

A Service of

ZBW

Leibniz-Informationszentrum Wirtschaft Leibniz Information Centre for Economics

Mier, Mathias; Siala, Kais; Govorukha, Kristina; Mayer, Philip

Working Paper Costs and benefits of political and physical collaboration in the European Power Market

ifo Working Paper, No. 343

Provided in Cooperation with: Ifo Institute – Leibniz Institute for Economic Research at the University of Munich

Suggested Citation: Mier, Mathias; Siala, Kais; Govorukha, Kristina; Mayer, Philip (2020) : Costs and benefits of political and physical collaboration in the European Power Market, ifo Working Paper, No. 343, ifo Institute - Leibniz Institute for Economic Research at the University of Munich, Munich

This Version is available at: https://hdl.handle.net/10419/226807

Standard-Nutzungsbedingungen:

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Terms of use:

Documents in EconStor may be saved and copied for your personal and scholarly purposes.

You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.

If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.



WWW.ECONSTOR.EU

ifo WORKING PAPERS

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

Mathias Mier, Kais Siala, Kristina Govorukha, Philip Mayer



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 Telephone +49(0)89 9224 0, Telefax +49(0)89 985369, email ifo@ifo.de www.ifo.de

An electronic version of the paper may be downloaded from the ifo website: www.ifo.de

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

Abstract

We use the cross-impact balance analysis to develop narratives that differ in the level of political collaboration (in terms of the stringency of the EU climate policy) and physical collaboration (possible expansion of transmission capacity between countries) in the European power market. Applying a CGE model and two power market models, we quantify the impact of the two dimensions on emission, abatement cost, and electricity prices until 2050. The most collaborative narrative leads to CO₂ emissions of 90 to 139 Mt, abatement cost of 245 to 271 EUR/ton CO₂, and prices of 56 to 67 EUR/MWh in 2050. The least collaborative one has emissions of 848 to 1013 Mt, cost of 378 to 559 EUR/ton, and prices of 47 to 57 EUR/MWh. In all narratives, countries at the periphery of the European market tend to experience lower prices and abate more, whereas prices are higher and abatement lower in central and Southeast Europe.

JEL code: C61, C68, Q40, Q41

Keywords: Collaboration, energy transition, decarbonization, European power market, transmission, renewable energy, energy system modeling

Mathias Mier* ifo Institute – Leibniz-Institute for Economic Research at the University of Munich,

Kristina Govorukha Technische Universität und Bergakademie Freiberg Kais Siala Chair of Renewable and Sustainable Energy Systems Technical University of Munich

Philip Mayer Technische Universität und Bergakademie Freiberg

*_Corresponding author: mier@ifo.de.

1. Introduction

Imminent climate change due to massive carbon emissions demands for prompt actions. Incumbent firms but also new investors need to redirect capital from emissionintensive 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 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.

We analyze the impact of two different dimensions of collaboration—political collaboration in terms of stringency of European climate policy, and physical collaboration within the European power market in terms of allowed transmission grid expansion between countries—on the resulting technology mix, abatement, related cost, and electricity prices. We start with applying the cross-impact balance (CIB) analysis to develop socioeconomic context scenarios for European decarbonization pathways with a focus on power markets. The macro-economic computable general equilibrium (CGE) model PACE translates the descriptors of the narratives into macro-economic values (e.g., fuel prices). These values are used with further descriptors from the narratives to calibrate the two power market models EUREGEN and urbs.

The most important differences between the narratives are the stringency of the European climate policy and the transmission grid expansion between countries two dimensions of collaboration. The most collaborative narrative (called "Towards a green revolution", *GREEN*) leads to high CO₂ 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 CO₂ 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.

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 the *GREEN* narrative (139 Mt in EUREGEN and 90 Mt in urbs). The *NATION* narrative 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 of the *GREEN* revolution in comparison to the other two narratives. Abatement costs are highest in the *NATION* narrative (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 "Stagnation of the EU", the narrative with medium collaboration, must be considered as costs or benefits of collaboration, respectively. Given abatement costs of 313 EUR/t (EUREGEN) or 296 EUR/t (urbs) in *EU* narrative, the costs of a non-collaborative future are strikingly higher than the possible benefits from collaboration.

Countries differ with respect to the burden of abatement and resulting electricity prices. It is mainly countries at the periphery of the European market (e.g., Spain and Finland) that carry the highest burden of abatement. This pattern is constant for all considered narratives. However, the role of Germany, Czech Republic, Poland, and Italy differs by narratives. Those countries keep on having highest emission intensities but are closer to other European countries in a *GREEN* revolution and more far away when there is a return of the *NATION* state. When it comes to electricity prices, we observe a shift in the periphery in all three narratives. Countries like Spain, which used to have one of the highest electricity prices in 2015, benefit from good wind and solar resource potentials to reduce their emission intensity but also lower their electricity prices. However, when normalizing electricity prices with GDP per capita, the poorest countries in Eastern Europe remain those with the highest prices per unit of GDP. In short: dirty may become clean, some stay dirty, some stay clean, but poor stays poor, and rich stays rich.

Section 2 introduces the CIB analysis, used model frameworks, and describes the coupling of CIB analysis and models. Section 3 introduces the narratives. Section 4 presents results that are discussed in Section 5. Section 6 concludes.

