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# Collaboration, Decarbonization, and Distributional Effects

Abstract

We conduct a hybrid scenario exercise to analyze decarbonization pathways of the European power market and related distributional effects across countries as well as between consumers and producers. Our CIB analysis reveals qualitative scenarios that differ in the level of political (stringency of climate policy) and physical collaboration (transmission grid expansion). We use a CGE model to quantify those scenarios for further usage in a power market model. Consumers generally experience considerably higher electricity prices, whereas producers observe higher rents. Electricity prices are lowest in the least collaborative future. Producer rents in turn are highest in the most collaborative one. Patterns hugely differ by country, making 13 countries to profiteers of the least collaborative future and 12 countries to profiteers of the most collaborative one. Only 3 countries profit from medium collaboration. Countries that profit from the most collaborative future experience substantially higher producer rents. Countries that profit from the least collaborative one in turn experience lowest electricity prices.

JEL Code: C61, Q40, Q41, Q52
Keywords: Hybrid scenario analysis, CIB method, 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 does not achieve the proposed temperature target. Legislative changes following from the *European Green Deal* would resolve those issues, at least for the climate change contribution of the European Union. 2022 energy price development in turn places pressure on delaying final implementation and reinforces disagreement of European countries about how to achieve decarbonization targets. In particular, countries face diverging national interests with regard to climate change, consumer prices, producer interests, 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 combine cross-impact balance (CIB) method (to create qualitative scenarios), computational general equilibrium (CGE) modeling (to quantify outcomes from the qualitative scenarios for further usage), and power market modeling (to obtain detailed results). We reflect sources of diverging national interest by focusing on distributional impacts across and within European countries. In particular, we analyze scenario-specific (changes in) carbon emission intensities, electricity prices, and producer rents for each of the 28 countries of the European power market, which allows us to find countries that profit from different levels of collaboration.

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 interdependencies. This way, the analysis can include softer and more diffuse concepts such as political stability or environmental awareness (e.g., Rothman et al., 2007). There are many methods for generating qualitative scenarios (Börjeson et al., 2006, Bradfield et al., 2005, Bishop et al., 2007), but the CIB method is particularly suitable for generating those with environmental and energy dynamics (Weimer-Jehle, 2006). The CIB method follows an explorative approach, discovering possible future developments without defining specific paths or normative objectives (Börjeson et al., 2006). 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.[1]

*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. Nev-

[1] Schweizer and Kriegler (2012) show retrospectively, by means of the CIB analysis, that not all underlying scenarios of the IPCC's Special Report on Emissions Scenarios achieve complete internal consistency.

ertheless, qualitative approaches and their combination with qualitative ones (*hybrid scenarios*) 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 insight, whereas a quantitative analysis offers structure, discipline, and rigor.[2] When it comes to environmental-energy dynamics, quantitative scenarios deliver a precise assessment of the implications of related policies for possible future developments and transformation pathways 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 (e.g., 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 (e.g. 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 that usually are found in the underlying narrative (Grubler et al., 2018).

Our hybrid scenario exercise determines diverging futures focusing on the decarbonization of the European power market. Applying the CIB analysis, we find 51 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 *narratives*. 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 (Towards a green revolution, *GREEN*) leads to high $CO_2$ prices (176 €/t in 2050) and the possibility of unconstrained expansion of transmission lines between countries from 2035 onwards. The least collaborative narrative (Return of the nation state, *NATION*) leads to low $CO_2$ prices (44 €/t in 2050) and no transmission grid expansion from 2035 onwards. Stagnation of the EU (*EU*) delivers the middle way with 132 €/t and possible transmission grid expansion in line with a 25% interconnectivity target. The macro-economic CGE model PACE helps to quantify some of the descriptors (e.g., fuel prices) for the power market model. Those quantified descriptors are used with further descriptors from the narratives to calibrate the power market model EUREGEN to assess the development of the European power market until 2050.

The coupling of the CGE model with the power market model via the CIB method ensures the consistency of the described context. We link CGE and power market model only one-directional

[2]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).

because the CGE model is just used as tool to translate qualitative scenario outcomes into quantitative variations of descriptors so that they can be used in the power market model. We also do not concentrate on the outcomes of the CGE model beyond the scope of the power market and beyond the quantification. We thus refrain from hard-linking those models until arriving at similar equilibria, for example, in terms of $CO_2$ prices and emissions.[3] In turn, we focus on the impact of the two dimensions of collaboration on the resulting technology mix, decarbonization, resulting $CO_2$ emission intensity, electricity prices, and producer rents. We focus on the change in emission intensity (as proxy for the level of transformation) and distributional effects across countries and between consumers and producers. In particular, we analyze electricity prices and producer rents by narrative and country to determine *profiteers* of different collaboration levels. We further analyze in which countries consumers are better (or worse) off (taking electricity price changes as proxy) and in which producers (taking producer rents changes as proxy).

There is a considerable amount of studies analyzing distributional effects. Most of them focus on the impact of policies. Wang et al. (2016) reviews the literature about distributional effects of carbon taxation. Landis et al. (2021) gives a comprehensive representation of distributional effects from harmonizing $CO_2$ prices in the EU between and within countries by using a multi-region CGE model with disaggregated households. The authors are only aware of econometric studies analyzing distributional effects in the power sector. Hirth and Ueckerdt (2013) find that carbon pricing increases producers surplus and decreases consumers surplus. Our results support that finding. In particular, the most collaborative narrative *GREEN* yields highest producer rents and considerable higher electricity prices. Prata et al. (2018) provide a case study for the Iberian market and shows how wind variations impact Portuguese consumers. Egerer et al. (2016) analyze distributional effects in the German electricity market assuming a Northern and Southern price zone. Also Neuhoff et al. (2013) analyze distributional effects in Germany, thereby focusing on the impact of renewables subsidies. Gambardella and Pahle (2018) in turn focuses on distributional effects across different consumer groups. Our contribution is novel to the literature by using an intertemporal optimizing (i.e., assuming perfect foresight) power market model to analyze long-run changes in distributional effects. Our driving force is not a particular policy (such as carbon pricing or renewables subsidies) but rather a possible state of the future containing different intensities of carbon pricing (political collaboration) and possible grid expansion (physical collaboration).

There are only few studies analyzing the effect of collaboration (Sueyoshi, 2010, Göransson et al., 2019, Weissbart, 2020). The authors are not aware of any study analyzing jointly the impact of collaborative efforts and distributional impacts. In particular, this is the first paper determining the impact of collaboration on the decarbonization of power market.[4] This is also the only other paper besides Landis et al. (2021)—at least as far as the authors are aware of—undertaking the task of analyzing distributional effects across a huge set of countries (here, 28 countries) for both consumers and producers.

Section 2 introduces our hybrid scenario methodology by explaining the applied CIB analysis,

[3] Böhringer and Rutherford (2008, 2009) demonstrate the methodological complexity of such a task. Our focus is not on methodological improvements of the integration (Böhringer and Rutherford, 2008) or decomposition (Böhringer and Rutherford, 2009) of bottom-up and top-down but rather on the comparison of different levels of collaboration and how those effect distributional impacts across countries and between consumers and producers.

[4] This paper is a structural advancement of Mier et al. (2020). Hybrid scenario exercise methodology and underlying data is the same. However, the focus is not on the finalization of narratives including context developments but rather on distributional effects in the power sector. Such an analysis of distributional effects is completely missing in Mier et al. (2020).

resulting narratives, used model frameworks, and how we translate CIB outcomes into CGE and power market model. Section 3 describes the most important assumptions used to calibrate the EUREGEN model. Section 4 presents basics of the EUREGEN model and our evaluation metrics used to determine electricity prices, producer rents, and $CO_2$ emission intensities. Section 5 contains results. Section 6 discusses results by giving on overall assessment. Section 7 concludes.

## 2. Methodology

### 2.1. CIB method

*Overview.* The CIB method (or analysis) assesses interactions between the defined system under investigation within the defined time horizon and social, political, technological, and economical context developments. The CIB method 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) introduced the CIB method 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 method describes the system under investigation and provides a systematic depiction of relevant descriptors, their possible future developments (*variations*), and their mutual interdependence (*cross-impacts*) (Gordon and Hayward, 1968). 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 method 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.

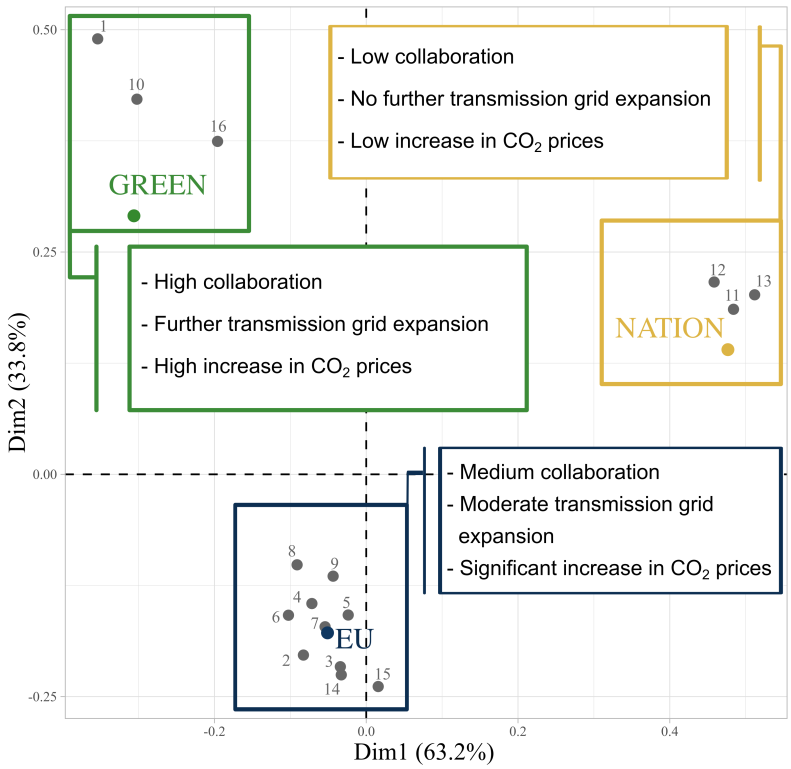
*Clustering process.* A thorough review of relevant literature and an assessment of the market structure give a comprehensive overview of the fundamental elements of the European power market. We identify 51 key system elements at three workshops and via a questionnaire with 24 experts with varying professional backgrounds working in the field of energy economics.[5] The workshops result in the selection of 22 descriptors that cover four key categories (social, political, technological, economical) and their respective interactions.[6] Our CIB method yields 16 internally consistent scenarios that are grouped into three narratives: stagnation of the *EU*, towards a *GREEN* revolution, and return of the *NATION* state.[7] Figure 1 shows the landscape of scenarios and their corresponding narratives with key descriptors in two-dimensional space. 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.

[5]Appendix A contains a more detailed description of the process for conducting the CIB method.

[6]Appendix B characterizes all descriptors and describes variations. Descriptors indicated with ND are not modeled in the quantifying tasks of the hybrid scenario exercise but rather serve as context descriptors only.

[7]Appendix C gives a complete representation of the scenario landscape including narrative-affiliation with all descriptors and variations.

Figure 1: Landscape of scenarios (1–16, in gray) and narratives (*NATION*, *EU*, and *GREEN*) with 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.

Narratives must be interpreted as vectors with the length equal to the total number of descriptors and values corresponding to the effective variation of the descriptor. Color dots present the center mass of the respective scenario group (narrative) relative to the other scenarios. Distances between the displayed points in the graph do not have a particular interpretation, but the relative position of the points do. This presentation allows to see the scenario clusters that have a 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. *EU* in turn is quite close to *GREEN* with regard to Dim1 but differs fundamentally in Dim2.

*Narratives.* The CIB analysis 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 (mainly D9, $CO_2$ prices). The physical dimension of collaboration describes the creation of the infrastructure necessary to achieve these objectives (mainly D2, grid infrastructure). Moreover, the descriptors ND7 (Cooperation in Europe and political culture) 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:

*NATION* with *low collaboration*: 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.

*EU* with *medium collaboration*: European cooperation in both the political and physical dimension is stagnating due to institutional and bureaucratic hurdles. This development leads to an unfavorable environment for large European-wide infrastructure investments in the energy sector.

*GREEN* with *high collaboration*: International relations are characterized by a collaborative effort to jointly solve the challenges of a transformation towards a carbon-neutral power system. Strategies at the European level to achieve climate targets are preferred to those at the country level.

### *2.2. Translation*

We apply a CGE and a power market model to quantify the narratives from the CIB analysis. The time horizon for both models 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).[8] The power market model neglects all remaining countries (of the world). The CGE model, which is used to quantify individual aspects of the CIB scenarios to provide exogenous input parameters for the power market model, groups all of them into one region and accounts for interactions of that rest-of-the-world region with the respective 28 countries.

*CGE model.* The CGE model PACE is a dynamic-recursive *top-down* multi-sector and multi-regional model (Böhringer et al., 2009). 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. PACE is set up to a business-as-usual (*BAU*) that covers all EU climate policies as currently implemented and all major macroeconomic developments (GDP, energy demand, population growth) as projected by the Joint Research Center of the European Union, Institute for Prospective Technological Studies (JRC-IPTS). In *BAU*, PACE estimates a $CO_2$ price of 88 €/t in 2050. PACE gives a consistent collection of region-specific fuel prices, trade flows of energy resources, and sector-specific energy demand.

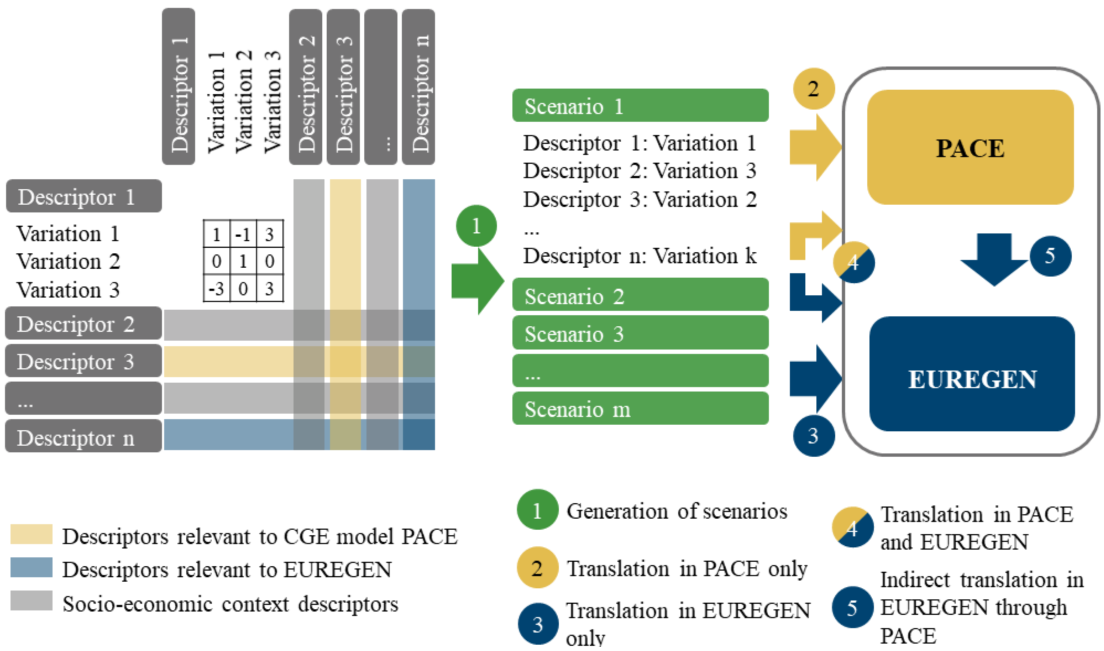
*Power market model.* EUREGEN closes the gap to PACE by providing a detailed *bottom-up* representation of the power sector. EUREGEN is a power market model that optimizes dispatch, capacity expansion, and decommissioning (generation, storage, transmission) within the European power market intertemporally.[9] EUREGEN applies an algorithm for choosing and weighting time steps to reduce the temporal complexity. It scales the timeseries so that total demand by region and full-load hours of wind, solar, and hydro technologies are consistent with annual values.

