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Decarbonization of Power Markets under Stability and Fairness: Do They Influence Efficiency?*

Abstract

Market integration is seen as a complementary measure to decarbonize energy markets. In the context of power markets, this translates into regions that coordinate to maximize welfare in the power market with respect to a climate target. Yet, the maximization of overall welfare through cooperation leads to redistribution and can result in the reduction of a region's welfare compared to the case without cooperation. This paper assesses why cooperation in the European power market is not stable from the perspective of single regions and identifies cost allocations that increase fairness. In a first step, the EU-REGEN model is applied to find the future equilibrium outcome of the European power market under a cooperative, subadditive cost-sharing game. Secondly, resulting cost allocations are analyzed by means of cooperative game theory concepts. Results show that the value of cooperation is a € 69 billion reduction in discounted system cost and rational behavior of regions can maintain at most 16 % of this reduction. The evaluation of alternative cost allocations reveals the trade-off between accounting for robustness against cost changes and individual rationality. Moreover, the cost-efficient decarbonization path of the European power sector under the grand coalition is characterized by the interplay between wind power, gas power, and biomass with geologic storage of CO_2. Last, with singleton coalitions only, the market outcome shifts to a higher contribution from nuclear power.

JEL Code: C6, C7, L9, Q4
Keywords: European power market, cooperative game theory, cost sharing

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1. Introduction

The creation of a decarbonized economy with a fully integrated energy market is one of the main goals of the European Commission's (EC) "Energy Union", which purpose is to coordinate the transformation of the European energy supply [1]. In terms of power markets, this means the creation of a single European market in order to keep the cost of transformation at a bearable level. This corresponds to the first-best solution from economic theory. If a group of players is subject to a market-wide and binding constraint, coordination allows them to reach the cost-effective allocation. Meaning, if players can coordinate and share information, they are able to reach the first-best outcome, e.g. [2]. In the context of power markets this translates into regions that try to maximize their welfare in the power market with respect to a climate (carbon) target. Regions coordinate their abatement efforts until marginal abatement cost across all regions are equal. If regions fail to coordinate, average abatement cost increase, which results in a welfare loss.

Yet, EU member countries started to announce additional national climate and energy targets[1]. For instance, Germany aims at a reduction of the economy-wide CO_2-emissions of at least 80 % by 2050 [3]. Similarly, France introduced a law on the transition of its power sector limiting the share of generation from nuclear power to 50 % from 2025 on and targeting a CO_2-emission reduction of 50 % by 2030 and 80 % by 2050 [4].[2] These national climate targets indicate a certain degree of self-interest and are an additional source of disturbance. This shows that single regions or countries pursue power-market-specific objectives that go beyond economic efficiency in general. It is assumed that competitive markets yield the cost-effective supply of electricity. Yet, the private optimum does not consider social costs that evolve from power market externalities. In addition to environmental issues, regulators want to address further objectives with respect to energy markets [5]. These can comprise energy independence

[1] For an overview on existing national climate targets (of EU member countries) see e.g. the *IEA/IRENA Global Renewable Energy Policies and Measures Database*, which can be accessed under https://www.iea.org/policiesandmeasures/renewableenergy/.

[2] All CO_2-emissions reduction targets stated in this paragraph refer to 1990 levels.

[5], resource adequacy [6], energy security [7], employment effects [8], technological innovation [9], and redistributive effects [10].

Redistributive effects lead to the phenomena that cooperation is not always rational from the perspective of a single region. The maximization of overall welfare through cooperation leads to redistribution and can result in a reduction of a region's welfare compared to the case without cooperation. This reflects the trade-off between economic efficiency and redistribution that is often referred to in climate and energy economics [11]. Here, redistribution can be examined between geographic regions or producers and consumers, among others. In general, it is important to discuss distributional effects in order to promote broad acceptance for climate policies and avoid lock-ins into inefficient paths [12].

So far, the perspective on redistributive issues has focused on the market power of individual firms. For example, [13] analysis on the effect of renewable energy sources (RES) support schemes and CO_2-emission pricing on redistributive flows between producers and consumers in power markets. Similarly, [14] investigation of the presence of market power of generators and consumers in the context of transmission rights, while [15] analyzing to what degree market power is exercised in the Californian power market at plant level.

The behavior of countries or regions has, to the best of the authors knowledge, only been researched by [16], [17], [18] and [19]. [16] looks at the distribution of gains from regional cooperation in the case of the Indian power market. This analysis is based on the theory of cooperative games. In analogy, [17] elaborates on the regional effects of cooperation in the northern European power market. The authors in [18] analyze the importance of cooperation by setting different levels of cross-boarder transmission capacity. A more advanced approach is implemented by [19], which endeavors to find the Nash equilibrium between zonal planners that maximize their welfare from transmission capacity investments.

The paper at hand adds to this by an extended application of cooperative game theory and, hence, tries to apply a bottom-up model in a framework that looks beyond a single market-wide optimum[3]. The aim of the analysis is to quantify the impact of fairness considerations on the equilibrium path of the EU power market[4]. Therefore, the following research questions will be answered: Firstly, how does the first-best outcome manifest in quantities and prices? Secondly, why is it not rational from the perspective of individual countries to cooperate with respect to a common carbon budget? Thirdly, how would an equilibrium look if regions refuse to enter coalitions that are not rational? Finally, how can fairness be improved if it is derived from rational behavior or the relative importance of each region?

In general, power markets allow for (at least) two channels of cooperation between regions. First, the utilization of cooperative advantages with respect to abatement cost. Regions that form a coalition can shift emission reductions among them and, hence, individual regions (within a coalition) can exceed or fall below their emission budget (compared to the case of national emission budgets). This is closely related to the concept of international environmental agreements (IEAs) (see e.g. [23] and [24]), where regions form coalitions in order to jointly set a carbon target. Yet, in the case of IEAs, regions outside a coalition maximize their welfare without setting a climate target. Thus, there exists the possibility of side payments in order to create economic incentives for regions outside a coalition to reduce emissions [25].

Second, regions cooperate for the sake of providing electricity at low marginal cost (excluding cost for emission certificates) and, thus, engage in cross-boarder electricity trade. This mainly refers to the utilization of comparative advantage and is in line with the market efficiency rationale of trade agreements in general, e.g. [26], and electricity market integration in particular, e.g. [27][5]. In general, the economic motive for trade agreements assumes that the exchange of goods and services is mutually beneficial. Nonetheless, economic incentives for international trade can be set, e.g. in the form of

[3] A similar research approach has been taken in other fields, e.g. by [20] and [21].

[4] The analysis in this paper exclusively focuses on cooperation within the European power market and does not consider other markets or regions outside of Europe as in e.g. [22].

[5] Apart from utilizing differences in marginal cost of generating electricity, cross-boarder electricity trade is also a consequence of balancing demand and supply of electricity, which can be stored under high cost only [28].

foreign direct investments or counter trade [29].

The extent of cooperation in this paper primarily aims at the sharing of emission budgets. Regions form coalitions in order to utilize the most efficient abatement sources under a common CO_2-emissions reduction target. This is equal to the introduction of a single market price for emissions and leads to a shift in the distribution of cost among regions. Hence, cooperation does not have to be rational *per se*. These distributional consequences with respect to benefits and costs of the introduction of such a uniform price signal are well-known from environmental economics. Moreover, this paper assumes that regions outside the coalition of interest set their own carbon target, which can be well motivated by the national climate policies that are already existing and mentioned for the case of Germany and France above. However, it is assumed that the market under consideration, nonetheless, fulfills the properties of a perfect market and regions engage in cross-boarder electricity trade.

Having these assumptions in mind, the framework of cooperative game theory is suitable for analyzing this type of cooperation for two reasons: First, the relevant concepts of gain-sharing can still be applied while maintaining the efficient solution approach of a bottom-up power market model. Second, the equilibrium outcome for different coalitions can be compared with respect to a variety of market variables, e.g. capacity investment path, and the approach can, thus, go beyond a pure cost perspective.

For this analysis, the EU-REGEN model is applied in order to find the long-run equilibrium for the European power market under a tight climate policy. Results indicate, that in the absence of transfer payments only a small share of the gains from full cooperation can be maintained. Hence, this paper shows that the phenomena of only small-sized coalitions being stable, also holds for the power market. Moreover, the analysis indicates that accounting for fairness goes in hand with balancing robustness against cost changes and individual rationality or core stability, respectively.

The paper is organized in the following way. To begin, section 2 provides an overview on the game theoretic framework and the quantification of costs in this paper. Then, section 3 presents the respective results. Finally, the paper closes with a discussion of the applied methodology and conclusions in section 4.

2. Methodology

This section presents the game theoretic framework, the relevant solutions concepts, and the quantification of costs used in this analysis.

2.1. Framework

This paper assumes a cooperative game framework[6], which generally describes the bargaining problem of coalitions with a focus on identifying feasible and stable coalitions and distributing the gains from cooperation [30][7]. The coalition game is characterized by the player set $N := \{1, ..., n\}$ and the function $v : 2^n \to \mathbb{R}$ that assigns a value $v(S)$ to each coalition. Coalitions are the non-empty subsets $S \subseteq N$ with N being the grand coalition and $\{i\}$ the singleton coalitions.

In the context of this paper, the regions of the European power market are regarded as the set of players N. The analysis looks at $2^n - 1 - n$ possible coalitions[8], which comprise the grand coalition N that represents the first-best outcome with full cooperation and, thus, the cost-efficient market equilibrium.

Moreover, the permutation $c \in \mathbb{R}^n$ assigns cost $c_i(S)$ to each player. The cost of player i with being in a coalition and if the initial cost allocation is realized is $c_i(S)$. On the contrary, $c_i(\{i\})$ is the cost under singleton coalitions only. The cooperative cost-sharing game is assumed to still meet the properties of a perfect market. Hence, even though coalitions $S \subset N$ are in place, finding the market-wide cost minimum is

[6] In general, the interaction between players can be distinguished into cooperative and non-cooperative games. Cooperative games focus on payoffs from cooperation, whereas the latter one mainly addresses the strategic actions of players. Non-cooperative games capture the strategic interaction of players, which aim at optimizing their payoff function. Each player's strategy of the choice variable is a function of the available information. One prominent solution concept to non-cooperative games is the Nash equilibrium. It is based on the notion of best responses. Each player chooses his choice variable under the belief that the choice of the other players is given. Accordingly, a solution is stable if no player has the incentive to deviate from her action under the assumption that all other players keep their choice constant.

[7] The same rational applies to games where players share payoffs instead of cost.

[8] In general, n players can from $2^n - 1$ non-empty coalitions. Yet, this number also comprises n singleton coalitions of cardinality $|S| = 1$. Consequently, the number of $2^n - 1$ coalitions is corrected for the n singleton coalitions.

regarded as a valid solution approach and even though two neighboring regions are not comprised in a coalition, cross-boarder flows of electricity are still feasible. Consequently, a respective (climate) coalition can have minor impacts on regions that are not comprised. However, for the sake of simplicity and in order to be in line with the formalism of cooperative games, the remainder of this paper assumes that regions outside a coalition are confronted with the cost under the singleton coalitions only case $c_i(\{i\})$. Hence, this paper works with the (N, v) characteristic function [31], which maps coalition structures to individual cost for all players $i \in S$ [9]. Moreover, the game can be transfered into a cost saving game by defining the value of a coalition $v(S)$ as the sum over the cost-savings from all members of a coalition:

$$v(S) = \sum_{i \in S} (c_i(\{i\}) - c_i(S)) \quad \forall\, S \subseteq N$$

Furthermore, this paper distinguishes between transferable utility (TU) games and non-transferable utility games (NTU). In terms of TU games, the total gain from cooperation $v(S)$ can be transfered between players. This is based on the assumptions that utilities are expressed in units of a common numeraire good and utility functions are quasi linear. In this case, coalitional games aim at maximizing the worth of the coalition $v(S)$. In contrast to that, NTU games do not allow for transfer payments between players. Hence, it is the goal of the game to find the coalitional setting with the Pareto-optimal cost distribution.

