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

F. Reutter[1,2*] and P. Lehmann[1,2]

Abstract

Background Renewable energies are key to reduce CO_2 emissions and other environmental impacts of fossil-fueled electricity generation. However, renewable energy systems can also cause negative environmental effects. In this paper, we analyze the potential environmental trade-offs associated with different spatio-technical (de)centralization options for a renewable electricity system. For this purpose, we first review the potential environmental life cycle impacts of key technologies for renewable electricity systems. Subsequently, we develop a framework identifying which factors determine actual environmental effects of renewable electricity systems. We apply the framework to four basic spatio-technical (de)centralization options for the future Germany electricity system.

Results Our analysis shows that all (de)centralization options are associated with potential environmental trade-offs. We find that the (de)centralization of the system is a relevant factor determining these trade-offs. For instance, the two more centralized options considered have lower environmental impacts related to PV, whereas the two more decentralized options have lower environmental impacts related to grid infrastructure. However, we also find that the trade-offs depend on the specific way (de)centralization is pursued. For instance, only in one of the two considered more decentralized development options, there is a potential environmental trade-off between higher impacts related to battery storage and lower impacts related to offshore wind power.

Conclusions Our analysis reveals that the spatio-technical (de)centralization of a renewable electricity system plays a role for its environmental trade-offs while further factors like the institutional and stakeholder management in place also shape the environmental trade-offs. Policy makers should acknowledge the identified potential environmental trade-offs and their influencing factors when making policies favoring certain spatio-technical (de)centralization options.

Highlights

- Review of potential environmental impacts of key renewable technologies
- Framework on determinants of actual environmental effects of electricity systems
- Review of electricity system (de)centralization scenarios for Germany
- Application of framework to four spatio-technical (de)centralization options
- Environmental trade-off analysis for the four (de)centralization options

Keywords Renewable electricity systems, Spatio-technical (de)centralization options, Environmental trade-offs, Germany

*Correspondence:
F. Reutter
felix.reutter@web.de
Full list of author information is available at the end of the article

Background

On the way to a climate-neutrality, electricity systems worldwide are transitioned to renewable energy sources. Such a transition is not only reasonable to mitigate climate change. It also helps to reduce other negative environmental impacts of fossil-fueled power generation [1]. Nonetheless, also renewable technologies can have various different negative environmental impacts for humans and nature [2, 3]. These potential impacts may include, for instance, noise emissions from wind turbines, or the release of toxic chemicals during the manufacturing process of PV cells. The deployment of renewable energy sources can, therefore, imply environmental trade-offs.

In this paper, we analyze how these environmental trade-offs are related to (de)centralization options for a renewable electricity system. Decentralization can concern different system aspects [4–7]. Among other things, this involves actor-related questions looking at, for instance, whether a system is run by a rather small number of large actors or by a rather large number of small actors [8]. Another aspect of (de)decentralization concerns the spatio-technical properties of a system [9]. Renewable electricity generation capacities may be concentrated in space, or be more distributed spatially. The spatial concentration (or distribution) of generation capacities depends on the renewable energy technology chosen as well as on the spatial allocation of capacity for each renewable energy technology. The degree of spatial concentration of generation capacities also has implications for the necessary amount of complementary infrastructures, such as transmission and storage capacities. In this paper, we focus on these spatio-technical aspects of (de)centralization of renewable electricity systems. More specifically, we analyze the potential environmental trade-offs related to selected spatio-technical (de)centralization options exhibiting different degrees of spatial concentration of renewable electricity generation capacity.

There are already numerous studies in the literature that examine different renewable electricity system scenarios which differ with regard to spatio-technical decentralization. For instance, Child et al. [10], Neumann [11], Neumann and Brown [12], Tröndle et al. [13], and Zappa et al. [14] consider different 100% renewable scenarios for Europe. Such studies also exist for individual countries (see, for example, the publications cited in Table 2 on Germany). However, all these studies focus on techno-economic effects and do not explore the environmental trade-offs of the scenarios considered. Another strand of literature combines energy system models with life cycle assessment (LCA) to analyze the environmental impacts of future electricity system scenarios [15–19]. Yet, these studies do not explicitly examine how the environmental impacts of renewable electricity systems hinge on their decentralization properties. To our knowledge, so far only Xu et al. [20] analyze the environmental impacts of two different energy system development scenarios which differ in terms of their spatio-technical decentralization. In this paper, we go beyond this and consider four different (de)centralization options for a future renewable electricity system. Moreover, we also include environmental impacts which are not covered by conventional LCA analyses, for instance, bird collisions with wind turbines. As a further innovation, we present a general framework identifying the system properties on which the environmental effects—and thus environmental trade-offs—of electricity system development options depend.

We conduct our analysis as follows. First, we review and systemize the potential environmental impacts of key technologies used in renewable electricity systems. Then we develop an analytical framework to identify and structure the determinants which influence the actual environmental effects of an electricity system. As part of the framework, we elaborate which of the determinants may (and may not) depend on a system's spatio-technical (de)centralization. We apply the framework to the case of Germany. We analyze four basic (de)centralization options for the future German electricity system which we derive reviewing ten modeling studies. An "offshore wind option" and an "import option" imply a more centralized development, whereas a "distributed onshore wind option" and a "PV option" imply a more decentralized development in spatio-technical terms. We then discuss the potential environmental trade-offs that come with the four (de)centralization options and also address further aspects that should be considered in this context.

The remainder of the paper is structured as follows. The next section reviews the potential negative environmental impacts of key renewable electricity system technologies. Then, we outline our analytical framework. After that we derive the four considered (de)centralization options. Subsequently we provide the trade-off analysis and discuss the results. Finally, we conclude, point out policy implications of the analysis, and highlight avenues for further research.

Review of potential negative environmental impacts of key technologies

Different elements of a renewable electricity system can potentially have negative environmental impacts. In the following, we review the potential environmental impacts of five technologies that can be expected to play key roles in future renewable electricity systems. These key technologies are photovoltaics (PV), battery storage, offshore wind power, onshore wind power, and grid infrastructure. We discuss PV and batteries jointly as their environmental impacts are similar to a large extent. We look at the entire product life cycles of these technologies, from (1) raw material sourcing & manufacturing, over (2) installation & operation, to (3) decommissioning & end-of-life.

We do not consider other renewable technologies such as bioenergy, hydro power, and geothermal. This is because, in terms of quantities, these technologies are only of minor importance in scenarios for the future electricity system in our case study region, Germany (see below). Reasons for this include low technical, economic and socially accepted potentials of the named technologies, i.a. because these technologies partly would require very large areas of land and have very high local conflict potentials [21–23]. Such trade-offs of the mentioned technologies do not only exist in Germany, but apply to other countries as well [24].

We also do not consider hydrogen as a separate technology because the conversion of hydrogen to electricity can be regarded as widely environmentally harmless. More than 90% of the potential environmental impacts of hydrogen originate from the electricity used for its production, even when renewable energy sources are used [25]. Thus, the potential environmental impacts of hydrogen generated in a renewable electricity system will largely concern the environmental impacts of renewable electricity system technologies, which we consider explicitly. The reviewed studies do account for possible increases in electricity demand due to domestic hydrogen production. With respect to the production of imported hydrogen, basically the same considerations hold that we will make later in our analysis regarding imported electricity.