[8] We model national power markets and refrain from existing cross-country ones, as, for example, MIBEL that contains those of Portugal and Spain. The results must then be interpreted as differences that might reinforce market splitting.

[9] See Weissbart and Blanford (2019) for the basics of the model and Weissbart (2020), Mier and Weissbart (2020), Azarova and Mier (2021), Mier and Azarova (2021), Mier et al. (2021), Siala et al. (2022) for applications and updates.

*Model coupling.* Figure 2 shows the connecting structure between the CIB analysis, the CGE model PACE, and the power market model EUREGEN. Descriptors are shown on the left by the CIM. The results from the CIM are incorporated into scenarios (1), which differ in variations of descriptors. Not all descriptors can be modeled in one of the model frameworks or are redundant from the modeling perspective. We thus need to distinguish between modeled descriptors (D1 to D13) and non-modeled descriptors (ND1 to ND9).[10] Some of the modeled descriptors are directly placed into PACE (2), others are directly placed into EUREGEN (3), and a third group of descriptors is placed in both (4). Finally, the data flow (5) describes (quantitative) outcomes from PACE that are used as inputs in EUREGEN.

Figure 2: Linking process of CIB and modeling frameworks




*Translation.* We apply different translation approaches due to the diverging model structures, that is, bottom-up (power market model) vs. top-down (CGE model), technological aggregation, and varying system boundaries. Table 1 shows overlaps of descriptors which are translated into PACE as well as into EUREGEN (D2, D4). We translate the development of the European power grid structure (D2) only implicitly in PACE by adjusting the respective Armington elasticity. EUREGEN in turn considers 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 (D9) shows fundamental deviations from the *BAU* scenario price calculated by PACE (88 €/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. Next, the adjustment of energy sources and available reserves in PACE leads to consistent natural gas and coal prices (D10, D11). Those

[10] Appendix B gives a detailed interpretation of descriptors, describes variations stemming from the CIB analysis, and clarifies final implementation of descriptors in models. Appendix D summarizes modeled (Table D.3) and non-modeled descriptors (Table D.4) for each narrative.

consistent prices are directly implemented in EUREGEN. Moreover, PACE is not able to consider technology-specific investment costs of the respective technologies (D1). We thus connect PACE and D1 via descriptor D7 (R&D focus), that is, decreasing costs follow from higher focus on R&D by adjusting autonomous energy efficiency indices for respective technologies. EUREGEN implements the investment costs directly but is not able to reflect the R&D focus. This dual implementation strategy ensures that the modeling results of the frameworks remains as congruent as possible within the analyzed narratives.

Table 1: Implementation of descriptors in CGE and power market model

| No | Descriptor | CGE model (PACE) | Power market model (EUREGEN) |
|---|---|---|---|
| D1 | Investment costs | * | Direct implementation |
| D2 | Grid infrastructure | Increase or decrease of Armington elasticities for domestic and imported electricity to match power market model projections | Upper and lower bounds for the endogenous expansion of transmission capacity between neighboring countries |
| D3 | RES incentives | Adjustment of capital subsidies for electricity generation from RES (in comparison to $BAU$) | ** |
| D4 | Nuclear perception | Upper bound on input of nuclear energy | Adjustment of investment costs to reflect risk and regulatory premia |
| D5 | CCS perception | * | Adaptation of the available CCS potential and direct adjustment of investment costs to reflect risk and regulatory premia |
| D6 | Urbanization | Adjustments of urbanization rates (in comparison to $BAU$) | ** |
| D7 | R&D focus | Changes in autonomous energy efficiency index for respective technologies | ** |
| D8 | Global economic cohesion | Variation of import tariffs in relation to $BAU$ | ** |
| D9 | $CO_2$ prices | Direct implementation of $CO_2$ price variations | Implementation of changing $CO_2$ prices from CGE model outcome |
| D10 | Natural gas prices | Adjustment of country-level (and rest-of-the-world) endowments of natural gas (in comparison to $BAU$) | ** |
| D11 | Coal prices | Adjustment of country-level (and rest-of-the-world) endowments of coal (in comparison to $BAU$) | ** |
| D12 | Land use policy | * | Adaptation of country-level RES potentials |
| D13 | Agriculture for the power sector | * | Adjustments of bioenergy potential and price |

* The CGE model is not able to implement technology-specific changes beyond energy, capital, and labor inputs.
** The changes in the CGE model impact varying fuel prices, which are directly implemented in the power market model. Note that electricity demand by narrative is fixed by assumption (in the CGE model) and also the $CO_2$ variations are given from the CIB outcome.

Finally, the CIB method 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 $CO_2$ 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 ensures consistency between CIB outcome and PACE modeling results.

## 3. Calibration

We now present the most relevant data used to calibrate EUREGEN. Table 2 shows average commodity prices for oil, coal, gas, lignite, and uranium. There is almost no differences across narratives for those five commodities. In particular, oil, coal, and gas are outcomes from the CGE model and slightly differ from 2020 onwards between narratives. However, differences are in digits and thus negligible.[11] Lignite and uranium prices are the same for each narrative. Bioenergy in turn differs for *NATION*. Indeed, bioenergy prices are 50% lower in *NATION* due to descriptor D13 (agriculture for the power sector). $CO_2$ prices differ even more fundamental and are outcomes from the CGE model as well. In particular, the *EU* price is 50% above the 88 €/ton in 2050 (the price from the PACE business-as-usual). The *NATION* price in turn is 50% lower and the *GREEN* price is indeed 100% higher. Finally, electricity demand also comes from the CGE model. However, the CGE model is forced to deliver the same electricity demand across narratives to make them comparable (see Subsection 2.2). Observe that electricity demand more than doubles from 3,000 TWh in 2015 to 6,200 TWh in 2050.

Table 2: Average commodity prices (€/MWh thermal), $CO_2$ prices (€/ton), and electricity demand (TWh)

| Commodity | Narrative | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Oil | | 40.26 | 41.02 | 41.34 | 41.68 | 42.22 | 42.72 | 43.34 | 43.86 |
| Coal | | 8.35 | 8.26 | 8.16 | 8.05 | 7.95 | 7.86 | 7.79 | 7.72 |
| Gas | | 20.65 | 20.43 | 20.20 | 19.91 | 19.66 | 19.46 | 19.28 | 19.10 |
| Lignite | | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 |
| Uranium | | 2.33 | 2.33 | 2.33 | 2.33 | 2.33 | 2.33 | 2.33 | 2.33 |
| Bioenergy | NATION | 12 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| | EU & GREEN | | 12 | 12 | 12 | 12 | 12 | 12 | 12 |
| $CO_2$ | NATION | 7.75 | 15 | 18 | 19 | 34 | 34 | 42 | 44 |
| | EU | | | 22 | 27 | 56 | 68 | 102 | 132 |
| | GREEN | | | 23 | 31 | 68 | 85 | 132 | 176 |
| Electricity demand | | 3,017 | 3,089 | 4,153 | 4,500 | 5,081 | 5,480 | 5,830 | 6,204 |

Presented prices for oil, coal, and gas are outcomes from the CGE model PACE for *EU*. Differences to *NATION* and *GREEN* are negligible. Lignite and uranium prices depend on assumptions as does the bioenergy price for *EU* and *GREEN*. The lower bioenergy price for *NATION* is a narrative outcome (D13). $CO_2$ prices again are outcomes from the CGE model but driven by narrative outcomes (D9). Electricity demand is also an outcome from the CGE model but the CGE model is set-up so that electricity demand is the same for each narrative.

[11] The presented values refer to the *EU* narrative.

Table 3 shows investment cost and depreciation times for generation, storage, and transmission technologies. D1 (investment costs) sets the general trend for investment cost. D4 (nuclear perception) and D5 (CCS perception) force differences in investment cost across narratives. In particular, CCS technologies are structurally cheaper in *NATION* because perception of CCS is higher. In turn, perception of nuclear power is lower so that nuclear investment cost do not observe a decreasing trend over time. Note that CCS does not only comes with 20% lower efficiencies but also additionally carbon storage cost in the range of 12 to 15 €/ton (depending on the respective country). For all remaining technologies, investment cost do not differ.[12]

Table 3: Investment cost and depreciation time (in years) for generation (€/kW), storage (€/kW), and transmission (€/MW per km) technologies

| | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 | Depreciation |
|---|---|---|---|---|---|---|---|---|---|
| Bio-CCS | 4,361 | 4,361 | 4,272 | 4,272 | 4,228 | 4,183 | 4,183 | 4,139 | 25 |
| in *NATION* | 4,317 | 4,317 | 4,183 | 4,094 | 3,961 | 3,827 | 3,694 | 3,605 | |
| Coal-CCS | 3,415 | 3,415 | 3,278 | 3,210 | 3,176 | 3,142 | 3,142 | 3,108 | 40 |
| in *NATION* | 3,381 | 3,381 | 3,210 | 3,077 | 2,975 | 2,875 | 2,775 | 2,707 | |
| Gas-CCS | 1,495 | 1,495 | 1,495 | 1,495 | 1,495 | 1,495 | 1,495 | 1,495 | 25 |
| in *NATION* | 1,480 | 1,480 | 1,464 | 1,433 | 1,401 | 1,368 | 1,320 | 1,302 | |
| Nuclear | 6,006 | 6,006 | 5,346 | 5,082 | 4,818 | 4,488 | 4,488 | 4,356 | 40 |
| in *NATION* | 6,600 | 6,600 | 6,600 | 6,600 | 6,600 | 6,600 | 6,600 | 6,600 | |
| Bioenergy | 3,489 | 3,489 | 3,418 | 3,418 | 3,382 | 3,346 | 3,346 | 3,311 | 25 |
| Coal | 1,500 | 1,500 | 1,440 | 1,410 | 1,395 | 1,380 | 1,380 | 1,365 | 40 |
| Gas-CCGT | 850 | 850 | 850 | 850 | 850 | 850 | 850 | 850 | 25 |
| Gas-OCGT | 437 | 437 | 437 | 437 | 437 | 437 | 437 | 437 | 25 |
| Gas-ST | 850 | 850 | 850 | 850 | 850 | 850 | 850 | 850 | 25 |
| Geothermal | 11,993 | 11,993 | 11,622 | 11,498 | 11,251 | 11,127 | 11,004 | 11,004 | 30 |
| Lignite | 1,640 | 1,640 | 1,640 | 1,640 | 1,640 | 1,640 | 1,640 | 1,640 | 40 |
| Oil | 822 | 822 | 822 | 822 | 822 | 822 | 822 | 822 | 25 |
| Solar PV | 1,027 | 1,027 | 936 | 858 | 819 | 780 | 741 | 715 | 25 |
| Wind offshore | 3,024 | 3,024 | 2,700 | 2,520 | 2,376 | 2,268 | 2,160 | 2,088 | 25 |
| Wind onshore | 1,397 | 1,397 | 1,368 | 1,339 | 1,325 | 1,310 | 1,310 | 1,296 | 25 |
| Power-to-gas | 1,520 | 1,520 | 1,520 | 1,520 | 1,520 | 1,520 | 1,520 | 1,520 | 20 |
| Battery | 1,740 | 1,740 | 1,440 | 1,120 | 1,120 | 780 | 780 | 440 | 16 to 22 |
| AC-Line | 770 | 770 | 770 | 770 | 770 | 770 | 770 | 770 | 50 |
| DC-Cable | 1,152 | 1,152 | 1,152 | 1,152 | 1,152 | 1,152 | 1,152 | 1,152 | 50 |

Lignite and oil expansion is restricted to *NATION*. Hydro and pump storage capacity is restricted to existing capacity and we thus refrain from showing cost and depreciation times. We assume energy-to-power ratios (MWh/MW) of 720 for power-to-gas and 4 for batteries. Pump storage ratios are 4 in Slovenia (185 MW installed generation capacity) and 3,685 in Norway (1,344 MW installed generation capacity).

Note that transfer capacity cost (AC-line and DC-cable) are the same for each narrative but possible expansion is restricted. *NATION* uses the ten-year-network-development-plan (TYNDP, see ENTSOE, 2020) as lower and upper bound until 2030. Bounds do not increase from 2035

[12]We refrain from depicting fixed and variable cost because those differ for existing and newly build capacities in each period (at least for variable cost due to changing commodity prices) and for each period of installation (for fixed and variable cost), which makes the depiction overwhelming. Moreover, fuel prices and investment cost together with $CO_2$ are the driving forces of technology deployment.

onwards. *EU* uses the TYNDP as lower bound and a 25% interconnectivity target as upper bound. Note that the 25% interconnectivity target is dynamically changing over time because electricity demand (and thus load) more than doubles from 2015 to 2050. *GREEN* uses the TYNDP as lower bound until 2030 as well, and 25% interconnectivity as lower bound from 2035 onwards. Upper bounds until 2030 are set by 25% interconnectivity and are free from 2035 onwards. Moreover, transfer capacity needs to be build in both directions. In particular, the exporting country always carries the cost burden. We do so to avoid underestimation of transfer capacity cost due to the fact that politically boundaries often restrict used capacity below the available level.

## 4. Evaluation metric

EUREGEN uses the installed capacity $Q$ across the vintages $v = 1960, 1965, ..., 2050$ to generate $Y$ in hour $h$ and period $t = 2015, 2020, ..., 2050$ to meet demand $D$. The model is capable of expanding the capacities by installing capacity $IQ$ starting from $t = 2020$. $Q$ is equal to $IQ$ in the period of installation but endogenous decommissioning can reduce capacity below installed one in future periods. $Q$ vanishes when $IQ$ reaches the end of its lifetime.

*Generation.* Let $i$ denote a generation technology and $r$ a country within the European power market. In the following equations, $i$ and $r$ are used as subscripts, whereas $h$, $v$, and $t$ are shown in parentheses. For example, $Y_{i,r}(h, v, t)$ is the generation in hour $h$ and period $t$ of capacity $Q_{i,r}(v, t)$ that is originally installed as $IQ_{jr}(v)$ in period $v$. Moreover, generation is restricted by capacity, $Y_{i,r}(h, v, t) \leq \alpha_{i,r}(h, v) Q_{i,r}(v, t)$, where $\alpha_{i,r}(h, v) \in [0, 1]$ is the hourly availability of capacity.