This paper assumes TU games to be superadditive[10]. So, the sum of the value of two disjoint coalitions is strictly smaller than the value of the grand coalition, which comprises the players of both coalitions [33]:

$$v(s_1 \cup s_2) > v(s_1) + v(s_2)$$

2.2. Solution Concepts

Solution concepts to cooperative games can be distinguished with respect to the underlying requirements on cooperation. This analysis focuses on concepts addressing stability and fairness.

[9] An alternative concept is the partition function [32], which considers the cost to all players $i \in N$.

[10] This is identical to the subadditivity assumption for a cost-sharing game.

2.2.1. Stability Concepts

Concepts of stability rather look at the stability of each individual coalition S than just at the grand coalition N. For that purpose, the cost distribution $\hat{x}_i(S)$ of the total cost is defined as the first-best cost incurred by a given player i if coalition S is formed.

2.2.1.1. Internal and External Stability

The notion of internal and external stability was introduced in [34] and [35] and further applied in e.g. [23]. Accordingly, a coalition S is stable if the cost distribution meets the criteria of internal and external stability. Concerning the former one, a coalition is stable if no member of a coalition has the incentive to stay outside the coalition[11]:

$$\hat{x}_i(S) \leq c_i(S \setminus \{i\}) \quad \forall\, i \in S$$

For the latter one, no player outside the coalition prefers to join the coalition, which can be formalized as

$$c_i(S) \leq \hat{x}_i(S \cup \{i\}) \quad \forall\, i \notin S.$$

2.2.1.2. Core Stability and Individual Rationality

The individual rationality constraint [37], or Nash solution, imposes a condition on stability according to which no player can be better off by deviating from the assigned strategy with constituting a singleton coalition, which can be formalized by

$$\hat{x}_i(S) \leq c_i(\{i\}) \quad \forall\, i \in S.$$

For the remainder, it is assumed that all individual rational allocations are comprised in the set $I(v)$:

$$I(v) = \{\hat{x} \in \mathbb{R}^n : \hat{x}_i(S) \leq c_i(\{i\}) \quad \forall\, i \in S\}$$

The individual rationality property is also implied by the concept of core stability [38]. Yet, whereas individual rationality and internal/external stability evaluates the stability of coalitions of any cardinality, the concept of the core looks in particular at the stability of the grand coalition. The core aims at finding the vector $y \in \mathbb{R}^n$, the

[11] The notion of internal stability has been extended by [36] to the potentially internally stable coalition, which reads as follows: $\hat{x}_i(S) \leq \sum_{i\in S} c_i(S \setminus \{i\})$.

distribution of the value of a coalition with y_i being the allocation towards player i, which fulfills the characteristics of efficiency and coalitional rationality (see e.g. [39]). For efficiency, the total gain of a respective coalition must be distributed among all players, which can be formalized by

$$\sum_{i \in N} y_i = v(N).$$

Concerning coalitional rationality, the sum of gains of members of a coalition must not be smaller than the value of the coalition

$$\sum_{i \in S} y_i \geq v(S) \quad \forall S \subseteq N.$$

Hence, the set of all core stable allocations is defined as

$$C(v) = \{y \in \mathbb{R}^n : \sum_{i \in N} y_i = v(N) \quad and \quad \sum_{i \in S} y_i \geq v(S) \quad \forall\, S \subseteq N\}.$$

2.2.2. Allocation Concepts

TU games include the possibility of transfer payments where the exact design of transfers can impose a higher degree of fairness on coalitions. There exists a big strand of literature that focuses on allocation concepts for gain-sharing. These concepts assign a unique allocation vector $x_i^* \in \mathbf{R}$ to each game.

Existing methods are based on different views on fairness. One strand looks at the fair selection from the subset of cores $C(v)$ and is represented by e.g. the core center (see e.g. [40]) and the least core. Alternatively, concepts can be based on the power or contribution of individual players. Here, very basic methods propose an equal or production-dependent distribution. More elaborate mechanisms, like the kernel (see e.g. [41]), Shapley value, and nucleolus, are based on game theoretical considerations[12]. Within this analysis the least core, Shapley value, and nucleolus will be used to elaborate on the fair allocation of cost.

2.2.2.1. Least Core

The concept of the least core x_i^{LC} was introduced by [45]. It is the cost allocation that

[12] A more extensive overview on gain-sharing mechanisms can be found in, e.g., [42], [43], and [44].

minimizes the maximum satisfaction ε for any coalition. Thus, it is assumed to be the cost allocation that players object the least [46]. The implementation in this paper is taken from [47] and can be described by the following linear program:

$$\min_{x_i^{LC}} \quad \varepsilon \tag{1}$$

subject to:

$$\sum_{i \in N} x_i^{LC} = \hat{x}_i(N) \tag{2}$$

$$\sum_{i \in S} x_i^{LC} \leq \sum_{i \in S} \hat{x}_i(S) + \varepsilon \quad \forall S \subset N, \ S \neq \emptyset \tag{3}$$

2.2.2.2. Shapely Value

In the field of game theoretical approaches, the average contribution of each player to the formation of the coalition, underlies the formulation of the Shapley value [48]. The average is taken over all possible permutations in which the coalition can be set up. Hence, it can be interpreted as the marginal benefit from one player joining a coalition if all orderings of players are equally likely [49]. The Shapley value can be formalized as

$$x_i^{SHP} = \sum_{S \subset N} \frac{|S|! \ (N - |S| - 1)!}{N!} \ (v(S) - v(S \setminus \{i\})).$$

2.2.2.3. Nucleolus

Finally, the nucleolus is a sharing mechanism that builds on the notion of the "unhappiness" of the coalition, which is measured by the excess of a coalition $\varepsilon(S,x)$ with $\varepsilon(S,x) = v(S) - \sum_{i \in S}(c_i(\{i\}) - \hat{x}_i(S))$ [50]. This can be interpreted as the part of the value of a coalition that the members of the coalition cannot appropriate under a given allocation x.

The values of $\varepsilon(S,x)$ for different coalitions and allocations can then be comprised in the vector $e(x) \in \mathbf{R}^{2^n-2}$ and sorted in non-increasing order. Hence, the element $\varepsilon_1(x)$ represents the maximal unhappiness from allocation x. This allows for comparing two allocations x and y by applying the following rule: x is preferred to y if it is lexicographic smaller with $\varepsilon(x) \preceq_{lx} \varepsilon(y)$. The nucleolus of the (N,v) game is then characterized by the following set

$$NC(N,v) = \{x \in X(N,v) : \varepsilon(x) \preceq_{lx} \varepsilon(y) \quad \forall y \in X(N,v)\}.$$

The computational implementation the nucleolus in this analysis is based on the approach proposed in [51] and [52]. It can be computed by solving the sequence of linear programs outlined in Appendix A.

The very general concept of the nucleolus, which is based on the total excess, resulted in alternative definitions. The author in [53] introduced the per capita nucleolus as a relative measure, which looks at the per capita excess and aims at minimizing the per capita dissatisfaction. Its formally defined as[13]

$$\varepsilon^{PC}(S,x) = \frac{v(S) - \sum_{i \in S}(c_i(\{i\}) - \hat{x}_i(S))}{|S|}.$$

Other authors adjusted the concept of the per capita nucleolus to the research design of their analysis, e.g. [55]. The same line of reasoning can be applied to the context of this paper by introducing a relative measure for the excess that is, however, based on the joint carbon emission reductions of a coalition[14]. For the remainder of the paper, this measure is called carbon nucleolus. Instead of dividing by the cardinality of a coalition $|S|$, the carbon nucleolus uses the total amount of reduced emissions in 2050 (compared to 2015 levels) $\sum_{i \in S}(CO2_i^{2015} - CO2_i^{2050})$. It aims at prioritizing coalitions that contribute high emission reductions and, thus, minimizes the dissatisfaction per units of emission reductions.

2.3. *Quantification of Costs*

This paper applies the EU-REGEN model in oder to quantify the first-best cost distribution $\hat{x}_i(S)$ of the future equilibrium outcome of the European power market under a cooperative, subadditive cost-sharing game for each coalition S[15]. The model minimizes the total discounted system cost with respect to a set of constraints. For this analysis, the system cost of the EU-REGEN equilibrium outcome that arises from

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[13] Please note that the concept of the nucleolus was not only developed further towards the per capita nucleolus. Other variants are the propensity to disrupt [16] or its generalized concept, the disruption nucleolus [54].

[14] I want to thank an anonymous referee for drawing my attention at the development of an alternative definition of the per capita nucleolus.

[15] The minimization of overall system cost is regarded as an appropriate solution approach since this paper aims at comparing the efficient market outcome under different coalitions.

capacity investment and electricity generation (among others) in a specific region are interpreted as the costs of a region $\hat{x}_i(S)$ under coalitions S. These regional costs underly the individual gain from cooperation, which is understood as the saving in system cost compared to the case when each region constitutes a singleton coalition $c_i(\{i\})$. Hence, the value of each coalition is approximated by $v(S) = \sum_{i \in S}(c_i(\{i\}) - \hat{x}_i(S))$.

2.3.1. The EU-REGEN Model

The EU-REGEN model[16] [56] is a long-term dispatch and investment model for the European power sector. The model was developed to generate quantitative scenarios that represent a cost-effective and consistent decarbonization path for the European power system towards 2050 for regions i, time periods t, and intra-annual time steps s[17]. The linear, deterministic optimization model minimizes the total discounted system cost c^{tot} that comprise investment cost for generation capacity $c^{\mathrm{gc}}_{i,t}$, transmission capacity $c^{\mathrm{tc}}_{i,t}$[18], cost from generation operation $c^{\mathrm{vc}}_{i,t}$[19], maintenance cost for generation capacity $c^{\mathrm{fom}}_{i,t}$, and operation and maintenance cost for transmission $c^{\mathrm{tvo}}_{i,t}$ and $c^{\mathrm{tfm}}_{i,t}$. The factor DF_t accounts for the period-specific discounting of cost:

$$c^{tot} = \sum_i c^{tot}_i = \sum_t (c^{\mathrm{gc}}_{i,t} + c^{\mathrm{tc}}_{i,t} + c^{\mathrm{vc}}_{i,t} + c^{\mathrm{fom}}_{i,t} + c^{\mathrm{tvo}}_{i,t} + c^{\mathrm{tfm}}_{i,t}) \cdot \mathrm{DF}_t$$

The model is set-up as a partial equilibrium model that assumes complete markets with perfect information. The main equilibrium constraint is that the market clears in each time segment[20]. Accordingly, the (simplified) market clearing condition below

[16] The notation in this paper has been adjusted, compared to [56], in order to be consistent with section 2.

[17] Please note that the presentation of the EU-REGEN model in this paper abstracts from the existence of different generation technologies and their vintages.

[18] The cost that one region occurs from investing in one additional unit of transmission capacity only represent the investment cost for one direction. The neighboring region must undertake the same investment separately in order to be able to export. This assumption tries to guarantee consistency with empirical estimates for upper bounds on transmission capacity investments.

[19] The variable generation cost do not comprise the cost for emission certificates. This is based on the assumption that revenues from the auctioning of certificates are distributed in proportion to emissions as it is currently done in the EU ETS [57].