PV and batteries

Raw material sourcing and manufacturing

From a life cycle perspective, major environmental impacts of PV systems occur during the raw material sourcing and manufacturing phase [26]. The same applies to storage batteries [27]. The main environmental impacts associated with the production of PV modules and batteries relate to the use of raw materials, energy, and hazardous substances [28, 29]. With regard to raw materials, one major environmental issue is that the majority of metals encountered in PV cell and battery production (like silicon or lithium) are scarce natural resources and partly even rare-earth elements [26, 30]. Moreover, mining and manufacturing processes for PV modules and batteries involve numerous components and chemicals that are highly toxic and carcinogenic. These production processes may harm humans and ecosystems if there is insufficient worker protection, or if hazardous chemicals leach into soils and drinking water [27, 31, 32]. Currently, raw material sourcing as well as the manufacturing of PV and battery systems—and thus the related environmental impacts—are strongly concentrated in a few countries, particularly China [33].

Installation and operation

In the case of ground-mounted PV, land is required for the installation and operation of systems. Though not inevitable, this can potentially cause negative impacts on local vegetation and habitats [34] as well as on the living quality of local residents particularly due to visual disamenities [35]. While some studies find statistically significant negative effects of ground-mounted PV for residents, others do not [36]. Some environmental impacts during operation like water consumption and pollution may also occur, for example, when systems need to be cleaned and maintained [26]. However, there may be also environmental synergies during the operation phase, for instance, when PV is co-located with crop production as agrivoltaic systems [37]. Overall, the environmental impacts during the installation and operation of PV modules (especially of rooftop panels) and storage batteries can be assumed to be rather small compared to the environmental impacts that are associated with the manufacturing of these technologies [26, 27]. This is also valid when transports are taken into account [26, 29].

Decommissioning and end-of-life

After decommissioning PV modules and storage batteries, there is a potential risk of environmental contamination with hazardous substances [31, 38]. A professional waste management and recycling of PV modules and batteries can contribute to avoiding environmental pollution [39, 40]. Solar-panel and battery recycling also enables the conservation of natural resources [27, 41]. However, the recycling of Li-ion batteries (as used for PV storage batteries) is so far limited and a vast amount of batteries is disposed instead of being recycled [40]. With respect to PV modules, various recycling methods are available [42]. But even with recycling, it is eventually necessary to dispose some environmentally dangerous materials like liquid wastes, sludge, fly ash, and contaminated glass of PV panels at hazardous waste landfill sites [43].

Onshore wind

Raw material sourcing and manufacturing

The most relevant environmental impacts that occur during the sourcing process of raw materials for and the manufacturing of wind turbines are to date fossil energy use-related carbon dioxide emissions [44]. Environmental impacts which are related to air pollution and waste during the first life cycle step of wind turbines are only of minor relevance (ibid.).

Installation and operation

The environmental impacts of the installation process of wind turbines, for example, caused by the use of construction vehicles, are in total non-substantial [45]. Moreover, the greenhouse gas and pollutant emissions associated with the operation and maintenance of wind turbines occurring, for instance, when fossil-fueled vehicles and machinery are used for necessary repairs, are marginal [46]. Still, the operation of onshore wind turbines can have some other considerable environmental impacts. In a broad sense, these are associated with the land occupation by wind turbines. First, wind turbines can pose a threat to nature and species conservation. Particularly, birds and bats can be affected by onshore wind turbines [47–49]. Wind turbines can have direct mortality effects (collision losses) and indirect effects such as avoidance behavior effects, barrier effects, and habitat loss effects [50]. Wind turbines can also cause disamenities for residents living next to them. These perceived disamenities are mainly related to sound emissions of wind turbines [51] and the visual appearance of wind turbines, their shadow flickering, and night marking lights [52]. Studies show that the disamenities of wind turbines can result in deteriorations in the subjective well-being of residents living near wind turbines [53, 54]. Moreover, wind turbines can also have impacts on the scenic beauty of landscapes that are perceived as negative by people—regardless of their home locations [55, 56]. Usually, empirical studies show that the local environmental impact per unit of capacity installed declines if larger wind turbines are installed, or more wind turbines are clustered in one location [57].

Decommissioning and end-of-life

A potentially major environmental problem after the decommissioning of wind turbines is the handling of the rotor blades' composite materials [58]. Theoretically, recycling methods are available, but currently business cases for recycling are often lacking (ibid.). However, multiple life cycle assessment studies consistently conclude that the environmental impacts in the end-of-life stage of onshore wind turbines are still the least critical of all life cycle steps, even if decommissioned parts that are not recycled are combusted or landfilled [45].

Offshore wind

Raw material sourcing and manufacturing

As with onshore wind turbines, the most relevant environmental impacts that occur during the raw material sourcing and manufacturing phase of offshore wind turbines are CO_2 emissions stemming from the use of fossil energies [44]. It may be noted that offshore wind energy projects (including also all necessary components) can have a significantly larger carbon footprint than onshore wind energy projects, especially if concrete foundations are used offshore [59]. Air pollution and waste occurring during the first life cycle step of offshore wind turbines are only minor [44].

Installation and operation

The review by Kaldellis et al. [60] finds several environmental impacts related to the installation and operation of offshore wind energy. Construction noise, vibration and sedimentation occurring during the erection of offshore wind turbines may impair communication among marine mammals and fish, disturb or destroy breeding and feeding habitats, and displace animals overall. Toxic discharges of anti-fouling and lubricants pose further risks for marine species. Offshore wind turbines can also cause visual disamenities for humans. In addition, the operation of offshore wind turbines may result in collision fatalities, displacement, and barrier effects for birds [61]. Bats may also be negatively affected by offshore wind turbines [62]. Further environmental concerns relate to possible negative impacts of electromagnetic fields around the connection cables of offshore wind turbines on marine species [63]. However, studies on this are rare and inconclusive [60]. Apart from the named negative effects, it should also be noted that offshore wind turbines potentially can also have positive ecological effects for flora and fauna as they allow artificial reefs to develop on the wind turbines' foundations [64].

Decommissioning and end-of-life

In addition to end-of-life recycling issues, which are basically the same as described above for onshore wind turbines, the potential environmental impacts of decommissioning offshore wind turbines also include fuel emissions from workboats, contamination from pollutant chemicals, and underwater noise from deconstruction activities [60]. Still, considering all life cycle steps, the decommissioning and end-of-life phase of offshore wind turbines plays rather a minor role in terms of environmentally harmful emissions [65–67]. For reasons such as avoiding noise generated during decommissioning which could cause problems for marine species and to protect artificial reefs at turbine foundations, it may even be environmentally beneficial not to remove offshore wind farms entirely after their service life but to leave foundations in place [68, 69].

Table 1 Potential environmental impacts of key technologies for a renewable energy system by life cycle steps (darker grey boxes: major potential impacts; brighter grey boxes: minor potential impacts)

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

Grid

Raw material sourcing and manufacturing

Apart from fossil fuel emissions, the most substantial environmental impact associated with the raw material sourcing and manufacturing of grid infrastructure is considered to be resource depletion [15, 16]. Still, compared to the resource depletion associated with other key components of a renewable electricity system like PV modules and wind turbines, the resource depletion associated with grid infrastructure manufacturing is small [16]. The same also holds for further potential environmental impacts during the manufacturing phase. Both effects are due to the fact that the additional critical resources required for the build-up of the additional grid infrastructure to accommodate renewable electricity supply are relatively small compared to those needed for manufacturing the corresponding renewable energy installations (ibid.).