*Storage.* Let $j$ denote a storage technology that can be used for discharge ($Y^{dis}$) and charge ($Y^{cha}$). Discharge and charge is restricted by charge and discharge capacity (assumed to be the same), i.e., $Y^{dis}_{j,r}, Y^{cha}_{j,r} \leq Q_{j,r}(v, t)$, and the storage balance: $B_{j,r}(h, v, t) = B_{j,r}(h-1, v, t) \eta^{bal}_{j,r} - Y^{dis}_{j,r} + Y^{cha}_{j,r} \eta^{cha}_{j,r} \leq Q^{sto}_{j,r}(v, t)$. $\eta \in (0, 1)$ indicate efficiency losses from operations. In particular, $\eta^{bal}$ is the hourly storage efficiency (how much is left after one hour), $\eta^{cha}$ is the charge efficiency (how much arrives at the storage), and $Q^{sto}$ the storage capacity.

*Transmission.* Let $k$ denote a transmission technology and $r \to r'$ a country pair that is eligible for transmission exchange. $Y_{k,r \to r'}$ is the amount of exports from $r$ to $r'$ and restricted by the transmission capacity, i.e., $Y_{k,r \to r'}(h, v, t) \leq Q_{k,r \to r'}(v, t)$.

*Optimization problem.* EUREGEN minimizes the stream of investment cost $IC$ from investing into capacity $IQ$ at cost $c^{IQ}$, fixed cost $FC$ from operating and maintaining capacity $Q$ at cost $c^{Q}$, and variable cost $VC$ from generation $Y$ at cost $c^{Y}$ (including cost for fuel and $CO_2$) over the entire time horizon (2015 to 2050) applying discounting ($\delta(t)$ is the discount factor), i.e.,

$$\min_{\mathbf{IQ}, \mathbf{Q}, \mathbf{Y}} \sum_{t} \delta(t) \sum_{r} \left( IC_r(t) + FC_r(t) + VC_r(t) \right), \tag{1}$$

where $\mathbf{IQ}$, $\mathbf{Q}$, and $\mathbf{Y}$ are the vectors of investment, capacity, and production decisions for all generation, storage, and transmission technologies.

*Demand constraints.* EUREGEN optimizes the power system subject to multiple constraints. We refrain from presenting each constraint (see Weissbart and Blanford (2019) for the basics of the EUREGEN model) but the most important ones are the *demand-equal-supply constraint* that enforces that generation must reach a certain level (that grows over time) and the *resource adequacy constraint* that ensures that there is sufficient secured capacity, i.e.,

$$
\begin{aligned}
\frac{D_r(h,t)}{\eta_r^{loss}} &= \sum_{v\le t}\sum_i Y_{i,r}(h,t) + \\
&\sum_{v\le t}\sum_j \left(Y_{j,r}^{dis}(h,v,t)\,\eta_{j,r}^{dis} - Y_{j,r}^{cha}(h,v,t)\right) + \\
&\sum_{v\le t}\sum_k\sum_{r'}\left(Y_{k,r\to r}(h,v,t) - \frac{Y_{k,r\to r'}(h,v,t)}{\eta_{k,r\to r'}^{exp}}\right), \qquad (2)
\end{aligned}
$$

$$
\frac{D_r(h_{r,peak},t)}{\eta_r^{loss}} \le \sum_{v\le t}\left[\sum_i \beta_i Q_{ir}(v,t) + \sum_j \beta_j Q_{jr}(v,t) + \sum_k\sum_{r'}\beta_k Q_{k,r'\to r}(v,t)\right]. \qquad (3)
$$

Equation (2) is the demand-equals-supply constraint. The total amount generated (right side of the equation) must exactly match demand (left side of the equation) including distribution grid losses—reflected by the distribution grid efficiency $\eta^{loss}$, i.e., more than one generation unit is necessary to deliver one unit to final consumers. Observe that storage discharge contributes in meeting the constraint (subject to the discharge efficiency $\eta^{dis}$), whereas storage charge hampers meeting demand. Note that discharge is taken from the storage and each unit taken from the storage leads to less than one unit on the market. Charge in turn is directly taken from the market (and leads to less than one unit in the storage, as reflected in the storage balance). Moreover, imports (indicated by $r' \to r$) contribute in meeting demand as well, whereas exports ($r \to r'$, subject to export efficiency $\eta_k^{exp} \in (0,1)$) hamper meeting demand. The implicit assumption is that efficiency losses from transmission are born on the exporting side.

Equation (3) 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 $\beta$ to determine the secured capacity. For example, $\beta = 0.898$ for coal power plants and $\beta = 0.1$ for all transmission technologies. Note that charge and discharge capacity is the same and transmission capacity matters only on the importing side.

*Electricity prices.* $\lambda$ (for Equation (2)) and $\mu$ (for Equation (3)) are the corresponding Lagrangian or Karush-Kuhn-Tucker multipliers, respectively, of the optimization problem. The multipliers are measured in net present value terms because the objective is to minimize the net present value of cost (due to discounting). We need to re-discount marginals by dividing with the discount factor to obtain the hourly price $p$ in current values, i.e.,

$$
p_r(h,t) = \frac{\lambda_r(h,t) + \mu_r(h,t)}{\delta(t)}. \qquad (4)
$$

Such a price includes the mark-up from the resource adequacy constraint, which reflects the existence of a reserve market on top of an energy-only market. The annual electricity price follows from

$$
p_r(t) = \frac{\sum_h p_r(h,t)\,D_r(h,t)}{\sum_h D_r(h,t)}. \qquad (5)
$$

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

$$\overline{p}(t) = \frac{\sum_{r,h} p_r(h,t)\, D_r(h,t)}{\sum_{r,h} D_r(h,t)}. \tag{6}$$

*Producer rents.* Producer rents can be calculated for each region by taking the difference between revenues from selling electricity and regional investment, fixed, and variable cost. We take into account whether an investment is still under depreciation. Let $\Lambda$ be a binary parameter that takes the value 1 when the investment is still under depreciation and 0 else, i.e.,

$$\Lambda(v,t) = \begin{cases} 1 & \text{if } t \leq v + t_{depr}(v), \\ 0 & \text{if } t > v + t_{depr}(v), \end{cases} \tag{7}$$

where $t_{depr}(v)$ is the depreciation time of an investment. We assume that an investment is financed by lended capital only and investment cost already contain a mark-up to deliver a return on investment. The annuity factor $a$ reflects a constant stream of interests ($\nu$ is the interest rate, assumed to be 7%) and repayment, i.e.,

$$a(v) = \frac{\nu(1+\nu)^{t_{depr}(v)}}{(1+\nu)} - 1. \tag{8}$$

Assuming that each country bears cost of providing and maintaining the exporting side of transmission lines, we calculate cost (in country $r$ and period $t$) from

$$\begin{aligned} IC_r(t) &= \sum_{v\leq t}\sum_{i} c^{IQ}_{i,r}(v)\, IQ_{i,r}(v)\, \Lambda_i(v,t)\, a_i(v) + \\ &\quad \sum_{v\leq t}\sum_{j} c^{IQ}_{j,r}(v)\, IQ_{j,r}(v)\, \Lambda_j(v,t)\, a_j(v) + \\ &\quad \sum_{v\leq t}\sum_{k,r'} c^{IQ}_{k,r\to r'} IQ_{k,r\to r'}(v)\, \Lambda_k(v,t)\, a_k(v), \end{aligned} \tag{9}$$

$$\begin{aligned} FC_r(t) &= \sum_{v\leq t}\sum_{i} c^{Q}_{i,r}(v,t)\, Q_{i,r}(v,t) + \\ &\quad \sum_{v\leq t}\sum_{j} c^{Q}_{j,r}(v,t)\, Q_{j,r}(v,t) + \\ &\quad \sum_{v\leq t}\sum_{k,r'} c^{Q}_{k,r\to r'}(v,t)\, Q_{k,r\to r'}(v), \end{aligned} \tag{10}$$

$$VC_r(t) = \sum_{v\leq t}\sum_{h}\sum_{i} c^{Y}_{i,r}(v,t)\, Y_{i,r}(h,v,t), \tag{11}$$

$$\begin{aligned} VC^*_r(t) &= \sum_{v\leq t}\sum_{h}\sum_{j} p_r(h,t)\, Y^{cha}_{j,r}(h,v,t) + \\ &\quad \sum_{v\leq t}\sum_{h}\sum_{k,r'} p_r(h,t)\, Y_{k,r\to r'}(h,v,t)\, \frac{1-\eta^{exp}_{k,r\to r'}}{\eta^{exp}_{k,r\to r'}}. \end{aligned} \tag{12}$$

Equation (9) calculates the investment cost. The first line shows cost from generation technologies, the second from storage technologies, and the third from transmission technologies. Observe that $v \leq t$ indicates the current cost from all capacities that are already installed. Equation (10) corresponds to fixed cost, and Equation (11) to variable cost. Observe that there are no variable cost of storage and transmission operations but rather losses reflected by the respective efficiencies. Those cost does not matter from the system perspective but do so for calculating country-specific producer rents. We thus add $VC^*$ in Equation (12) to account for cost from producers perspective. In particular, firms need to pay for storage charge (first line) and face cost of exporting losses. Here, the fraction $\frac{1-\eta^{exp}}{\eta^{exp}}$ presents the transmission losses of exporting one unit to a neighboring country. Cost of this loss are opportunity cost of not selling this electricity at the current price domestically.

Total revenues $R$ follow from selling electricity domestically and abroad, i.e.,

$$\begin{aligned} R_r(t) \;=\; & \sum_{v\leq t}\sum_h p_r(h,t)\left(\sum_i Y_{i,r}(h,v,t)+\sum_j Y_{j,r}^{dis}(h,v,t)\,\eta_{j,r}^{dis}\right)+ \\ & \sum_{v\leq t}\sum_h\sum_{r'} p_{r'}(h,t)\sum_k Y_{k,r-r'}(h,v,t)\,. \end{aligned} \tag{13}$$

The first line of Equation (13) are domestic revenues from selling electricity (domestic rents). Firms sell less than one unit on the market when discharging one unit, which is reflected by the discharge efficiency $\eta^{dis} \in (0,1)$. The second line are revenues from selling abroad (transfer rents). The relevant price is the price of the importing country $p_{r'}$. Observe that revenues from transmission are not subject to losses due to the specification of export efficiencies. Profits then follow from $\Pi_r(t) = R_r(t) - IC_r(t) - FC_r(t) - VC_r(t) - VC_r^*(t)$. We divide by the regional demand to make profits for generators and prices for consumers comparable. In particular, the rent is given by $\pi_r(t) = \Pi_r(t) / \sum_h D_r(h,t)$. European rents $\overline{\pi}(t)$ calculate from regional rents in the same way as European prices from regional ones (see Equation (6)).

Observe that revenues follow from selling generation, thereby neglecting distribution grid losses. We thus implicitly assume that distribution grid losses are not carried by producers but rather consumers, for example, via regular network charges as it is the case in most European countries. Such assumption is also the main reasoning for adding cost $VC^*$ (Equation (12)) to the producer perspective of cost, whereas it is not necessary to do so in the objective of the cost minimization problem (Equation (1)).

*Surplus loss.* Note that producer rents are calculated per unit of demand to make electricity prices and rents comparable in size. We can then compare the *change* in electricity prices (as proxy for a change in consumer surplus) and producer rents (as proxy for a change in producer surplus) to make an assessment how the transformation of the system effects each country, consumers, and producers. In particular, $\Delta p = p(\text{"2050"}) - p(\text{"2015"})$ is the *change* in electricity prices and $\Delta\pi = \pi(\text{"2050"}) - \pi(\text{"2015"})$ is the change in producer rents. Note that positive electricity price changes make consumers worse off and positive rent changes are good for producers. Thus, $\Delta p - \Delta\pi$ is a measure of *surplus loss* change. Such a metric normalizes initial endowments by taking 2015 values as starting point and allows us to determine relative profiteers of the respective narratives, that is, whether (or not) a country is better of with the one or the other narrative. Such a metric is useful when the overall tendency (the absolute level of surplus loss) seems to be unavoidable due to existing resource potentials of the country itself or neighboring countries.

*Emission intensities.* Let $E_r(t)$ be the $CO_2$ emissions on a country-level. The emission intensity per unit of energy then follows from

$$e_r(t) = \frac{E_r(t)}{\sum_h D_r(h,t)}. \tag{14}$$

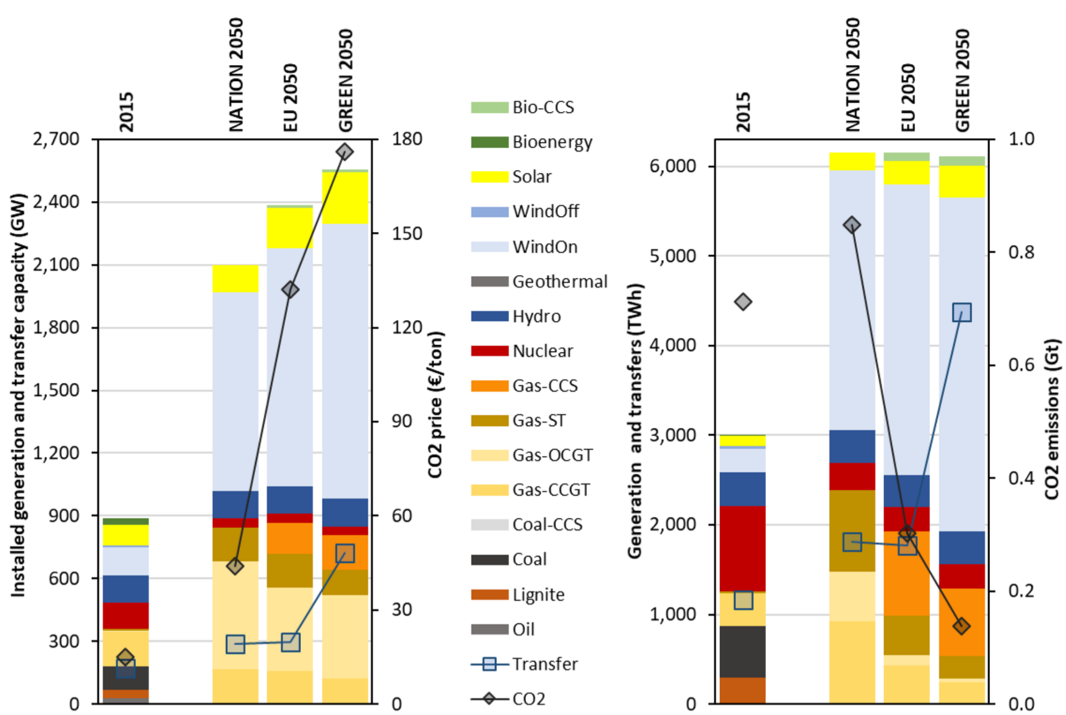
European emission intensities $\overline{e}(t)$ calculate from regional intensities in the same way as European prices from regional ones (see Equation (6)).

## 5. Results

### 5.1. European results

We start analyzing results by focusing on European indicators. Figure 3 consists of two panels. The left panel shows installed generation and transfer capacity (left axis, in GW) with the $CO_2$ price (right axis, in €/ton) and the right panel generation and transfers (left axis, in TWh) with $CO_2$ emissions (right axis, in Gt). Both panels shows 2015 values and compare the narratives *EU*, *GREEN*, and *NATION* for 2050. 2015 $CO_2$ prices are at 7.75 €/ton for all three narratives. Prices for all narratives increase until 2050 (*NATION* 44 €/ton, *EU* 132 €/ton, and *GREEN* 176 €/ton). Increasing generation, the $CO_2$ price development, and the possible expansion of transfer capacity are the main drivers of technology deployment. Whereas generation is the same for each narratives, the $CO_2$ price and possible transfer expansion constitute differences across narratives.