[20] The version of the EU-REGEN model used in this paper does not allow for the endogenous adjustment of demand, e.g. by setting a short- or long-run price-elasticity of demand.

requires that generation $g_{s,i,t}$, plus electricity imports $im_{s,ii,i,t}$, less electricity exports $ex_{s,i,ii,t}$ has to meet demand $\mathrm{D}_{s,i,t}$[21]. More detailed information on the temporal, spatial, and technological resolution of the EU-REGEN model can be found in Appendix B and [56].

$$g_{s,i,t} + \sum_{ii} im_{s,ii,i,t} - \sum_{ii} ex_{s,i,ii,t} \geq \mathrm{D}_{s,i,t} \qquad \forall s \in \mathcal{S}, i \in \mathcal{I}, t \in \mathcal{T}$$

2.3.2. Derivation of Cost Allocations by Coalition

In order to elaborate on the impact of considerations of fairness on the market equilibrium and, thus, derive the first-best cost allocation $\hat{x}_i(S)$ for any given coalition S, this paper analyzes the equilibrium market outcome under perfect information for a wide number of coalitions. The solution under perfect information is found by solving the cost-minimization problem of the EU-REGEN model for all decision variables simultaneously. Here, transmission capacity investment, generation capacity additions, and dispatch are optimized. Depending on the coalition S under scrutiny, different carbon market constraints are applied. This solution approach is solved for two groups of coalitions:

Concerning the first one, the first-best scenario applies a market-wide carbon budget by assuming full cooperation and is interpreted as the grand coalition. Meaning, all regions share a common (time period-specific) carbon budget B_t. Hence, in order to solve the EU-REGEN model for the grand coalition, the following carbon market constraint is added to the program:

$$\sum_{s,i} g_{s,i,t} \cdot CO2 \leq B_t \quad \forall i \in N, t \in \mathcal{T}$$

with $CO2$ being the average emission factor. Of course, the grand coalition is closely related to the existing EU Emissions Trading System (EU ETS). Here, all participating countries[22] try to reach a joint emission budget. The EU ETS considers all CO_2, N_2O,

[21] Please note that this constraint does not allow for the curtailment of demand. An alternative approach would be allowing for demand curtailment by valuing unserved load at the price cap in the market, the value of lost load (VOLL) [58]. A too low set VOLL can trigger the so-called *missing money* problem where revenues do not fully cover cost [59]. Hence, the set-up of the EU-REGEN model excludes from the possibility of encountering the missing money problem.

[22] The EU ETS comprises the countries of EU28, Iceland, Liechtenstein, and Norway.

and Perfluorocarbons (PFCs) emissions from more than 10 sectors of the economy[23]. As with the grand coalition in this analyses, the rationale of the EU ETS is about market participants that coordinate their abatements efforts (by trading emission allowances) to use abatement sources in the ascending order with respect to their marginal abatement cost.

The quantification of the market-wide carbon budget B_t is taken from the energy and climate policies set by the EC. These targets indicate a 40 % and 80 % (compared to 1990 levels) reduction of economy-wide GHG-emissions by 2030 and 2050, respectively. This paper uses the European Commission's impact assessment on the "[...] policy framework for climate and energy in the period from 2020 up to 2030" [60] for the translation into a power sector-specific target. According to this assessment, the level of CO_2-emissions has to reach a 56 % reduction by 2030 and a 98 % decrease of emissions by 2050[24]. Furthermore, the EC's assessment assumes that annual electricity generation in 2050 amounts to 5,050 TWh. For the time-steps in between, this paper assumes a linearly decreasing CO_2-emission budget and increasing electricity demand. The framework in this paper assumes no energy and climate policy apart from CO_2-prices through CO_2-emission control.

The second group of coalitions comprises each possible coalition $S \subset N$. Based on section 2 and the framework of the EU-REGEN model with $n = 13$ model regions, this results in $2^n - 1 - n = 8,178$ possible coalitions between regions[25]. For this group of coalitions, shared carbon budgets are assumed for regions constituting a coalition $i \in S$. Each region outside the coalition $i \notin S$ is subject to its own carbon budget[26]. These regional carbon budgets $B_{i,t}$ assume a 98 % reduction target for each region by

[23] The current version of the EU ETS comprises the power and heat generation, oil refineries, steel works and production of iron, aluminum, metals, cement, lime, glass, ceramics, pulp, paper, cardboard, acids, bulk organic chemicals, and civil aviation sector.

[24] The carbon price resulting from this constraint represent only the marginal abatement cost in the power market.

[25] Please note that this number also includes the grand coalition which falls under the first group of coalitions.

[26] This means that regions outside the coalition can not utilize geographic differences in marginal abatement cost.

2050. The shared carbon budget for coalitions is the sum of regional carbon budgets $B_{i,t}$ for regions in a coalition. In order to solve the EU-REGEN model for this group of coalitions, the following two carbon market constraints are included in the program

$$\sum_{s,i} g_{s,i,t} \cdot CO2 \leq \sum_{i} B_{i,t} \quad \forall i \in S, t \in \mathcal{T},$$

$$\sum_{s} g_{s,i,t} \cdot CO2 \leq B_{i,t} \quad \forall i \notin S, t \in \mathcal{T}.$$

2.3.3. Adjustment of Cost Allocations

In order to fully capture the incentives for electricity exchange, the regional system costs have to be adjusted for electricity exports and imports. Hence, total regional system costs, obtained from solving the linear program of the EU-REGEN model, are adjusted for the value of these quantities[27]. Total regional system cost c_i^{tot} are understood as the sum of discounted cost that arise from capacity investment, electricity generation, and distribution in a certain region. Yet, to consider the benefits of trade, cost from electricity generation should be assigned to the region that actually consumes the generated quantities. Hence, the final total regional system cost $\hat{x}_i$ for a respective coalition are the initial system cost c_i^{tot} adjusted for the value of imported and exported quantities and can be written as

$$\hat{x}_i = c_i^{tot} + \sum_{s,ii,t} (im_{s,ii,i,t} \cdot p^{im}_{s,ii,t} - ex_{s,i,ii,t} \cdot p^{ex}_{s,i,t}) \cdot \mathrm{DF}_t.$$

The market-clearing prices in exporting and importing regions, $p^{ex}_{s,i,t}$ and $p^{im}_{s,ii,t}$, are derived from the shadow prices on the regional market clearing constraints.

Please note again that the cost for the case of singleton coalitions only $c_i(\{i\})$ are obtained by assuming that all regions $i \in N$ are subject to an own carbon budget. Moreover, the resulting first-best cost allocations $\hat{x}_i(S)$ are assumed to be the cost that members of a coalition $i \in S$ incur if joining the coalition S under scrutiny. Both, $c_i(\{i\})$ and $\hat{x}_i(S)$, will be analyzed in the subsequent section 3.

[27] I want to thank Prof. Christoph Weber for drawing my attention, at the International Ruhr Energy Conference 2017, on the cost adjustment discussed in this paragraph.

3. Results

The presentation of results starts with characterizing the underlying fist-best cost distribution, results on the stability and fairness of allocations, and, finally, an evaluation of these allocations. This is followed by a comparison of the market outcome under the grand coalition and singleton coalitions only.

3.1. The Cost-Sharing Game

3.1.1. Characterization of Costs

The first-best cost distribution of this cost-sharing (cooperative) game is quantified by obtaining the total regional system cost from the EU-REGEN model for all $2^n-(n-1)$ scenarios.

The value of forming the grand coalition N shows to be a € 69 billion reduction in total discounted system cost compared to the case of singleton coalitions only. This represents a 4 % reduction. 73 % of this reduction goes to capital cost and the remaining 27 % to operational cost. These values equal the share of capital and operational cost, respectively, in total cost in the case of singleton coalitions $\{i\}$ only. Hence, cooperation equally impacts both cost types.

Yet, the value of N to each individual region is highly heterogeneous. It ranges from a € 20 billion (11 %) cost decrease in the case of South Germany to a € 9 billion (4 %) increase for the North-West of Eastern Europe. The different directions of changes reveal that, from the perspective of single regions, it is not rational to enter N. Table 1 shows the cost allocation for $\{i\}$ and N, as well as the relative change between both for each model region.

The change in regional system cost, when moving from $\{i\}$ to N, can then be explained by changes in the cost structure of the technology mix. In the case of Scandinavia, higher investment in capital-intensive RES substitutes investment in gas power, which is subject to high fuel cost. Due to the high penetration level of variable RES, the marginal generator in the Scandinavian market is a RES technology with low marginal cost for most time segments. Hence, exported quantities are valued at low prices and do not fully recover the investment cost. Moreover, imported quantities from neighboring regions compensate the intermittency of RES, which are, hence, mostly valued at the high marginal cost of flexible gas power.

A first approach towards fair cost-sharing is the marginal contribution v_i of a region to N. This can be calculated by contrasting the value of the grand coalition, $v(N)$, with the value of a coalition that comprises all regions except for the region of interest, which can be formulated as $v_i = v(N) - v(N \setminus \{i\})$. Results are depicted in Table 1. Values indicate that the contribution of all regions is in the same range. Though, Britain, Iberia, and South-East Eastern Europe show to have a slightly increased value to N.

Table 1: Characterization of Cost-Sharing Game and Stable Cost Distributions in [€ billion]

	$C_i(\{i\})$	$\hat{x}_i(N)$	Δ	v_i	$\hat{x}_i(s^R)$	$\hat{x}_i(s^{IS})$	$\hat{x}_i(s^{ES})$
Britain	260	257	−0.01	40	260	258	260
France	293	286	−0.03	35	293	293	293
Benelux	140	125	−0.11	38	140	140	128
Ger-N	149	146	−0.02	34	149	149	147
Ger-S	196	176	−0.11	37	196	196	176
Scandinavia	70	71	+0.01	39	70	70	77
Iberia	290	274	−0.06	42	279	290	275
Alpine	39	31	−0.02	35	39	39	39
Italy	233	225	−0.03	35	233	225	227
EE-NW	210	219	+0.04	38	210	210	222
EE-NE	13	14	+0.12	38	13	13	14
EE-SW	44	45	+0.04	35	44	44	44
EE-SE	94	94	−0.01	40	94	93	95

The small difference between the individual values of each region can also be obtained from looking at the value of a coalition as a function of its cardinality. Figure C.5 (see Appendix C) shows the maximum and minimum saving (in total system cost) for all coalition cardinalities, which is the number of members. The conclusion from the previous paragraph is verified by the minor difference in the maximum and minimum coalition value for coalitions of cardinality $|N| = 12$. Furthermore, it can be seen that coalitions with a cardinality ranging from 4 to 9 are subject to greater differences between minimum and maximum value. Consequently, the composition of coalitions matters the most for medium size cooperations.

3.1.2. Stability of Coalitions

The concepts for identifying stable coalitions were introduced in section 2.2.1. In the following, stability will be analyzed based on the core, individual rationality, and internal and external stability.

Testing the first-best cost allocation of the grand coalition $\hat{x}_i(N)$ with respect to the core, reveals that the allocation is not core-stable. There are 946 coalitions of smaller size whose members would be confronted with lower cost if they form. Thus, the grand coalition N cannot be reached without the implementation of transfers.

Now solely abstracting to the individual rationality constraint, or Nash solution, aims at identifying individual disincentives for cooperation. Results show that only 15 coalitions (out of $8,178$) fulfill the individual rationality constraint. The set of coalitions comprises only small-sized coalitions with a maximum cardinality of four coalition members. Consequently, the grand coalition can not be reached under the stability criteria of individual rationality. The coalition, out of these 15, with the highest value, s^R, comprises the following regions: {Britain, Iberia}. The coalition s^R leads to a cost reduction of € 11 billion. This represents 16 % of the gains of N. The cost distribution of s^R is shown in Table 1.