Installation and operation

Installation of grid infrastructure only produces minor environmental impacts [70]. More severe environmental impacts of grid infrastructure can be attributed to the land occupation by the grid infrastructure during its operation [15, 16]. In a fully renewable system, the land required for grid infrastructure can be about the same size as the land required for the entire electricity production [16]. Regarding disamenities from grid infrastructure, landscape impacts play a key role [71, 72]. In addition, there are also disamenities stemming from concerns of people, i.a. regarding health effects of power lines' electromagnetic fields (ibid.). With respect to biodiversity, electricity grids primarily pose a threat to birds: overhead power lines and associated infrastructure are a major source of anthropogenic bird mortality through collisions and electrocution [73]. The above described environmental impacts on humans and wildlife during the operating phase of an electricity grid can be mitigated by an increased deployment of underground cables instead of overhead lines [71, 73, 74].

Decommissioning and end-of-life

Potential environmental impacts in connection with the decommissioning and end-of-life of grid infrastructure can occur, i.a. through inadequate handling of dismantled components that are harmful to the environment [75]. However, overall the final life cycle stage of electricity grid infrastructure does rather not imply major environmental impacts (ibid.). Environmental benefits from recycling grid infrastructure (in terms of avoided environmental impacts from alternative resource extraction) may even outweigh the end-of-life impacts [76].

Summary

Based on the review above, Table 1 provides an overview showing at which life cycle steps the technologies under consideration have the most severe potential environmental impacts. Since potential environmental impacts can occur at all stages of the life cycle, this assessment is not about black and white statements, but rather about lighter and darker shades of grey within each technology row. It should also be noted that we generally consider potential fossil energy use-related CO_2 emissions associated with the technologies as rather uncritical since renewable technologies currently typically have a positive energy and carbon payback over their entire life cycles and potential CO_2 emissions during the technologies' life cycles can be expected to be reduced in the future when renewable energies are increasingly used [29, 44].

Analytical framework: what determines environmental effects of (de)centralized renewable electricity systems

An impact assessment is needed to include environmental effects in decisions on policies for the future electricity system. From an economic perspective, this requires a cost assessment of potential environmental impacts. The environmental costs depend, first, on the extent of actual *physical impacts* of the technologies installed and, second, on the *economic valuation* of these impacts. On a conceptual level, we suggest that the physical impacts and their valuation are influenced by at least five

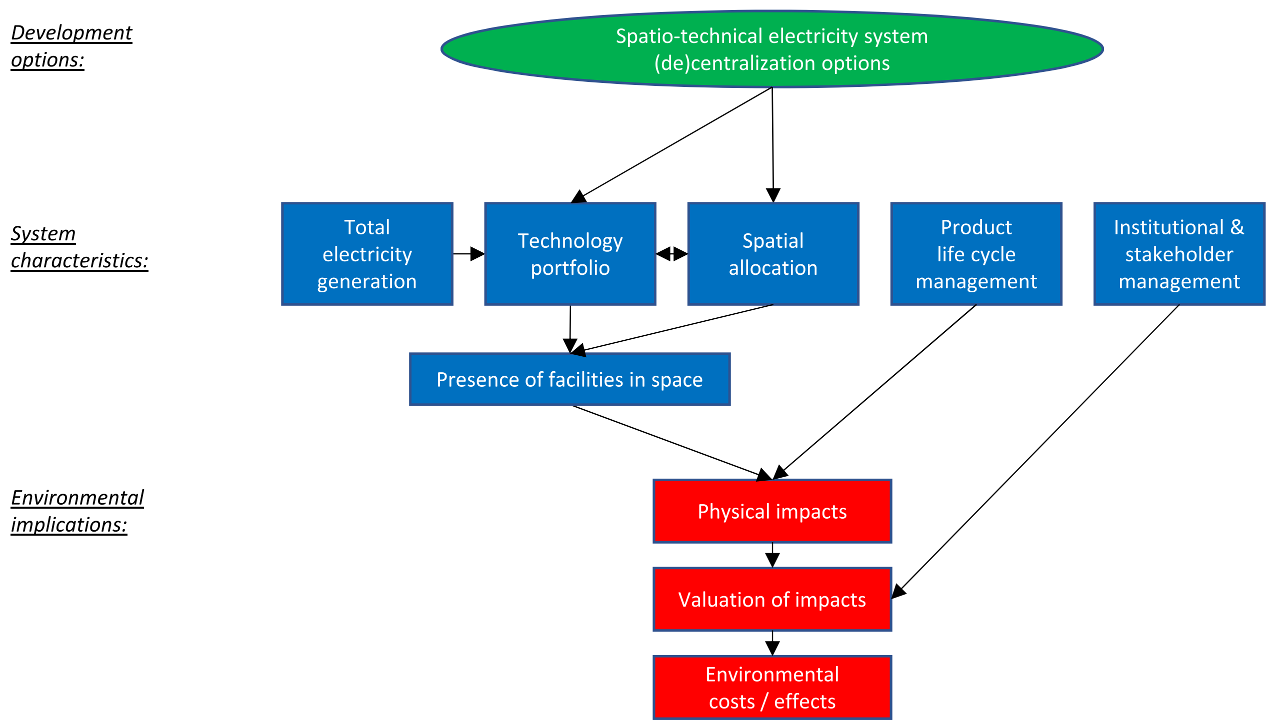

Fig. 1 Determinants of environmental effects of different spatio-technical electricity system (de)centralization options

characteristics of an electricity system, as elaborated in the following (see also Fig. 1).

The first relevant system characteristic is *electricity generation* (and demand) since this is decisive for the electricity system infrastructure deployment. Electricity generation that is avoided does not have any physical impacts. In contrast, electricity that is generated can potentially induce environmental impacts caused by the used technologies.

Second, as environmental impacts differ across technologies (see above), the *technology portfolio* is relevant for the actual physical impacts of an electricity system. This concerns the generation sector (e.g., how many onshore wind turbines are installed), the grid sector (e.g., how many overhead transmission lines are installed), and the flexibility sector (e.g., how much battery storage is installed). This also covers the question which specific technology variants are deployed (e.g., how large the wind turbines installed are). From a national perspective, it is also relevant in the technology portfolio context how much electricity is provided by domestic generation and how much by imports. It should be noted that technology portfolio decisions can also have implications for the spatial allocation of electricity system infrastructure. If, for instance, more onshore wind power is to be used, additional sites need to be deployed somewhere.

Third, the *spatial allocation* of renewable energy infrastructure affects the actual physical impacts of a renewable electricity system. This aspect includes both a more macro level and a more micro level perspective. On the macro level, for example, a spatial concentration of wind turbines in very windy regions can imply that overall fewer wind turbines need to be installed. Thus, such macro level siting decisions can affect the technology portfolio and thereby also the environmental impacts of an electricity system (see above). Apart from portfolio effects, macro level siting can also mean that, for instance, certain regions are kept free of wind turbines while other regions are used more. Such macro siting decisions can also be relevant for the environmental impacts (e.g., on birds) of an electricity system. For instance, Gauglitz et al. [77] find that a concentration approach for wind turbines can be beneficial from an environmental perspective compared to alternative more even allocations. Micro siting relates to the question, for instance, where wind turbines are locally sited within a certain region. Micro-siting is relevant from an environmental perspective since impacts of renewable energy infrastructure can vary vastly depending on local conditions. In the case of wind turbines, for instance, it matters where exactly birds breed and residents live [78, 79].

Altogether, the three aforementioned system characteristics determine directly and indirectly the presence of facilities in space. From an environmental perspective, this is an essential factor for the physical environmental impacts of an electricity system and thus ultimately for the environmental costs of an electricity system.