Figure 3: Technology mix, transfer volume, and resulting decarbonization by narrative




2050 wind capacity increases to 952 GW (1,140 GW, 1,315 GW) for *NATION* (*EU*, *GREEN*). 2050 solar differences are even more pronounced (132 GW, 190 GW, 245 GW). Nuclear capacity is unaffected but *NATION* heavily relies on the deployment of conventional gas (gas-CCGT, gas-ST, gas-OCGT) whereas the other two narratives use gas-CCS. Total gas capacity is still quite stable, but *EU* and *GREEN* employ (small amounts of) bio-CCS. The capacity patterns are also reflected in the generation mix. Differences between gas capacities are now considerable. Gas shares are 39% in *NATION* but only 31% in *EU* and 21% in *GREEN*. Resulting $CO_2$ emissions are thus highest for *NATION* (0.85 Gt) and lowest for *GREEN* (0.14 Gt), driven by lowest or highest $CO_2$ prices, respectively.

Differences in transfer capacity expansion and transfer volume between *EU* and *NATION* are negligible but *GREEN* expands to 724 GW in 2050 (compared to around 300 GW in the other two narratives), resulting in a final transfer volume of 4,375 TWh (compared to 1,813 TWh in *NATION* or 1,768 TWh in *EU*, respectively). Also lower biomass prices and higher biomass potentials in *NATION* do not impact results, because neither bioenergy (for all narratives) nor bio-CCS is a competitive technology due to low $CO_2$ prices (in *NATION*). Similarly, lower gas-CCS investment cost in *NATION* do not impact results either. Moreover, differences in nuclear cost do not influence the technology mix and thus prices as well as rents, because nuclear capacity and generation is stable across narratives. Thus, the diverging political collaboration is the key distinguishing feature between *NATION* and *EU*. As a consequence, price changes must be mainly dedicated to the three times higher 2050 $CO_2$ price in *EU* compared to *NATION*. The *GREEN* narrative in turn is strikingly diverging with regard to transfer capacity and volume, pushing also for higher importance of transfers.

Table 4 presents differences between narratives by showing electricity prices, producer rents, and $CO_2$ emission intensities in 2015 and 2050. 2015 electricity prices are at 37.2 €/MWh and increase over time, finally ending at 56.9 €/ton in *NATION*. Prices in *EU* and *GREEN* are structurally higher. Conversely, the producer rent is only at 0.62 €/MWh in 2015. This rent keeps almost unaffected until 2050 in *NATION* but grows considerably in *EU* and even more pronounced in *GREEN*. $CO_2$ emission intensities are at 330 kg/MWh in 2015 and fall for each narrative. *NATION* finally produces 136 kg/MWh in 2050 but *GREEN* only 22 kg/MWh. This drop in emission intensity cannot be directly observed in Figure 3 when only looking at absolute $CO_2$ emissions. Indeed, *NATION* is still a transformation narrative towards a fundamental cleaner system, which heavily relies on gas and wind power. However, the transformation processes are structurally more advanced in the other two narratives.

Table 4: Electricity prices, producer rents, surplus loss, and $CO_2$ emission intensity by narrative

| | 2015 | 2050 | | |
|---|---|---|---|---|
| | | *NATION* | *EU* | *GREEN* |
| Electricity price (€/MWh) | 37.2 | 56.93 | 67.51 | 67.26 |
| Producer rent (€/MWh) | 0.62 | 0.73 | 4.67 | 7.55 |
| $CO_2$ emission intensity (kg/MWh) | 330 | 137 | 49 | 22 |
| Electricity price change (€/MWh) | | 19.73 | 30.31 | 30.06 |
| Producer rent change (€/MWh) | | 0.11 | 4.05 | 6.93 |
| $CO_2$ emission intensity change (kg/MWh) | | -193 | -281 | -308 |
| Surplus loss change (€/MWh) | | 19.62 | 26.26 | 23.13 |

Table 4 also shows the surplus loss change. Remember that a positive value indicates transformation losses because rising electricity prices (falling rents) are bad for consumers (producers). The transformation burden is lowest in *NATION* with 19.62 €/MWh and highest in *EU*, suggesting that the non-collaborative future in *NATION* leaves Europe better off and making it to a NATION profiteer. However, the European results neglect country-specific differences. We thus analyze emissions intensities, electricity prices, producer rents, and surplus losses for all 28 countries of the European power market in the remainder of this section.

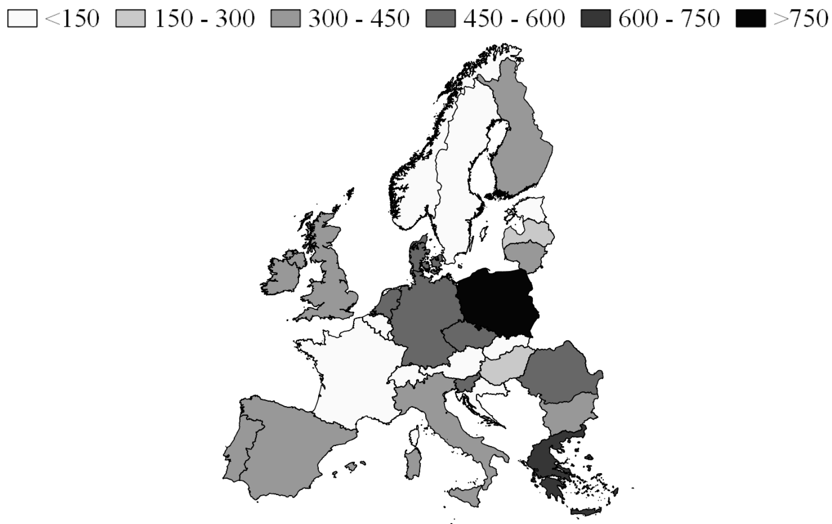
### 5.2. $CO_2$ emission intensity

Figure 4 shows specific $CO_2$ emissions at country-level (in kg/MWh). It consists of four maps depicting all countries of the European power market. Map (a) shows 2015 values. Maps (b) to (d) show 2050 values of the respective narratives *NATION*, *EU*, and *GREEN*. We use a different scale and color scheme for 2015 to better depict differences across countries (from <150 in white to >750 kg/MWh in black). 2050 maps range from <–40 in dark blue to >200 kg/MWh in intense red. In 2015, we can cluster countries into three groups. The first group contains low and zero emission countries (<150 kg/MWh) due to high hydro generation (Austria, Croatia, and Norway), high nuclear (Belgium, France, and Slovakia; Luxembourg through neighboring countries via transfers), both hydro and nuclear (Sweden, Switzerland), or substantial biomass (Estonia). The second group contains countries whose generation is dominated by conventional gas technologies (gas-CCGT, gas-ST, gas-OCGT) with specific emissions up to 450 kg/MWh (Bulgaria, Finland, Hungary, Ireland, Italy, Latvia, Lithuania, Portugal, Spain, and United Kingdom). The third group contains countries with considerable coal (and lignite) usage, so that specific emissions extend above 450 kg/MWh (Czech Republic, Denmark, Germany, Greece, Netherlands, Poland, Romania, and Slovenia). There is not a clear spatial pattern across Europe, because emission intensities are driven by past capacity planning choices (e.g., nuclear expansion in France, coal in Poland, lignite in Germany, natural gas in Italy) and the existing hydro potential. This quite diverse spatial pattern changes completely when looking at the (optimized) system transformation until 2050 in the three diverging narratives.

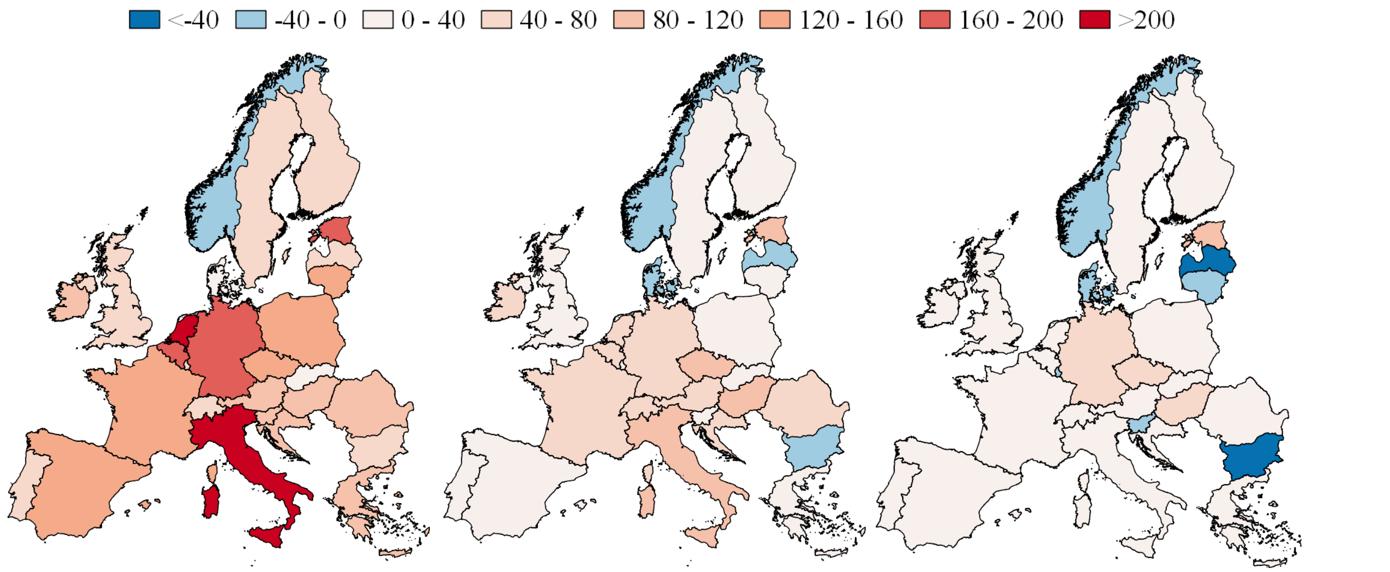
Start with *NATION*. Italy and Netherlands are now the dirtiest countries (>200 kg/MWh). Interestingly, Belgium and Estonia—both countries that belong to the first group with low emission intensities in 2015—are now considerable dirty with substantial shares of conventional gas and low production from solar and wind. Both countries have only little competitive wind spots (at the assumed $CO_2$ price). Germany keeps dirty. Coal and lignite drop out of the generation mix, but wind and solar potential is not good enough to decarbonize below 160 kg/MWh. Poland in turn uses the good wind spots at the Baltic sea and sees an extreme transformation from the dirtiest country to one comparable with European average. Norway keeps leading in emission intensity with zero emissions stemming from competitive hydro in combination with wind onshore. Slovakia keeps almost clean due to intensive use of nuclear. There is not much difference across remaining countries, but Switzerland, Sweden, and Finland keep slightly cleaner due to good hydro potential and Denmark, Portugal,, as well as United Kingdom use good wind onshore potential to reduce its emission intensity far below European average.

Next, turn to *EU*. Observe that emission intensities are substantially lower. The general reduction in emissions stems from the substitution of conventional gas by gas-CCS. The countries with highest intensities are now Czech Republic, Estonia, Hungary, and Italy (80 to 120 kg/MWh). Norway keeps clean, but Bulgaria, Denmark, and Latvia are now producing zero or even negative emissions as well due to generation from wind onshore and bio-CCS usage. Netherlands is now substantially cleaner but Italy remains one of the dirtiest countries because the good solar potential is not sufficient to meet the entire Italian demand. Interestingly, there is now quite a clear pattern of emission intensities across Europe. Central to South Europe faces highest intensities (e.g., France, Benelux, Germany, Alpine region, and Italy). Countries at the periphery of the European market in turn (e.g., Portugal, Spain, United Kingdom, Greece) have substantially lower emission intensities. The pattern is driven by the distribution of good wind spots across Europe. It is additionally complemented by good solar conditions in South-East Europe and Norwegian hydro generation.

Finally, observe that the aforementioned pattern reinforces in *GREEN*. Interestingly, Italy is




(a) 2015



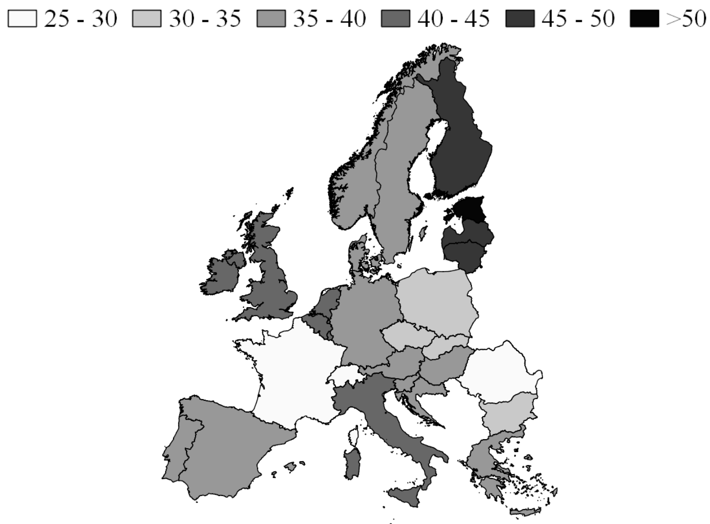

(b) *NATION* 2050 (c) *EU* 2050 (d) *GREEN* 2050

Figure 4: Specific $CO_2$ emissions (kg/MWh electric) in the power sector for European countries in 2015 and 2050 across the three narratives *NATION*, *EU*, and *GREEN*

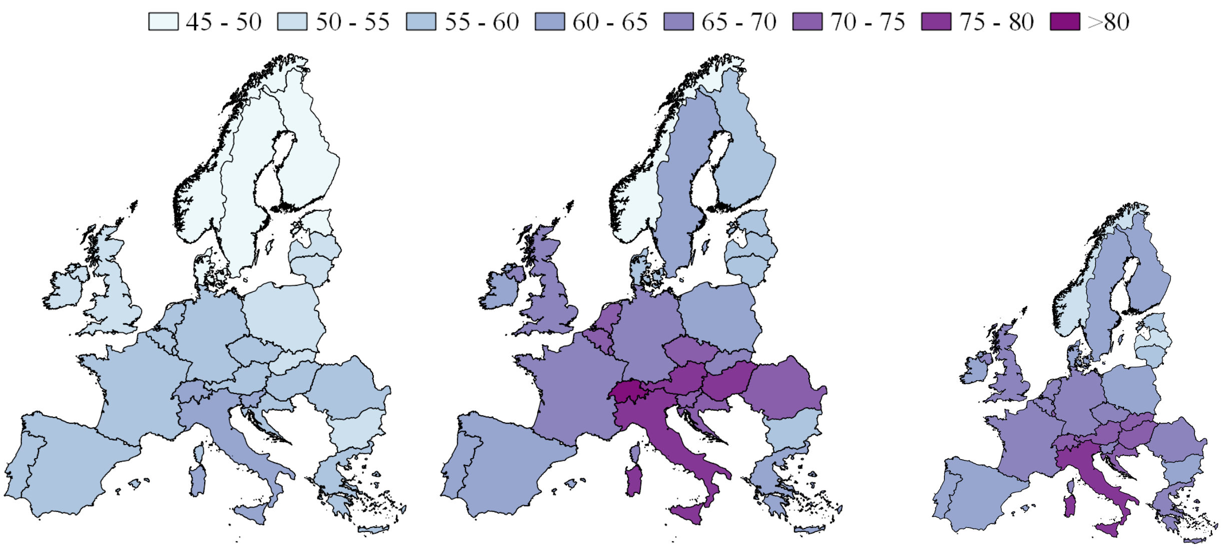
now almost carbon neutral. However, Czech Republic, Hungary, and Estonia keep on being the dirtiest countries, together with Germany that faces quite bad wind and solar potential compared to its size. Latvia and Bulgaria expand on their bio-CCS usage but in tendency the overall emission reduction stems primarily from wind onshore spots in Central and South Europe that are now competitive under *GREEN* $CO_2$ prices.