Finally, testing the coalitions in this cost-sharing game with respect to internal and external stability further indicates the strong impact of a stability criteria. Concerning internal stability, few coalitions (8 out of $8,178$) fulfill this criteria. Again, only small-sized coalitions with up to 4 coalition members pass the test. The internal stable coalition with the highest value, s^{IS} (shown in Table 1), saves € 10.8 billion, which accounts for 16 % of the gains of N. The coalition comprises {Britain, France, Italy, South East Eastern Europe}. The external stability criteria is met by 442 coalitions. By definition of the concept, this excludes the grand coalition. Yet, the set of external stable coalitions comprises coalitions with a cardinality of up to 12. For this criteria, the external stable coalition with the highest reduction in system cost, s^{ES} (as well shown in Table 1), has a value of € 34.2 billion (49 % of $v(N)$) and consists of all regions except for France and South West Eastern Europe. However, applying both criteria reveals that none of the coalitions are internally and externally stable at the same time. As indicated by [20], the result that no or only small-sized coalitions are internally and externally stable is in line with the theoretical findings on internal and external stability in [23] and [24].

It is important to emphasize that the concepts of core and internal/external stability build on different views on stability. Whereas the core assumes that the coalition under scrutiny does not form at all if one or multiple players deviate, the internal/external stability concept implies that coalitions form nonetheless [20]. Furthermore, this section revealed that under all concepts of stability (in this paper) the grand coalition cannot form. For the concepts looking at all coalitions $S \subseteq N$, the individual rationality concept reveals that, if regions act solely rational, at most 16 % of the full gains of cooperation can be reached. According to internal and external stability, no coalition is stable. Consequently, only small efficiency improvements can be realized in the absence of transfer payments, which will be analyzed in the subsequent section.

3.1.3. Fair Cost Sharing

Section 2.2.2 introduced concepts for fair cost-sharing under the assumption of a TU game. In the following, results from the application of the least core, Shapley value, nucleolus, and carbon nucleolus will be discussed.

Fair cost-sharing based on the least core x_i^{LC} builds on the notion of coalitional satisfaction. The values for the least core are shown in Table 2. However, the solution to the linear program is not unique. Hence, it should not be interpreted as an optimal cost allocation and will, thus, be neglected for the remainder of this paper.

In terms of the group of unique cost allocations, the Shapley value builds on the notion of fairness only. Yet, by definition, the nucleolus combines the underlying fairness concept with stability. The carbon nucleolus goes one step further and considers the absolute emission reduction by coalition for a fair and stable cost distribution. The respective cost allocations x_i^{SHP}, x_i^{NUC}, and x_i^{CNUC} are again displayed in Table 2.

This section shows cost allocations based on the least core, Shapley value, nucleolus, and carbon nucleolus. Though, the absolute values of these allocations offer little insight for an evaluation and comparison of these concepts. Thus, the following section 3.1.4 analyzes the general implications of the underlying methods with respect to robustness against cost changes, non-bindingness of commitments, and core stability.

Table 2: Cost Allocations in [€ billion]

	x_i^{LC}	x_i^{SHP}	x_i^{NUC}	x_i^{CNUC}
Britain	252	249	251	250
France	290	294	290	292
Benelux	135	134	135	136
Germany-N	146	149	146	142
Germany-S	188	189	189	190
Scandinavia	65	64	65	67
Iberia	282	277	282	281
Alpine	37	38	37	39
Italy	230	232	230	230
EE-NW	204	204	204	200
EE-NE	6	7	5	9
EE-SW	40	42	41	42
EE-SE	88	84	88	85

3.1.4. Evaluation of Allocations

Investment decisions in the power market have long-run implications for system cost and generation potentials. While economic agents base their contemporary decisions on information available at the time, future cost might deviate from these preconceived paths. In order to assess whether allocations (under different coalitions) are robust with respect to future cost changes, this paper takes a look at the so-called monotonicity property [61]. In this context, the monotonicity property is understood as the change of a cost allocation with a change of the worth of a coalition $v(S)$. Thus, it is another major criterion for fair cost-sharing. In the field of cooperative game theory, it can be differentiated between coalitional monotonicity, weak coalitional monotonicity, and aggregate monotonicity [40]. A cost allocation rule satisfies coalitional monotonicity if for an increase in total cost from $v(S)$ to $v(S)'$ each member suffers higher cost and vice versa, which can be written as

$$x_i < x_i^{'} \; \forall \; i \in S.$$

Weak coalitional monotonicity means if the same applies to the members of a coalition on the aggregate:

$$\sum_{i \in S} x_i < \sum_{i \in S} x_i^{'}$$

Finally, a method satisfies aggregate monotonicity if the same holds for all players of the game on the aggregate:

$$\sum_{i \in N} x_i < \sum_{i \in N} x_i^{'}$$

Concerning the nucleolus, [62] showed that it satisfies weak coalitional monotonicity. The Shapley value is the only strongly coalitional monotonic allocation among the methods in this paper [63]. At last, [53] verified the coalitional monotonicity of the per capita nucleolus. Since the carbon nucleolus is an analog concept, it satisfies this property as well. Table 3 summarizes the monotonic property of allocation methods.

In general, it is difficult to make the commitment to the grand coalition N binding. Under this assumption, an allocation x_i^* also has to be evaluated with respect to all strict subsets of N. Meaning, the excess of a permutation under $S \subseteq N$ determines its quality. The coalitional satisfaction $F(S)$ under an allocation captures this property. It is defined as the excess of allocated cost of players from N, x_i^*, over the total cost if coalition S acts independently and can be written as [44]

$$F(S) = \sum_{i \in S} (x_i(S) - x_i^*) \quad \forall \; S \neq \varnothing, \; S \subseteq N.$$

Taking the mean over all coalitions S results then in the average satisfaction F^{AV}:

$$F^{AV} = \frac{\sum_S F(S)}{|S|}$$

The average coalitional satisfaction values F^{AV} for all three methods are shown in Table 3. Although, the absolute values for F^{AV} should not be interpreted directly, the minor difference between all three methods shows that none of them is superior concerning that criteria.

Section 2.2.1 introduced core stability, which implies individual rationality, as one criteria for stability of coalitions. Since it captures individual incentives for cooperation, it should also be a criteria for a general evaluation of cost-sharing methods. The nucleolus and carbon nucleolus satisfies the individual rationality criteria by construction. Testing the Shapley value for this criteria reveals that it is not in the core.

Table 3: Overview on Evaluation of Allocations

	Monoton.	F^{AV}	Core Stability
Shapley	Strong coal.	€ 18.2 B	No
Nucleolus	Weak coal.	€ 18.3 B	Yes
Carbon Nucleolus	Coal.	€ 18.3 B	Yes

Table 3 summarizes the results for all three evaluation criteria. Since the average coalitional satisfaction shows little differences between methods, an overall comparison should be based on the monotonicity and individual rationality property. A positive characteristic of the Shapley value is its strong coalitional monotonicity property. At the same time, the nucleolus and carbon nucleolus proves to exhibit a core stable allocation. Consequently, choosing an allocation method would mean balancing robustness against cost changes and core stability and thus individual rationality.

3.2. Comparison of Market Outcomes

3.2.1. Generation Path

The previous section 3.1 focused on the general differences within the set of all possible coalitions. In the following, this paper will add to this by analyzing the differences between the two most extreme cases, full cooperation under N and no cooperation under $\{i\}$.

The development of the future generation path under a 98 % CO_2 reduction target and full cooperation is depicted in Figure 1. Accordingly, wind power is the dominating technology for the EU decarbonization path. Its generation increases more than fivefold until 2050. The attractiveness of wind power can be explained by an expected reduction of investment costs, increasing availability factors, and its positive correlation with load[28]. The latter one reflects the seasonal correlation of availability factors with demand. Both, maximum generation from wind power and demand peak, appear during winter times. The bulk of generation is from onshore capacity. Generation from offshore installations proves to be hardly economically viable with its accumulated annual generation constantly staying below 40 TWh.

The generation share of variable RES increases over the model horizon from 12 % in 2015 to 40 % in 2050. Yet, this is mainly driven by wind power. The generation share of all solar power technologies increases from 5 % to 8 % in 2050 only. This weak market penetration can be explained in analogy to the attractiveness of wind power. Although, solar power technologies have in general lower availability factors, lower investment costs are not able to compensate for that. Additionally, there is a negative seasonal correlation between generation from solar technologies and demand in most model regions[29].

In economic terms, the difference in the market penetration between wind and solar power represents each technologies' substitution elasticity with dispatchable technologies. The time-profile of wind power leads to its higher substitution elasticity with dispatchable technologies.

The development of dispatchable technologies in the first-best scenario is characterized by investment in gas power technologies and divestment from coal-fired technologies[30]. The former one almost triples its generation share to 21 % and functions as complementary technology to wind power. The contribution of coal-fired technologies is monotonically decreasing and falls from 25 % in 2015 to 0.05 % in 2050.

[28] Increasing availability factors are assumed due to a higher expected conversion-efficiency at lower wind speeds.

[29] Only the Iberian model region shows a positive seasonal correlation between demand and solar irradiation.

[30] The extensive market penetration of gas power has to be interpreted with respect to the framework of the EU-REGEN model. Due to the missing consideration of storage technologies, gas power, as the most flexible generation technology, is a natural complement to intermittent wind power. Consequently, in a framework with detailed modeling of storage, the market penetration of gas power could be lower due to utilization of electricity storage.

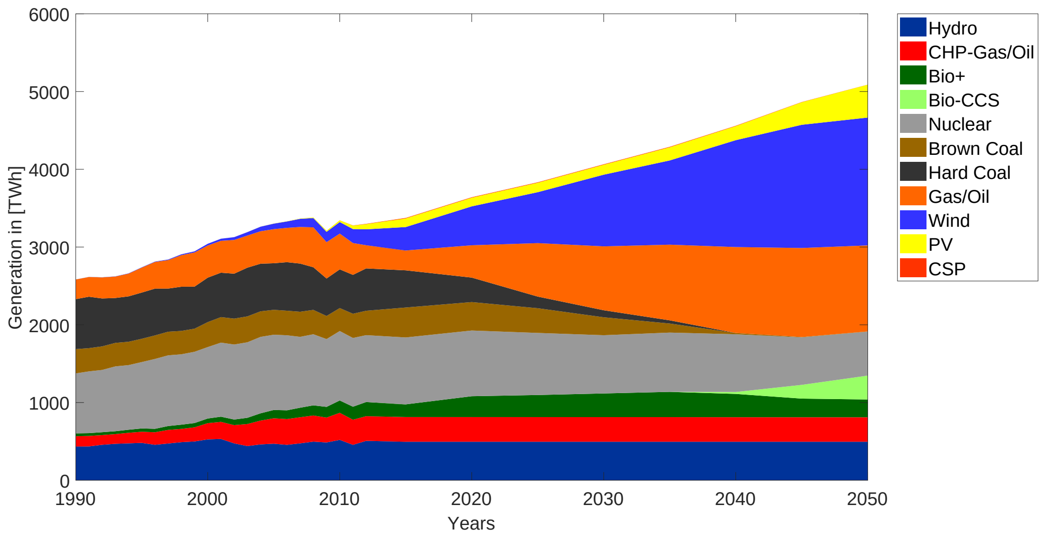

Figure 1: Long-Run Generation Path Under Grand Coalition.