2. Method

There are many methods for generating qualitative scenarios [1, 2, 3]. We apply the cross-impact balance (CIB) analysis [4] to construct a consistent set of qualitative context scenarios (called *narratives* in the following). The CGE model PACE is applied to deliver the macro-economic context of the those narratives. Subsequently, we use two different model types to assess the development of the European power market until 2050. Subsection 2.1 introduces the concept of narratives and their value in environmental and energy modeling. Subsection 2.2 describes the CIB analysis, which is used to generate a set of consistent narratives. 2.3 provides a description of the applied model frameworks. Finally, Subsection 2.4 describes the soft-coupling process of CIB analysis with the models.

2.1. The need for narratives

The description of possible futures through the creation of scenarios is a formalized way to make statements about possible future development paths using knowledge from the present and insights from the past. A fundamental distinction can be made between qualitative and quantitative scenarios. Qualitative scenarios, often also called *narratives* or *storylines*, are largely based on verbal descriptions of potential futures [e.g., 5]. Methods for developing such narratives are usually flexible in terms of the parameters they require, allowing to consider a range of different social, economical, technical, and environmental parameters. This way, softer and more diffuse concepts such as political stability, or environmental awareness can be included in the analysis. Computer-based quantitative scenarios, on the other hand, allow for numerical insight into the system under consideration. Alcamo [6] argues that quantitative approaches are more transparent than their qualitative counterparts because their model assumptions are expressed as mathematical equations. Craig et al. [7] contrast this with the fact that, for energy forecasts, there are necessarily implicit assumptions about human behavior, including social, institutional and personal interactions, as well as human innovation.

Quantitative scenarios are predominant in the field of environmental and energy research [e.g., 8, 9]. Nevertheless, qualitative approaches to support comprehensive scenario analyses have gained momentum in recent years. Alcamo [6] introduced the concept of story and simulation, which combines qualitative and quantitative scenario techniques. He argues that this procedure is "the best answer to achieving the goals of a scenario analysis" [6, p. 126]. Raskin et al. [10] underline this argument by pointing out that the use of narratives "offers texture, richness, and in-sight, while quantitative analysis offers structure, discipline, and rigor" [10, p. 40]. Indeed, some comprehensive scenario analyses have already been based on this interconnection [e.g., 5, 11, 12]. Neither Alcamo [6] nor Raskin et al. [10] commit themselves to a specific procedure in their observations. Various approaches and terms address this challenge, such as shared socioeconomic pathways [13], integrated scenarios [14], hybrid scenarios [15], or narratives to numbers [16].

2.2. CIB analysis

The CIB analysis assesses interactions between social, political, technological, and economic developments. Prior to the analysis, the boundaries of the system under investigation must be determined and the time horizon defined. 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 [4]. However, Weimer-Jehle [4] argues 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" [4, p. 337]. Weimer-Jehle [4] introduced the CIB to address this issue.

Several studies emphasize the special suitability of CIB analysis in the field of energy and environmental scenarios. Weimer-Jehle et al. [17] demonstrate the ability of the method to deal with a heterogeneous input data set to make the context uncertainty of energy scenarios tangible. Schweizer and Kriegler [18] show retrospectively, by means of CIB analysis, that not all underlying narratives of the IPCC's Special Report on Emissions Scenarios achieve complete internal consistency.

Model-based energy scenarios deliver a quantitative assessment of the implications of energy and climate policies for possible future developments and transformation pathways of the energy system and the economy in general [e.g., 8]. Recent studies stress a need of new complex scenario techniques and methods combining climatic, social, technical, and economical factors in a comprehensive manner [13, 19, 20, 21]. Comprehensive energy scenarios require to consider a macroeconomic framework. This can be achieved by linking a landscape of models with a narrative [e.g., 22]. Alternatively, this can be achieved by soft-linking power market models 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 [23, 24, 25].

However, the linking of power market models and macro-economic models can be challenging due to their diverging system boundaries and overlaps. A number of studies highlight the significance of qualitative aspects that cannot directly be depicted by quantitative modeling frameworks [18, 26]. Yet, many studies tend to disregard such context aspects, like changes in the social dimension [27] that usually are found in the narrative storylines. The systematic and comprehensive integration of those factors into the landscape of models is possible with the implementation of scenario techniques like the CIB analysis. The coupling of macro-economic CGE with power market models via the CIB ensures the consistency of the described context. The coupling further covers the existing gap between iteratively combined narratives, top-down (e.g., CGE), and bottom-up (e.g., power market) models.

A thorough review of relevant literature and an assessment of the market structure gave a comprehensive overview of the fundamental elements of the European power market. Forty-four (44) key system elements (*descriptors*) were identified at three workshops and via a questionnaire with experts working in the field of energy economics. The workshops resulted in the selection of 22 descriptors that cover four key categories (social, political, technological, economical) and their respective interactions.

The cross-impact matrix (CIM) at the core of the CIB analysis [28] describes the system under review 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" [29, p. 8].

In contrast to the original cross-impact method, the CIB 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. Weimer-Jehle [4, p. 340] suggests a range of integers from -3 (strongly restricting influence) to +3 (strongly promoting influence), where 0 corresponds to a lack of direct influence. In order to provide higher flexibility in the evaluation of cross-impacts, we use a range of +5 to -5.

