Decarbonization of Power Markets and Fairness: An Application of Cooperative Game Theory

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Cost-Efficient Decarbonization Through Cooperation

- If regions/players can coordinate and share information, they are able to reach the social optimum *(e.g. Montgomery 1972)*

- In the context of power markets:
  - Regions try to maximize their welfare in the power market
  - Under the presence of a climate (carbon) target

- Regions coordinate their abatement efforts until marginal abatement cost across all regions equal

- If regions fail to coordinate, average abatement cost increase

National Targets Go Beyond Efficiency

- Yet, single regions pursue power market specific objectives that go beyond economic efficiency

- These can address:
  - Energy independence *(Gillingham and Sweeney 2010)*
  - Resource adequacy *(Paulus et al. 2011)*
  - Employment effects *(Roques 2008)*
  - Technological innovation *(Frondel et al. 2010)*
  - Redistributive effects *(Strunz et al. 2016)*

- Redistribution can be examined between e.g. producers and consumers or geographic regions

Redistributive Effects in European Power Market Models

- Existing literature on national interests focuses on transmission planning:
  - Equilibria in national-strategic investment in transmission capacity investments (e.g. *Huppmann and Egerer 2015*)
  - Application of cooperative game theory to transmission planning (e.g. *Nylund 2014*)
  - Technical restrictions on additions to transmission capacity (e.g. *Schlachtberger et al. 2017*)
- Yet, three fundamental questions regarding the burden-sharing for the decarbonization of the European Power Market remain:
  - Why is it not rational from the perspective of individual countries to cooperate?
  - How would an equilibrium look like if all regions behave rational?
  - How can fairness be improved and implemented?

Game Theoretic Background

Framework of a *(N,v) cost-sharing game*

- Players $N := \{1, ..., n\}$ can form subsets of players $S \subseteq N$, the coalitions
- Function $v : 2^n \to \mathbb{R}$ that assigns a worth $v(S)$ to each coalition
- Permutation $x \in \mathbb{R}^n$ assigns cost $x_i(S)$ to each player
- The value of each coalition S to player i is $x_i(\{i\}) - x_i(S)$
- Games can be transferable utility (TU) games or non-transferable utility (NTU) games

Game Theoretic Background (*ctd.*)

Which coalitions are stable?

- Individual rational imputations, i.e. $x_i(\{i\}) \geq x_i(S) \quad \forall i \in S$. (*Nash 1953*)
- Coalitional rational imputations, i.e. $\sum_{i \in S} x_i(\{i\}) - x_i(S) \geq v(S)$. (*Gillies 1959*)
- Internal and external stable coalitions, i.e. $x_i(S) \leq x_i(S \setminus \{i\}) \quad \forall i \in S \quad \wedge \quad x_i(S) \leq x_i(S \cup \{i\}) \quad \forall i \notin S$. (*Barrett 1994*)

Game Theoretic Background (*ctd.*)

How to improve fairness?

- Shapley Value: Cost-sharing relative to average contribution of each player (*Shapley 1953*)
- Nucleolus: Cost-sharing relative to (un)happiness of a coalition (*Schmeidler 1969*)

Approach in this Paper

1. Apply the EU-REGEN Model to find the future equilibrium outcome of the European power market
   - Cooperative and superadditive cost-sharing game
   - Discounted system cost of each region serve as cost function
   - Individual gains are understood as $x_i(\{i\}) - x_i(S)$
   - For $2^n - (n-1)$ possible coalitions
   - N represents the first-best outcome with full cooperation and the cost-efficient market equilibrium
2. Analyze resulting cost functions $x_i(S)$ by means of concepts of stability and fairness

The EU-REGEN Model

- *Type*: Partial equilibrium and perfect-foresight model
- *Endogenous features*: Optimizes generation dispatch, investment, and transmission simultaneously
- *Geographic resolution*: EU28 plus Switzerland & Norway
- *Temporal resolution*: base year 2015 with 5-year time steps, model horizon 2050, and intra-annual time segments
- *Technology*: 25 generation technologies, distinguished into 73 generation assets by region

Model Structure

Objective function:

$$\min \quad c^{tot} = \sum_i c_i^{tot} = \sum_t (c_{i,t}^{\text{gc}} + c_{i,t}^{\text{tc}} + c_{i,t}^{\text{sc}} + c_{i,t}^{\text{vc}} + c_{i,t}^{\text{fom}} + c_{i,t}^{\text{tvo}} + c_{i,t}^{\text{tfm}}) \cdot \text{DF}_t$$