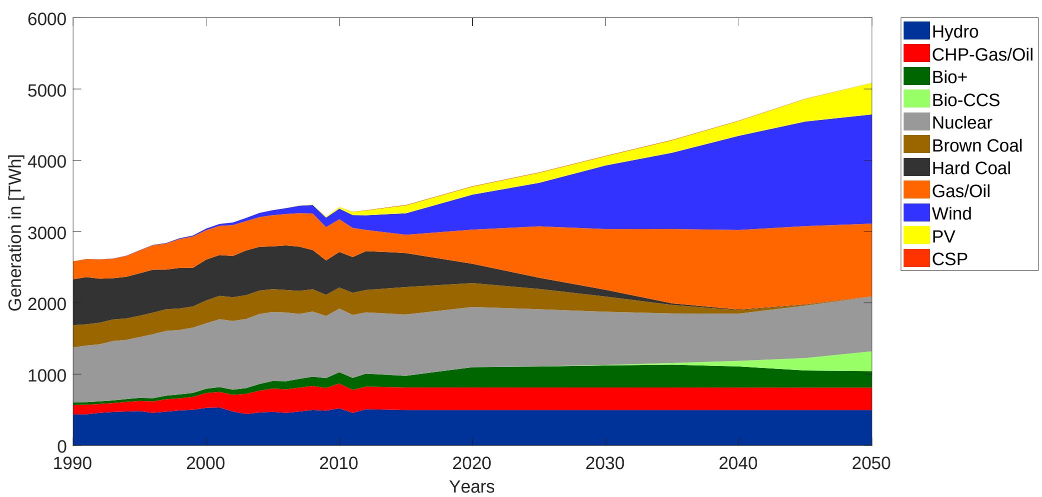

Figure 2: Long-Run Generation Path Under Singleton Coalitions.

The increasing generation-share of gas-powered technologies in this low CO_2-emission scenario is only feasible due to the market entrance of carbon capture and storage (CCS) with bioenergy (BECCS), which is characterized by a negative carbon intensity. Investments in BECCS arise from 2040 on and allow for a generation share of 6 % in 2050[31].

[31] The carbon intensity of BECCS is negative due to the removal of CO_2 from the atmosphere in the biomass growing phase in combination with the geologic storage of CO_2 emissions from the biomass

The overall generation path in the scenario with singleton coalitions shows little differences (see Figure 2). The generation paths between N and the singleton coalitions $\{i\}$ differ with respect to the utilization of low-carbon generation technologies. Moving from N to $\{i\}$ increases the generation from nuclear power and PV, on the one hand, and reduces the contribution from wind power, gas power, BECCS, and CSP, on the other hand. This can be seen in more detail when looking at the regional generation patterns.

The respective development of regional generation paths can be found in Figures D.6, D.7, D.8, and D.9[32] (see Appendix D). Under the grand coalition, the quality of wind and solar resources shows to be the main driver for the geographic distribution of wind and solar power generation. This is in contrast to other papers that emphasize the benefit of a geographic distribution, which utilizes a geographic averaging effect to smooth overall wind power generation [65]. The model region Britain becomes dominating in wind power application with reaching an annual generation of 400 TWh by 2050, accounting for approximately 25 % of 2050 total wind power generation. Moreover, also France and Scandinavia experience a significant increase in generation from wind power. Generation from solar resources is mainly added in the southern regions, namely Iberia, France, and Italy[33].

Comparing that to the results for the singleton coalitions, two patterns can be observed. On the one hand, with singleton coalitions we see the switch from wind power to nuclear power. The generation path for France indicate this development clearly. On the other hand, there is also a geographic shift of generation from gas power. This becomes obvious when comparing Germany and North-Western Eastern Europe in both scenarios.

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combustion. The general importance of BECCS in low CO_2-emission scenarios has been emphasized in e.g. [64].

[32] The generation path in Figures D.6d and D.8d comprises both German model regions.

[33] The market penetration of solar power in these countries can be explained by regional resource quality which strongly correlates with latitude.

3.2.2. Capacity Investment Path

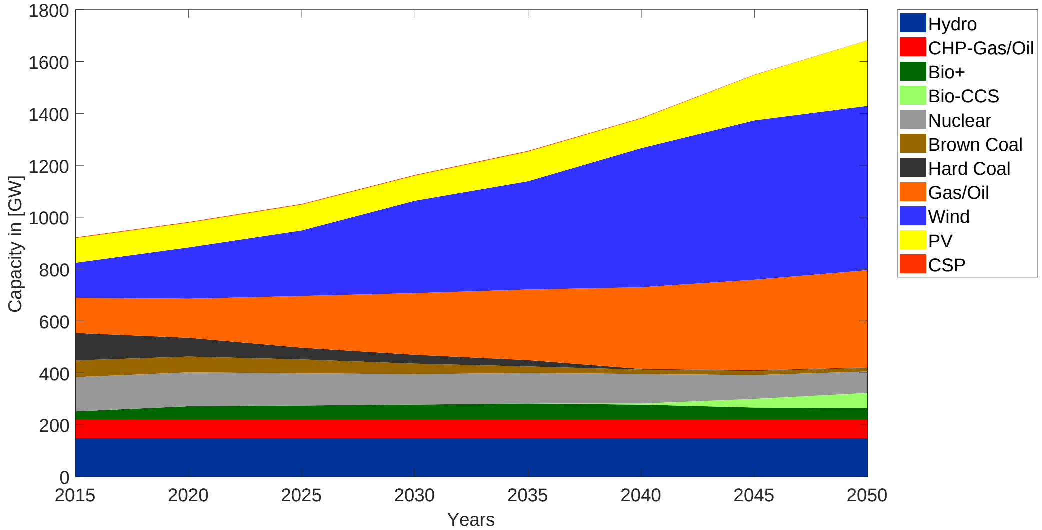

Figure 3: Long-Run EU Capacity Path Under Grand Coalition.

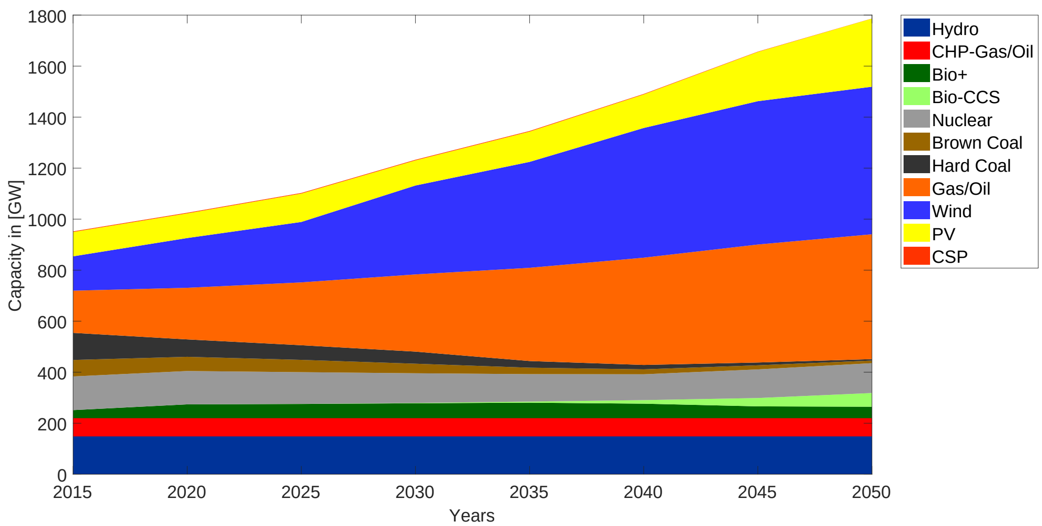

Figure 4: Long-Run EU Capacity Path Under Singleton Coalitions.

The development of the long-run generation path is reflected in capacity investment. Figure 3 shows the underlying capacity path for the grand coalition. The strong build-up of solar and, especially, wind power capacity is necessary because of the low substitution elasticity with dispatchable generation technologies. Due to the lower availability factors and intermittency of variable RES, greater amounts of capacity are required to substitute dispatchable, and CO_2-emitting, generation technologies.

Furthermore, a look at the timing of solar power investments reveals the importance of its decreasing investment costs. The majority of new capacity is added in the mid- and long-run, where investment costs experience a strong decrease. In terms of technology, only photovoltaic power proofs to be an economically attractive technology. Concentrated solar power (CSP) hardly penetrates the market. Meaning, its higher availability factors and flexibility through storage does not compensate for higher investment costs.

Moreover, Figure 3 indicates the gradual phase-out of coal-powered technologies. By 2050 only 15 GW of coal power capacity remains active, which corresponds to 9 % of the capacity installed in 2015. The stock of nuclear power capacity decreases by one-third[34].

In contrast to that, the capacity investment path under singleton coalitions (see Figure 4) shows an almost stable capacity level of nuclear power. This goes in hand with a reduction in the wind power capacity. Furthermore, results show that, even though, the generation from gas power is lower in the singleton coalition scenario, the level of installed capacity in 2050 increases. This reveals a lower utilization of the capacity and, hence, a loss in economic efficiency.

3.2.3. Prices

In addition to the market-clearing condition, the carbon budget is another main equilibrium constraint in the context of this analysis. The shadow price on the market clearing and carbon budget condition provides insight in the energy-only prices and marginal abatement cost, respectively. Table 4 shows the development of both prices.

The relative market-wide energy-only price (compared to the level of 2015) experiences an increase in, mainly, the mid-run (until 2040)[35] (see Table 4). Prices rise to 1.14 in 2030 and balance out around 1.30 by the end of the model horizon. This can be

[34] The gradual decrease of the nuclear power capacity is driven by the exogenous technical life-time of generation technologies (60 years for nuclear power) and the absence of new investments in the cost-efficient market outcome.

[35] The market-wide energy-only price is calculated as the generation-weighted average of all regional market-clearing prices.

interpreted as a 30 %-price increase compared to 2015 due to the low-emission target in this paper. The underlying regional energy-only prices are depicted in Table D.7 (see Appendix D), which indicate a heterogeneous development of regional energy-only prices. Relative regional prices by 2030 range from a decrease to 0.99 in the case of Britain to an increase to 1.38 in South-East Eastern Europe. For 2050, prices in Britain are at a level of 1.13 and the South-East of Eastern Europe reaches a level of 1.44. The differences between regions are, on the one hand, driven by varying growth patterns of future electricity demand and, on the other hand, by regional variable RES availability and quality, among others.

The relative market-wide energy-only price under singleton coalitions is characterized by a lower increase then in the case of the grand coalition (see Table 4). Values are at a level of 1.08 by 2030 and reach 1.23 in 2050. Thus, the marginal cost for generating electricity even decrease under no cooperation. Consequently, the economic consequences from singleton coalitions mainly translate into an increase of capacity costs, which is also indicated by the increase of overall generation capacity (see Figures 3 and 4). Moreover, the regional energy-only prices (see Table D.8 in Appendix D) follow the same pattern as under the grand coalition.

Table 4: Relative Energy-Only and CO_2-Prices

Grand Coalition	2020	2025	2030	2035	2040	2045	2050
Relative energy-only price	1.05	1.13	1.14	1.18	1.26	1.29	1.30
CO_2-prices in [€/tCO_2]	7.4	19.6	24.5	35.6	57	84.5	95.5
Singleton Coalitions	2020	2025	2030	2035	2040	2045	2050
Relative energy-only price	1.04	1.10	1.08	1.14	1.19	1.22	1.23
CO_2-prices in [€/tCO_2]	11.8	21.5	28.5	39.8	59.7	84.4	103.5

The marginal abatement cost in the European power market under the grand coalition increase constantly to 24 €/tCO_2 in 2030 and reach 95 €/tCO_2 in 2050. Usually it is assumed that these abatement cost are recovered in the economy. Yet, from the perspective of consumers, there is empirical evidence that emission cost are passed-through to electricity prices [66] [67]. This would translate into an even stronger increase of energy-only prices.

As pointed out in section 1, non-cooperation leads to regional differences in marginal abatement cost. In the case of singleton coalitions, there is a band of regional abatement costs that varies from 39 €/tCO_2 to 162 €/tCO_2 in 2050. A region like Alpine, that does not have access to low abatement cost through high quality RES, ends up with marginal abatement cost of 162 €/tCO_2. On the contrary, the wind resource rich region Scandinavia reaches a level of 69 €/tCO_2 by 2050. Finally, the average marginal abatement cost[36] in this scenario reach a level of 104 €/tCO_2 by the model horizon and, hence, further indicate the loss in efficiency from singleton coalitions.