The physical impacts of an electricity system are, however, not only determined by the mere presence of facilities in space. They also depend on the *product life cycle management* of the deployed technologies "from cradle to grave" or in the case of recycling "from cradle to cradle" [80, 81]. First, this concerns the manufacturing stage of the deployed technologies. For instance, the environmental impacts of PV modules and batteries during the manufacturing stage depend on the applied environmental protection standards to prevent soil and groundwater contamination (see above). Second, a prudent layout and operation of facilities can reduce their environmental impacts. In the case of wind turbines, for example, operation related on-site management measures like the use of electronic bird detectors that temporally shutdown wind turbines when birds approach may mitigate the physical environmental impacts of wind turbines [82]. Third, the environmental management during the end-of-life stage of technologies is relevant for their overall environmental impacts. Especially, recycling measures can influence the negative environmental impacts positively when facilities need to be decommissioned (see above).

While the aforementioned system characteristics influence the physical impacts of an electricity system, the associated environmental costs, as noted earlier, also depend on how the physical impacts are valued by humans. A fifth important system characteristic is therefore the *institutional and stakeholder management* shaping the valuation of occurring physical impacts. For example, procedural and financial participation of citizens in the development of wind power projects may increase acceptance towards projects and affect the valuation of their physical environmental impacts [83].

The spatio-technical (de)centralization of a renewable electricity system typically affects at least some of the above-mentioned system characteristics, particularly the *technology portfolio* and *spatial allocation*. In the next section, we will explain this nexus in detail for selected spatio-technical (de)centralization options. The remaining three system characteristics (*total electricity generation*, *product life cycle management*, *institutional and stakeholder management*) are not necessarily directly affected by the spatio-technical (de)centralization chosen for an electricity system. Still, comprehensive assessments of spatio-technical (de)centralization options also have to take possible implications of these characteristics into account. We will discuss this in more detail later when we turn to the trade-off analysis.

Review of (de)centralization scenarios for Germany

We apply the proposed framework to different (de)centralization options for the future German electricity system. In this section, we look at the links between the upper part (development options) and the middle part (system characteristics) of the framework depicted in Fig. 1. After that, we discuss the links to the lower part of the framework concerning associated environmental effects.

Our analysis is based on electricity system scenarios from various modeling studies for Germany. We consider studies that contain long-term scenarios targeting at 2040–2050 with close to or fully renewable systems that differ with respect to the used technology portfolios and, if available, also provide information on spatial allocations of system facilities. To obtain a large data set, we consider both journal papers and gray literature studies written in English and German. To our knowledge, there are in total 10 studies that fulfill these criteria and which we therefore refer to in our analysis [84–93]. It may be noted that in addition to the considered long-term studies, there are also similar studies that look at the rather medium future of the German electricity system [94–98]. However, for our analysis, we only consider the longer term scenarios listed before to ensure consistency.

A review of the considered studies reveals that four basic spatio-technical (de)centralization options are typically considered:

1. "Offshore wind option": Offshore wind capacities are strongly expanded. This results in a comparatively high concentration of generation capacities in the seas in the North of Germany and the transmission of this electricity to other parts of the country. We consider this as a spatio-technical centralization option.
2. "Distributed onshore wind option": Onshore wind capacities are not primarily concentrated at the windiest locations, but instead distributed more evenly in space. We consider this as a spatio-technical decentralization option.
3. "PV option": PV capacities are strongly expanded. This results in a more even spatial allocation of generation capacities compared to scenarios with lower PV generation. We consider this as a spatio-technical decentralization option.
4. "Import option": Large amounts of electricity are imported from abroad and transmitted across the country instead of being generated and consumed domestically. We consider this as a spatio-technical centralization option.

Table 2 Considered scenarios from modeling studies (Germany, 2040–2050)

Publication	Scenario in publication	Associated option in the present study	Wind offshore (GW)	Wind onshore (GW)	PV (GW)	Import (TWh)	Grid expansion	Battery capacities
[84] Fraunhofer ISE (2020)	Reference	[Reference case]	75	189	415	NV	NV	153 GWh
	Unacceptance	PV	40	77.5	646	NV	NV	396 GWh
[85] 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
[86] 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
[87] 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
[88] 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
[89] Luderer et al. (2021)	Focus PV	PV	40	130	400	NV	NV	NV
	Focus Wind	[Reference case]	40	180	200	NV	NV	NV
[90] 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)
[91] Öko-Institut & Prognos (2019)	Reference	[Reference case]	51	178	154	−97	NV	94 GWh
	Focus Solar	PV	51	115	313	−92	NV	190 GWh
[92] 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
[93] Rogge et al. (2020)	Pathway A	Offshore wind	~50	~20	~1	~125	NV	NV
	Pathway B	PV	~5	~50	~70	~220	NV	NV

These four development options are not necessarily completely mutually exclusive. Moreover, in reality, also different degrees of (de)centralization may be possible with respect to the general development options. However, the four development options assumed describe different key strategies for future electricity system development in Germany. Table 2 provides an overview of the studies and their modeling scenarios which the four considered options are based on. Building on this, Table 3 shows for the technology portfolios of all four development options the marginal effects of the associated study scenarios relative to the relevant alternative scenarios of the respective studies. We only relate scenarios of the same study to each other because of substantial methodological differences between the studies. These differences are related to model structures (e.g., regarding the optimization approach or the spatial and temporal resolution) as well as the model assumptions (e.g., regarding technology costs or electricity demand). In the following, we will discuss these relative effects particularly with respect to the system characteristics *technology portfolio* and *spatial allocation*, as these are the system characteristics that are primarily affected by different options for spatio-technical (de)centralization. Note that the referenced studies do not necessarily distinguish between ground-mounted and roof-top PV, which is why we do not differentiate between these two PV installation types. While the installation type may be relevant for environmental impacts during the operation stage, it is not relevant for the environmental impacts at the beginning and end of the product life cycle (see above).

"Offshore wind option"

Technology portfolio

Per scenario definitions, the offshore wind power capacities are expanded particularly strongly in the scenarios

Table 3 Marginal effects of the considered study scenarios regarding the technology portfolios relative to the alternative scenarios of the respective studies (grey: technology change defining the scenarios)

Considered development option	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"	Aggregated	↑↑↑↑↑	↓↓↓↓↓	↓↓↓↓⇅	↓⇅ -- -- --	↑↑⇅ -- --	↓↓↓↓ --
	[86] Gils et al. (2019)	↑	↓	⇅	⇅	⇅	↓
	[87] Kendziorski et al. (2022)	↑	↓	↓	--	↑	↓
	[90] Möst et al. (2021)	↑	↓	↓	--	--	↓
	[92] Reiner Lemoine Institut (2013)	↑	↓	↓	--	↑	↓
	[93] Rogge et al. (2020)	↑	↓	↓	↓	--	--
"Distributed onshore wind"	Aggregated	→→	↑↑	→↑	→ --	↓↓	↓ --
	[85] Fraunhofer ISI et al. (2017)	→	↑	→	→	↓	--
	[92] Reiner Lemoine Institut (2013)	→	↑	↑	--	↓	↓
"PV"	Aggregated	↓↓↓↓⇀⇂→→	↑↑↑↑↓↓↓	↑↑↑↑↑↑↑	↑↑↓ -- -- -- --	↓↓→ -- -- -- --	↑↑↑↑↑ -- --
	[84] Fraunhofer-ISE (2020)	↓	↓	↑	--	--	↑
	[86] Gils et al. (2019)	⇀⇂	↑	↑	↓	↓	↑
	[87] Kendziorski et al. (2021)	↓	↑	↑	--	↓	↑
	[89] Luderer et al. (2021)	→	↓	↑	--	--	--
	[90] Möst et al. (2021)	↓	↑	↑	--	--	↑
	[91] Öko-Institut & Prognos (2019)	→	↓	↑	↑	→	↑
	[93] Rogge et al. (2020)	↓	↑	↑	↑	--	--
"Import"	Aggregated	→⇀↾	↓⇅	↓↓	↑↑	↑↑	⇅ --
	[86] Gils et al. (2019)	⇀↾	⇅	↓	↑	↑	⇅
	[88] Kost et al. (2019)	→	↓	↓	↑	↑	--

↑ 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

that we consider for the "offshore wind option" (see Table 2 for the corresponding values and Table 3 for the associated marginal effects, also for the following findings). With respect to the installed onshore capacities, all considered studies suppose that these are considerably lower in the offshore scenarios compared to the respective alternative scenarios.