Main equilibrium constraint: *Market clearing*

$$(\sum_{j,v} g_{s,j,v,i,t} - \sum_{ii} ex_{s,i,ii,t} - ns_{s,i,t}) \cdot \text{H}_s \quad \geq \quad \text{D}_{s,i,t} \cdot \text{H}_s$$

Deep Decarbonization Scenario

- Climate policy: 98 % reduction of CO_2-emissions by 2050 (*European Commission 2014*)
- Applied to set of all $2^n - (n-1) = 8180$ coalitions
- Cooperation through shared carbon budgets, i.e.

$$\sum_{s,j,v,i} g_{s,j,v,i,t} \cdot CO2_j \leq \sum_i B_{i,t} \quad \forall i \in S$$

$$\sum_{s,j,v} g_{s,j,v,i,t} \cdot CO2_j \leq B_{i,t} \quad \forall i \notin S$$

What are Regions Cooperating on?

- Wind power becomes the dominating technology for the EU decarbonization path
- Its generation-share increases more than 5 times until 2050
- The geographic distribution of wind power capacity is driven by the resource quality and not the temporal profile

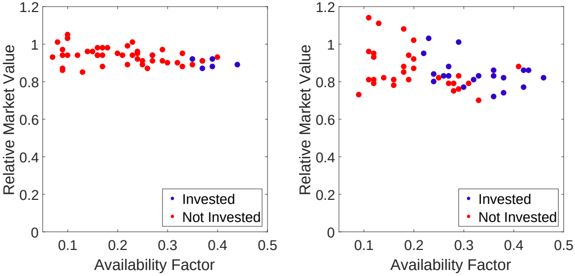
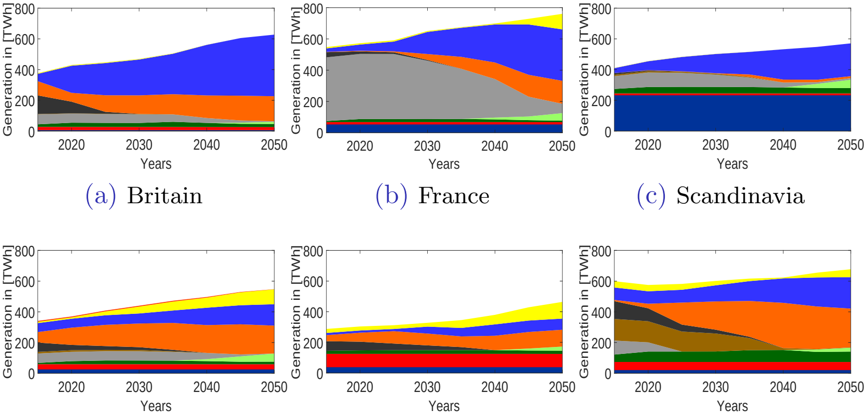


Figure: 2020 and 2050 Wind Power Market Values

What are Regions Cooperating for? (*ctd.*)

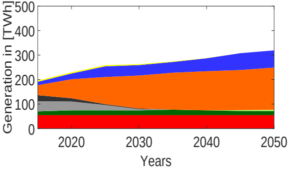


(a) Britain (b) France (c) Scandinavia

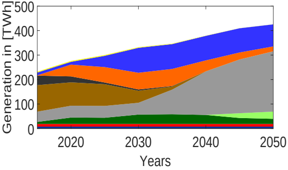
(d) Iberia (e) Italy (f) Germany

Figure: Long-Run Regional Generation Paths

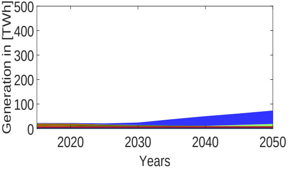
What are Regions Cooperating for? (*ctd.*)



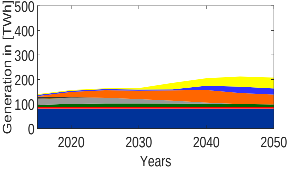
(a) Benelux



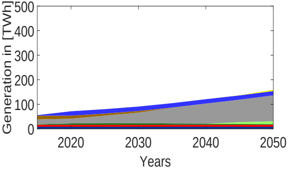
(b) NW Eastern Europe



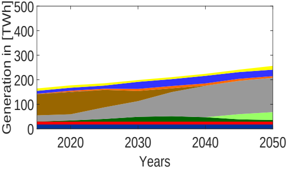
(c) NE Eastern Europe



(d) Alpine



(e) SW Eastern Europe



(f) SE Eastern Europe

Figure: Long-Run Regional Generation Paths (*ctd.*)

The Cost-Sharing Game

- The value of the grand coalition N is EUR 69 billion
- This represents a 4 % reduction in total discounted system cost
- The coalition value differs especially for medium-size coalitions