3.2.4. Geographic Distribution of CO_2-Abatement

The access to CO_2-abatement at low marginal cost, e.g. variable RES, is one of the main driver for differences in regional CO_2-emission reductions. Neglecting regional differences in abatement costs and not utilizing those would mean, in this scenario, that each region reduces its CO_2-emissions by 98 %. Yet, the cost-efficient partial equilibrium from the EU-REGEN model shows the regional emission-reduction paths shown in Table 5 to be optimal[37].

The presented values show that Iberia is the only region for which it is optimal to reach a 2050 level that is equal to the market-wide target as it reaches an emission level of 2 % compared to 1990 levels. All other regions either over- or under-fulfill the 98 % reduction target. Scandinavia, France, and the Eastern European regions even reach negative emission levels[38]. Especially Scandinavia shows a high reduction of relative emissions by reaching a negative emission level of the same magnitude as the 1990 positive emission level. This is, on the one hand, driven by the strong market penetration of variable RES and, on the other hand, by the application of BECCS. The regions with the highest remaining emission levels are Benelux, South Germany, and Alpine.

By design of the singleton coalitions scenario with a carbon budget for each region,

[36] The abatement cost are calculated as the emission-weighted average of all regional marginal abatement costs.

[37] CO_2-emission values in Table 5 are normalized to 1990 levels.

[38] Negative emissions arise from the application of BECCS.

Table 5: Development of Regional CO_2-Emissions (relative to 1990 levels)

	2015	2020	2025	2030	2035	2040	2045	2050
Britain	0.72	0.46	0.23	0.19	0.20	0.21	0.20	0.16
France	0.71	0.38	0.28	0.37	0.51	0.43	0.38	−0.09
Benelux	0.59	0.61	0.60	0.70	0.73	0.76	0.73	0.74
Ger-N	0.78	0.71	0.58	0.51	0.36	0.14	0.08	0.06
Ger-S	0.79	0.74	1.20	1.13	1.14	1.20	0.95	0.69
Scandinavia	0.41	0.31	0.20	0.18	0.20	0.13	−0.44	−1.02
Iberia	1.18	1.04	0.98	0.95	0.86	0.54	0.30	0.02
Alpine	0.85	0.81	0.72	0.80	0.97	1.18	1.04	0.93
Italy	0.68	0.69	0.63	0.50	0.37	0.27	0.18	0.06
EE-NW	0.69	0.62	0.53	0.33	0.14	0.05	−0.04	−0.08
EE-NE	0.36	0.29	0.11	0.04	0.01	0.00	−0.08	−0.16
EE-SW	0.84	0.67	0.46	0.35	0.04	0.00	−0.27	−0.41
EE-SE	0.86	0.91	0.72	0.43	0.17	0.03	−0.13	−0.20

regional emissions follow the assumed 98 % reduction target. Hence, emissions in each region end up at a level of 2 % compared to 1990 levels.

4. Discussion and Conclusions

In the presented study, two scenario groups were analyzed. Firstly, cooperative game theory was applied to investigate effects of cooperation. The total system cost under the grand coalition decrease by 4 % compared to the case with singleton coalitions. Looking at the stability of all possible coalitions reveals that only small-sized cooperations pass the test for individual rationality and none fulfills the criteria of internal and external stability at the same time. Finally, the identification of fair cost allocations indicates a trade-off between considering robustness against cost changes and individual rationality.

Secondly, in case of the grand coalition (the first-best), the interplay between wind power, gas power, and BECCS is shown to be the cost-effective equilibrium for the decarbonization of Europe's power sector. Onshore wind power shows to be the most crucial generation technology with a generation share of over 30 % by 2050. The flexible dispatch pattern of gas power backs up this strong market penetration. Moreover, the market-wide marginal abatement costs in 2050 end up at 95 €/tCO_2. Under singleton coalitions, the generation and capacity investment paths show a greater contribution from nuclear power, which substitutes generation from wind power. Hence, this analysis finds different technology lock-ins under the grand coalition and singleton coalitions, respectively. For the regional marginal abatement costs, the average of these costs reaches a level of 104 €/tCO_2 by 2050.

Finding the equilibrium market outcome by means of a bottom-up power market model offers great insights into the underlying investments and capacity utilization. Yet, using such a model for analyzing coalitions and also the concepts of cooperative game theory themselves imply a variety of limitations. Three of these issues are addressed in the following paragraph[39].

Results show, that differences in the main variables between the grand coalition N and the singleton coalition $\{i\}$ are minor. With respect to that, it is important to emphasize the low-emission path that is underlying this analysis. The system-wide 98 % reduction target is a tight constraint, that deeply limits the solution space. Conducting

[39] The topics addressed in this section should be understood as a selection of critical issues. Of course, there are further issues connected to the methodology in this paper.

the same analyses with a 80 % reduction target instead, validates the great impact of the tighter reduction target. With a 80 % reduction target, the total system cost under $\{i\}$ increases by 7 % (compared to 4 % in section 3.1.1). Yet, it is not clear whether that can be interpreted, such that a tight climate target is one way to limit inefficient behavior of individual countries or regions. This should be subject to further analysis.

The question of the explanatory power of total system cost is closely related to that. The analysis in this paper shows that even under the grand coalition N and singleton coalitions $\{i\}$, the difference in total system cost is minor. This has been emphasized by e.g. [68] and [69]. They show that a great number of near-optimal scenarios can represent observed market developments as well. Furthermore, it is shown in the literature, that equilibria with similar total system cost can represent very different transition paths. Insights from this analysis indicate that, i.e., the marginal abatement costs are a more suitable indicator. Yet, the adjustment of total cost for imported and exported quantities in this paper already tries to address this point of criticism.

Moreover, one general weakness of this approach is the one-dimensionality of coalitions. The framework assumes that while one coalition is formed, all the other regions constitute singleton coalitions. Yet, this leaves out the possibility of alternative cooperations, that could be formed in parallel. The main reason for sticking to this one-dimensional perspective is the computational capacity. The setting in this paper requires $8,178$ model runs to quantify the full cost-space for this cost-sharing (cooperative) game. Looking into a second round of coalition formation would not allow for quantifying the cost-sharing game anymore.

The analysis in this paper provides general implications with respect to the EU ETS. The research design in this study allows to gain insight in the direction of potential transfer payments in order to reach the grand coalition and the cost-effective equilibrium. However, this raises the question of how to implement a system of transfer payments and which institutions would be required. As mentioned in section 2.3.2, the concept of cooperation in this paper exhibits a close relationship to the one of the EU ETS. With respect to the EU ETS, one channel of reallocation is the sharing of auctioning revenues. This reallocation scheme should consider the economic rationality of single countries as discussed in this paper. Looking at the data for the allocation of revenues from the auctioning of emission allowances for the years 2013 - 2015 shows that national revenues are distributed (roughly) in proportion to the amount of national emissions (for auctioned allowances)[40]. Thus, Germany received 22 % of revenues, followed by Italy and the United Kingdom with 12 % each. Moreover, the available data from [57] shows to which extent countries spend revenues on international uses related to climate purposes. The cost allocations in section 3.1.3 revealed that (based on the carbon nucleolus) South Germany, Benelux, Iberia, Alpine, and Italy would be the main contributors to a transfer scheme. So, these countries should also have significant spendings (of allocation of revenues) for international purposes[41]. The observed numbers show that the two Iberian countries Spain and Portugal dedicate less than one percent to international climate uses. Though, Germany allocates 8 %, Austria 13 %, and Italy 50 % of its revenues to international purposes[42]. Another source of transfer in the current EU ETS is the free allocation of allowances for the modernization of electricity generation. For the years 2013-2015, these free allowances were given to Bulgaria, Cyprus, Czech Republic, Estonia, Hungary, Lithuania, Poland, and Romania [70]. According to the proposed cost allocation (based on the carbon nucleolus) all Eastern European regions would receive transfers. Hence, the existing allocation of transfers through free allowances for the modernization of electricity generation and the observed reallocation of auctioning revenues is mainly in line with the results obtained from the analysis in this paper.

However, the present analysis addresses only the European power sector, which is in contrast to the more than 10 sectors of the EU ETS. Since it can be assumed that more and more ETS sectors will move from freely allocated allowances to auctioning in the future, a similar analysis, that comprise all of these sectors, should be conducted in order to fully capture the implications for the EU ETS.

Related to that, there is also the necessity for analyses that look at alternative

[40] I want to thank an anonymous referee for drawing my attention at the existing allocation of revenues from the auctioning of emission allowances.

[41] Please note that these numbers do, unfortunately, not reveal which European country receives these transfers.

[42] Due to incomplete data availability, the share of auctioning revenues that goes to international climate uses cannot be evaluated for the countries of the Benelux region.

ways for setting economic incentives, which could be derived from the literature on international trade agreements. For instance, the concept of foreign direct investments could be used in order to think of cross-border capacity payments.

Moreover, when it comes to future market designs, it is of great importance to identify potential path dependencies that arise from smaller, stable coalitions. These results can be valuable when thinking about second-best solutions for reaching the decarbonization of the EU power market.

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Appendix A. Implementation of the Nucleolus

The nucleolus can be found by a sequence of linear programs. The first model of this sequence tries to find the optimal pre-imputation x_i^{NUC}, which maximizes the excess ε across all coalitions S. Conditions (A.2) and (A.3) ensure that ε equals the minimum excess and that the efficiency condition is met.

$$\max_{x_i^{NUC}} \quad \varepsilon \tag{A.1}$$

subject to:

$$\varepsilon + \sum_{i \in S} x_i^{NUC} \leq \sum_{i \in S} \hat{x}_i(S) \quad \forall S \subset N,\ S \neq \emptyset \tag{A.2}$$

$$\sum_{i \in N} x_i^{NUC} = \sum_{i \in N} \hat{x}_i(N) \tag{A.3}$$

$$x_i^{NUC} \geq 0 \tag{A.4}$$

Yet, the solution to this problem is not necessarily unique. As shown in [51], only the sequence of $k = 2^n - 2$ linear programs finds the unique solution to the gain-sharing problem. The program above represents the first program with $k = 1$ in this sequence. The subsequent programs ($k > 1$) are formulated by means of the following conditions:

$$\max_{x_i^{NUC}} \quad \varepsilon_k \tag{A.5}$$

subject to:

$$\varepsilon_k + \sum_{i \in S} x_i^{NUC} \leq \sum_{i \in S} \hat{x}_i(S) \quad \forall S \subset N,\ S \notin F_k \tag{A.6}$$

$$\varepsilon_l + \sum_{i \in S} x_i^{NUC} = \sum_{i \in S} \hat{x}_i(S) \quad \forall S \in F_l,\ l \in \{1, ..., k-1\} \tag{A.7}$$

$$\sum_{i \in N} x_i^{NUC} = \sum_{i \in N} \hat{x}_i(N) \tag{A.8}$$

$$x_i^{NUC} \geq 0 \tag{A.9}$$

As in the case of $k = 1$, constraints (A.6) and (A.9) secure that ε_k is minimized and the program's efficiency holds. Condition (A.7) additionally ensures that the excess of all coalitions, comprised in the set F_l, must equal the excess of the lth program. The set F_l is determined for each program k and contains all coalitions fulfilling the condition

$\sum_{i \in S} x_i^{NUC} + \varepsilon_{k-1} = \sum_{i \in S} \hat{x}_i(S)$. Furthermore, set F_k is determined iteratively by $F_k = \cup_{l<k} F_l$.