2.3. 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 multisector and multi-regional model [30]. 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, CO₂ 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 [31] and urbs [32] are power market models that 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.

2.4. Model coupling

Figure 1 shows the connecting structure between the CIB analysis, the CGE model PACE, and the power market models EUREGEN and urbs.



Figure 1: Linking process of CIB and quantitative modeling frameworks

The CIB analysis allows to relate a heterogeneous set of descriptors. Relevant

descriptors for the CGE model, the power market models, as well as socioeconomic context descriptors are shown on the left. The CIB analysis is represented here by the CIM that comprises different variations of descriptors and assessment ratings of cross-impacts between them. The results of the evaluation of 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. The detailed translation of the qualitative and quantitative descriptors into inputs for PACE and the power market models is shown in Appendix A.

3. Narratives

Our CIB analysis yields 16 (see Figure 2) scenarios that are grouped into four clusters: stagnation of the EU (referred to as EU), dash for gas (GAS), towards a green revolution (GREEN), and return of the nation state (NATION). Scenarios within the identified clusters show only minor deviations, providing ancillary accents to the clustered paths. A presentation of the full scenario landscape is available in Appendix B.

In the following subsections, we provide short descriptions of the narratives EU, GREEN, and NATION. The narrative GAS is not discussed further because it delivered very similar results to the narrative EU when used in the power system models (notice their proximity in Figure 2). For the sake of completeness, its qualitative description is provided in Appendix C.

Stagnation of the EU. Political cooperation in the EU stagnates due to considerable institutional and bureaucratic hurdles. These factors together do not allow for large but only moderate infrastructure projects within the power market, such as transmission grid extensions, or European-wide use of CCS storage and transport facilities. National power markets further integrate towards a joint European power market, in accordance with already existing regulations and institutions only. Under such circumstances, the power market strives for further liberalization, not least by removing subsidies for renewable energy sources. This trend is associated with a large decrease in investment costs for renewable technologies induced by intensive R&D initiatives and steep learning curves. As a result, the growing demand for flexibility opens a larger niche for various storage technologies and flexible generators.



Figure 2: Landscape of scenarios (1–16, in gray) and their corresponding narratives

Towards a green revolution. International relations are characterized by collaboration and political concordance. With regard to energy and climate policy, collective decision-making processes on the EU level prevail over nation-wide policy measures. The elimination of trade barriers and the deployment of new trade routes decrease energy prices significantly. Efforts towards a unified climate and energy policy manifest themselves in a strengthening of the EU ETS. Additionally, the expansion of new international transmission capacities foster the development of a fully integrated power market. Society exhibits a very positive attitude towards sustainability. Sustainable behavior becomes the predominant lifestyle, which drives a transformation in all economic sectors. For example, companies focus on corporate social responsibility activities. The general public prefers an energy system based mostly on renewable energy. At the same time, fossil fuels are perceived as environmentally harmful and CCS technology lacks public acceptance. Due to collective research and development (R&D) activities in low-carbon technologies and to high prices for CO_2 certificates, renewable energy expansion does not rely on additional policy incentives.

Return of the nation state. Prevailing international competition and national protectionism leads to a renunciation of transnational trade agreements. As a consequence, there is no significant exploration of new trade routes with growing fossil fuel prices in Europe. The collaboration in planning, operating and optimizing the European power system is low and there are no collective efforts in designing a unified European power market. Hence, transnational infrastructure projects like large interconnectors have low priority. Furthermore, 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. Additional policy incentives are introduced to stimulate investment in renewable energy as a means for a higher level of energy autarky. Sharing economy concepts become popular and regional value-added chains are broadly utilized. However, the extended regionalization of economic activities puts the local environment under additional stress, which results in a society that attaches high importance to sustainability and environmental protection on a local level.

4. Results

This section starts by providing an overview of the implications of the narratives for the future development of the electricity system within Europe, then follows with 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 4.1 as well as abatement costs at EU level in Subsection 4.2. The following Subsections 4.3 and 4.4 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 4.5.

4.1. 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.



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)

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 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, cf. [33]).

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 considerable with increasing demand. A high price for CO_2 emissions coupled with a decrease in specific investment costs for renewable energy sources results 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.

The two narratives GREEN and EU show a considerably higher expansion of generation capacities, particularly for renewable technologies, than NATION. Crosscountry 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. From 2035 onwards, a higher level of physical collaboration in EU and GREENallows 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 in order to transfer energy to the demand centers.

4.2. 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 in particular. We now turn our focus to the resulting cost by applying the abatement cost metric (equation (E.12)) from Appendix E.

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)



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

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 1. By design, this metric contains accumulated system cost as well as accumulated abatement over the entire model horizon (2015 to 2050), because CO₂ emissions impact climate change as stock. Thus, annual values can only provide a snapshot of the transformation and are inadequate for reflecting the impacts of long-term investments.



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

Table 1: 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. [33] 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—we see this narrative as most likely to occur in the future—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 CO₂ (urbs). The costs from not collaborating (*NATION* narrative) are much higher than the potential cost, i.e., between 65 (EUREGEN) and 263 EUR/t CO₂ (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.