Regarding the installed PV capacities in the scenarios with high offshore capacities, the cited studies mostly point at the same direction: the PV capacities of the offshore scenarios are lower than in almost all alternatively assumed scenarios. This can be explained by the possibility that additional offshore power generation can reduce the need for PV power generation. Only in the case of the import scenario by Gils et al. [86], the PV capacities are estimated to be slightly lower than in the offshore scenario. This suggests that a more developed European grid and additional imports may replace PV capacities similarly like additional offshore capacities.

On the question of what role imports and exports might play with an offshore option compared to alternative options, only two of the considered studies provide information. Rogge et al. [93] find for their offshore scenario a clearly lower level of imports compared to the alternative scenario considered. The modeling of Gils et al. [86] for their offshore scenario shows that imports can be either relatively high or low, depending on the alternative scenario that is being compared to. One decisive factor in this context seems to be how well developed the European grid is. Thus, the studies considered suggest that in general no clear statement can be made on what a strong offshore wind power expansion would imply for electricity imports and exports.

In regard to grid expansion needs, three of the five considered studies provide information: Gils et al. [86], Kendziorski et al. [87], and Reiner Lemoine Institut [92]. They generally indicate higher grid expansion requirements for an offshore option compared to other development options. The higher grid expansion requirements result from the fact that additional offshore power generation needs to be transported to the load centers within the country. Only in the import scenario of Gils et al. [86] an even higher grid expansion requirement is indicated than in the offshore scenario, indicating that similar to an increased expansion of offshore wind power, also an increased international electricity exchange will lead to high grid expansion requirements.

Battery storage capacities can be supposed to be rather low in the case of an offshore option compared to alternative development options according to the four relevant studies considering battery storage. The reason may be that battery storage, with its charging cycles, is rather not a complementary technology to a relatively steady offshore wind energy generation.

Spatial allocation

Due to the geographical circumstances, the high offshore capacities are deployed in the North of Germany in the North Sea and the Baltic Sea. Regarding the spatial allocation of the other system facilities, only two of the considered studies provide data. Reiner Lemoine Institut [92] models that in their offshore scenario, less PV is added in the southern regions, while the capacities of all other technologies are nearly equal in their distribution across regions compared to the alternative scenarios. Kendziorski et al. [87] also model for their scenario with high offshore shares that less PV plants are added in the South, and that less onshore wind turbines are added in the South compared to the alternative scenario with lower offshore capacities. This is because these capacities can be substituted by an increased offshore wind generation.

"Distributed onshore wind option"

Technology portfolio

In terms of total installed onshore capacities, it can be expected that these are higher for a distributed onshore option than for a spatially more concentrated option with more capacities at the windiest sites (see Table 2 for the corresponding values and Table 3 for the associated marginal effects, also for the following findings). The reason is that overall more turbines are needed to generate the same amount of electricity if not primarily the windiest sites with the highest full load hours (in the North) are used. Accordingly, Fraunhofer ISI et al. [85] and Reiner Lemoine Institut [92] expect the total installed onshore capacities to be higher for their scenarios with more evenly distributed onshore power compared to their reference scenarios.

According to the two considered studies for the "distributed onshore wind option", the total amount of installed PV capacities could be either the same or slightly higher if onshore capacities are distributed more dispersed instead of more concentrated. This suggests that, to a small extent, additional PV capacities may compensate generation decreases in onshore wind energy generation when wind turbines are distributed more evenly. However, the PV expansion does not necessarily have to be affected by the spatial distribution of onshore wind power capacities.

The offshore wind power capacities are neither necessarily affected by the question how dispersely onshore capacities are distributed, according to both studies considered for the "distributed onshore wind option". In fact, according to the corresponding scenarios of the two relevant studies, the expansion of offshore capacities is the same regardless of changes in the spatial distributions of onshore wind power capacities.

Only Fraunhofer ISI et al. [85] provide an indication how imports and exports could develop with a distributed onshore option compared to a more spatially centralized option. In this study, imports in 2050 are about the same in the assumed scenario with more spatially distributed onshore capacities as in the assumed more centralized reference scenario. This suggests that also the question of imports and exports can be largely independent of the spatial distribution of onshore wind power capacities.

According to both considered studies for the "distributed onshore wind option", grid expansion needs can be expected to be lower than with a development option where wind power capacities are more concentrated. The reason for this is that with a more spatially distributed system configuration the transmission needs can be decreased.

Reiner Lemoine Institut [92] also provides information regarding battery storage capacities: this study expects battery storage capacities to be slightly lower in the scenario with more distributed onshore capacities than in the scenario with more concentrated onshore capacities. One reason for this may be that a spatially more even distribution of onshore wind power capacities can smoothen the total generation of wind power over time and thereby reduce storage needs.

Spatial allocation

The "distributed onshore wind option" is particularly characterized by the fact that onshore wind energy capacities are not concentrated at the windiest locations, but are instead more evenly distributed spatially.

Fraunhofer ISI et al. [85] contrasts a reference scenario, in which the locations of onshore wind turbines are optimized in a cost-minimizing way and turbines are thus primarily built in a concentrated manner in the North of Germany, with an alternative scenario, in which onshore wind energy is expanded in proportion to the regional generation potentials, which results in a significantly more even spatially onshore wind expansion than in the reference scenario. The spatial distribution of the other technologies hardly differs in both scenarios. The decentralized scenario of Reiner Lemoine Institut [92] is built on the assumption of regional minimum construction targets for onshore wind (and PV). The technology deployment of the decentralized scenario is significantly less spatially polarized in wind power in the North and PV in the South compared to the assumed cost-minimizing centralized scenario (while the cumulative generation capacities of both scenarios are largely the same as outlined above).

"PV option"

Technology portfolio

By definition, PV capacities of all scenarios that we consider for the "PV option" are high relative to the respective alternative scenarios (see Table 2 for the corresponding values and Table 3 for the associated marginal effects, also for the following findings).

Offshore wind capacities under the "PV option" can be supposed to be either the same or lower compared to alternative options, according to the considered studies. The reason is that additional PV capacities can potentially substitute offshore wind power capacities to some degree. In terms of the onshore wind capacities of an "PV option", the considered studies are inconclusive. Three of the considered studies indicate lower and four of the considered studies indicate higher onshore wind capacities for their scenarios with high PV capacities compared to the respective alternative scenarios. One relevant factor in this context is whether the scenarios are based on assumptions about local load balancing requirements that affect not only PV deployment but also onshore wind power deployment.