If the (N, v) game exhibits an empty core, the linear program additionally requires the individual rationality constraint [52]

$$x_i^{NUC} \leq c_i(\{i\}). \tag{A.10}$$

Appendix B. Resolution of the EU-REGEN Model

The EU-REGEN model represents the European power market. Its geographic scope includes all countries of the European Union (EU28) - except for the island countries Malta and Cyprus. Additionally, Switzerland and Norway are included, which have a central position in the European system or are endowed with great renewable energy sources (RES) potentials, respectively. To reduce the size of the model, these 28 countries are grouped into 13 model regions. The aggregation is based on geographic characteristics and current configurations of the European power markets. Table B.6 provides an overview on the composition of model regions. The model horizon in this

Table B.6: Composition of Model Regions

Region	*Countries*
Britain	United Kingdom, Ireland
France	France
Benelux	Belgium, Luxembourg, Netherlands
Ger-N	Northern Germany
Ger-S	Southern Germany
Scandinavia	Denmark, Finland, Norway, Sweden
Iberia	Portugal, Spain
Alpine	Austria, Switzerland
Italy	Italy
EE-NW	Czech Republic, Poland, Slovak Republic
EE-NE	Estonia, Latvia, Lithuania
EE-SW	Croatia, Hungary, Slovenia
EE-SE	Bulgaria, Greece, Romania

setting is 2050. The base year is 2015, where no capacity additions are allowed, and dispatch and investment are optimized in 5-year time steps up to 2050, resulting in eight time steps. Similar to the spatial aggregation, the model reduces the number of time segments within each time step for computational reasons. The default version of the model uses 123 intra-annual time segments. However, this reduced-form approach means the loss of the chronological order hours, which compromises the modeling quality of e.g. electricity storage.

The model comprises 25 different types of generation capacity. To account for different characteristics of power plants of the same type or varying resource quality of RES, EU-REGEN further distinguishes each type into generation blocks, resulting in 73 different generation blocks. Moreover, existing generation units are grouped into vintages to allow for different heat rates among generation blocks. Each vintage covers a period of five years and includes all units that went online during this period.

New capacity can be added to each technology block through investment. Similar to existing installations, additions in different model periods are grouped into vintages to assign specific technological characteristics to each vintage. Moreover, generation capacity can be subject to upper bounds on additions or accumulated capacity. In its default setting, EU-REGEN applies limits on additions to nuclear power and accumulated capacity of each variable RES technology. The latter one, reflects the constraint availability of land-area for the respective installations.

EU-REGEN abstracts from intra-regional electricity distribution and models electricity exchange between regions only. Existing transmission capacities between regions serve as starting values. In each time-period, new transmission capacity can be added between neighboring regions or regions with an already existing transmission link. However, those additions are subject to upper bounds.

The EU-REGEN model allows for the geological storage of CO_2 (CCS). In the model, capacity for CCS can be added through investment into new capacity or conversions of existing conventional power plants. Capacity for new CCS generation technologies can be added in combination with new generation capacity for lignite, coal, natural gas, or biomass power. Conversion of existing conventional generation capacity is enabled for lignite, coal, and biomass power plants. Apart from costs, investment into CCS capacity is driven by the limited geological storage capacity for CO_2.[43]

[43] More detailed information on the EU-REGEN model structure and the underlying data set can be found in [56].

Appendix C. Cost-Sharing Game Results

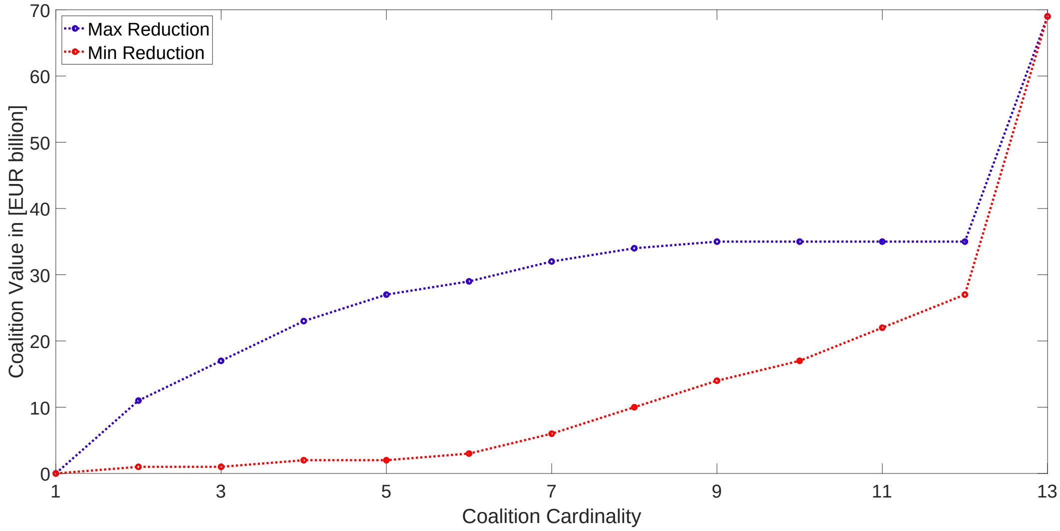


Figure C.5: Coalition Value by Coalition Cardinality.

Appendix D. Market Outcomes

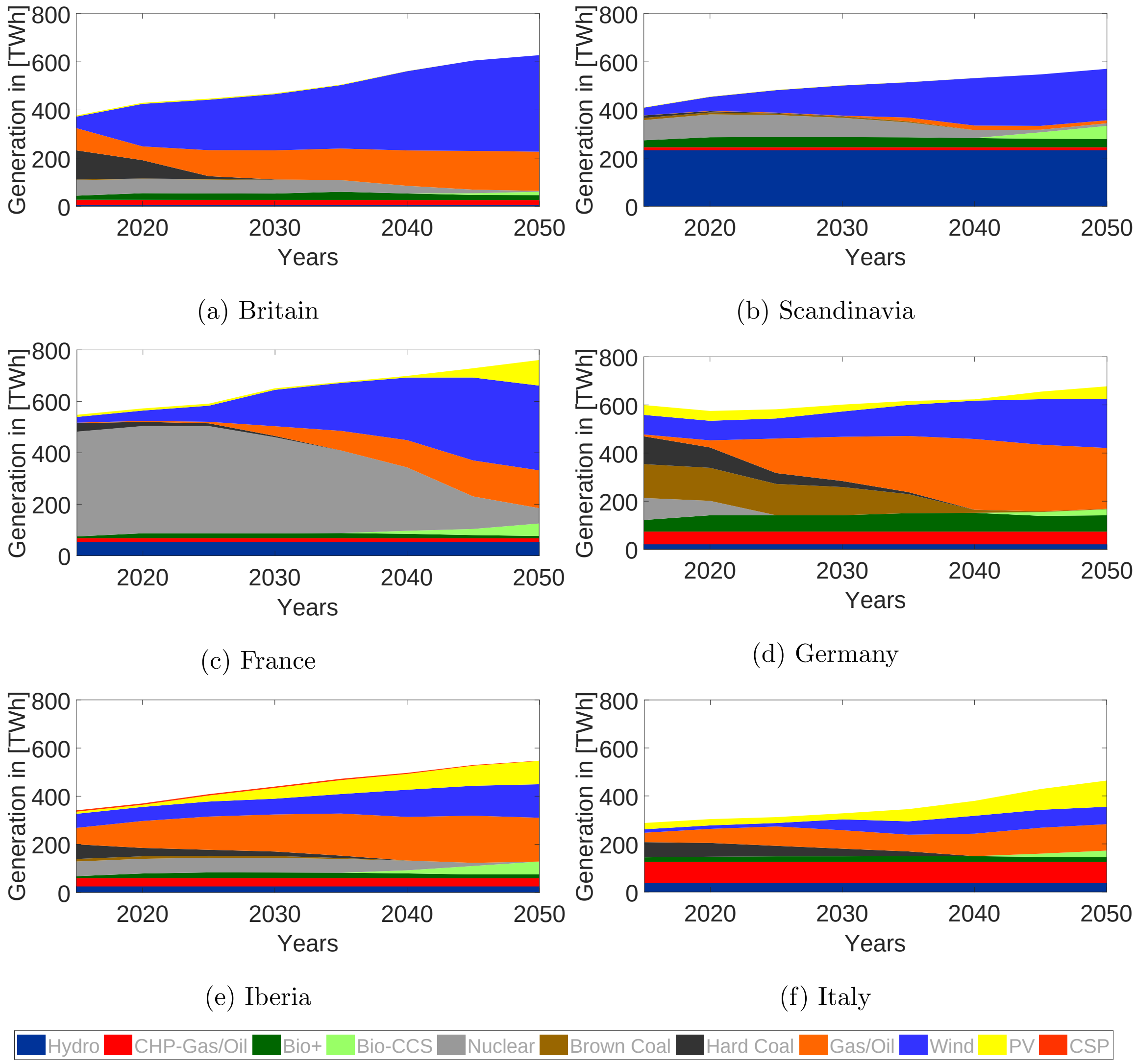
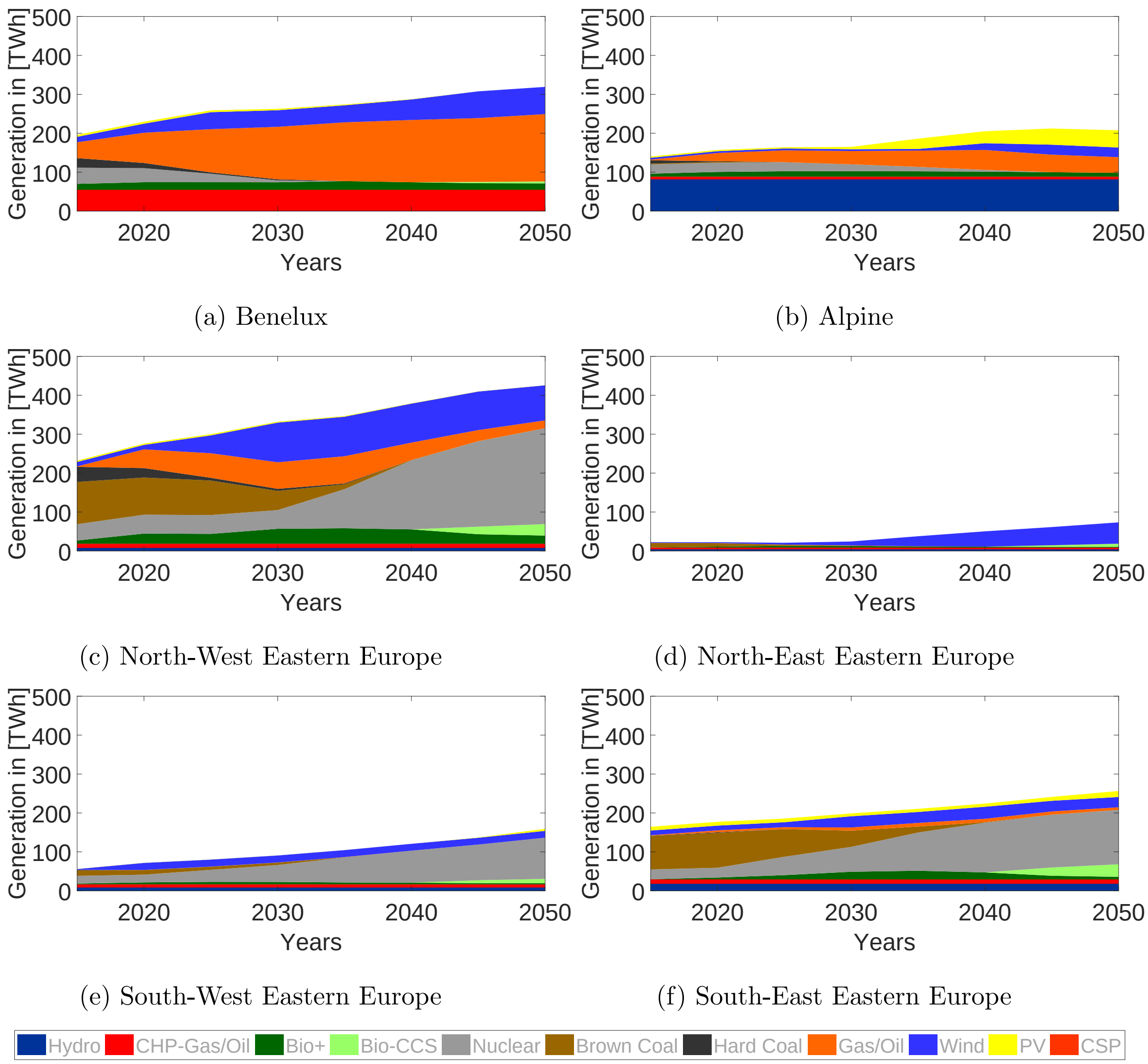


Figure D.6: Long-Run Regional Generation Paths Under Grand Coalition.



