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Phasing out support schemes for renewables in neighbouring countries: an agent-based model with investment preferences

PREPRINT Version

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Abstract: Support schemes have been central to the expansion of renewable electricity globally and in the European Union. As technologies mature, individual member states may decide to phase out these policies. While previous research has shown that such policy changes affect investors' decisions, we investigate how they affect pathways and electricity prices by simulating investment decisions in an agent-based model in two case countries. This paper contributes and applies an adapted investment decision algorithm that incorporates empirically observed technology and return preferences and is calibrated by return observations. The new algorithm yields more refined and stronger effects compared to its predecessor. Results show that the phase-out of auctions in Germany and the Netherlands slows down their deployment of renewable capacity by up to ~60% and ~35%, respectively. With the exception of photovoltaics and onshore wind projects in the Netherlands, the targeted capacities can only be reached by continuing support in both countries. Furthermore, ending support in a large country like Germany leads to higher electricity prices and fosters a market-driven but insufficient capacity expansion in smaller neighbours like the Netherlands. As the electricity grids in many countries are strongly interconnected, such cross-border effects are of international relevance. Our findings suggest that continued auctions may be necessary and that countries should coordinate policy changes to stay on track for meeting their renewables targets.

Keywords: Electricity markets, support schemes, agent-based models, cross-border effects, renewable energy, energy policy.

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1 Introduction

Countries around the world have committed to transform their electricity systems in response to the climate crisis. For instance, the European Union (EU) has set itself the goal of achieving climate-neutrality by 2050 [1]. Renewable power sources[1] like photovoltaics (PV), onshore wind and offshore wind will play an essential role in these transformations. A high share of renewable power is attainable but requires a massive and rapid expansion of capacity [2]. While renewable capacity has increased considerably [3], at least another doubling is needed by 2030. To attain this goal, EU member states have established National Energy and Climate Plans (NECPs). The specific instrumentation to expand renewables is a member state competence, but the European Commission specifies what policies and designs are allowed. Notably, all member states that want to support renewables are required to use auctions as their central support scheme [4].

Following the shift from feed-in tariffs to auctions, there is now an ongoing debate in science and politics about the future of support schemes [5]. As renewables mature, individual governments may decide that auctions have become obsolete. However, it is still unclear if market incentives alone can provide sufficient momentum to scale up renewables and meet short- and long-term targets. Should EU member states miss their targets, this will not only pose a political problem but may also jeopardise climate change mitigation efforts.

Moreover, discontinuing support has potential side-effects. First, if support for specific technologies ends at different times, investors who prefer low-risk investments are likely to move to less mature technologies that still receive support [6]. The resulting shift to these more expensive technologies may increase transition costs, at least in the short term. Second, large-scale changes in the deployment of renewables may have cross-border effects in neighbouring, interconnected countries. For example, the expansion of renewables in larger countries has contributed to lower electricity prices in smaller ones, affecting investors in both countries [7].

While research has investigated market-based versus supported systems [67], more research is needed to reveal the extent to which renewable energy pathways alter following the phase-out of support. There is also a paucity of knowledge about cross-border effects following policy changes and reason to expect that such effects threaten efforts to achieve targets across borders. These are complex issues, depending on several system variables like costs, prices, demand, policies, investors' behaviours and their preferences, and hence, require a modelling approach. As these open questions are also relevant for upcoming decisions of European policymakers, we answer three research questions: (1) What are the domestic effects of phasing out support on electricity prices and renewables deployment; (2) What are the cross-

[1] In the remainder of this paper referred to as renewables.

border effects if only one country phases out support; And (3) can countries reach their targets without support?

We investigate these questions in the context of assumed policy changes in 2025 and two tightly interconnected power systems, the Netherlands and Germany. An agent-based model (ABM) simulating investors' reactions to market and policy changes is refined and used. The article's novelty and contribution to gaps in the literature is twofold: First, we contribute to the understanding of the domestic/cross-border effects of phasing out support schemes for renewables. Results show that such effects can be counterintuitive and thus pose a risk for investors. Previous literature has not sufficiently focused on these effects and their risks, especially not in the context of the recent debate about phasing out support for renewables.