### *5.3. Electricity price*

Figure 5 compares electricity prices across European countries. The composition matches Figure 4. Start with the 2015 map that uses again a different color scheme and scale. Observe that France, Switzerland (due to nuclear) and Romania (due to lignite) face lowest electricity prices (between 25 and 30 €/MWh). Estonia in turn faces highest. The remaining Baltic countries and Finland are quite expensive as well. Norway (hydro), Poland (coal), Czech Republic (coal), Slovakia (coal and hydro), and Bulgaria (coal) belong to cheaper countries as well. Germany lies within the European average, and periphery countries such as Ireland, United Kingdom, and Italy are quite expensive, as it is the Benelux region.




(a) 2015




(b) *NATION* 2050 (c) *EU* 2050 (d) *GREEN* 2050

Figure 5: Electricity price (€/MWh) for European countries in 2015 and 2050 across the three narratives *NATION*, *EU*, and *GREEN*

Now turn to 2050 values in the *NATION* narrative. Interestingly, prices are now far more equal than before. Italy, Slovenia, and Switzerland are the most expensive countries and Northern Europe contains cheapest countries. However, the range is within 10 €/MWh, whereas 2015 values differ by more than 25 €/MWh. The main driver of this development are similar optimized power systems (in each country) that mainly rely on conventional gas technologies. Wind onshore and solar PV potentials make only minor differences and nuclear only plays a role when investments are already planned (old nuclear is mainly decommissioned). The North-South differential mainly bases in cheap hydro potential in Norway and Sweden. The systems of Estonia and Denmark as well as Finland are optimized around this hydro availability. In general, running Norwegian hydro potential in an optimized system allows for substantially lower prices than running it in non-optimized (i.e., 2015) systems.

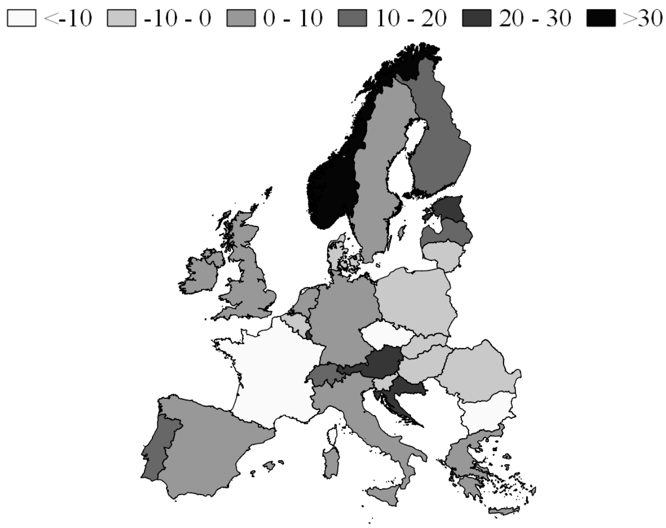
In the *EU* narrative, the pattern of prices is slightly different with substantially higher prices in Central and Southern Europe. In particular, Switzerland is the most expensive country. Switzerland indeed abandons its nuclear capacity and fills with quite expensive technologies due to little and bad wind onshore and solar PV potentials. Italy, Austria, and Hungary are also quite expensive. In turn, the countries at the periphery of the European market see substantially lower prices (e.g., Ireland due to good wind onshore potentials and Greece as well as Bulgaria due to good solar PV potentials combined with reasonable wind potential). Sweden is quite interesting here. Before, Sweden belongs to the cheapest countries but seems to suffer from tighter political collaboration. In particular, the transfer flows in Europe shift, with Sweden as pass-through country, making Sweden more expensive than before.

Turning to *GREEN*, observe that Italy is now the most expensive country, whereas Switzerland, Austria, and Hungary are now cheaper than Italy. The remaining countries are similar to the prior narrative but, in tendency, differences across countries are fundamentally smaller. In particular, Norway is still the cheapest country but expanding transfer capacity increases transfers from Norway via Sweden and Denmark to other European countries and, in turn, leads to increasing Norwegian electricity prices; making Norwegian consumers worse off from physical collaboration. However, producers in Norway might profit from that shift. We thus analyze producer rents in the next subsection.

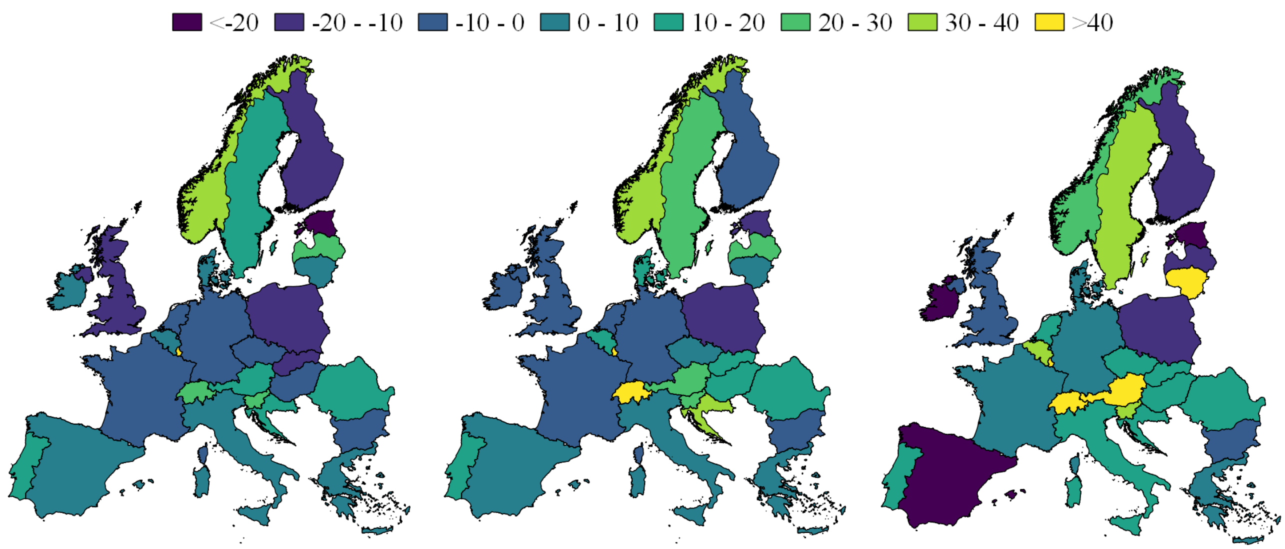
### *5.4. Producer rent*

Figure 6 shows producer rents across European countries. Again, the composition matches Figure 4 with diverging color schemes and scales for 2015 and 2050 maps. Start with 2015 values again. Norway has again an extraordinary status. Remember that Norway has reasonable high electricity prices in 2015 (between 35 and 40 €/MWh). However, Norway is the only country with rents above 30 €/MWh. Neglecting transfer rents indeed shows that Norway produces electricity at cost of around 5 to 10 €/MWh, which is only possible due to its substantial hydro potential and sunk cost considered with past investments. Austria and Croatia face similar patterns due to their high hydro production. Interestingly, France—the country with the lowest electricity prices (due to nuclear)—is also the one with the lowest producer rents (due to nuclear). Indeed, producer rents are negative, hinting that, at the used cost assumptions, the France nuclear system is based on high subsidies. Furthermore, it seems that countries at the periphery of the European market face substantially higher rents and Central European countries lower ones.

In *NATION*, the position of Norway as country with (almost) highest rents remains. Luxembourg is an interesting outlier here because it is mainly used as pass-through country with very low own production, making the producer revenues extremely high due to transfer rents. The country worst off is Estonia, a recurring extreme case in our analysis. Estonia always faces quite high emission intensities but its price pattern is in line with its region and underlying initial endowment and potentials. Regarding rents, Estonia extremely differs from neighboring countries in the optimized 2050 system with rents below –20 €/MWh. However, also Finland has quite low rents, mainly due to quite expensive nuclear that is pushed into the system due to past (non-optimized) investment decisions. Latvia in turn has substantial rents (20 to 30 €/MWh). In general, it seems that periphery-central pattern does not apply for rents anymore. In particular, countries with considerable hydro generation (Switzerland, Austria, Slovenia, Croatia, Sweden, and Norway) experience high rents. United Kingdom, France, Germany, and Poland seem to be an axis within Europe with negative producer rents, making investments in those countries quite unattractive.




(a) 2015




(b) *NATION* 2050 (c) *EU* 2050 (d) *GREEN* 2050

Figure 6: Producer rent (€/MWh) for European countries in 2015 and 2050 across the three narratives *NATION*, *EU*, and *GREEN*

Increasing collaborative actions in *EU* changes the pattern only slightly. Most countries stay where they are before. Sweden, Finland, and Estonia increase rents slightly, as does United Kingdom. Switzerland and Croatia become leading in producer rents and also Austria improves in that regard.

*GREEN* changes the status of Norway by interchanging the rent position with Sweden, which now has substantially higher rents. Indeed, Sweden's good wind potential shows merits so that hydro generation does not dominate Northern rents anymore. However, hydro generation pushes Austria to one of the top positions in terms of producer rents. Spain is an interestingly outlier with considerable negative rents (note that electricity prices keep almost unchanged between narratives). In general, the rent pattern is now more diverse compared to the other two narratives.

### 5.5. Surplus loss

Some dynamics are unavoidable for countries no matter which narrative finally realizes. Figure 7 thus plots the change in surplus loss (x-axis, in €/MWh) and the change in $CO_2$ emission intensity (y-axis, in kg/MWh) as proxy for the ongoing system transformation.[13] Outcomes for each country are depicted for all three narratives. Dots are connected via lines to mark country-affiliation. The first dot always refers to *NATION* and is marked by the respective country code, the second dot to *EU*, and the to *GREEN*.[14] The black tree is the European outcome as shown in Table 4. The *NATION* dot is the uppermost one and thus blue (lowest $CO_2$ emission intensity change). The *EU* dot is red and the one of *GREEN* is indeed green.

Observe that there is a general pattern for $CO_2$ emission intensity changes. Changes are lowest for *NATION* and generally highest for *GREEN*. Denmark and Norway are special here. Higher $CO_2$ prices in *GREEN* do not lead to deeper $CO_2$ emission intensity changes compared to *EU*. For Denmark, the competitive wind potential is already fully exploited in *EU*, so that higher $CO_2$ prices do nwot enforce further decarbonization. Changes for Norway are negligible because it is already clean due to tremendous hydro generation, leaving (almost) no space for further decarbonization.

NATION profiteers (in blue) might profit in terms of decarbonization (or transformation) from collaboration but in terms of consumer and producer surplus they actually are best with low $CO_2$ prices and no further transmission grid expansion after 2030. 13 countries (Bulgaria, Denmark, Estonia, Germany, Greece, Ireland, Italy, Latvia, Poland, Portugal, Romania, Spain, and United Kingdom) belong to that cluster. However, the level of collaboration impact not all of them similarly. For example, Denmark, Latvia, and Greece show only minor differences to the *EU* narrative in terms of surplus loss but quite extreme differences to the *GREEN* narrative, making them clear losers of such a future. In tendency, most NATION profiteers tend to be worse off with a *GREEN* future. Germany, Italy, and Romania are exceptions here. They indeed profit similarly from *NATION* and *GREEN*, but are structurally worse off with *EU*.

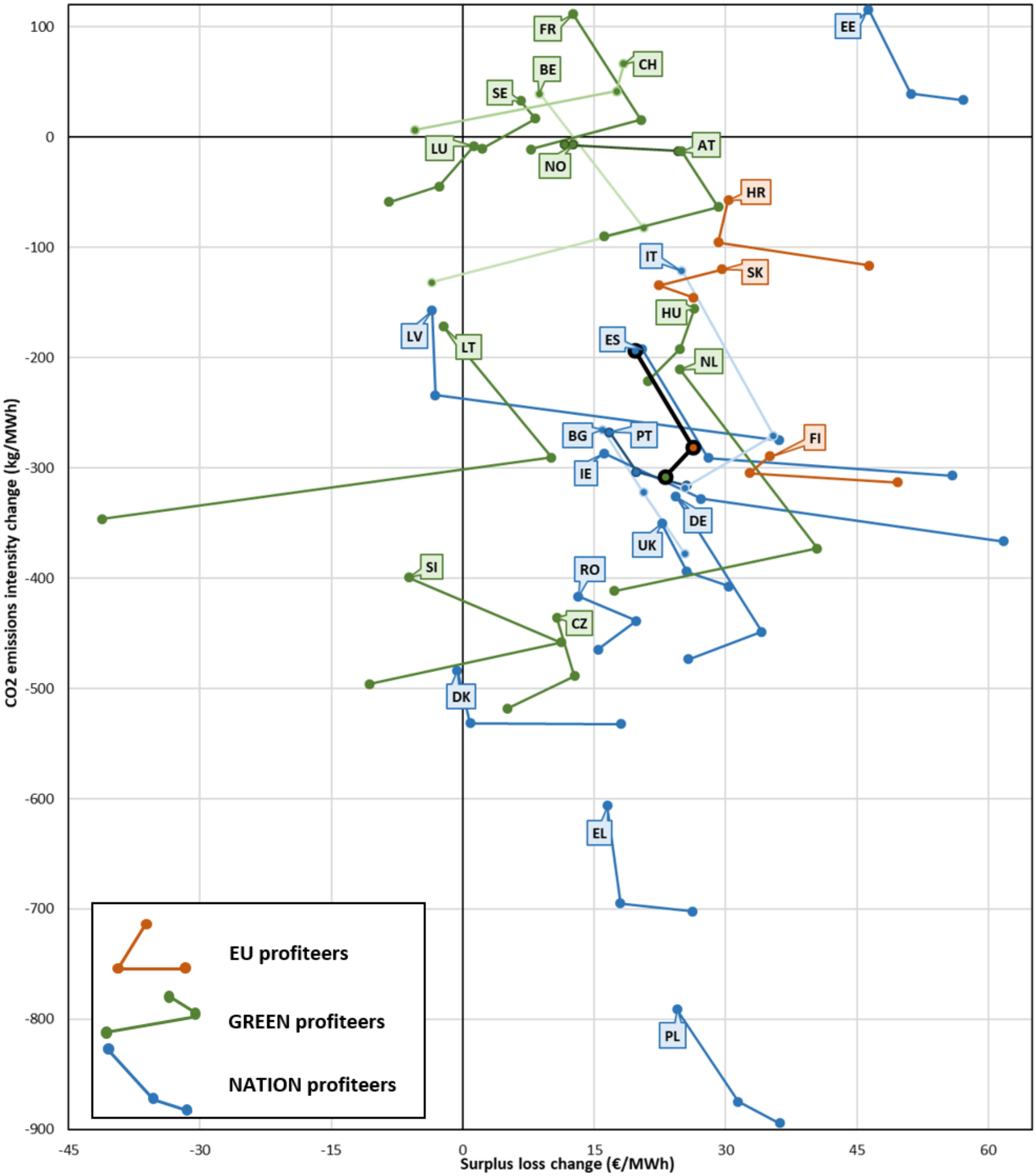
GREEN profiteers (in green) clearly profit of highest $CO_2$ prices and physical collaboration in terms of transfer capacity expansion. 12 countries belong to that group (Austria, Belgium, Czech, France, Hungary, Lithuania, Luxembourg, Netherlands, Norway, Slovenia, Sweden, and Switzerland). Those countries experience a structurally lower system transformation compared to *NATION* profiteers, and are additionally mainly located in North-Western Europe. The general pattern is as follows: Most of those countries lose in the *EU* narrative but gain from additional collaborative efforts leaving them considerably better off in *GREEN* (compared to *NATION*). Luxembourg and Hungary are (small) outliers here that are also better of in *EU* (compared to *NATION*). Norway is also an outlier with very similar surplus loss in *GREEN* and *NATION* but also considerable losses in *EU*.