The reviewed studies provide also inconclusive results how imports and exports could change with a "PV option" in comparison to alternative development options. Three of the studies considered contain data on this question. Öko-Institut and Prognos [91] find lower exports for the scenario with higher PV shares than for the alternative scenario with lower PV shares. Gils et al. [86] indicate lower imports for their scenario with high PV capacities compared to their other two scenarios considered. Rogge et al. [93] find much more imports for the scenario with high PV capacities than for their alternatively considered scenario. Hence, the review of the studies suggests that the amount of electricity imports and exports taking place is not necessarily influenced in one clear direction by the amount of domestic PV capacity deployment.

The grid expansion needs of an "PV option" are presumably roughly the same or lower compared to alternative development options according to the reviewed literature. Three of the considered studies provide information on grid expansion demands. Öko-Institut and Prognos [91] estimate the grid expansion demand to be almost the same in the scenario with higher and lower PV shares. Gils et al. [86] and Kendziorski et al. [87] find the grid expansion needs to be lower in their scenarios with high PV capacities than in their scenarios with lower PV capacities. Comparatively low-grid expansion requirements can be explained by the fact that with increasing PV generation occurring close to loads, less electricity may need to be transported across longer distances.

According to all four considered studies that provide scenario data on battery storage, battery capacities of a "PV option" would be relatively high compared to alternative development options. The reason for this presumably is that battery storage can be considered as a complementary technology to PV systems, because the technical characteristics of both technologies fit well together.

Spatial allocation

Concerning the spatial distribution of facilities under a "PV option", three of the studies reviewed offer information. Kendziorski et al. [87] find for their scenario with high PV capacities a stronger expansion of PV capacities in the South and also more onshore capacities in the South in comparison to the alternative assumed scenario with lower PV capacities. Presumably this is due to the general local load balancing requirements that are set for the scenario with high PV capacities. Luderer et al. [89] model for their scenario with high PV capacities also a comparatively strong expansion of PV capacities in the South. However, in contrast to Kendziorski et al. [87], they model only comparatively few wind power capacities in the South for their scenario with high PV capacities. This is because in total fewer wind sites need to be deployed in their PV scenario and, therefore, less windy sites (which are primarily located in the South) can be omitted. Öko-Institut and Prognos [91] find also a stronger expansion of PV plants in the South and West of Germany in their PV scenario compared to their reference scenario. The spatial distribution of onshore wind capacities is the same in both scenarios due to a fixed modeling assumption for the spatial onshore wind power capacity allocation in both scenarios. The comparatively high PV capacities in the South in all three named PV scenarios can be explained by higher solar radiation in the South compared to the North of Germany.

"Import option"

Technology portfolio

By assumption, net imports are much higher in the import scenarios than in the alternative scenarios (see Table 2 for the corresponding values and Table 3 for the associated marginal effects, also for the following findings).

According to the studies considered, the onshore capacities of the import scenarios are medium or rather low if compared to alternative scenarios. Gils et al. [86] calculate for their import scenario onshore capacities that are between the onshore capacities of their offshore wind scenario and their decentralized scenario. Kost et al. [88] find lower onshore capacities for their import scenario than for their reference scenario. This suggests that electricity imports could to some degree substitute onshore capacities.

Offshore wind capacities may be hardly affected by an "import option" according to the reviewed literature. Gils et al. [86] calculate for their import scenario the same offshore capacities as for their decentralized scenario and less offshore capacities than for their offshore scenario. The import scenario and the reference scenario from Kost et al. [88] both have the same offshore capacities according to their presented modeling results. This indicates that the amount of electricity exchanges with other countries is not necessarily decisive for the offshore wind power expansion since other elements of the electricity system might be more responsive to changes in the import and export balance.

PV capacities can be assumed to be comparatively low with an "import option" compared to alternative development options according to both studies considered for the "import option". This suggests that electricity imports can to some degree replace PV generation.

The grid expansion needs coming with an "import option" are comparatively high according to the relevant scenarios of reviewed studies. This is intuitively understandable because additionally imported electricity needs to distributed through the power grid.

Only Gils et al. [86] provide data for battery storage capacities. For their import scenario, they find that the amount of installed battery capacities ranges between the capacities of their other two scenarios. This suggests that international electricity trade is not a particularly decisive factor in determining whether a large or small number of battery storage units are deployed in an electricity system. This may be because for technological and economic reasons other system characteristics may play a more important role for battery storage deployment.

Spatial allocation

The studies considered provide no insights on the spatial deployment of technologies for their import scenarios compared to their alternative scenarios.

Trade-off analysis and discussion

Potential environmental trade-offs of (de)centralization options

Next, we derive the potential environmental trade-offs from the properties of the four development options described before with respect to the system characteristics *technology portfolio* and *spatial allocation* of our framework. Table 4 provides an overview of that.

The centralizing "offshore wind option" is associated with a trade-off of rather high potential environmental impacts from offshore wind and grid vs. rather low potential impacts from onshore wind as well as from PV and battery storage. More specifically, this means that in the case of an "offshore wind option" rather pronounced potential maritime impacts and also potential terrestrial impacts from grid infrastructure can be expected which are, however, counterbalanced by relatively low potential terrestrial onshore wind turbine impacts and rather low potential production and end-of-life environmental impacts associated with PV modules and battery storage. Thus, an "offshore wind option" is characterized rather by environmental impacts occurring during the operation phase and not during the raw material sourcing and manufacturing phase or the decommissioning and end-of-life phase. From a spatial perspective, apart from the comparatively high offshore impacts in the North of Germany, an offshore option could possibly result in lower potential environmental impacts from onshore wind power in the South of Germany. A potential spatial trade-off in this respect thus exists between keeping potential environmental impacts in certain regions low and achieving a spatially even distribution of potential terrestrial environmental impacts.

The decentralizing "distributed onshore wind option" is first of all characterized by a spatial trade-off: lower potential environmental impacts from onshore wind power in the North of Germany come with higher respective potential impacts in the South of Germany occurring during the operation phase. Moreover, the "distributed onshore wind option" is also characterized by a technology portfolio trade-off between higher potential environmental impacts related to onshore wind power and lower environmental impacts related

Table 4 Major implications of the considered development options for the renewable electricity systems' potential environmental life cycle impacts constituting potential trade-offs (environmental advantages are indicated by thumbs up, disadvantages by thumbs down)

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 life cycle steps)		

to grid infrastructure. This is because with the "distributed onshore wind option", overall more wind turbines and less transmission capacity are needed. Overall, the environmental trade-offs of a "distributed onshore wind option" thus mostly concern potential impacts occurring during the operation phase.

The decentralizing "PV option" is characterized by a trade-off between rather high potential environmental impacts resulting from using PV and battery storage and rather low potential environmental impacts related to offshore wind power and possibly also transmission infrastructure. Thus, the trade-off concerns rather high potential environmental impacts from PV and battery production and end-of-life opposed by rather low potential environmental impacts during the operation stage. Regarding a spatial perspective, the studies considered do not indicate a clear trade-off of a "PV option".

The centralizing "import option" is especially characterized by a trade-off between high potential environmental impacts from foreign generation and rather high potential impacts related to grid infrastructure on the one hand and (domestically) rather low potential environmental impacts related to PV as well as possibly also relatively low potential environmental impacts from onshore wind power on the other hand. Thus, this option implies rather high potential environmental impacts associated with the generation of imported electricity and with the grid during the operation phase, while possibly impacts occurring during the raw material sourcing and manufacturing and end-of-life of PV modules can be avoided. However, additional impacts from grid infrastructure during the operation phase might possibly be contrasted to some degree by avoided impacts from onshore wind at the same time. With respect to a spatial perspective, the studies considered do not indicate explicit trade-offs.