Second, we extend the ABM to integrate empirically observed technology and return preferences and calibrate it with real return observations. This contribution follows a call for research to better understand the relevance of societal parameters in models [37].

2 Background

2.1 The debate about future support

Over the last two decades, EU member states have adopted feed-in tariffs and tradable green certificates to support immature renewables [8]. These policies successfully triggered the expansion of renewable capacity [9]. However, there is no consensus on how these mechanisms should develop in the future. Some argue that deployment policies fail to provide market incentives [11,13], are neither efficient [12] nor cost-effective [14], and thus, should be replaced entirely by carbon pricing as the only means of ensuring the reduction of greenhouse gas emissions across the entire economy. Others find that support schemes should continue as they tackle several market failures [15], reduce policy [16] and financial risks [10,17], hedge against interest rate fluctuations [18], and fulfil secondary policy objectives, e.g. for local economies [5]. While it is questionable that fully liberalised markets could meet deep decarbonisation targets without regulatory interventions [19], an alternative to abandoning support in a single step is a gradual transfer of market risks to investors [20], e.g. through auctions [21].

The decreasing generation costs of renewables and the occurrence of support-free projects [68] have strengthened the case for abandoning support and letting renewables compete on the general electricity markets. European institutions envisage support to end between 2021–2030 [4] or as soon as technologies will have become mature [22]. Germany [23] and the Netherlands [24] likewise expect to reach targets without support from the mid-2020s. Here, we contribute to this debate by showing the domestic/cross-border effects of abandoning support for single or all technologies.

2.2 Cross-border effects

Price developments in large countries can depress prices in smaller neighbours if markets are sufficiently interconnected [25]. Such interactions have occurred, for example, in Switzerland due to developments in Germany and France [7]. While these cross-border effects can redistribute welfare, they may have negative impacts like an increased price volatility [27]. Joint support schemes can mitigate such unwanted impacts [26,27] if they are well-designed [28]. This is one reason why the EU now mandates to open national support schemes for other countries. However, if individual countries phase out support completely, joint policies may not be an option anymore.

Furthermore, as European countries head towards a continental electricity market—a comparably low-cost option [29]—their transmission and interconnection capacities will increase, making cross-border effects more important. However, it is unclear how strong and relevant these effects will be if individual countries phase out support at the same time. As the strength of effects depends not only on the deployment of renewables and transmission capacities but also on investors' decisions [31], as well as carbon and fuel prices [30], a quantitative electricity system analysis is required. We perform such an analysis using an ABM.

2.3 Heterogeneity in agent-based modelling

Sustainability transitions require researchers to reconsider prevalent modelling approaches [33]. Specifically, there is a need to better integrate behavioural and social aspects [38]. While models like integrated assessment models (IAMs) have advanced in representing techno-economical details, they do not represent the behavioural aspects very well [36,27]. However, as new actors in the electricity market differ in their investment preferences, behavioural heterogeneity increases [34,35]. Therefore, research on alternatives like agent-based models is growing [32,42]. ABMs feature heterogeneous actors acting on limited information about the future and model emergent side-effects of policies [39]. They have gained increasing popularity as a means to answer a multitude of energy and climate policy questions regarding carbon price design [31,41], support scheme design [40], and market liberalisation [19].

Following a call for research on societal parameters in (future) energy models [37], we focus on which parameters are appropriate to represent heterogeneity and myopic investment behaviours. Parameters used in this article are based on empirical data, which can be more accurate than assumptions [43]. However, data collection is costly, so modellers need to know if empirically grounded parameters influence model results or if well-informed guesses are sufficient. We cover this gap by integrating technology and return preferences of real investors in an ABM.

3 Method

3.1 Model

The ABM EMLab-Generation, here referred to as EMLab (1&2), is used to simulate electricity producers' behaviour in electricity markets and the domestic/cross-border effects of their investment decisions on capacity deployment and electricity prices. Using an ABM, previous research [6] is extended by translating (parts of) empirical investment preferences into actual activity.

3.1.1 Base model

EMLab considers short- and long-term developments: in the short term, the bidding and selling, and in the long term, investments in power plants. Previous research applied an earlier version of the model (EMLab 1) to study climate and energy policy, security of supply, and investment decisions [39]. The model represents the electricity sector, including power generating technologies, two interconnected electricity markets, energy producers, carbon policies, different fuels, and dynamic load profiles.