EU profiteers (in red) are better of with the medium collaboration in *EU*. Only Croatia, Finland, and Slovakia belong to that group. All of them face quite low differences in system transformation between narratives. Croatia and Finland are structurally worse off in *GREEN* and Slovakia is worst off in *NATION*.

[13] The $CO_2$ emission intensity change does not contribute in distinguishing between profiteers of different collaboration levels but rather adds information to understand transformation processes.

[14] Country codes are as follows: Austria (AT), Belgium (BE), Bulgaria (BG), Croatia (HR), Czech Republic (CZ), Denmark (DK), Estonia (EE), Finland (FI), France (FR), Germany (DE), Greece (HL), Hungary (HU), Ireland (IE), Italy (IT), Latvia (LV), Lithuania (LT), Luxembourg (LU), Netherlands (NL), Norway (NO), Poland (PL), Portugal (PT), Romania (RO), Slovakia (SK), Slovenia (SI), Spain (ES), Sweden (SE), Switzerland (CH), and United Kingdom (UK).

Figure 7: Profiteers of collaboration and level of system transformation




Dots present narrative outcomes for each country (first dot with country code for *NATION*, second for *EU*, third for *GREEN*). Negative x-axis-values indicate profiteers. Negative y-axis-values reflect a reduction in $CO_2$ emission intensity. Colors within narrative profiteers vary for better readability. Black lines show European averages with the blue dot referring to *NATION*, the red dot to *EU*, and the green dot to *GREEN*.

Observe that there is no clear tendency across clusters in the level of surplus loss. It seems that the average loss is somewhere between 15 and 45 €/MWh. Most dots outside this area stem from the *GREEN* narrative, which produces changes in both directions. Interestingly, there are only few overall winners. Lithuania and Slovenia experience surplus gains (negative surplus losses) in *NATION* and *GREEN*, Luxembourg in *EU* and *GREEN*, Belgium and Switzerland in *GREEN*, Latvia in *NATION* and *EU*, and Denmark in *NATION* only. However, it is not clear whether or not it is the consumers or the producers that benefit from collaboration (and related system transformation). We thus compare changes in electricity prices and producer rents in the next subsection.

### *5.6. Consumers vs. producers*

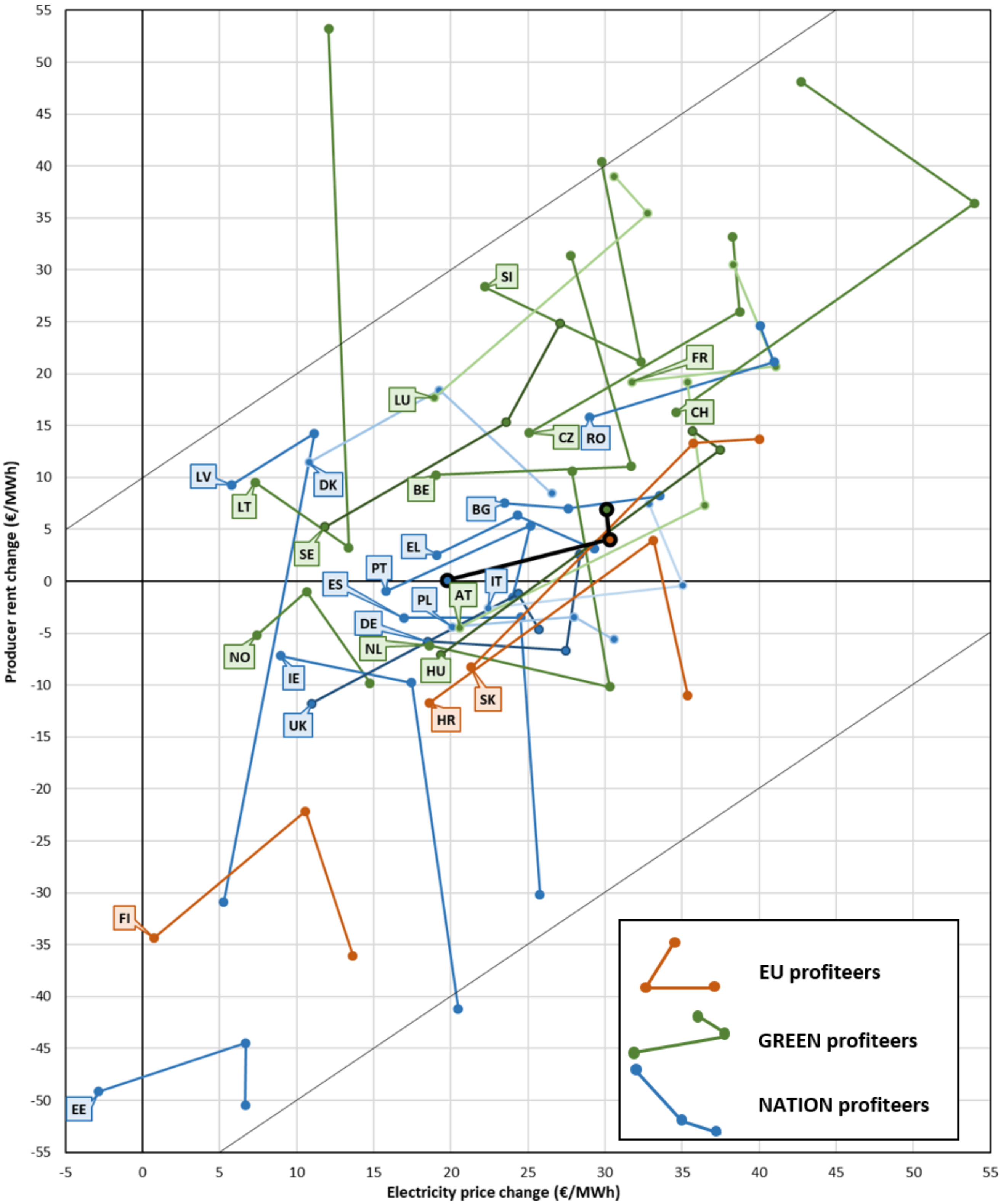
Figure 8 shows the trade-off between consumer losses and producer gains when it comes to the transformation of the European electricity system by showing how electricity prices (x-axis, in €/MWh) and producer rents (y-axis, in €/MWh) change over time in respective countries. The clustering of countries into profiteers and corresponding color codes are the same as in Figure 7. European averages are again shown by the black tree. We do so to find patterns of consumer losses and producer gains among clusters. The skew lines mark indifference between consumer losses and producer gains, so that countries on the *right-top* are winners in terms of producers and losers in terms of consumers. Observe that all countries in all narratives (except Estonia in *NATION*) experience an increase in electricity prices, making consumers worse off in the future. Most countries indeed experience an increase in prices between 15 and 40 €/MWh, which is observable already from the European values in Table 2. However, the allocation of producer rents goes in both directions but is fundamentally closer to zero than electricity price changes.

GREEN profiteers have structurally higher producer surplus gains and NATION profiteers lower ones. This pattern is slightly reversed for electricity price changes, which are highest for GREEN profiteers and lowest for NATION profiteers. EU profiteers does not have a clear tendency because there are only three countries in that cluster. However, all three experience lowest electricity price changes in *NATION* and highest in *GREEN*. Producers in Croatia and Finland are best off in *EU*, but producers in Slovakia indeed in *GREEN*. GREEN profiteers generally see an increase in producer rents and electricity prices in *GREEN*. The electricity price change is least pronounced in *NATION* and highest in *EU*.

Norway is again an interesting outlier with lower producer rents in *GREEN* (compared to the other two narratives). Also Lithuania is an interesting outlier with fundamentally higher producer rents in *GREEN*. Belgium, Netherlands, and Slovenia also experience tremendous producer rent increases in *GREEN* (compared to *EU*). Czech, Luxembourg, Sweden, and Switzerland see a considerable producer rent increase already in *EU*.

NATION profiteers are more diverse in patterns. Ireland, Latvia, and Spain experience sharp drops in producer rents in *GREEN* (compared to *NATION* and *EU*), that are not compensated by electricity price gains. The status as NATION profiteer is somehow mainly driven by electricity prices for the other NATION profiteers. For example, Estonia is the only country with decreasing (in *NATION*) or only just slightly increasing electricity prices (in *EU* and *NATION*), whereas producer rents differences are far smaller. Romania is a similar example with regard to the dominance of the electricity price increase. Moreover, Romania also has the highest increases in producer rents from all NATION profiteers (for all narratives).

Figure 8: Electricity price and producer rent changes




Dots present narrative outcomes for each country (first dot for *NATION*, second for *EU*, third for *GREEN*). Colors indicate overall profiteers from Figure 7 and colors within narrative profiteers vary for better readability again. Negative x-axis-values indicate consumer gains. Positive y-axis-values indicate producer gains. Black lines show European averages with the blue dot referring to *NATION*, red dot to *EU*, and the green dot to *GREEN*.

## 6. Discussion

Analyzing distributional effects for 28 countries, each for consumers as well as producers, in three narrative is overwhelming. We thus summarize results by developing a metric to clearly assess which country (consumer, producer) is a winner or loser, respectively, of the ongoing system transformation by taking a robust prediction of future developments. In particular, we weight narrative outcomes according to the frequency of the 16 scenarios in narrative clusters. Three scenarios belong to *NATION*, ten scenarios to *EU*, and three to *GREEN*. We obtain average changes in (1) surplus loss, (2) electricity prices, and (3) producer rents. We then assign the calculated changes to clusters in ranges of 10 €/MWh from very strong winners (++++) to extreme losers (– – – – –). Table 5 shows the outcome of that tasks and allows to easily access distributional effects across countries and across consumers and producers.[15] Observe that we cluster countries by their profiteer status. The first cluster (Bulgaria to United Kingdom) contains NATION profiteers, the next are the EU profiteers (Croatia, Finland, and Sweden), and the third one consists of GREEN profiteers (Austria to Switzerland). Remember that Europe in total is a NATION profiteer. Moreover, Europe is a strong loser with surplus losses between 10 to 20 €/MWh. The losing part stems from higher electricity prices (strong loser as well). In terms of producer rents, Europe is indeed a weak winner (changes between 0 and 10 €/MWh).

NATION profiteers tend to be strong losers in terms of electricity prices but kind of neutral (between weak loser and weak winner) for producers. Surplus loss changes are thus dominated by electricity price changes (between strong and very strong loser again). Estonia and Romania are outliers in that cluster. Estonia's overall assessment is dominated by its status as extreme loser in terms of producer rents, whereas electricity prices increase only weakly. Producer rents does not dominate the overall assessment of Romania but at least contribute similar as the electricity price changes. In particular, Romanias' producers are strong winners, whereas Romanias' consumers belong to the group of very strong losers.

EU profiteers (very) strong losers. Croatia and Slovakia behave similarly but Finland experiences fundamentally lower price changes (weak loser) and structurally higher rent losses (strong loser). GREEN profiteers are generally better off than EU and NATION profiteers. Their price assessment is quite similar (strong to very strong loser, Switzerland is even extreme loser) but producer rents are structurally higher. In particular, at least five (out of the twelve) GREEN profiteers (Czech Republic, France, Luxembourg, Slovenia, Switzerland) are strong winners in terms of producers and only two are weak losers (Netherlands, Norway).

GREEN profiteers are also generally small- to medium-sized (in terms of electricity demand). France is the only bigger country in that cluster due to its complete system transformation away from nuclear power (with substantial negative rents) towards gas and wind power (with slightly positive ones). NATION profiteers in turn are structurally bigger. In particular, with Germany, Italy, Poland, Romania, Spain, and United Kingdom six out of the seven biggest countries belong to that cluster. This fact indeed constitutes that Europe is a NATION profiteer and strong loser.

Taking an average value over all narratives clearly shows that consumers are generally worse off, whereas producers are gaining rents. No country is a winner in terms of consumers, whereas 18 countries are winners in terms of producers. In particular, nine countries are even at least very strong losers in terms of consumers (price change $>$ 30 €/MWh), whereas only one country (Estonia) belongs to that group in terms of producers. For surplus loss changes, countries thus tend to lose from a future system transformation. Lithuania and Luxembourg are the only countries

[15] Tables E.5 to E.7 in Appendix E show the outcome of that task for each narrative.

Table 5: Winners and losers of system transformation

| | Surplus loss | Price | Rent | Assessment | Profiteer |
|---|---|---|---|---|---|
| Bulgaria | (– – –) | (– – –) | (+) | Strong **loser** | NATION |
| Denmark | (–) | (– –) | (++) | Weak **loser** | NATION |
| Estonia | (– – – – –) | (–) | (– – – – –) | Extreme **loser** | NATION |
| Germany | (– – – –) | (– – –) | (–) | Very strong **loser** | NATION |
| Greece | (– –) | (– – –) | (+) | Medium **loser** | NATION |
| Ireland | (– – – –) | (– –) | (– –) | Very strong **loser** | NATION |
| Italy | (– – – –) | (– – – –) | (+) | Very strong **loser** | NATION |
| Latvia | (–) | (–) | (+) | Weak **loser** | NATION |
| Poland | (– – – –) | (– – –) | (–) | Very strong **loser** | NATION |
| Portugal | (– – –) | (– – –) | (+) | Strong **loser** | NATION |
| Romania | (– –) | (– – – –) | (+++) | Medium **loser** | NATION |
| Spain | (– – – –) | (– – –) | (–) | Very strong **loser** | NATION |
| United Kingdom | (– – –) | (– – –) | (–) | Strong **loser** | NATION |
| Croatia | (– – – –) | (– – – –) | (–) | Very strong **loser** | EU |
| Finland | (– – – –) | (–) | (– – –) | Very strong **loser** | EU |
| Slovakia | (– – –) | (– – – –) | (+) | Strong **loser** | EU |
| Austria | (– – –) | (– – – –) | (+) | Strong **loser** | GREEN |
| Belgium | (– –) | (– – –) | (++) | Medium **loser** | GREEN |
| Czech Republic | (– –) | (– – – –) | (+++) | Medium **loser** | GREEN |
| France | (– –) | (– – – –) | (+++) | Medium **loser** | GREEN |
| Hungary | (– – –) | (– – – –) | (+) | Strong **loser** | GREEN |
| Lithuania | (+) | (– –) | (++) | Weak **winner** | GREEN |
| Luxembourg | (+) | (– – –) | (++++) | Weak **winner** | GREEN |
| Netherlands | (– – – –) | (– – –) | (–) | Very strong **loser** | GREEN |
| Norway | (– –) | (– –) | (–) | Medium **loser** | GREEN |
| Slovenia | (–) | (– – –) | (+++) | Weak **loser** | GREEN |
| Sweden | (–) | (– – –) | (++) | Weak **loser** | GREEN |
| Switzerland | (– –) | (– – – – –) | (++++) | Medium **loser** | GREEN |
| (++++) | 0 | 0 | 2 | Very strong **winner** | |
| (+++) | 0 | 0 | 4 | Strong **winner** | |
| (++) | 0 | 0 | 4 | Medium **winner** | |
| (+) | 2 | 0 | 8 | Weak **winner** | |
| (–) | 4 | 3 | 7 | Weak **loser** | |
| (– –) | 7 | 4 | 1 | Medium **loser** | |
| (– – –) | 6 | 12 | 1 | Strong **loser** | |
| (– – – –) | 8 | 8 | 0 | Very strong **loser** | |
| (– – – – –) | 1 | 1 | 1 | Extreme **loser** | |
| Europe | (– – –) | (– – –) | (+) | Strong **loser** | NATION |

We weight narrative outcomes according to the frequency of the 16 scenarios in narrative clusters (3 scenarios belong to *NATION*, 10 scenarios to *EU*, and 3 to *GREEN*) to obtain an average change (in price – rent, price, or rent, respectively). Changes (in €/MWh) for price – rent and price are evaluated as follows: –40 to –30 (very strong winner), –30 to –20 (strong winner), –20 to –10 (medium winner), –10 to 0 (Weak winner), 0 to 10 (Weak loser), 10 to 20 (medium loser), 20 to 30 (strong loser), 30 to 40 (very strong loser), and >40 (extreme loser). Changes for rents are reversed, i.e., <–40 indicates extreme loser and 30 to 40 very strong winner.

that are (weak) winners, whereas again nine countries are at least very strong losers (Estonia again). However, Denmark, Latvia, Slovenia, and Sweden are at least only weak losers. In turn, a couple of big countries such as Germany, Italy, Netherlands, Poland, and Spain are very strong loser of the upcoming transformation processes.