4.3. Regional abatement

The European decarbonization pathways and related abatement cost are just depicting the uppermost level. An analysis at country-level is necessary to show who is actually bearing the burden of decarbonization. In Figure 6 we depict CO_2 emission intensity at country-level (see equation (E.4) in Appendix E). The first line presents 2015 values from EUREGEN and urbs. The middle line presents outcomes for the three narratives in 2050 for EUREGEN and the lower line 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.



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

4.4. Electricity prices

Electricity prices differ within Europe across narratives. Table 2 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 E.6 in Appendix E 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). Differences between models can be traced back to modelspecific 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. On one hand, 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 weight them to reduce the error to the hourly time series. On the other hand, 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) to compare regional differences of the models across narratives.

		EUREG	EN	EN 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		

Table 2: European electricity prices by model and narrative in EUR/MWh

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 costly and also restricted by political boundaries that even reduce the available capacity below its physical limits. 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 in Appendix E. An index value of 1 means that a country has exactly the European average price.

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 was 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.



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

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 (CO₂ 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.

4.5. GDP-adjusted electricity prices

Comparing absolute values does not reflect the reality in Europe because countries differ in their GDP per capita (see Tables D.2 and D.3 in Appendix D 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 Appendix E, 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. 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 F instead). In a nutshell, poor countries stay poor and experience the highest normalized prices, whereas rich countries stay rich.



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

5. Discussion

The CIB analysis follows an explorative approach [1], discovering possible future developments without defining specific paths or normative objectives. A closer look at the narratives revealed that an essential distinguishing feature lies in two dimensions of international 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 technical infrastructure necessary to achieve these objectives. The CIB analysis provides a comprehensive way to incorporate these interpretations of collaboration as provided by multiple experts. The descriptor "Cooperation in Europe" has one of the leading active cross-impacts: It determines variations of other descriptors and forces differences in the scenarios by the degree of political and physical collaboration between the states.

In *GREEN*, a common vision of a low-carbon electricity system prevails within the EU. This is reflected both in economic aspects, such as the strengthening of international trade, and in political aspects, such as the joint setting of stricter emission targets and the associated higher CO_2 prices. To link the European electricity markets more closely together, not only in regulatory terms, great importance is attached to the expansion of net transfer capacities. In this scenario, the achievement of climate protection targets is thus 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. Emissions in the electricity sector will accordingly be avoided where the most favorable conditions prevail and the efficient realization of the European potential for the development of renewable energy will not be hampered by regulatory barriers or lack of capacity of an international transmission system. Electricity trade in Europe will expand considerably compared to today and regional differences in wholesale electricity prices converge, at least in absolute terms.

In sharp contrast to this is the *NATION* narrative. A trend is emerging here, which attaches greater importance to questions of national decision-making within the EU. This is also reflected in the cutbacks in international institutions such as the EU ETS. The integration within the European power market is not a priority of national policy and, as a consequence, the expansion of trade capacities is not pushed further. In the power sector, the unrestricted primacy of climate protection does not apply; instead, issues of energy security and independence from electricity imports are given priority. Thus, the use of fossil fuels is seen as an option for ensuring national energy self-sufficiency. Consequently, in this narrative, regional potentials of renewable energy can only be exploited to the extent that they can be used for national electricity supply. Due to the stronger focus on national expansion

targets, differences in electricity prices in the various regions persist. At the same time, this situation requires a higher use of fossil fuels to provide the residual load. As a result, the intensity of emissions in the countries under examination is linked to geographical conditions. While some countries with favorable conditions realize a considerable reduction in emissions through the national expansion of renewable energy technologies, other regions will not achieve any decarbonization through the continuous use of fossil fuels.

The EU narrative is caught in the middle. Although the importance of international collaboration to realize a low-carbon power system is not completely negated, the integration of power markets is only moderately advanced. This also applies to the strictness of European climate policy, which is reflected in the development of the CO₂ price. Although the CO₂ price is higher than in *NATION*, this does not provide a sufficient incentive to push ahead with a comprehensive transition of the power system. Political and economic hurdles intensify this problem. Efforts to establish an integrated European power system are stagnating and the European Union is not implementing an ambitious common climate policy. While the use of coal to generate electricity is losing importance, natural gas remains an essential energy source. Consequently, the decarbonization of the European power market is not as extensive as in a *GREEN* revolution. In fact, the limited physical collaboration (compared to *GREEN*) in conjunction with a high level of political collaboration (compared to *NATION*) leads to the highest variance of electricity prices among European countries.

6. Conclusion

We apply the CIB analysis to develop narratives with consistent scenarios 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 narratives mainly differ in terms of political and physical collaboration. Carbon prices of 132 EUR/t and some possible expansion of interconnectors from 2035 onwards lead to a medium collaborative world, called restoration of the EU. The most collaborative narrative (towards a *GREEN* revolution) yields the highest carbon prices (176 EUR/t, due to high political collaboration) and unconstrained transmission expansion (due to high physical collaboration). The least collaborative narrative (return of the *NATION* state) leads to lowest carbon prices (44 EUR/t) and no transmission expansion after 2030. Expansion of renewable energy technologies is high in all three narratives but highest in *GREEN*, as are energy transfers, resulting in lowest carbon emissions. *NATION* is characterized by high emissions, with even some coal power active in 2050. The differences between the three analyzed narratives show quite well the costs and benefits of collaboration, on a system as well as on a regional level. Moving away from our benchmark narrative, EU, can be interpreted as beneficial in terms of lower electricity prices and lower abatement costs when collaboration increases (*GREEN*). Heading into the direction of a non-collaborative world (*NATION*) leads to costs much higher than the possible benefits from a *GREEN* revolution. There might even be additional "costs" when considering distributional impacts. A return of the *NATION* state leads to more differences between countries in terms of the burden of decarbonization and electricity prices. However, in all three narratives, it is the poor countries that carry the highest burden of decarbonization by having effectively the highest electricity prices per unit of GDP.