With this paper, EMLab 2 was rewritten and optimised for computational efficiency. The second version is similar to the first, except for a redesigned "engine". A comprehensive description of the different components, roles, domains and classes of EMLab 1 is covered elsewhere [44,45]. Here, the focus lies on the changes and additions to the investment behaviour and the implemented auction module [40]. The model[2] is open-source software and written in Java and R.

3.1.2 Investment algorithms

The main agents in EMLab are energy producers. An investment decision algorithm defines a producer's investment behaviour. If producers invest, other producers notice their investment activity and adapt their decisions. Investments occur either because of market signals or if a producer wins an auction (see Section 3.1.4). In the former case, producers act in the free market according to an investment decision algorithm. This algorithm evaluates and selects projects until the predicted future demand is met or producers run out of capital for loan down payments. The original algorithm in EMLab 1 (labelled NPV-algorithm) assumes that producers decide rationally, i.e. they first evaluate if capacity additions are reasonable. Second, the NPV-algorithm iterates through all technologies and markets, and producers select the one project with the highest net present value (NPV) per MW [44].

[2] https://doi.org/10.5281/zenodo.5526127

NPV is defined as:

$$NPV_g = C_{\mathrm{Profit,g}} - C_{\mathrm{OM,g}} - I_{\mathrm{g}}$$

Equation 1

with $C_{\mathrm{Profit,g}}$ as gross profit, $C_{\mathrm{OM,g}}$ as fixed operation and maintenance costs and I_{g} as investment cost of a project g. Monetary values $C_{\mathrm{Profit,g}}$ and $C_{\mathrm{OM,g}}$ are discounted according to:

$$\frac{C}{(1+\mathrm{WACC})^t}$$

Equation 2

with C as a cash flow, WACC as the weighted average cost of capital and t as simulation year.

In this paper, a new decision algorithm is developed and tested (labelled preference-algorithm). It goes beyond the single-factor evaluation of a positive NPV to a joint consideration of multiple investment characteristics. The preference-algorithm is based on utility theory [46,47] and assumes that actors strive to maximise their total utility. The total utility of a product, or investment, follows a conjoint consideration of attributes for which investors have varying preferences. Random utility theory considers that repeated choices are inconsistent [47], and so overall utility is:

$$U = \sum_{i=1}^{m} (u_i + e)$$

Equation 3

with u_i as the part-worth utilities of m attributes and an error term e. Moreover, an assumed error of 5% adds a slight variation.

The data originates from a previous conjoint analysis study that assessed the investment preferences of 93 heterogeneous investors [6]. This study identified part-worth utilities for four different investment characteristics: technology, country, (expected) return on equity (ROE), and the support mechanism. Our study differentiates between distinctive technology and ROE preferences, whereas policy and country preferences are constant[3] (**Table 1**). Although the referenced study assessed a wide range of part-worth utilities, quantified by the standard deviation (SD), our paper only uses the mean values to represent the eight investors (of renewables). This simplification clarifies the analyses and results while also being in line with previous EMLab studies, which rely on relatively few energy producers.

[3] Auctions are considered, but they are not part of the preference-investment algorithm. Also, our study assumes that investors only invest in their own country.

Table 1: Attributes and attribute levels. Adopted from the conjoint analysis deriving the preference data used in this paper**.** Source: [6].

Attribute	**Levels**
Technology	PV, onshore and offshore wind
Return on equity	5%, 6% and 7%

In principle, the technology and return attributes are representable in EMLab. However, the model uses the NPV instead of ROE as decision criteria. Hence, several intermediate steps are needed to map the simulated NPV values, which producers calculate in the algorithm, to the empirical part-worth utilities. The discounted ROE is defined as

$$R_g = \frac{ROI_g}{r_E} \mid ROI_g = \frac{NPV_g}{I_g \cdot t_{eL}}$$

Equation 4

with ROI_g as return on investment, r_E as rate of equity and NPV_g, I_g as shown in Equation 1. Dividing by the expected lifetime t_{eL} results in a yearly average return. In the preference-algorithm, producers select projects with the highest total utility. Still, a positive NPV is a precondition to avoid bankruptcy.