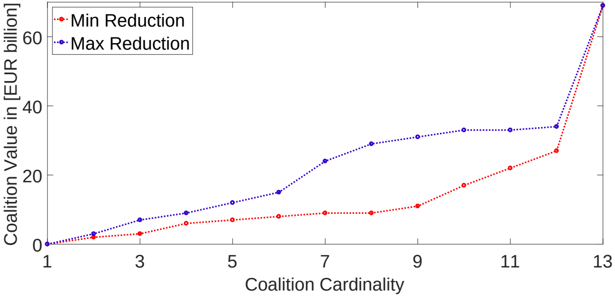


Figure: Coalition Value by Cardinality

- Value of N to each individual region is highly heterogeneous

The Cost-Sharing Game (*ctd.*)

Table: Cost in [EUR billion]

	$x_i(\{i\})$	$x_i(N)$	Δ
Britain	260	257	−0.01
France	293	286	−0.02
Benelux	140	125	−0.11
Ger-N	149	146	−0.02
Ger-S	196	176	−0.10
Scandinavia	70	71	0.01
Iberia	290	274	−0.06
Alpine	39	31	−0.21
Italy	233	225	−0.03
EE-NW	210	219	0.04
EE-NE	13	14	0.08
EE-SW	44	44	0.02
EE-SE	94	94	0.00

Stable Coalitions

Coalitional rationality - core stability

- Set $C(v)$ contains $5,393$ coalitions that are core stable
- By definition, $C(v)$ includes N; $N \in C$

Individual rationality

- The set $I(v)$ contains 15 coalitions that satisfy the rationality constraint $x_i(\{i\}) - x_i(S) > 0$
- The element with the highest coalition value s^R yields a EUR 9.5 billion reduction; maintaining 14 % of the gains of N

Internal and external stability

- The internal and external stabiliy criteria is fulfilled by 87 and 1,924 coalitions, respectively
- 23 coalitions fulfill both stability criteria
- The coalition with the hightest value s^{IES} saves EUR 4 billion of total system cost; 6 % of the gains of N

Fair Cost-Sharing

Fairness

- Fair selection from subset of cores $C(v)$ or
- Distribution of total cost among regions, given the relevance (power) of each region

Fair core allocation

- Core center: Uniform distribution $U(C(v))$ over set $C(v)$ with expectation $\mu(v) := E(U(C(v)))$
- Least core: Maximization of the minimum satisfaction of coalitions

Fair preimputations

- Shapley: Cost allocation is based on fairness only
- Nucleolus: Brings together fairness and stability; only preimputation that guarantees the implementation of N

Fair Cost Allocations

Table: Costs in [EUR billion]

	x_i^{CC}	x_i^{MIN}	x_i^{MAX}	x_i^{LC}	x_i^{SHP}	x_i^{NUC}
Britain	251	253	265	252	250	251
France	290	278	305	290	289	290
Benelux	135	125	141	135	135	135
Ger-N	146	134	167	146	145	146
Ger-S	189	171	197	188	189	189
Scandinavia	65	68	83	65	66	65
Iberia	282	262	291	282	280	282
Alpine	37	31	41	37	38	37
Italy	230	221	238	230	228	230
EE-NW	204	207	229	204	203	204
EE-NE	6	12	16	6	9	6
EE-SW	40	42	48	40	42	40
EE-SE	87	89	104	88	88	87

Evaluation of Allocations

Now: all potential cost allocations are comprised in set M with $M := \{x_i^{LC}, x_i^{NUC}, x_i^{SHP}\}$

Cost allocations can be analyzed with respect to:

- Uncertainty - Monotonicity
- Non-Binding Commitment - Coalitional Satisfaction
- Individual Rationality

Evaluation of Methods

Table: Overview on Allocations

	Monoton.	Coal. Sat.	Ind. Rat.
Shapley	Strong coal.	EUR 17.5 B	No
Nucleolus	Weak coal.	EUR 17.0 B	Yes
Least Core	Weak coal.	EUR 18.0 B	No

Summary

- *Questions*
  - Why is it not rational from the perspective of individual countries to cooperate?
  - How would an equilibrium look like if all regions behave rational?
  - How can fairness be improved?
- *Methods*
  - Find equilibrium outcome for set of all possible coalitions with the EU-REGEN model
  - Analyze results with concepts of cooperative game theory
- *Results*
  - Full cooperation has an value of $v(N) = 69$ EUR billion
  - Paper shows that only small-sized coalitions fulfill the criteria of individual rationality and internal/external stability, respectively
  - Uncertainty of cost and individual rationality have to be balanced for fair cost-sharing