(a) Benelux

(b) Alpine

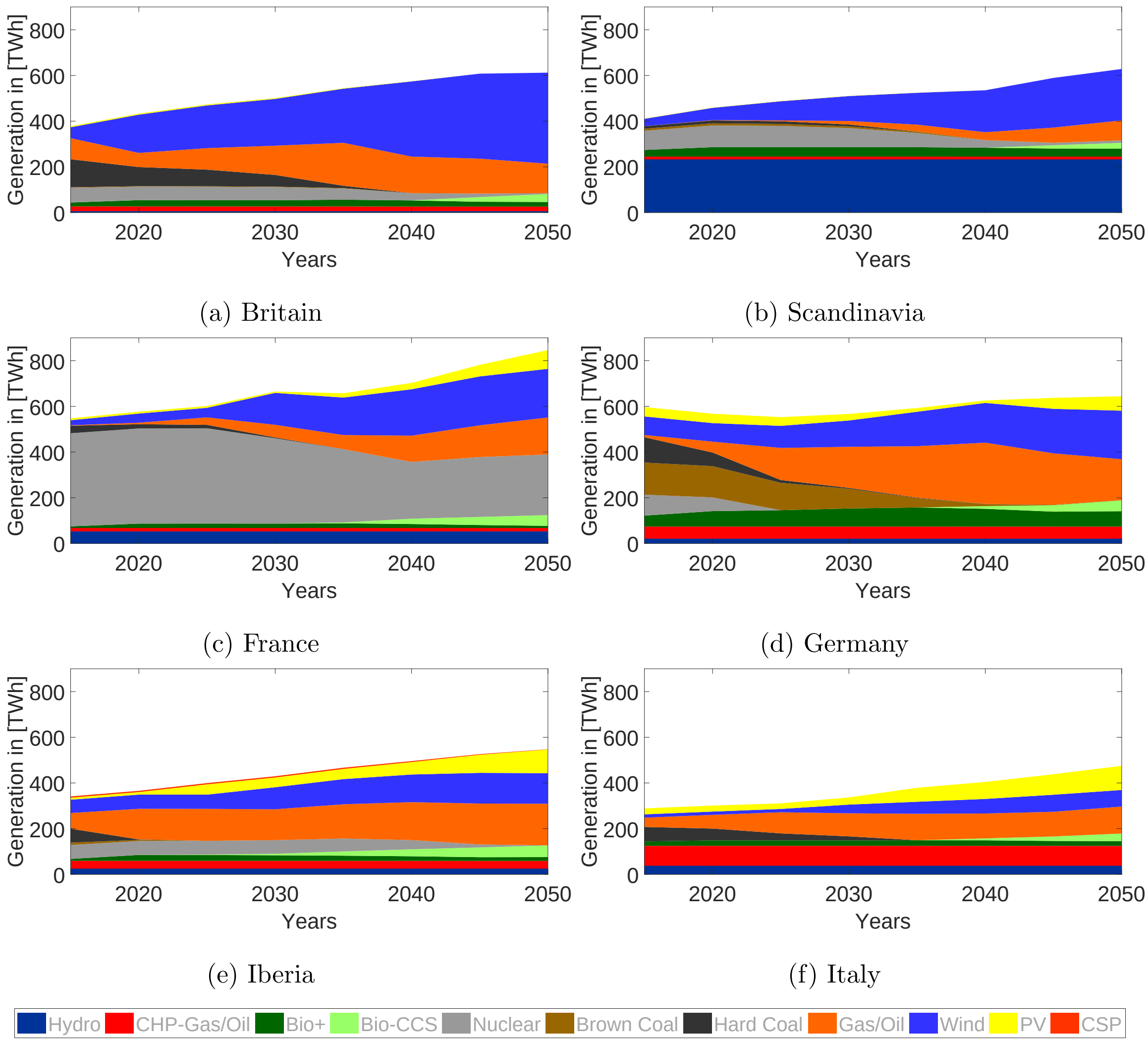
(c) North-West Eastern Europe

(d) North-East Eastern Europe

(e) South-West Eastern Europe

(f) South-East Eastern Europe

Figure D.7: Long-Run Regional Generation Paths Under Grand Coalition (continued).

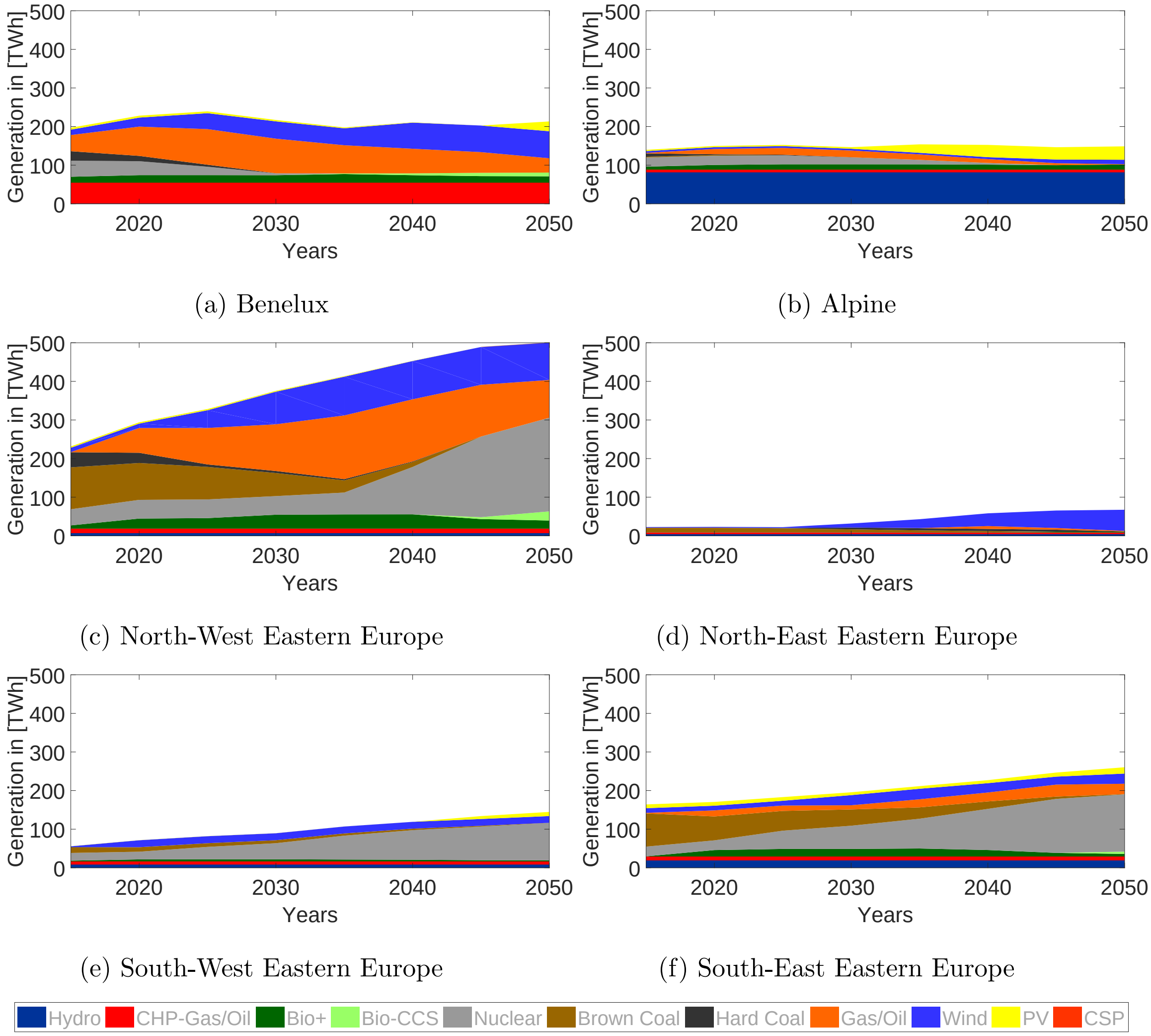


(a) Britain (b) Scandinavia

(c) France (d) Germany

(e) Iberia (f) Italy

Figure D.8: Long-Run Regional Generation Paths Under Singleton Coalitions.



(a) Benelux

(b) Alpine

(c) North-West Eastern Europe

(d) North-East Eastern Europe

(e) South-West Eastern Europe

(f) South-East Eastern Europe

Figure D.9: Long-Run Regional Generation Paths Under Singleton Coalitions (continued).

Table D.7: Regional Relative Energy-Only Prices Under Grand Coalition

	2020	2025	2030	2035	2040	2045	2050
Britain	0.90	0.99	0.98	1.01	1.08	1.12	1.13
France	1.03	1.18	1.15	1.21	1.29	1.33	1.35
Benelux	1.04	1.11	1.14	1.19	1.31	1.36	1.40
Ger-N	1.11	1.20	1.22	1.26	1.35	1.39	1.41
Ger-S	1.13	1.21	1.23	1.29	1.42	1.47	1.47
Scandinavia	1.06	1.10	1.10	1.19	1.30	1.36	1.36
Iberia	1.06	1.11	1.13	1.15	1.22	1.26	1.26
Alpine	1.08	1.14	1.17	1.21	1.31	1.33	1.32
Italy	1.05	1.12	1.12	1.14	1.21	1.24	1.27
EE-NW	1.03	1.07	1.07	1.11	1.12	1.12	1.13
EE-NE	1.07	1.07	1.02	0.98	1.07	1.09	1.08
EE-SW	1.01	1.06	1.08	1.09	1.13	1.15	1.16
EE-SE	1.32	1.37	1.38	1.40	1.42	1.43	1.44

Table D.8: Regional Relative Energy-Only Prices Under Singleton Coalitions

	2020	2025	2030	2035	2040	2045	2050
Britain	0.87	0.88	0.86	0.89	1.01	1.06	1.07
France	1.00	1.11	1.06	1.20	1.23	1.25	1.25
Benelux	0.98	1.05	1.11	1.23	1.27	1.35	1.37
Ger-N	1.04	1.15	1.18	1.25	1.31	1.35	1.37
Ger-S	1.06	1.17	1.21	1.29	1.36	1.38	1.39
Scandinavia	1.01	1.03	0.99	1.10	1.20	1.25	1.28
Iberia	1.20	1.27	1.17	1.18	1.18	1.18	1.17
Alpine	1.03	1.09	1.11	1.15	1.20	1.22	1.22
Italy	1.05	1.11	1.11	1.13	1.16	1.18	1.19
EE-NW	0.99	1.03	1.00	1.04	1.07	1.10	1.12
EE-NE	0.96	0.97	0.94	0.97	1.05	1.08	1.06
EE-SW	1.00	1.03	1.04	1.06	1.10	1.12	1.11
EE-SE	1.47	1.35	1.37	1.38	1.39	1.40	1.42

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