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 renewable energy. Those non-collaborative actions also prevent a convergence of abatement burdens and electricity prices across Europe. However, climate policy or physical collaboration in terms of transmission grid expansion across countries is not a panacea to address distributional differences in Europe. Given that rich countries stay rich and poor countries stay poor (in relative terms), the GDP-normalized electricity prices remain low in the rich countries and high in the poorest ones (entire Eastern Europe, Greece, and Portugal).

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., [34]). 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.

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.

CRediT author statement

Mathias Mier: Conceptualization, Methodology, Investigation, Writing - Original Draft; Kais Siala: Conceptualization, Methodology, Investigation, Visualization, Writing - Original Draft; Kristina Govorukha: Conceptualization, Methodology, Writing - Original Draft; Philip Mayer: Conceptualization, Methodology, Writing - Original Draft; Philip Mayer: Conceptualization, Methodology, Writing - Original Draft.

References

- L. Börjeson, M. Höjer, K.-H. Dreborg, T. Ekvall, G. Finnveden, Scenario types and techniques: towards a user's guide, Futures 38 (2006) 723–739.
- [2] R. Bradfield, G. Wright, G. Burt, G. Cairns, K. Van Der Heijden, The origins and evolution of scenario techniques in long range business planning, Futures 37 (2005) 795–812.
- [3] P. Bishop, A. Hines, T. Collins, The current state of scenario development: an overview of techniques, Foresight 9 (2007) 5–25.
- [4] W. Weimer-Jehle, Cross-impact balances: A system-theoretical approach to cross-impact analysis, Technological Forecasting and Social Change 73 (2006) 334–361.
- [5] B. C. O'Neill, E. Kriegler, K. L. Ebi, E. Kemp-Benedict, K. Riahi, D. S. Rothman, B. J. van Ruijven, D. P. van Vuuren, J. Birkmann, K. Kok, M. Levy, W. Solecki, The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century, Global Environmental Change 42 (2017) 169–180.
- [6] J. Alcamo, Chapter Six The SAS Approach: Combining Qualitative and Quantitative Knowledge in Environmental Scenarios, in: [26], pp. 123–150.

- [7] P. P. Craig, A. Gadgil, J. G. Koomey, What can history teach us? A retrospective examination of long-term energy forecasts for the United States, Annual Review of Energy and the Environment 27 (2002) 83–118.
- [8] M. Zampara, M. Obersteiner, S. Evangelopoulou, A. De Vita, W. Winiwarter, H.-P. Witzke, S. Tsani, M. Kesting, L. Paroussos, L. Höglund-Isaksson, D. Papadopoulos, P. Capros, M. Kannavou, P. Siskos, N. Tasios, N. Kouvaritakis, P. Karkatsoulis, P. Fragkos, A. Gomez-Sanabria, A. Petropoulos, P. Havlík, S. Frank, P. Purohit, K. Fragiadakis, N. Forsell, M. Gusti, C. Nakos, EU reference scenario 2016 – Energy, transport and GHG emissions trends to 2050, Report, European Commission, 2016.
- [9] ENTSOs, Ten-Year Network Development Plan 2020: Scenario Report, Technical Report, ENTSO-E, ENTSO-G, 2020.
- [10] P. Raskin, F. Monks, T. Riberio, M. Z. van Vuuren, Chapter Two: Global Scenarios in historical perspective, in: S. R. Carpenter, P. L. Pingali, E. M. Bennett, M. B. Zurek (Eds.), Ecosystems and human well-being, volume 2 of *Ecosystems and human well-being: Scenarios*, Island Press, Washington DC., 2005, pp. 35–44.
- [11] V. J. Schweizer, B. C. O'Neill, Systematic construction of global socioeconomic pathways using internally consistent element combinations, Climatic Change 122 (2014) 431–445.
- [12] E. Kriegler, J. Edmonds, S. Hallegatte, K. L. Ebi, T. Kram, K. Riahi, H. Winkler, D. P. Van Vuuren, A new scenario framework for climate change research: the concept of shared climate policy assumptions, Climatic Change 122 (2014) 401–414.
- [13] B. C. O'Neill, E. Kriegler, K. Riahi, K. L. Ebi, S. Hallegatte, T. R. Carter, R. Mathur, D. P. van Vuuren, A new scenario framework for climate change research: the concept of shared socioeconomic pathways, Climatic change 122 (2014) 387–400.
- [14] T. O'Mahony, Integrated scenarios for energy: A methodology for the short term, Futures 55 (2014) 41–57.
- [15] J.-C. Hourcade, M. Jaccard, C. Bataille, F. Ghersi, hybrid modeling: New answers to old challenges introduction to the special issue of "the energy journal", The Energy Journal (2006) 1–11.