3.1.3 Assigning part-worth utilities and mapping data to models

An essential step in the investment algorithm is the assignment of the empirically assessed part-worth utilities to simulated values[4]. This assignment is straight-forward for the technology attribute because it is already present in the original algorithm of EMLab, but for the ROE attribute, it is more complex. In principle, simulated returns could be assigned to the corresponding levels to get the part-worth utilities. However, the original part-worth utilities are only valid for a narrow return range of 5–7%. While these are reasonable for most power plants in Germany and the Netherlands in 2017 (**Table 2**), simulated values can lie far beyond this range because of two reasons. First, models do not accurately replicate the actual socio-economic and technical context. Second, small markets offer less balancing capacity, so investors may expect more lost load events in small countries (i.e., hours with very high electricity prices).

[4] The "own country" and "no policy" levels are assigned to all renewables-investors.

Table 2: Observed returns on equity (±SDs) for renewables in 2017. Sources: onshore wind and PV in DE: [17]; other figures estimated from capital costs: [48].

	Germany	Netherlands
Onshore wind	6 ±2%	7 ±2%
Offshore wind	8 ±2%	11 ±2%
PV	5 ±2%	7 ±2%

In summary, the literature only provides part-worth utilities for realistic returns. However, if simulated return expectations differ strongly from the realistic values, the part-worth utility assignment becomes problematic. Extreme returns may even dominate in the total utility[5] and become the only decisive factor. To better integrate the conjoint consideration, a mapping function is developed in this paper. Namely, the model is aligned with the data context (**Table 2**) by limiting and rescaling the simulated ROE values. The linear mapping function comprises a slope and an intercept for each market and technology. The remapped ROE R_{re} is defined as

$$R_{\text{re}} = \frac{\bar{R}_{\text{sim, 10-90\%}}}{\bar{R}_{\text{obs}}} + R_{\text{sim}} \cdot \frac{R_{\text{sim, 90\%}} - R_{\text{sim, 10\%}}}{R_{\text{obs, max}} - R_{\text{obs, min}}}$$

Equation 5

with R_{sim} as the simulated ROE; for the intercept, $\bar{R}_{\text{sim, 10-90\%}}$ and $\bar{R}_{\text{obs}}$ as mean values of simulated and observed ROEs; and for the slope, $R_{\text{sim, x\%}}$ as x^{th}-percentiles of the simulated ROEs and $R_{\text{obs, max/min}}$ as the range of actually observed ROEs (see Table 2). Values between the 10% and 90% percentiles are considered for the simulated values to give less weight to outliers[6]. It is also considered that utility decreases with increasing gains [49] by limiting the function, i.e. high values are all the same.

3.1.4 Policy module implementations

To investigate policy phase-outs, a policy module from a previous EMLab study is adopted [40]. That study has simulated policies as a combination of design elements which allow to represent and simulate auctions like those in Germany and the Netherlands. Here, three technology-specific tenders per country are simulated, granting a yearly payment to cover producers' levelized costs of energy (Table 3). The modelled policy is simplified and a compromise between the real German and Dutch schemes. There are several differences between the modelled and actual schemes, including the pricing rules and pre-qualification criteria. First, the model applies uniform pricing to award most producers higher remunerations than pay-as-bid. Second, it

[5] E.g. if simulated ROEs are 1–4%, all projects would receive the same part-wort utility of the 5% level; the lowest observed value.

[6] We recode heavy outliers that skew the final mapping function.

omits pre-qualifications to allow more investors to take part (which may lower bids). Finally, all simulated support payments last for 17 years. Moreover, the model is adjusted to allow auctions to end at any given time (nevertheless, producers will continue to receive payments if they have a running support contract).

The technology-specific quantity targets of auctions are based on "renewable energies' share of gross electricity consumption" in the NECPs of Germany [51] and the Netherlands [24]. These targets and their policy implementations are valid for 2021–2030. The relative targets for all simulation years are interpolated using a general linearised model. The interpolation resulted in relative target pathways for 2015–2050, in which renewables approach a share of 95–99% in 2050 (**Figure 1**). To show that results are reasonable, they are compared to reference scenarios from the literature [52] (see next section).