## 7. Conclusion

We conduct a hybrid-scenario exercise consisting of (1) a CIB analysis that delivers 16 qualitative scenarios that are clustered to three diverging narratives, (2) the translation of qualitative descriptors into quantitative values by using a CGE model, and (3) the final quantification of the impact on the European power market by means of a power market model. We thereby concentrate on distributional effects across countries in terms of decarbonization, electricity prices, and producer rents as well as across consumers and producers.

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

Independent of the three narratives, the European power system undertakes a significant system transformation away from coal, lignite, and nuclear towards gas and wind power. Whereas electricity demand more than doubles until 2050, $CO_2$ emission intensities drop from 330 kg/MWh in 2015 to 137 (*NATION*), 49 (*EU*), or 22 kg/MWh (*GREEN*, respectively. Different wind power deployment rates explain only small parts of those differences but CCS technologies the major remaining share. Indeed, the low *NATION* $CO_2$ prices are not sufficient to make CCS technologies competitive. The system transformation goes hand in hand with increasing electricity prices. The increase is lowest in *NATION* (from 37 €/MWh in 2015 to 57 €/MWh in 2050) mainly due to the low *NATION* $CO_2$ prices. *EU* (68 €/MWh) and *GREEN* (67 €/MWh) see considerable higher prices in 2050. Interestingly, *GREEN* prices are lower than *EU* ones although $CO_2$ prices are higher by 33%. Unconstrained transmission grid expansion and related transfers across European countries favor the usage of the very best wind and solar spots in Europe. Producer rents keep almost unchanged in *NATION*, whereas deeper system transformation and the possibility of grid expansion from 2035 onwards yields rising producer rents in *EU* (from 0.62 to 4.67 €/MWh) and *GREEN* (to 7.55 €/MWh). However, Europe in total is still a *NATION* profiteer (lowest surplus loss change), whereas the medium collaborative future (*EU*) is least desirable.

The burdens or benefits of carbon abatement, electricity price increases, or rising producer rents, respectively, are unequally shared across Europe. The convergence of countries with regard to $CO_2$ emission intensities is highest in *GREEN* and lowest is *NATION*. High $CO_2$ prices (in *GREEN*) leave the countries only little possibilities and force them into the same direction (similar deployment of wind and CCS in each country). Low $CO_2$ prices (in *NATION*) in turn lead to quite unequal deployment rates of wind power (and no CCS adoption at all). This linear pattern (high $CO_2$ prices mean low emission intensities) breaks completely when looking at country-specific electricity prices and producer rents. Indeed, electricity prices are most similar in *NATION* because conventional gas technologies are price-setting. Differences are highest in *EU* and slightly lower again in *GREEN* because rising transfer volumes equalize prices across countries. On the other hand, producers structurally benefit from those rising transfer volumes, which is reflected in highest producer rents in *GREEN*. However, there is a general tendency across all three narratives which countries have high producer rents and which not. Conversely, the electricity price pattern is mainly dominated by the availability of good wind and solar spots, leading to structurally lower prices in the periphery of the European market (more wind in the Northern and Western shore countries, more solar in the Southern countries).

Those unequal developments within Europe make 13 countries to *profiteers* (lowest change in surplus loss) of the *NATION* narrative, 12 countries to profiteers of *GREEN*, and only three countries to EU profiteers. NATION profiteers observe higher changes in emission intensities than GREEN and EU profiteers. Moreover, NATION profiteers experience considerably lower producer rents, whereas GREEN profiteers see quite high ones. NATION profiteers tend to be strong losers of the ongoing system transformation, whereas at least the GREEN profiteers are in tendency better off. The importance of NATION profiteers is reinforced by the fact that six of the seven biggest European countries (in terms of population) belong to that cluster.

Our results explain (non-)collaborative efforts (or at least the risk of those) when bargaining about the future of the European climate policy. In particular, policy makers need to consider and understand country heterogeneity and resulting distributional impacts. 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. The risk of such a future is even greater when considering current energy price crisis, hinting that final reforms seeking to achieve 2045 carbon neutrality targets might get delayed.

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 CGE 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 from the CGE model (e.g., results from other sectors) because the power market model and the CGE model do not have a similar equilibrium. Next, 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. The risk of a returning *NATION* state is, despite current energy price developments, low. Finally, analyzing distributional effects across 28 countries both for consumers and producers in different narratives is overwhelming. We thus focus on the identification of trends that constitute differences across countries and narratives. Focusing on a detailed analysis of the outlier countries in respective narratives such as Estonia, France, and Norway would be an interesting topic for future work.

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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.

## Appendix B. Descriptors and variations

| No | Descriptor | Interpretation | Variation | Implementation |
|---|---|---|---|---|
| D1 | Investment costs | Development of specific investment costs. Typical technologies are aggregated (e.g., RES, coal, gas, nuclear, CCS) and absolute values converted to annual average (negative) growth rates. | **V1:** Weak decrease. Only RES will achieve little improvements (Schröder et al., 2013).<br>**V2:** Moderate decrease, especially for RES and nuclear technologies. Coal and gas technologies experience a small decrease (IEA, 2016).<br>**V3:** Strong decrease, especially for RES and CCS but also slight decrease for coal, gas, and nuclear technologies (IEA, 2016). | No adjustments possible in CGE model.<br>Direct implementation in power market model. |
| 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).<br>**V2:** Moderate expansion (beyond the existing TYNDP plan) to reach 20% interconnectivity by 2050.[16]<br>**V3:** Further grid expansion (beyond the existing TYNDP plan), reaching at least an interconnectivity of 25% by 2050 (with regard to the respective generation capacity of each state). | Increase or decrease of Armington elasticities for domestic and imported electricity to match power market model projections; upper and lower bounds for the endogenous expansion of transmission capacity between neighboring countries with<br>**V1:** Grid expansion as specified by TYNDP until 2030 but not beyon from 2035 onwards.<br>**V2:** Upper bound of 25% interconnectivity from 2035 onwards when TYNDP is not already on a higher level.<br>**V3:** Lower bound of 25% interconnectivity or TYNDP and no upper bound from 2035 onwards. |

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

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| No | Descriptor | Interpretation | Variation | Implementation |
|---|---|---|---|---|
| D3 | RES incentives | Incentives are regulative measures which support RES technologies 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.<br>**V2:** Moderate incentives: Additional incentives in terms of monetary and indirect subsidies for small power stations and emerging technologies only.<br>**V3:** Weak incentives: Monetary and indirect subsidies abolished. | Adjustments of capital subsidies for electricity generation from RES technologies in CGE model.<br>Only indirectly covered via fuel prices in power market model. |
| D4 | Nuclear perception | 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 way towards a resilient as well as save power system. The use or development of nuclear power plants is not restricted by policy intervention.<br>**V2:** Nuclear power is a high-risk technology. Higher security requirements and taxes decrease the profitability of nuclear power. | Adjustments of the upper bound on supplied nuclear energy in CGE model<br>Investments restrictions to that expansion is possible only in countries that already have nuclear capacity and adjustments to investment costs to reflect risk and regulatory premia in power market model |

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| No | Descriptor | Interpretation | Variation | Implementation |
|---|---|---|---|---|
| D5 | CCS perception | 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.<br>**V2:** CCS is a climate mitigation option, but considered as local pollution. CCS potential is partly accessible.<br>**V3:** CCS is a climate mitigation option and not considered as local pollution. CCS potential is fully accessible. | No adjustments possible in CGE model.<br>Adaptation of the available CCS potential and direct adjustment of investment costs to reflect risk and regulatory premia. |
| D6 | 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.<br>**V2:** Rate is stable (+0.2%/year).<br>**V3:** Rate decreases (-0.2%/year). | Implemented as cited in CGE model.<br>Only indirectly covered via fuel prices in power market model. |
| D7 | R&D focus | 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 a system based on conventional technologies burning fossil fuels. | **V1:** Focus towards a low carbon system. Nuclear power is categorized as low carbon power.<br>**V2:** Focus towards a fossil system. Fossil fuel power plants using CCS technologies are categorized as fossil power. | Changes in autonomous energy efficiency index for respective technologies in CGE model.<br>Altered timeseries that depict higher availability of variable RES over time in power market model. |

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| No | Descriptor | Interpretation | Variation | Implementation |
|---|---|---|---|---|
| D8 | 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). | Increase or decrease of Armington elasticities for all traded goods between European countries and the rest-of-the world in CGE model. Only indirectly covered via fuel prices in power market model. |
| D9 | $CO_2$ prices | Development of EU emission allowance prices (EUA prices). The $CO_2$ price depends on the reduction targets set on the national or international level, respectively, all supplementary energy and climate policies in place as well as consumption taxes on pollutive goods, 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. | Implemented as deviations from the *BAU* in the CGE model by accounting for all policies as predicted by the JRC-IPTS. **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. Direct implementation of CGE outcome in power market model. |

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| No | Descriptor | Interpretation | Variation | Implementation |
|---|---|---|---|---|
| D10 | Natural gas prices | This descriptor discusses the European crude oil and natural gas price developments. European natural gas prices reveal correlated with oil prices in the long-term (more than one year) and with a delay of three to five months (Albrecht et al., 2014). Although crude oil indexation of natural 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 natural 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 crude 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.<br>**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.<br>**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).<br>**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. | Adjustment of country-level (and rest-of-the-world) endowments of natural gas (in comparison to $BAU$) in CGE model.<br>Direct implementation of CGE outcome in power market model. |
| D11 | 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).<br>**V2:** Stable prices (+0%/year).<br>**V3:** Trend towards low prices (40$/t in 2040, -1%/year). | Adjustment of country-level (and rest-of-the-world) endowments of coal (in comparison to $BAU$) in CGE model.<br>Direct implementation of CGE outcome in power market model. |

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| No | Descriptor | Interpretation | Variation | Implementation |
|---|---|---|---|---|
| D12 | 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 to use land within European countries. The land-use trend will be described with four 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).<br>**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).<br>**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.<br>**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. | No adjustments possible in CGE model.<br>Adaptation of country-level RES potentials in power market model. |
| D13 | 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.<br>**V2:** Growth of bioenergy production is maintained in the limits of the determined bioenergy potential. | No adjustments possible in CGE model.<br>Adjustments of bioenergy potential and price in power market model. |

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| No | Descriptor | Interpretation | Variation | Implementation |
|---|---|---|---|---|
| ND1 | Consumer behavior | 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 in the used model version (Mier and Weissbart, 2020). |

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| No | Descriptor | Interpretation | Variation | Implementation |
|---|---|---|---|---|
| ND2 | 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.<br>**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.<br>**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. |
| ND3 | 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%).<br>**V2:** Potential is moderately utilized (between 20% and 50%).<br>**V3:** Slight increase in the utilization of the DSM potential (between 10% and 20%). | Context descriptor that is not implemented in the used model version (Mier and Weissbart, 2020). |

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| No | Descriptor | Interpretation | Variation | Implementation |
|---|---|---|---|---|
| ND4 | 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.<br>**V2:** Moderately increase.<br>**V3:** Additional demand does not require large investments in increasing flexibility. | Context descriptor that is not implemented in the used power market model version (Mier and Weissbart, 2020). |
| ND5 | 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.<br>**V2:** Welfare increases and equality decreases.<br>**V3:** Welfare stagnates or increases very slowly and equality increases.<br>**V4:** Welfare increases slowly and equality decreases. | Context descriptor that is not implemented. However, ND5 is validated in the CGE model with GDP as proxy but finally we decided for aiming for similar GDP levels across narratives to make narratives comparable. |

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| No | Descriptor | Interpretation | Variation | Implementation |
|---|---|---|---|---|
| ND6 | 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.<br>**V2:** Enhancement of current market rules. Current policies are basically continued. European authorities take regulatory action to increase the flexibility of the system.<br>**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, D9, D10, and D11. |
| ND7 | 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.<br>**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).<br>**V3:** Full harmonization approach. All decisions on the national level must receive the approval of a supraordinate 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, D9, D10, D11, D12, and D13. |

*Continued on next page*

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| No | Descriptor | Interpretation | Variation | Implementation |
|---|---|---|---|---|
| ND8 | 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.<br>**V2:** The European population stagnates.<br>**V3:** The European population follows a decreasing trend (-0.12%/year) until 2050. | Context descriptor that is not implemented. However, ND8 is validated in the CGE model via the scaling of labor intensities in production. Finally, we decided not to touch this descriptor any further because only one of 16 scenarios showed a variation. |
| ND9 | 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.<br>**V2:** Available reserves of coal grow more compared to the current trend. Available reserves of gas grow less compared to the current trend.<br>**V3:** Available reserves of coal and gas grow less compared to the current trend.<br>**V4:** Available reserves of gas grow more compared to the current trend. Available reserves of coal grow less compared to the current trend. | Context descriptor that is not implemented directly, but indirectly via D10 and D11. |

# Appendix C. Scenarios

<table>
<tr><th></th><th></th><th colspan="10">EU</th><th colspan="3">GREEN</th><th colspan="3">NATION</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>Investment costs</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>RES incentives</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>Nuclear perception</td><td colspan="16">V2</td></tr>
<tr><td>D5</td><td>CCS perception</td><td colspan="16">V1</td></tr>
<tr><td>D6</td><td>Urbanization</td><td colspan="16">V2</td></tr>
<tr><td>D7</td><td>R&D focus</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>D8</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>D9</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>D10</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>D11</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>D12</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>D13</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>ND1</td><td>Consumer behavior</td><td colspan="6">V1</td><td colspan="4">V1</td><td colspan="3">V1</td><td colspan="3">V3</td></tr>
<tr><td>ND2</td><td>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>ND3</td><td>Realization of DSM potential</td><td colspan="16">V2</td></tr>
<tr><td>ND4</td><td>Demand for flexibility</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>ND5</td><td>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>ND6</td><td>Regulation</td><td colspan="6">V1</td><td colspan="4">V1</td><td colspan="3">V3</td><td colspan="3">V1</td></tr>
<tr><td>ND7</td><td>Cooperation 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>ND8</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>
<tr><td>ND9</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>
</table>