- [16] E. Kemp-Benedict, Going from narrative to number: Indicator-driven scenario quantification, in: Recent Developments in Foresight Methodologies, Springer, 2013, pp. 123–131.
- [17] W. Weimer-Jehle, J. Buchgeister, W. Hauser, H. Kosow, T. Naegler, W.-R. Poganietz, T. Pregger, S. Prehofer, A. von Recklinghausen, J. Schippl, S. Vögele, Context scenarios and their usage for the construction of socio-technical energy scenarios, Energy 111 (2016) 956–970.
- [18] V. J. Schweizer, E. Kriegler, Improving environmental change research with systematic techniques for qualitative scenarios, Environmental Research Letters 7 (2012) 044011.
- [19] R. H. Moss, J. A. Edmonds, K. A. Hibbard, M. R. Manning, S. K. Rose, D. P. Van Vuuren, T. R. Carter, S. Emori, M. Kainuma, T. Kram, et al., The next generation of scenarios for climate change research and assessment, Nature 463 (2010) 747–756.
- [20] E. Kriegler, J. P. Weyant, G. J. Blanford, V. Krey, L. Clarke, J. Edmonds, A. Fawcett, G. Luderer, K. Riahi, R. Richels, et al., The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies, Climatic Change 123 (2014) 353–367.
- [21] E. Trutnevyte, Does cost optimization approximate the real-world energy transition?, Energy 106 (2016) 182–193.
- [22] E. Trutnevyte, J. Barton, Á. O'Grady, D. Ogunkunle, D. Pudjianto, E. Robertson, Linking a storyline with multiple models: a cross-scale study of the UK power system transition, Technological Forecasting and Social Change 89 (2014) 26-42.
- [23] T. Martinsen, Introducing technology learning for energy technologies in a national CGE model through soft links to global and national energy models, Energy Policy 39 (2011) 3327–3336.
- [24] K. S. Andersen, L. B. Termansen, M. Gargiulo, B. P. Ó. Gallachóirc, Bridging the gap using energy services: Demonstrating a novel framework for soft linking top-down and bottom-up models, Energy 169 (2019) 277–293.
- [25] H. Lee, S. W. Kang, Y. Koo, A hybrid energy system model to evaluate the impact of climate policy on the manufacturing sector: Adoption of energyefficient technologies and rebound effects, Energy 212 (2020) 118718.

- [26] J. Alcamo (Ed.), Environmental Futures: The Practice of Environmental Scenario Analysis, volume 2 of *Developments in Integrated Environmental Assessment*, Elsevier, 2008.
- [27] A. Grubler, C. Wilson, N. Bento, B. Boza-Kiss, V. Krey, D. L. McCollum, N. D. Rao, K. Riahi, J. Rogelj, S. De Stercke, J. Cullen, S. Frank, O. Fricko, F. Guo, M. Gidden, P. Havlík, D. Huppmann, G. Kiesewetter, P. Rafaj, W. Schoepp, H. Valin, A low energy demand scenario for meeting the 1.5 C target and sustainable development goals without negative emission technologies, Nature energy 3 (2018) 515–527.
- [28] T. J. Gordon, H. Hayward, Initial experiments with the cross impact matrix method of forecasting, Futures 1 (1968) 100–116.
- [29] W. Weimer-Jehle, S. Vögele, W. Hauser, H. Kosow, W.-R. Poganietz, S. Prehofer, Socio-technical energy scenarios: state-of-the-art and CIB-based approaches, Climatic change (2020) 1–19.
- [30] C. Böhringer, A. Löschel, Computable general equilibrium models for sustainability impact assessment: Status quo and prospects, Ecological economics 60 (2006) 49–64.
- [31] C. Weissbart, G. J. Blanford, A framework for modeling the dynamics of power markets – The EU-REGEN model, ifo Working Papers No. 307 (2019).
- [32] J. Dorfner, M. Dorfner, K. Schönleber, S. Candas, smuellr, dogauzrek, wyaudi, yunusozsahin, adeeljsid, T. Zipperle, S. Herzog, L. Odersky, K. Siala, O. Akca, urbs: v0.7.3: A linear optimisation model for distributed energy systems, Chair of Renewable and Sustainable Energy Systems, Technical University of Munich, 2018. doi: 10.5281/zenodo.1228851.
- [33] K. Siala, M. Mier, L. Schmidt, L. Torralba-Díaz, S. Sheykkha, G. Savvidis, Which model features matter? An experimental approach to evaluate power market modeling choices, arXiv preprint:2010.16142 (2020).
- [34] J.-P. Sasse, E. Trutnevyte, Regional impacts of electricity system transition in central europe until 2035, Nature communications 11 (2020) 1–14.

Appendix A. Translation of descriptors into quantitative models

Addressing the specific calibration process of CGE models, PACE was 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 CO₂ price of 88 EUR/t in 2050. For the implementation of the CIB narratives described above, CO₂ prices defined in the descriptors were treated as exogenous input parameters. Some other relevant factors (e.g., changes in GDP development or changes in electricity demand) were not directly implemented into PACE, since they were strongly deviating from the BAU as described in JRC-IPTS future trends. Table A.1 provides an overview of the descriptors which are translated into PACE.