Table 3: Design elements of real and simulated policies. Real policies encompass the main German and Dutch renewables policies from 2021. The simulated policy is an assumption. Sources: [40]; for real policy: [50] and res-legal.eu.

Design-element	Description	Real German policy (EEG 2017)	Real Dutch policy (SDE+)	Modelled policy
Warranty	Support renewables by warranting either a price or a quantity.	Quantity for PV & wind if project > 750 kW.	Quantity for offshore wind. Price (premium) for wind and PV.	Quantity to follow NECP targets pathways.
Pricing rule	Pay-as-bid awards individual bids to winners. Uniform awards the highest winning bid to all winners.	Pay-as-bid and Uniform (from 2017).	Pay-as-bid.	Uniform (the only option in the policy module).
Contract with respect to the electricity price	The electricity price is accounted for ex-ante (before electricity prices are known) or ex-post (electricity price is known).	Tender: ex-post (sliding premium as the difference to yearly prices).	Premium: ex-post. Tender: ex-ante (considered in basic energy price).	Ex-post to lower risks for investors.
Technology specificity	Differentiation of support for technologies.	Specific tenders.	Specific tender and premiums.	Specific tender.
Duration	Duration from the start until the end of payments.	20 years.	15 years.	17 years (average).
Pre-qualification	Mechanisms to inhibit strategic biddings, like the need for permits or upfront payment.	Several (see sources in caption).	Several (see sources in caption).	None.

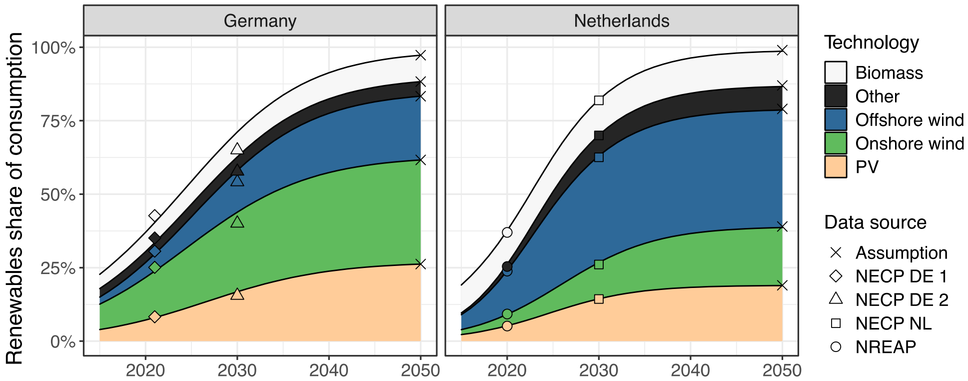

Figure 1: Relative targets for renewable capacity. This study determines quantities for auctions by targets. Due to model input needs, relative targets are used and interpolated from electricity consumption targets and own assumption (for 2050). "Other" denotes other renewables. Regression causes minor deviations. Sources: NECP DE1/2 (p. 154/48) [51]; NECP NL (p. 30) [24]; NREAP [53].

3.2 Assumptions and data

This section explains assumptions specific to this study. Model and data assumptions of the base model are covered elsewhere [44].

3.2.1 Model

EMLab simulates yearly changes in the electricity system, beginning in 2015. While this is before the papers' focus period, it leads to more balanced results as a lot of dismantling occurs early (several of the conventional and renewable power plants in the input data have exceeded our lifetime assumptions). Per scenario, 30 iterations are simulated. More iterations do not significantly affect capacity and price changes (differences are <5% for more iterations). Maximum investment limitations are applied to lignite, coal, nuclear and hydro to replicate bans on new investments and exhausted technology potentials. The deployment of the other technologies is not limited (see discussion in Section 5.3).

3.2.2 Countries and demand

The simulations comprise two power price areas with different demand developments, initial capacities, and auction targets. The focus lies on the interaction between the German and Dutch markets because they are well interconnected. This focus allows us to study the consequences of policy interactions between countries on power mixes and prices, in particular, between a large and small market. EMLab aggregates the load duration curve from 8760 hours to 20 segments for computational efficiency. The demand is based on hourly load data from 2015 [54]. As future demand is uncertain, randomly varying demand growth rates are assumed in each iteration (see Appendix A).

