Let λ (F.13) and μ (F.14) be the corresponding Kuhn-Tucker multipliers of the respective optimization problem. Assuming that $\delta = 1$ for urbs and $\delta \leq 1$ for EUREGEN, we obtain the hourly price p from

$$p_r(h,t) = \frac{\lambda_r(h,t) + \mu_r(h,t)}{\delta(t)}. \tag{F.15}$$

We calculate annual, regional values from

$$p_r(t) = \frac{\sum_h p_r(h,t) D_r(h,t)}{\sum_h D_r(h,t)}. \tag{F.16}$$

The European price $\overline{p(t)}$ follows from a weighted average of regional prices, i.e.,

$$\overline{p(t)} = \frac{\sum_{r,h} p_r(h,t) D_r(h,t)}{\sum_{r,h} D_r(h,t)}. \tag{F.17}$$

The electricity price index π_r reflects how much a specific country is above ($\pi_r > 1$) or below ($\pi_r < 1$) the European average. It is calculated from

$$\pi_r(t) = \frac{p_r(t)}{\overline{p(t)}} \tag{F.18}$$

F.7. GDP-normalized electricity price index

Let $\mathrm{GDP}_r(t)$ be the Gross Domestic Product (GDP) of a country and $\mathrm{POP}_r(t)$ its population. GDP per capita on a country level, $g_r(t)$, and the European weighted average, $\overline{g_r(t)}$, are given by

$$g_r(t) = \frac{\mathrm{GDP}_r(t)}{\mathrm{POP}_r(t)}, \tag{F.19}$$

$$\overline{g(t)} = \frac{\sum_r \mathrm{GDP}_r(t)}{\sum_r \mathrm{POP}_r(t)}. \tag{F.20}$$

By combining equations (F.18), (F.19), and (F.20), we obtain the GDP-normalized electricity price index by adjusting the price index:

$$\pi_r^{\mathrm{GDP}}(t) = \pi_r(t) \cdot \frac{\overline{g(t)}}{g_r(t)} \tag{F.21}$$

For the same electricity price $p_r(t)$, poorer countries (in terms of lower GDP per capita) experience higher GDP-normalized price indices $\pi_r^{\mathrm{GDP}}(t)$ than richer countries.

Appendix G. Supplementary figures

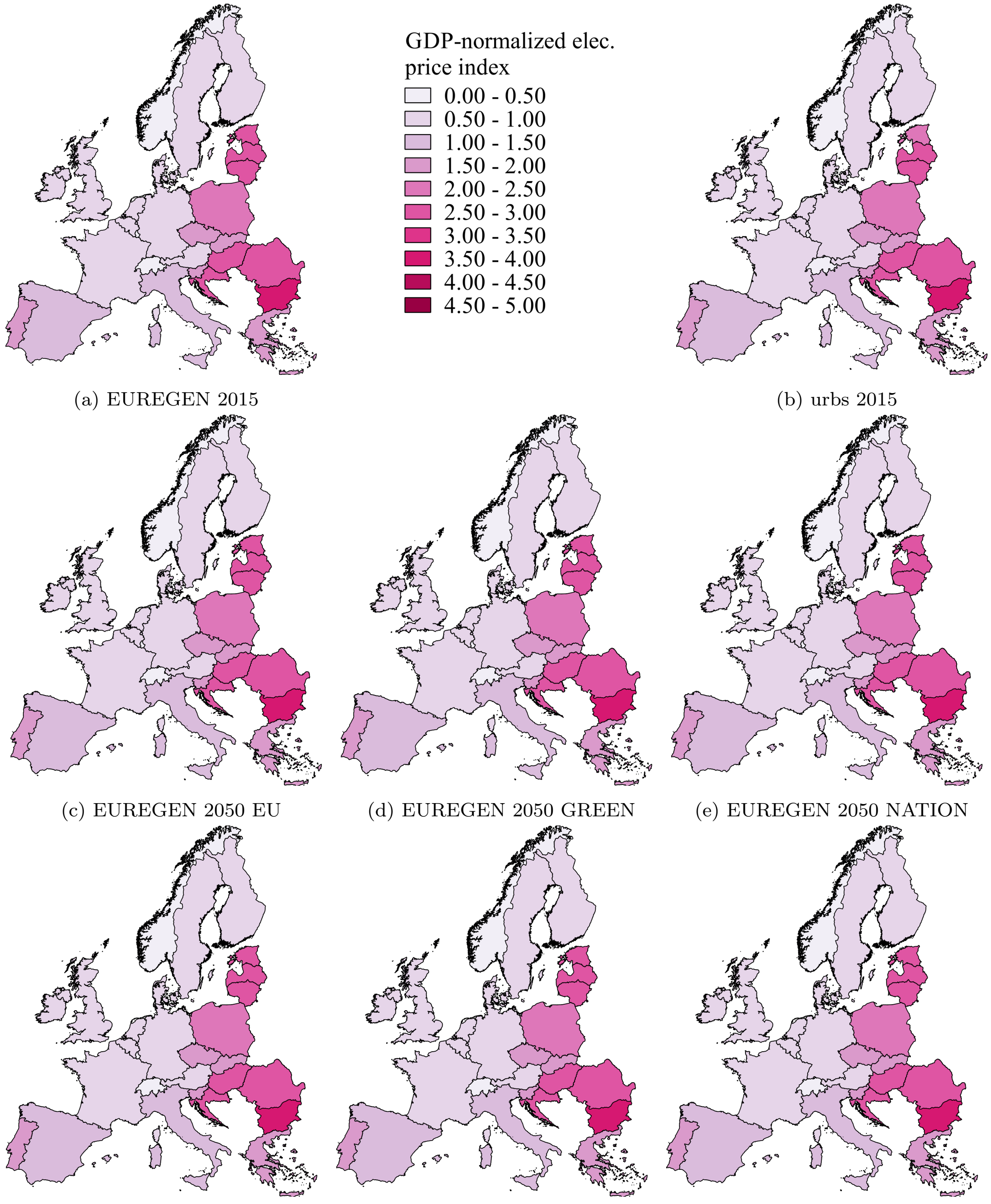

Figure G.1: GDP-normalized electricity price index for European countries in 2015 and 2050