## Appendix D. Modeled- and non-modeled descriptors

Table D.3: Modeled descriptors

| No | Descriptor | *EU* | *GREEN* | *NATION* |
|---|---|---|---|---|
| D1 | Investment costs | Moderate decrease | Moderate decrease | Weak decrease |
| D2 | Grid infrastructure | Moderate transmission grid expansion | Further grid expansion | No further transmission grid expansion |
| D3 | RES incentives | Weak policy incentives for RES | Weak policy incentives for RES | Strong policy incentives for RES |
| D7 | R&D focus | Mixed results between low carbon (also nuclear) and CCS usage | Focus on low carbon system | Mixed results between low carbon (also nuclear) and CCS usage |
| D8 | Global economic cohesion | Trend for bilateral and supra-national cooperation | Trend for bilateral and supra-national cooperation | Trend towards national protectionism and international competition |
| D9 | $CO_2$ prices | Low increase in prices | High increase in prices | Diminishing price trend |
| D10 | Natural gas prices | Natural gas independent on oil: low prices | Natural gas independent on oil: low prices | Natural gas dependent on oil: high prices |
| D11 | Coal prices | Stable prices | Trend towards low prices | High prices |
| D12 | Land use policy | Increase of industrial forestry reduces RES potential | Natural preservation reduces RES potential | Increase of industrial forestry reduces RES potential |
| D13 | Agriculture for the power sector | Bioenergy production is restricted so that prices are high | Bioenergy production is restricted so that prices are high | Bioenergy production is expanded so that prices are low |

There is no variation in narratives for D4 (nuclear perception is always low), D5 (CCS perception is always low), and D6 (urbanization rate is always stable)

Table D.4: Non-modeled descriptors

| No | Descriptor | *EU* | *GREEN* | *NATION* |
|---|---|---|---|---|
| ND1 | Consumer behavior | Raising the level of individual consumption | Raising the level of individual consumption | Sharing economy becomes popular in Europe |
| ND2 | Support for environmental sustainability | Support for sustainability is low | Support for sustainability is high | Support for sustainability is high |
| ND3 | Realization of the demand side management potential | EU potential is moderately utilized | EU potential is moderately utilized | EU potential is moderately utilized |
| ND4 | Demand for flexibility on the electricity market | Strongly increasing demand for flexibility | Moderately increasing demand for flexibility | Moderately increasing demand for flexibility |
| ND5 | Overall welfare and equality | Welfare increase and equality decreases | Welfare and equality increase | Welfare growth stagnates and equality increases |
| ND6 | Regulation of the European power market | Liberalized power market | Fully integrated approach | Liberalized power market |
| ND7 | Cooperation in Europe and political culture | Non-regulatory approach (autarky) | Full harmonization approach | Non-regulatory approach (autarky) |
| ND9 | 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 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 |

There is no variation in narratives for ND8 (no population growth).

## Appendix E. Discussion

Table E.5: Winners and losers with respect to surplus loss change by narrative

| | *NATION* | *EU* | *GREEN* | Average | Assessment |
|---|---|---|---|---|---|
| Austria | (– – –) | (– – –) | (– –) | (– – –) | Strong **looser** |
| Belgium | (–) | (– – –) | (+) | (– –) | Medium **looser** |
| Britain | (– – –) | (– – –) | (– – – –) | (– – –) | Strong **looser** |
| Bulgaria | (– –) | (– – –) | (– – –) | (– – –) | Strong **looser** |
| Croatia | (– – – –) | (– – –) | (– – – – –) | (– – – –) | Very strong **looser** |
| Czech | (– –) | (– –) | (–) | (– –) | Medium **looser** |
| Denmark | (+) | (–) | (– –) | (–) | Low **looser** |
| Estonia | (– – – – –) | (– – – – –) | (– – – – –) | (– – – – –) | Extreme **looser** |
| Finland | (– – – –) | (– – – –) | (– – – – –) | (– – – –) | Very strong **looser** |
| France | (– –) | (– – –) | (–) | (– –) | Medium **looser** |
| Germany | (– – –) | (– – – –) | (– – –) | (– – – –) | Very strong **looser** |
| Greece | (– –) | (– –) | (– – –) | (– –) | Medium **looser** |
| Hungary | (– – –) | (– – –) | (– – –) | (– – –) | Strong **looser** |
| Ireland | (– –) | (– – –) | (– – – – –) | (– – – –) | Very strong **looser** |
| Italy | (– – –) | (– – – –) | (– – –) | (– – – –) | Very strong **looser** |
| Latvia | (+) | (+) | (– – – –) | (–) | Low **looser** |
| Lithuania | (+) | (– –) | (+++++) | (+) | Low **winner** |
| Luxembourg | (–) | (+) | (+) | (+) | Low **winner** |
| Netherlands | (– – –) | (– – – – –) | (– –) | (– – – –) | Very strong **looser** |
| Norway | (– –) | (– –) | (– – –) | (– –) | Medium **looser** |
| Poland | (– – –) | (– – – –) | (– – – –) | (– – – –) | Very strong **looser** |
| Portugal | (– –) | (– –) | (– – –) | (– – –) | Strong **looser** |
| Romania | (– –) | (– –) | (– –) | (– –) | Medium **looser** |
| Slovakia | (– – –) | (– – –) | (– – –) | (– – –) | Strong **looser** |
| Slovenia | (+) | (– –) | (++) | (–) | Low **looser** |
| Spain | (– – –) | (– – –) | (– – – – –) | (– – – –) | Very strong **looser** |
| Sweden | (–) | (–) | (–) | (–) | Low **looser** |
| Switzerland | (– –) | (– –) | (+) | (– –) | Medium **looser** |
| (+++++) | 0 | 0 | 1 | 0 | Extreme **winner** |
| (++++) | 0 | 0 | 0 | 0 | Very strong **winner** |
| (+++) | 0 | 0 | 0 | 0 | Strong **winner** |
| (++) | 0 | 0 | 1 | 0 | Medium **winner** |
| (+) | 4 | 2 | 3 | 2 | Low **winner** |
| (–) | 3 | 2 | 3 | 4 | Low **looser** |
| (– –) | 9 | 8 | 4 | 7 | Medium **looser** |
| (– – –) | 9 | 10 | 8 | 6 | Strong **looser** |
| (– – – –) | 2 | 4 | 3 | 8 | Very strong **looser** |
| (– – – – –) | 1 | 2 | 5 | 1 | Extreme **looser** |

We weight narrative outcomes according to the frequency of the 16 scenarios in narrative clusters (3 scenarios belong to *NATION*, 10 scenarios to *EU*, and 3 to *GREEN*) to obtain an average change in surplus loss. Changes (in €/MWh) for surplus loss are evaluated as follows: <–40 (extreme winner), –40 to –30 (very strong winner), –30 to –20 (strong winner), –20 to –10 (medium winner), –10 to 0 (low winner), 0 to 10 (low looser), 10 to 20 (medium looser), 20 to 30 (strong looser), 30 to 40 (very strong looser), and >40 (extreme looser).

Table E.6: Winners and looser with respect to electricity price change by narrative

| | *NATION* | *EU* | *GREEN* | Average | Assessment |
|---|---|---|---|---|---|
| Austria | (– – –) | (– – – –) | (– – – –) | (– – – –) | Very strong **looser** |
| Belgium | (– –) | (– – – –) | (– – –) | (– – –) | Strong **looser** |
| Britain | (– –) | (– – –) | (– – –) | (– – –) | Strong **looser** |
| Bulgaria | (– – –) | (– – –) | (– – – –) | (– – –) | Strong **looser** |
| Croatia | (– –) | (– – – –) | (– – – –) | (– – – –) | Very strong **looser** |
| Czech | (– – –) | (– – – –) | (– – – –) | (– – – –) | Very strong **looser** |
| Denmark | (– –) | (– –) | (– – –) | (– –) | Medium **looser** |
| Estonia | (+) | (–) | (–) | (–) | Low **looser** |
| Finland | (–) | (– –) | (– –) | (–) | Low **looser** |
| France | (– – – –) | (– – – – –) | (– – – –) | (– – – –) | Very strong **looser** |
| Germany | (– –) | (– – –) | (– – –) | (– – –) | Strong **looser** |
| Greece | (– –) | (– – –) | (– – –) | (– – –) | Strong **looser** |
| Hungary | (– –) | (– – – –) | (– – – –) | (– – – –) | Very strong **looser** |
| Ireland | (–) | (– –) | (– – –) | (– –) | Medium **looser** |
| Italy | (– – –) | (– – – –) | (– – – –) | (– – – –) | Very strong **looser** |
| Latvia | (–) | (– –) | (–) | (–) | Low **looser** |
| Lithuania | (–) | (– –) | (– –) | (– –) | Medium **looser** |
| Luxembourg | (– –) | (– – – –) | (– – – –) | (– – –) | Strong **looser** |
| Netherlands | (– –) | (– – – –) | (– – –) | (– – –) | Strong **looser** |
| Norway | (–) | (– –) | (– –) | (– –) | Medium **looser** |
| Poland | (– – –) | (– – –) | (– – – –) | (– – –) | Strong **looser** |
| Portugal | (– –) | (– – –) | (– – –) | (– – –) | Strong **looser** |
| Romania | (– – –) | (– – – – –) | (– – – – –) | (– – – –) | Very strong **looser** |
| Slovakia | (– – –) | (– – – –) | (– – – – –) | (– – – –) | Very strong **looser** |
| Slovenia | (– – –) | (– – – –) | (– – –) | (– – –) | Strong **looser** |
| Spain | (– –) | (– – –) | (– – –) | (– – –) | Strong **looser** |
| Sweden | (– –) | (– – –) | (– – –) | (– – –) | Strong **looser** |
| Switzerland | (– – – –) | (– – – – –) | (– – – – –) | (– – – – –) | Extreme **looser** |
| (+++++) | 0 | 0 | 0 | 0 | Extreme **winner** |
| (++++) | 0 | 0 | 0 | 0 | Very strong **winner** |
| (+++) | 0 | 0 | 0 | 0 | Strong **winner** |
| (++) | 0 | 0 | 0 | 0 | Medium **winner** |
| (+) | 1 | 0 | 0 | 0 | Low **winner** |
| (–) | 5 | 1 | 2 | 3 | Low **looser** |
| (– –) | 12 | 6 | 3 | 4 | Medium **looser** |
| (– – –) | 8 | 8 | 11 | 12 | Strong **looser** |
| (– – – –) | 2 | 10 | 9 | 8 | Very strong **looser** |
| (– – – – –) | 0 | 3 | 3 | 1 | Extreme **looser** |

We weight narrative outcomes according to the frequency of the 16 scenarios in narrative clusters (3 scenarios belong to *NATION*, 10 scenarios to *EU*, and 3 to *GREEN*) to obtain an average change (in price). Changes (in €/MWh) for price are evaluated as follows: <–40 (extreme winner), –40 to –30 (very strong winner), –30 to –20 (strong winner), –20 to –10 (medium winner), –10 to 0 (low winner), 0 to 10 (low looser), 10 to 20 (medium looser), 20 to 30 (strong looser), 30 to 40 (very strong looser), and >40 (extreme looser).

Table E.7: Winners and looser with respect to producer rent change by narrative

| | *NATION* | *EU* | *GREEN* | Average | Assessment |
|---|---|---|---|---|---|
| Austria | (–) | (+) | (++) | (+) | Low **winner** |
| Belgium | (++) | (++) | (++++) | (++) | Medium **winner** |
| Britain | (– –) | (–) | (–) | (–) | Low **looser** |
| Bulgaria | (+) | (+) | (+) | (+) | Low **winner** |
| Croatia | (– –) | (+) | (– –) | (–) | Low **looser** |
| Czech | (++) | (+++) | (++++) | (+++) | Strong **winner** |
| Denmark | (++) | (++) | (+) | (++) | Medium **winner** |
| Estonia | (– – – – –) | (– – – – –) | (– – – – –) | (– – – – –) | Extreme **looser** |
| Finland | (– – – –) | (– – –) | (– – – –) | (– – –) | Strong **looser** |
| France | (++) | (+++) | (++++) | (+++) | Strong **winner** |
| Germany | (–) | (–) | (+) | (–) | Low **looser** |
| Greece | (+) | (+) | (+) | (+) | Low **winner** |
| Hungary | (–) | (++) | (++) | (+) | Low **winner** |
| Ireland | (–) | (–) | (– – – – –) | (– –) | Medium **looser** |
| Italy | (–) | (–) | (+) | (+) | Low **winner** |
| Latvia | (+) | (++) | (– – – –) | (+) | Low **winner** |
| Lithuania | (+) | (+) | (+++++) | (++) | Medium **winner** |
| Luxembourg | (++) | (++++) | (++++) | (++++) | Very strong **winner** |
| Netherlands | (–) | (– –) | (++) | (–) | Low **looser** |
| Norway | (–) | (–) | (–) | (–) | Low **looser** |
| Poland | (–) | (–) | (–) | (–) | Low **looser** |
| Portugal | (–) | (+) | (–) | (+) | Low **winner** |
| Romania | (++) | (+++) | (+++) | (+++) | Strong **winner** |
| Slovakia | (–) | (++) | (++) | (+) | Low **winner** |
| Slovenia | (+++) | (+++) | (+++++) | (+++) | Strong **winner** |
| Spain | (–) | (–) | (– – – –) | (–) | Low **looser** |
| Sweden | (+) | (++) | (+++) | (++) | Medium **winner** |
| Switzerland | (++) | (++++) | (+++++) | (++++) | Very strong **winner** |
| (+++++) | 0 | 0 | 3 | 0 | Extreme **winner** |
| (++++) | 0 | 2 | 4 | 2 | Very strong **winner** |
| (+++) | 1 | 4 | 2 | 4 | Strong **winner** |
| (++) | 7 | 6 | 4 | 4 | Medium **winner** |
| (+) | 5 | 6 | 5 | 8 | Low **winner** |
| (–) | 11 | 7 | 4 | 7 | Low **looser** |
| (– –) | 2 | 1 | 1 | 1 | Medium **looser** |
| (– – –) | 0 | 1 | 0 | 1 | Strong **looser** |
| (– – – –) | 1 | 0 | 3 | 0 | Very strong **looser** |
| (– – – – –) | 1 | 1 | 2 | 1 | Extreme **looser** |

We weight narrative outcomes according to the frequency of the 16 scenarios in narrative clusters (3 scenarios belong to *NATION*, 10 scenarios to *EU*, and 3 to *GREEN*) to obtain an average change (in rent). Changes (in €/MWh) for rent are evaluated as follows: <–40 (extreme looser), –40 to –30 (very strong looser), –30 to –20 (strong looser), –20 to –10 (medium looser), –10 to 0 (low looser), 0 to 10 (low winner), 10 to 20 (medium winner), 20 to 30 (strong winner), 30 to 40 (very strong winner), and >40 (extreme winner).