3.2.3 Producers and power plant list

Two types of energy producers are implemented (see **Table 4**). *Incumbent-investors* invest in conventional technologies, while *renewables-investors* only invest in renewables. Incumbent-investors decide according to the NPV-algorithm and renewables-investors according to the preference-algorithm. However, if auctions are available, *renewables-investors* have two investment options: first, renewables investments resulting from successful bidding in auctions, and second, activity in the free market (using the preference-algorithm). These options are important because it allows investors to shift to the free market and invest in more capacity than what governments put out to tender.

Preferences for renewables-investors are mainly based on empirical data from Germany. Preferences for Dutch investors are not available. However, investors' actual residence leads to less variation in preferences than the typical investment range of projects [6]. Therefore, it is differentiated between the investor types small, medium, large, and very large instead of the domicile.

The initial capital of producers determines how much activity is possible. Although the simulated capital is an informed estimate based on the projected capital requirements of the energy transition [55], the precise figure does not influence results much (a 25% variation is of little effect, see Appendix). Moreover, it is assumed that German renewables-investors have more initial capital than the Dutch because Germany is projected to have a 4–5 times higher demand in 2050. Also, the capital of incumbent-investors is lower than that of renewables-investors to discourage a significant expansion of fossil capacity. Moreover, risks are considered through a 10% discount rate for all investors.

Table 4: Energy producers/investors in the simulations. Information includes their count (N), country and initial capital.

Energy producer	Country	N	Initial capital
Renewables-investors	Germany	4	€24 billion
Renewables-investors	Netherlands	4	€6 billion
Incumbent-investors	Germany	3	€3 billion
Incumbent-investors	Netherlands	3	€3 billion

3.2.4 Technology assumptions and flexibility

The simulated power system comprises conventional and renewable electricity generating technologies (see Appendix A for assumptions like lifetimes, capacities, and fuel price trends). The initial power plant portfolio is based on national capacity figures from 2015 from ENTSO-E. Because of the large number of producers, data is aggregated to limit the calculation time and simplify data analysis. First, the total capacity is randomly distributed to the 14 energy producers (*renewables-investors* only invest in renewables), and second, power plants are aggregated to large-scale plants. Also, all types of producers dismantle power plants after the assumed lifetimes.

Load factors for conventional power plants are adopted from assumptions in the base model [39] and dynamic capacity factors derived for renewables from hourly simulations [56]. Past (up to 2019) and projected installation cost stem from IRENA (**Figure 2**).

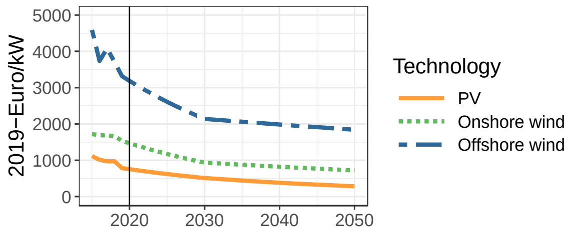

Figure 2: Historical and projected installation costs of renewables. Historical costs up to 2019 are based on average costs for Germany. Projections from 2020–2050 (starting from the vertical line) are based on expected global averages for 2030 and 2050. Sources: [9,57,58].

Due to increased intermittent generation, flexibility is essential, e.g., through flexible demand/supply, storage, and interconnectors. Although European countries lack clear and explicit plans to increase flexibility [59], gas-powered generation will likely remain relevant in the short term [51]. Hence, gas[7] turbines (CCGT/OCGT) are considered. Moreover, additional flexibility is provided through interconnectors with a capacity of 4.5 GW for the entire duration of the simulation [60].

EU member states may enact policies to phase out fossil-fuel-powered generation and accelerate emission reductions. Such policies are partly considered by banning new coal and lignite capacity[8]. Power plants are also subject to the EU Emission Trading Scheme (ETS). Therefore, a simplified carbon price system is simulated. Carbon prices start at €7 in 2015 and increase by €1.5 per year. As future prices are unknown, the sensitivity of this parameter is tested.

