Environmental trade-offs of (de)centralized renewable electricity systems

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INTRODUCTION

- Electricity systems worldwide are transitioning to renewables – for very good reasons
- However, also renewables can have various negative environmental impacts
- Shifting to renewable systems can therefore imply some environmental trade-offs
- Trade-offs may depend on the spatio-technical (de)centralization of the electricity system
  - spatio-technical (de)centralization: electricity can either be generated in a spatially concentrated manner and then be transmitted across the country, or in a more spatially distributed way
- There are degrees of freedom and choices to make on the way to fully renewable electricity systems in terms of their spatio-technical (de)centralization
  → in this context environmental trade-offs should be considered
- We propose a **framework to analyze the potential environmental trade-offs** that are related to different spatio-technical (de)centralization options for a fully renewable system **and apply it to the case of Germany**

APPROACH

Review of *potential*
negative environmental impacts
of key technologies

Analytical framework:
Factors determining *actual*
environmental effects of (de)centralized
renewable electricity systems

Application to the case Germany

- Derivation an analysis of 4 (de)centralization options from modeling studies

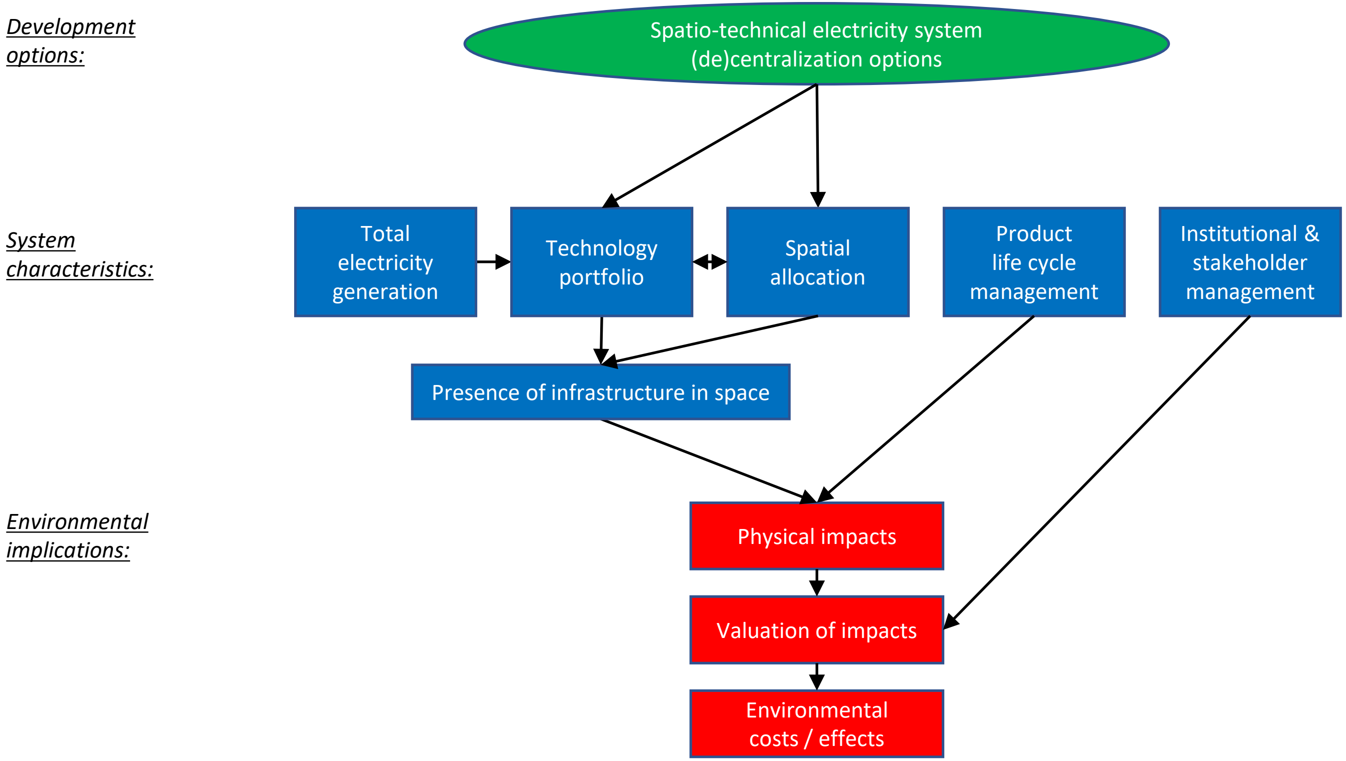
REVIEW OF POTENTIAL NEGATIVE ENVIRONMENTAL IMPACTS OF KEY TECHNOLOGIES ALONG THE LIFE CYCLE STAGES

Technology	Raw material sourcing & manufacturing	Installation & operation	Decommissioning & end-of-life
PV & battery storage	■	□	■
Onshore wind	□	■	□
Offshore wind	□	■	□
Grid	□	■	□

- threats to birds and bats / marine wildlife
- disamenities for residents and visitors

ANALYTICAL FRAMEWORK

What determines environmental effects of (de)centralized renewable electricity systems?