Overall, the environmental trade-offs between the considered more centralized and decentralized options can be roughly summarized as follows. The more centralized options have three advantages: (1) lower potential PV impacts; (2) possibly lower potential battery storage impacts—both points concern especially the raw material sourcing and manufacturing stage as well as the decommissioning and end-of-life stage; (3) possibly lower total potential onshore wind power impacts and lower potential onshore wind impacts in low-wind areas, which concerns especially the installation and operation stage. In contrast, the more decentralized options have the following three advantages: (1) lower potential grid infrastructure impacts; (2) possibly lower potential offshore wind power impacts; (3) lower potential onshore wind power impacts in high-wind areas. All three advantages of the more decentralized options concern especially the installation and operation stage.

However, there are also differences among the considered more decentralized and centralized development options, respectively. For example, when considering the two more decentralized options, there is potentially an environmental trade-off between higher PV and battery storage impacts and lower offshore wind power impacts in the case of the decentralizing "PV option", whereas such a trade-off is not to be expected in the case of the decentralizing "distributed onshore wind option". Similar observations can also be made for the more centralized options considered. For example, in the case of the centralizing "offshore wind option", there is potentially an environmental trade-off between lower offshore wind power impacts and higher battery storage impacts, whereas such a trade-off is not to be expected in the case of the centralizing "import option". With regard to the potential environmental trade-offs of different electricity system development options, this finding indicates that it is not sufficient to consider only whether an option strengthens a spatio-technical (de)centralization, but to consider also the option's specific properties.

Notably, different (de)centralization options also have important trade-offs regarding whether the environmental impacts occur domestically in Germany or abroad. The "import option" generally shifts environmental impacts to other regions abroad. The "PV option" may reduce domestic environmental impacts in Germany occurring during the installation and operation phase. But this reduction may come at higher environmental impacts abroad where the raw material sourcing and manufacturing of PV and complementary battery systems is currently mainly located.

Moreover, the temporal dimensions of environmental impacts should also be considered. Some of the environmental impacts may arise immediately when mines, factories or renewable infrastructures are installed, e.g., the destruction of natural habitats. Other impacts may occur rather constantly or gradually during the operation phase, e.g., air and water pollution from mining and manufacturing, or bird collision risks during the operation of wind farms. These impacts may also accumulate over time, implying, e.g., the risks of surpassing critical tipping points for local ecosystems. On the other hand, technological progress may also help to mitigate some environmental impacts over time, e.g., as technologies for recycling batteries or wind turbine blades improve further. In the case of disamenities experienced by people, there may also be habituation effects that can imply diminishing impacts over time. Overall, many environmental impacts may therefore be subject to considerable temporal uncertainty.

Finally, we cannot claim that our discussion of environmental trade-offs related to the selected (de) centralization options for renewable electricity systems is fully comprehensive because we have focused only on the impacts of the considered technologies. Certainly, different (de)centralization options can also have implications for the use of other, in terms of generate capacities, less deployed renewable energy technologies like in the German case, for instance, bioenergy or hydropower and their respective environmental impacts [1]. Moreover, different (de)centralization options may affect the use of hydrogen differently. While our analysis accounts for environmental impacts resulting from respective increases in electricity demand which might constitute the largest environmental impacts of hydrogen [25], there may still be also additional environmental impacts associated with hydrogen, e.g., related to water demand during production or hydrogen leakages during transportation [99, 100].

Further factors determining actual environmental trade-offs

In the prior discussion, we have paid attention to the first two system characteristics of our framework which are relevant for the environmental effects of (de)centralizing a renewable electricity system: the *technology portfolio* and the *spatial allocation*. As elaborated in the framework, these aspects determine the presence of facilities in space and thus are crucial for the physical environmental impacts of an electricity system (cf. Figure 1). However, certain aspects of these two system characteristics as well as further system characteristics that we have identified as important for the environmental effects of a renewable electricity system are not subject to the reviewed modeling study scenarios.

With respect to the *technology portfolio*, certain technical properties of the installed facilities are not addressed in the modeling study scenarios, but can matter for their environmental impacts. For instance, the heights of the wind turbines that are installed can be of relevance for their environmental impacts when it comes to local disamenities for residents [101]. With respect to the *spatial allocation*, local siting decisions are not addressed in the study scenarios, but can be decisive for their environmental impacts. The distances between wind turbines and sensitive birds and residents, for example, matter for the environmental impacts of onshore wind turbines [102]. Hence, certain technology portfolio decisions and local siting decisions which are basically independent of possible spatio-technical electricity system (de)centralization options may help to mitigate (but can also aggravate) their environmental effects and trade-offs.

The *total electricity generation* that we have identified in our framework as another relevant system characteristic for the environmental effects of electricity systems (cf. Figure 1) is no distinguishing feature in the modeling study scenarios considered. In all studies that we review, the amount of *total electricity generation* is assumed to be the same for the decentralization options under consideration in the respective studies. Increases or decreases in total electricity demand, and thus generation, which would affect the environmental impacts of an electricity system, may be possible with all (de)centralization option considered. Therefore, the possibility of easing or intensifying environmental trade-offs of possible electricity system (de)centralization options by reducing or increasing total electricity demand should be kept in mind.

The aspect of *product life cycle management,* which we found as another relevant system characteristic for the environmental effects of electricity systems (cf. Figure 1), is not at all addressed by the modeling study scenarios considered. Product life cycle management deals with the raw material sourcing and manufacturing, installation and operation, and decommissioning and end-of-life phases of the electricity system components. A sustainable product life cycle management during the raw material sourcing and manufacturing phase and decommissioning and end-of-life phase in form of high environmental manufacturing standards and recycling programs can avoid, for example, potential environmental impacts associated with PV modules and batteries (see above). This could then reduce the environmental effects of a "PV option". During the installation and operation phase, on-site management measures can be applied to avoid potential environmental impacts. For example, environmental impacts of onshore wind turbines could be mitigated if bird collisions are reduced through automatic detection and shutdown systems [82]. This could then reduce environmental effects of a "distributed onshore wind option". Thus, product life cycle management measures (including environmental production standards, on-site management measures, and recycling programs) can mitigate the potential environmental effects that are associated with different electricity system (de)centralization options. Therefore, the possibilities of such measures need also to be taken into account in the evaluation of environmental effects and trade-offs of possible future electricity system (de)centralization options.

The *institutional & stakeholder management* as the last identified system characteristic for the environmental effects of an electricity system (cf. Figure 1) barely plays a direct role in the modeling scenarios studied. In particular, it is not a distinguishing feature for spatio-technically identical systems in the studies. Yet, institutional and stakeholder settings can influence the valuation of physical environmental impacts which different spatio-technical electricity system (de)centralization options have. One example for this are policies for procedural

Table 5 Pros and cons of the considered development options in relation to the societal valuation of potential environmental impacts

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

participation of citizens in infrastructure projects [83, 103–105]. Such participation can potentially influence how physical environmental impacts of electricity system technologies are valued. For example, the physical environmental impacts of onshore wind turbines may be viewed as less severe if residents are informed and involved during planning processes [106]. Hence, such procedural participation could weaken a major argument against a "distributed onshore wind option". Therefore, institutional and stakeholder management possibilities, like procedural participation policies, have to be taken also into account when it comes to assessing the environmental effects and trade-offs of possible future electricity system (de)centralization options.