Descriptor	Method of implementation
Grid infrastructure	Increase or decrease in Armington elasticities
GHG certificate prices	Direct implementation of GHG certificate price variations
Global economic co- hesion	Variation of import tariffs in relation to BAU
Energy sources and available reserves	Adjustment of national endowments of natural gas and coal in comparison to BAU
Focus of R&D	Changes in autonomous energy efficiency index for respective technologies
Incentives for RES	Adjustment of capital subsidies for electricity generation from RES

Table A.1: Translation of descriptors in PACE

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. This is why EUREGEN and urbs are used in a second step. The results from PACE are used as input for the energy system models, which quantify descriptors character-ising different market regulation regimes, technology-specific investment costs, and, in particular, interconnectivity targets that cannot be directly considered in PACE. Table A.2 provides an overview of the descriptors which are directly translated into EUREGEN and urbs.

Descriptor	Method of implementation
Grid infrastructure	Upper- and lower bounds for the model endoge- nous expansion of NTCs
GHG certificate	Direct implementation
prices	
Specific investment	Direct implementation
costs	
Perception of nuclear	Adjustments of risk premiums for the expansion
power	of nuclear power
Perception of CCS	Adaptation of the available CCS potential
Land use policy	Adaptation of the available potentials for renew-
	able energy sources
Agriculture for the	Changes in biomass potential
electricity sector	

Table A.2: Translation of descriptors in power market models

Descriptor name	Stagnation of the EU	Dash for gas	Green revolution	Return of the nation state
Specific investment costs (generation and CCS)	Moderate decrease -0.57	Moderate decrease -0.57	Moderate decrease -0.57	Weak decrease -0.21
Grid infrastructure	Moderate transmission grid expansion	No further transmission grid expansion	Further grid expansion	No further transmission grid expansion
Incentives for RES	Weak policy incentives for RES	Weak policy incentives for RES	Weak policy incentives for RES	Strong policy incentives for RES
Consumer behaviour	Raising the level of indi- vidual consumption	Raising the level of indi- vidual consumption	Raising the level of indi- vidual consumption	Sharing economy becomes popular in Europe
GHG certificate 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
Perception of nuclear power	Nuclear power is per- ceived as a high-risk tech- nology	Nuclear power is per- ceived as a high-risk tech- nology	Nuclear power is per- ceived as a high-risk tech- nology	Nuclear power is per- ceived as a high-risk tech- nology
Support for environmen- tal sustainability	Support for sustainability is high on all levels (weak 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)
Urbanization	Urbanization rate is stable	Urbanization rate is stable	Urbanization rate is stable	Urbanization rate is stable
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
Realization of the de- mand side management (DSM) potential	EU potential is moder- ately utilised	EU potential is moder- ately utilised	EU potential is moder- ately utilised	EU potential is moder- ately utilised
Demand for flexibility on the electricity market	Strongly increasing de- mand for flexibility	Moderately increasing demand for flexibility	Moderately increasing demand for flexibility	Moderately increasing demand for flexibility

Appendix B. Descriptors and narratives

Continued on next page

Descriptor name	Stagnation of the EU	Dash for gas	Green revolution	Return of the nation state
CCS accepted storage potential	Storage potential is lack- ing public acceptance	Storage potential is lack- ing public acceptance	Storage potential is lack- ing public acceptance	Storage potential is lack- ing public acceptance
Overall welfare and equality	Welfare increase and equality decreases	The welfare increase and equality decreases	Welfare and equality in- crease	Welfare growth stagnates and equality increases
Global economic cohe- sion	Trend for bilat- eral/supranational co- operation	Trend for bilat- eral/supranational co- operation	Trend for bilat- eral/supranational co- operation	Trend towards national protectionism and interna- tional competition
Gas prices	Gas independent from oil: low gas	Gas independent from oil: low gas	Gas independent from oil: low gas	Gas dependent on oil: high gas
Coal price	Stable prices +0% p.a. (real)	Stable prices +0% p.a. (real)	The trend towards low prices	High coal price $+2.5\%$ p.a. (real)
Land use policy	Policy targets towards an increase in land use for forestry	Policy targets for a higher share of natural preserva- tion	Policy targets for a higher share of natural preserva- tion	Policy targets towards an increase in land use for forestry
Regulation of the EU electricity market	Liberalized electricity markets	Liberalized electricity market	Fully integrated approach	Liberalized electricity market
Energy sources and available reserves	Available reserves of gas grow higher than the cur- rent trend. Available re- serves of coal grow lower than the current trend	Available reserves of gas grow more compared to the current trend. Avail- able reserves of coal grow less compared to the cur- rent trend	Available reserves of coal and gas grow less com- pared to the current trend	Available reserves of gas grow more compared to the current trend. Avail- able reserves of coal grow less compared to the cur- rent trend
Cooperation in Europe and political culture	Non-regulatory approach (Autarky)	Non-regulatory approach (Autarky)	Full harmonization approach	Non-regulatory approach (Autarky)
Agriculture for the elec- tricity 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
Population growth	No population growth	No population growth	Population increases by 0.12% p.a.	No population growth

Appendix B – Continued from previous page

Appendix C. Description of the narrative Dash for gas

Global economic cohesion is hindered by the failure of large trade and cooperation agreements relying on strong bilateral liaisons, thereby inducing a moderate economic growth of the European region. It is accompanied by disentangled policy actions on the European level, autarky and national protectionism. Thus, stringent plans for the expansion of the transmission system are in place, allowing for no other projects than the ones already agreed upon (TYNDP 2018). The design of ETS ensures a moderate increase in CO_2 prices that reach 132 EUR/t in 2050. Due to the growth of the available gas reserves and the development of the LNG infrastructure, the demand for flexibility services is comparatively low, despite the increasing share of variable RES penetrating the market. The focus of R&D is shifted to projects aimed to retain the persistent shares of fossil fuels in the European generation mix. In contrast to these developments, citizens' attitudes towards sustainability remain strong, which is also true for the *EU* narrative, but now the regulator is encouraged to set stricter rules for national preservation areas, indirectly limiting potentials for land-specific RES installations and bioenergy sector.