3.3 Scenarios and reporting

The main results compare an auction scenario to different policy phase-out scenarios (Table 5). The baseline scenario is the auction scenario. In this, Germany and the Netherlands continuously support renewables during the entire simulation. Both countries follow their target trajectories (Figure 1). Investors are incumbent-investors and renewables-investors. Investing in the free market is still possible. Producers make free-market investments if they

[7] Here, natural gas. Other carriers like biogas play a minor role for electricity generation.
[8] Also, new capacity from nuclear- and hydropower is restricted for political reasons (decisions in Germany and lack of plans in the Netherlands) and technical limits (exhausted hydropower potentials), respectively. Sources: [51,24].

expect a high profit, even without support, and if foreseeable investments do not cover future demand.

In the phase-out scenarios, countries phase out auctions for renewables in 2025. This follows an unspecified political decision and is *not* a reaction to a model development (e.g., a cost threshold). To simulate situations without coordination between countries and investigate cross-border effects, one set of scenarios solely phases out support in Germany (scenarios 5–8), and another one solely in the Netherlands (scenarios 9–12).

In comparing the auction to the phase-out scenarios, the two values are divided and reported as percentages (relative to the auction scenario). Standard deviations quantify the variation between model iterations and years and are calculated based on the SDs of the individual averages as $SD_{\text{diff}} = \sqrt{SD_1^2 + SD_2^2}$. If SDs are higher than the average percentages, the effect is ambiguous, and interpreted as an effect of low significance.

Table 5: Scenarios and parameters. Support ends in every scenario in 2025 except in scenario 0 (support continues).

Nr	Scenario-name	Country where support ends	Technology for which support ends
0	Auction	N/A	N/A
1	Both all tech.	Both countries	All technologies
2	Both onshore	Both countries	Onshore
3	Both offshore	Both countries	Offshore
4	Both PV	Both countries	PV
5	DE all tech.	Only Germany	All technologies
6	DE onshore	Only Germany	Onshore
7	DE offshore	Only Germany	Offshore
8	DE PV	Only Germany	PV
9	NL all tech.	Only the Netherlands	All technologies
10	NL onshore	Only the Netherlands	Onshore
11	NL offshore	Only the Netherlands	Offshore
12	NL PV	Only the Netherlands	PV

4 Results

4.1 Continued auction schemes for renewables

In the auction scenario outcome, renewables continuously increase in both countries (**Figure 3**). Some conventional technologies like gas expand, but others have either reached political and technical limits (nuclear and hydro) or are banned from further expansion (coal and lignite). While all incumbent-investors are, by definition, active in the free market, most renewables-investors only participate in auctions (**Figure 4**). Nevertheless, some expansion is driven by the free market, e.g., by Dutch renewables-investors in later years.

Average electricity prices are €53–58 per MWh in both countries (**Figure 5**). There is some variation between iterations that increases over time. Nonetheless, the two countries' price developments are similar (indicated in **Figure 5** by a high correlation of prices). These prices are realistic and in line with official projections [61].