Taking decisions in the light of environmental trade-offs

For a decision-oriented assessment of environmental trade-offs of different (de)centralization options, a general societal valuation of all potential physical impacts is required (cf. Figure 1). As an example, one concrete relevant question in this context is: how are potential environmental PV and battery production and end-of-life impacts valued by society? If these potential environmental impacts are considered to be of high relevance, from an environmental perspective, this could argue for not relying on a decentralizing "PV option" but rather on a centralizing "offshore wind option" or "import option" with smaller amounts of these technologies. Potential environmental impacts related to PV and battery storage might not be valued highly in countries like Germany if societally no major significance is assigned to potential negative environmental impacts that may occur mainly abroad during the PV module and battery storage production, or if it is expected that no major environmental impacts will occur at all. This could be the case if it is supposed that high environmental standards are ensured wherever PV modules and batteries are produced and decommissioned.

Table 5 shows the societal valuations concerning potential environmental impacts which are key according to our analysis (cf. Table 4) for evaluating the environmental trade-offs of the four considered (de)centralization options. Table 5 also indicates the pros and cons of the four development options given that the potential environmental impacts are considered to be severe by society. If the potential environmental impacts are not considered to be severe, then the identified pros and cons lose in importance for environmental trade-off decisions.

Non-environmental goals and transferability to other countries

It is important to recognize that environmental aspects are, of course, only one of multiple target dimensions for energy policy. Additional societal goals may include system costs, security of supply, and equity. Different spatio-technical (de)centralization options can have different implications with respect to these goals. For example, Tröndle et al. [13] find that a spatio-technical decentralization option, which allows electricity to be generated and balanced only regionally, implies higher system costs than a more centralized Europe-wide optimized system. With respect to equity considerations, for instance, Drechsler et al. [107] and Sasse and Trutnevyte [108] find that spatio-technical centralization options for the deployment of renewable energies in Germany and Switzerland, which concentrate generation capacities at the most productive locations only, clearly deviate from regionally equitable development options. Therefore, in addition to environmental considerations, such further target dimensions should also be taken into account when discussing different spatio-technical (de)centralization options.

Regarding the transferability of our analysis to other countries, several aspects need to be considered. First, other (de)centralization options may need to be analyzed for other countries. This is because the available spatio-technical (de)centralization options may vary across countries. For instance, countries without coasts, unlike Germany, do not have offshore wind power potentials and therefore cannot pursue an "offshore wind option". Instead, in contrast to Germany, for example, hydropower potentials may play a relevant role in other countries, so that a "hydropower option" extensively exploiting these potentials might be a relevant possibility there. Also, the specific spatial economic patterns of a country must be taken into account when considering spatio-technical development options. For instance, the spatial location of load centers within a country can be important for grid expansion needs (and associated environmental impacts) of a particular development option. Moreover, it is possible that societal valuations of certain physical impacts may vary between countries due to cultural differences [109]. Overall, this means that both the available spatio-technical development options and the signs, extents, and societal valuations of associated environmental trade-offs may differ between countries. However, our framework and analytical approach are universal and could be used for further research to reveal environmental trade-offs of spatio-technical (de)centralization options for different countries and to disentangle relevant factors.

Conclusions

We analyzed the potential environmental trade-offs which are associated with different possible spatio-technical (de)centralization options for a future renewable electricity system. For this purpose, we first reviewed the potential environmental life cycle impacts of key technologies for renewable electricity systems. Subsequently, we developed a framework to identify which factors determine actual environmental effects of renewable electricity systems. We applied the framework to the case of the future German electricity system by reviewing four possible spatio-technical (de)centralization options which we derived reviewing ten modeling studies. We considered an "offshore wind option" and an "import option" as rather centralized development options and a "distributed onshore wind option" and a "PV option" as rather decentralized development options.

Our analysis shows that all (de)centralization options are associated with potential environmental trade-offs. We find that the (de)centralization of the system is a relevant factor determining these trade-offs. For instance, both centralization options examined are rather associated with lower potential environmental effects related to PV occurring especially during the raw material sourcing and manufacturing stage as well as during the decommissioning and end-of-life stage, while both decentralization options examined are associated with lower potential environmental effects from grid infrastructure occurring especially during the installation and operation stage. However, our analysis also yields that the occurrence of environmental trade-offs also depends on how spatio-technical (de)centralization is achieved. For instance, environmental trade-offs between potential environmental effects related to battery storage and potential environmental effects related to offshore wind power are found only for one of the two centralizing options considered as well as only for one of the two decentralizing options considered. Thus, the question of whether electricity system development options are more centralized or decentralized is not sufficient to comprehensively deduce their potential environmental trade-offs. Instead, the specific spatio-technical characteristics of centralization and decentralization development options (i.e., their specific technology portfolios and spatial allocations) also need to be considered.

In addition, our analysis reveals that actual environmental effects and trade-offs of electricity system development options depend also on other aspects than their spatio-technical (de)centralization. These aspects include the total electricity demand, local siting decisions, applied product life cycle management measures for the energy infrastructure components (e.g., on-site measures), and the institutional and stakeholder management (e.g., procedural participation opportunities). Moreover, a societal valuation of potential environmental impacts is required for a decision-oriented environmental trade-off assessment of different (de)centralization options. It also should be noted that, in addition to environmental trade-offs, there are, of course, also further criteria (e.g., system costs, security of supply aspects, and equity considerations) that need to be considered for a comprehensive evaluation of different electricity system (de)centralization options.

Various policy implications emerge from or findings. First, policymakers should be aware of the identified potential environmental trade-offs of different centralizing and decentralizing electricity system development options.

In a theoretical first-best world, however, policymakers would not have to decide on the issue of (de)centralization at all—even when there are environmental trade-offs involved. Rather, the first-best approach would be to price in all potential environmental effects (as well as all other technology costs and benefits). The socially optimal degree of (de)centralization would then arise endogenously. The political decision-makers could thus be agnostic about (de)centralization questions.

In practice, however, it will be impossible to accurately price in all factors due to regulatory constraints, such as only domestic regulatory jurisdiction, issues of political feasibility, and imperfect information of the regulator. Moreover, the use of price-based regulatory approaches may be impaired by methodological and ethical issues related to monetization of environmental impacts. In this case, influencing the (de)centralization of a renewable electricity system through policy interventions may be a second-best approach. Depending on the desired outcome, political interventions could include, for instance, regionalized site provision obligations for wind turbines, a general PV duty for all rooftops, or differentiations of subsidy levels for different renewable technologies. No-regret and possibly also low-regret measures that can avoid potential environmental trade-offs should be identified and implemented. Possible starting points for this may include environmental supply chain management regulations for the manufacturing stage and environmental on-site management regulations for the operation stage. However, it is important to keep in mind that the promotion of specific (de)centralization options will probably still remain ambivalent and involve trade-offs. In this case, policy decisions will inevitably require political valuations and prioritizations of different potential environmental effects (and further non-environmental effects). Science can at best offer some estimates in this context.

Avenues for future research may include the investigation of further electricity system development options—also in alternative country settings. Models with higher spatial resolutions could help to analyze trade-offs between different spatio-technical (de)centralization options in more detail. Moreover, the scope of analysis could be broadened from the electricity system alone to the energy system as a whole. Future research could also attempt to quantify the environmental trade-offs. In addition, future studies could also look at further non-environmental energy policy goals to provide a more holistic trade-off analysis for future electricity system development options.

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Author details
[1]Institute for Infrastructure and Resources Management, University of Leipzig, Ritterstraße 12, 04109 Leipzig, Germany. [2]Helmholtz Centre for Environmental Research, UFZ, Permoserstraße 15, 04318 Leipzig, Germany.

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