THE CASE OF GERMANY: 4 (DE)CENTRALIZATION OPTIONS

Review of electricity system scenarios from 10 long-term modeling studies for Germany:
four basic spatio-technical (de)centralization options:

(1) "**Offshore wind option**": Offshore wind capacities are strongly expanded. Comparatively high concentration of generation capacities in the North Sea and Baltic Sea and the transmission to other parts of the country → *spatio-technical* ***centralization***

(2) "**Distributed onshore wind option**": Onshore wind capacities are not primarily concentrated at the windiest locations, but instead distributed more evenly in space → *spatio-technical* ***decentralization***

(3) "**PV option**": PV capacities are strongly expanded. More even spatial allocation of generation capacities compared to scenarios with lower PV capacities → *spatio-technical* ***decentralization***

(4) "**Import option**": Large amounts of electricity are imported from abroad and transmitted across the country instead of being generated and consumed domestically → *spatio-technical* ***centralization***

THE CASE OF GERMANY: SYSTEM CHARACTERISTICS OF 4 (DE)CENTRALIZATION OPTIONS

(de)centralization option and corresponding study	Offshore wind (GW)	Onshore wind (GW)	PV (GW)	Imports (or export decline) (TWh)	Grid expansion (GW)	Battery capacities (GW or GWh)
Offshore wind option	**↑↑↑↑↑**	**↓↓↓↓↓**	**↓↓↓↓⇅**	**↓⇅ -- -- --**	**↑↑⇅ -- --**	**↓↓↓↓ --**
[84] Gils et al. (2019)	↑	↓	⇅	⇅	⇅	↓
[85] Kendziorski et al. (2022)	↑	↓	↓	--	↑	↓
[88] Möst et al. (2021)	↑	↓	↓	--	--	↓
[90] Reiner Lemoine Institut (2013)	↑	↓	↓	--	↑	↓
[91] Rogge et al. (2020)	↑	↓	↓	↓	--	--
Distributed onshore wind option	**→→**	**↑↑**	**→↑**	**→ --**	**↓↓**	**↓ --**
[83] Fraunhofer ISI et al. (2017)	→	↑	→	→	↓	--
[90] Reiner Lemoine Institut (2013)	→	↑	↑	--	↓	↓
PV option	**↓↓↓↓⇀⇂→→**	**↑↑↑↑↓↓↓**	**↑↑↑↑↑↑↑**	**↑↑↓ -- -- -- --**	**↓↓→ -- -- -- --**	**↑↑↑↑↑ -- --**
[82] Fraunhofer-ISE (2020)	↓	↓	↑	--	--	↑
[84] Gils et al. (2019)	⇀⇂	↑	↑	↓	↓	↑
[85] Kendziorski et al. (2021)	↓	↑	↑	--	↓	↑
[87] Luderer et al. (2021)	→	↓	↑	--	--	--
[88] Möst et al. (2021)	↓	↑	↑	--	--	↑
[89] Öko-Institut & Prognos (2019)	→	↓	↑	↑	→	↑
[91] Rogge et al. (2020)	↓	↑	↑	↑	--	--
Import option	**→⇀↿**	**↓⇅**	**↓↓**	**↑↑**	**↑↑**	**⇅ --**
[84] Gils et al. (2019)	⇀↿	⇅	↓	↑	↑	⇅
[86] Kost et al. (2019)	→	↓	↓	↑	↑	--

- **Marginal technology portfolio differences** of the considered (de)centralization options
- **Information on spatial allocations** of technologies

Legend	
↑	Higher compared to (all) alternative scenario(s)
↓	Lower compared to (all) alternative scenario(s)
⇅	Higher compared to one scenario but lower compared to another scenario
→	Same as in (all) alternative scenario(s)
⇀↿	Same as in one alternative scenario but higher than in another alternative scenario
⇀⇂	Same as in one alternative scenario but lower than in another alternative scenario
--	No values