Appendix D. Narrative results from PACE

Commodity	Narrative	2015	2020	2025	2030	2035	2040	2045	2050
	EU	40.26	41.02	41.34	41.68	42.22	42.72	43.34	43.86
Oil	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
	EU	8.35	8.26	8.16	8.05	7.95	7.86	7.79	7.72
Coal	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
	EU	20.65	20.43	20.20	19.91	19.66	19.46	19.28	19.10
Gas	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
	EU	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00
Lignite	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
	EU	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00
Bioenergy	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
	EU	7.75	15.00	22.00	27.00	56.00	68.00	102.00	132.00
$\rm CO_2$	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 D.1: Average commodity prices by narrative

Table D.2: GDP per capita by narrative

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

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

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

Appendix E. Evaluation metrics

E.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 Qacross 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.,

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

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.

E.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.,

$$Z^{\text{EUREGEN}} = \min_{\mathbf{Q}, \mathbf{Y}} \sum_{t} \delta(t) \sum_{r} C_{r}(t), \qquad (E.1)$$

where Z^{EUREGEN} is the cost function for EUREGEN, and **Q** and **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.,

$$Z^{\text{urbs}}(t) = \min_{\mathbf{Q},\mathbf{Y}} \sum_{r} C_{r}(t) .$$
(E.2)

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

E.3. Emission intensity

Let $E_r(t)$ be the CO₂ emissions on a country-level from the respective power market model. The emission intensity per unit of energy then follows from

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

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

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

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

E.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 CO₂ 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.,

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

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

$$IC_{r}(t) = \sum_{v \leq t} \sum_{j} c_{j,r}^{cap}(v) \left(Q_{j,r}(v) - Q_{j,r}^{pipe}(v) \right) \Lambda_{j}(v,t) a_{j}(v) + \\ \sum_{v \leq t} \sum_{k,r'} \frac{1}{2} c_{k,r \to r'}^{cap} \left(Q_{k,r \to r'}(v) - Q_{k,r \to r'}^{pipe}(v) \right) \Lambda_{k}(v,t) a_{k}(v) + \\ \sum_{v \leq t} \sum_{k,r'} \frac{1}{2} c_{k,r' \to r}^{cap} \left(Q_{k,r' \to r}(v) - Q_{k,r' \to r}^{pipe}(v) \right) \Lambda_{k}(v,t) a_{k}(v), \quad (E.7)$$

$$FC_{r}(t) = \sum_{v \leq t} \left[\sum_{j} c_{j,r}^{fom}(v,t) Q_{j,r}(v,t) + \right]$$

$$\frac{1}{2} \sum_{k,r'} \left(c_{k,r \to r'}^{\text{fom}}(v,t) \, Q_{k,r \to r'}(v) + c_{k,r' \to r}^{\text{fom}}(v,t) \, Q_{k,r' \to r}(v) \right) \right], \quad (E.8)$$

$$VC_{r}(t) = \sum_{v \le t} \sum_{j} \left(c_{j,r}^{\text{vom}}(v,t) + c_{j,r}^{\text{fuel}}(v,t) + c_{j,r}^{\text{CO}_{2}}(v,t) \right) Y_{j,r}(h,v,t).$$
(E.9)

Equation (E.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 (E.8) corresponds to fixed cost, and equation (E.9) to variable cost.

E.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^{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:

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

$$\zeta = \sum_{t} \left(E(t) - \widetilde{E}^{\text{PACE}}(t) \right)$$
(E.11)

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

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

E.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:

$$D_{r}(h,t) = \sum_{j} Y_{jr}(h,t) + \sum_{k} \sum_{r'} Y_{k,r-r'}(h,t), \qquad (E.13)$$

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

Equation (E.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 (E.14) is the resource adequacy constraint. Secured capacity (right side of the equation) must always be sufficient to meet demand in the countryspecific 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 (E.13) and μ (E.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

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

We calculate annual, regional values from

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

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

$$\overline{p\left(t\right)} = \frac{\sum_{r,h} p_r\left(h,t\right) D_r\left(h,t\right)}{\sum_{r,h} D_r\left(h,t\right)}.$$
(E.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

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

E.7. GDP-normalized electricity price index

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

$$g_r(t) = \frac{\text{GDP}_r(t)}{\text{POP}_r(t)}, \qquad (E.19)$$

$$\overline{g(t)} = \frac{\sum_{r} \text{GDP}_{r}(t)}{\sum_{r} \text{POP}_{r}(t)}.$$
(E.20)

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

$$\pi_r^{\text{GDP}}(t) = \pi_r(t) \cdot \frac{\overline{g(t)}}{g_r(t)}$$
(E.21)

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



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