THE CASE OF GERMANY: ENV. TRADE-OFFS OF THE 4 (DE)CENTRALIZATION OPTIONS

Development option	Major implications for the potential environmental impacts during the life cycle steps		
	Raw material sourcing & manufacturing	**Installation & operation**	**Decommissioning & end-of-life**
"Offshore wind" (centralization option)	👍 due to relatively low potential impacts related to PV and batteries	👎 due to relatively high potential impacts from offshore wind and grid infrastructure 👍 due to relatively low potential impacts from onshore wind	👍 due to relatively low potential impacts related to PV and batteries
"Distributed onshore wind" (decentralization option)	-	👎 due to relatively high potential impacts from onshore wind in total and regionally in the windless South of Germany 👍 due to relatively low potential impacts from grid infrastructure and regionally due to relatively low potential impacts from onshore wind in the windy North of Germany	-
"PV" (decentralization option)	👎 due to relatively high potential impacts related to PV and batteries	👍 due to relatively low (or at least not high) potential impacts from grid infrastructure and offshore wind	👎 due to relatively high potential impacts related to PV and batteries
"Import" (centralization option)	👍 due to relatively low potential impacts associated with domestic PV generation	👎 due to relatively high potential impacts from grid infrastructure 👍 due to possibly relatively low potential impacts from onshore wind	👍 due to relatively low potential impacts associated with domestic PV generation
	👎 possibly high potential impacts associated with foreign generation (concerns all three life cycle steps)		

FINDINGS AND CONCLUSION

- **all (de)centralization options** entail potential environmental **trade-offs**
- **(de)centralization is a relevant factor** determining some of the trade-offs
  - For instance, both centralization options have lower environmental impacts related to PV, whereas both decentralization options have lower impacts related to the grid
- **trade-offs also depend on *how*** spatio-technical (de)centralization is achieved
  - For instance, only one of the two decentralization options considered show a trade-off between env. impacts related to battery storage and offshore wind power
- actual environmental trade-offs of renewable electricity systems **depend also on other aspects** than their spatio-technical (de)centralization
- **policy-makers should consider env. trade-offs,** but also many other energy policy goals (further goals include, e.g., system costs, security of supply, and equity considerations)

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THANK YOU FOR YOUR ATTENTION!

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DECISION-MAKING IN THE LIGHT OF ENVIRONMENTAL TRADE-OFFS

Valuation of potential environmental impacts	**"Offshore wind"**	**"Distributed onshore wind"**	**"PV"**	**"Import"**
If potential impacts from **PV system production and end-of-life** are an important public concern	pro	-	con	pro
If potential impacts from **battery production and end-of-life** are an important public concern	pro	-	con	-
If potential **maritime impacts** are an important public concern	con	-	pro	-
If potential impacts from **grid infrastructure** are an important public concern	con	pro	pro	con
If **total amount of potential impacts from onshore wind** is an important public concern	pro	con	-	pro
If a **spatially uneven distribution of potential impacts from onshore wind** is an important public concern	-	pro	-	-
If **potential impacts from generation abroad** are an important public concern	-	-	-	con

"-" no relevance or ambiguous relationship according to studied literature

Publication	Scenario in Publication	Associated option in present study	Wind Offshore (GW)	Wind Onshore (GW)	PV (GW)	Import (TWh)	Grid Expansion	Battery Capacities
Fraunhofer ISE (2020)	Reference	[Reference case]	75	189	415	NV	NV	153 GWh
	Unacceptance	PV	40	77,5	646	NV	NV	396 GWh
Fraunhofer ISI et al. (2017)	Base Scenario	[Reference case]	15	75,4	69,3	105	36,5 GW	NV
	Regional Scenario	Distributed onshore wind	15	81,6	69,3	106	33,8 GW	NV
Gils et al. (2019)	Offshore	Offshore wind	45	105	185	73	58 GW	0 GW
	Decentralized	PV	29	129	283	37	0 GW	up to 298 GW
	Import	Import	29	117	161	107	130 GW	up to 104 GW
Kendziorski et al. (2022)	Centralized	Offshore wind	~50	~200	~255	NV	+15% (vs. decentralized)	~15 GW
	Decentralized	PV	~15	~215	~330	nv	see above	~30 GW
Kost et al. (2019)	Reference	[Reference case]	~30	~215	~255	~10	15 GW interconnect. to neighb.	NV
	Import	Import	~30	~200	~235	~80	30 GW interconnect. to neighb.	NV
Luderer et al. (2021)	Focus PV	PV	40	130	400	NV	NV	NV
	Focus Wind	[Reference case]	40	180	200	NV	NV	NV
Möst et al. (2021)	Centralized	Offshore wind	27	76,3	32,2	NV	NV	~120 GW (in Europe)
	Decentralized	PV	16,5	82,1	74,6	NV	NV	~350 GW (in Europe)
Öko-Institut & Prognos (2019)	Reference	[Reference case]	51	178	154	-97	NV	94 GWh
	Focus Solar	PV	51	115	313	-92	NV	190 GWh
Reiner Lemoine Institut (2013)	Centralized	[Reference case]	10	148	139,5	NV	21,5 GW	25,4 GWh
	Offshore	Offshore wind	30	113	123,5	NV	44,3 GW	22,4 GWh
	Decentralized	Distributed onshore wind	10	151	141,5	NV	17,8 GW	24,4 GWh
Rogge et al. (2020)	Pathway A	Offshore wind	~50	~20	~1	~125	NV	NV
	Pathway B	PV	~5	~50	~70	~220	NV	NV