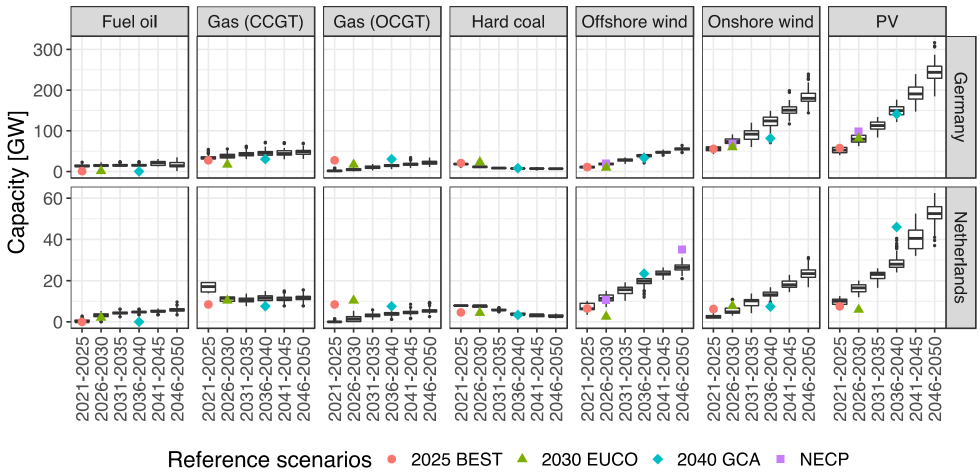

Figure 3: Capacity developments in the auction scenario. Boxplots depict medians and SDs over 5-year intervals and 30 model iterations. Small dots denote outliers. Reference scenarios are used for validation reasons. Depicted technologies encompass 90% of simulated capacity. Sources: ENTSO-E [52]; NECP targets: p.50 [51], p.75 [24].

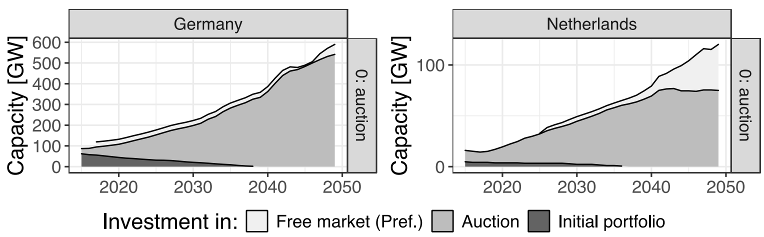

Figure 4: Origin of renewable capacity in the auction scenario. Pref. = with preference-algorithm. Areas depict mean averages of total capacities over 30 model iterations.

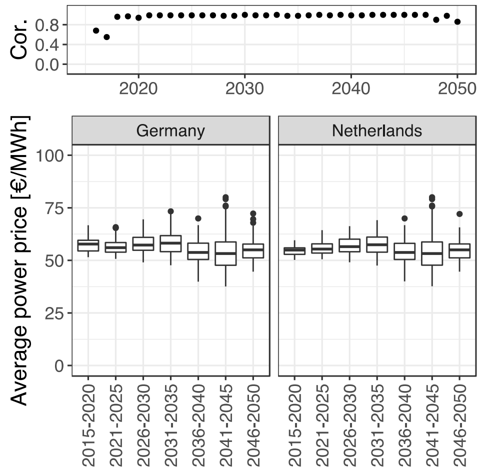

Figure 5: Average power price developments in the auction scenario. Boxplots depict the median and the variation in 5-year intervals over 30 model iterations. “Cor.” denotes the (Pearson’s r) correlation coefficient of the countries’ prices across all iterations.

To judge whether NECP and decarbonisation targets are met following a phase-out of support–a research question of this paper–the auction scenario should represent a realistic and expectable future pathway. This is the case because the auction scenario tracks targets well and is similar to other projections, as explained in the following passage. First, auction-based investments dominate, so the total deployment closely follows the quantity targets of auctions and, consequentially, the target pathways (see Figure 1). Second, the simulated deployments mostly match the absolute NECP targets (square points in Figure 3). Third, the simulated pathways for PV and offshore wind are in line with ambitious decarbonisation pathways, namely the 2040 GCA scenario in Figure 3 [52]. Because of these reasons, the auction scenario simulations are deemed suitable for comparisons with the phase-out scenarios (see next section).

4.2 Phasing out support for renewables

Compared to the auction scenario, the deployment of renewables is slower in most phase-out scenarios, and hence both countries fail their renewables targets (Figure 6a, showing differences in renewable[9] capacity between the auction and phase-out scenarios). The most substantial effects are observed if all support ends in 2025 (Scenario 1): resulting in as much as 61% and 34% less new renewable capacity in Germany[10] and the Netherlands, respectively. Furthermore, average electricity prices increase in the long term by up to 52% if countries expose renewables to the market (Figure 6b); conversely, expanding renewables depresses prices. Due to cross-border effects, such

[9] Results for conventional technologies are reported in Appendix B .
[10] Effects are almost the same in scenarios 1–4 and 5–8, which is expectable: the two groups exhibit the same policy changes, and cross-border effects from smaller countries usually remain small; minor differences are due to variations between iterations.

price changes occur in both countries, and even if only one country ends its support.

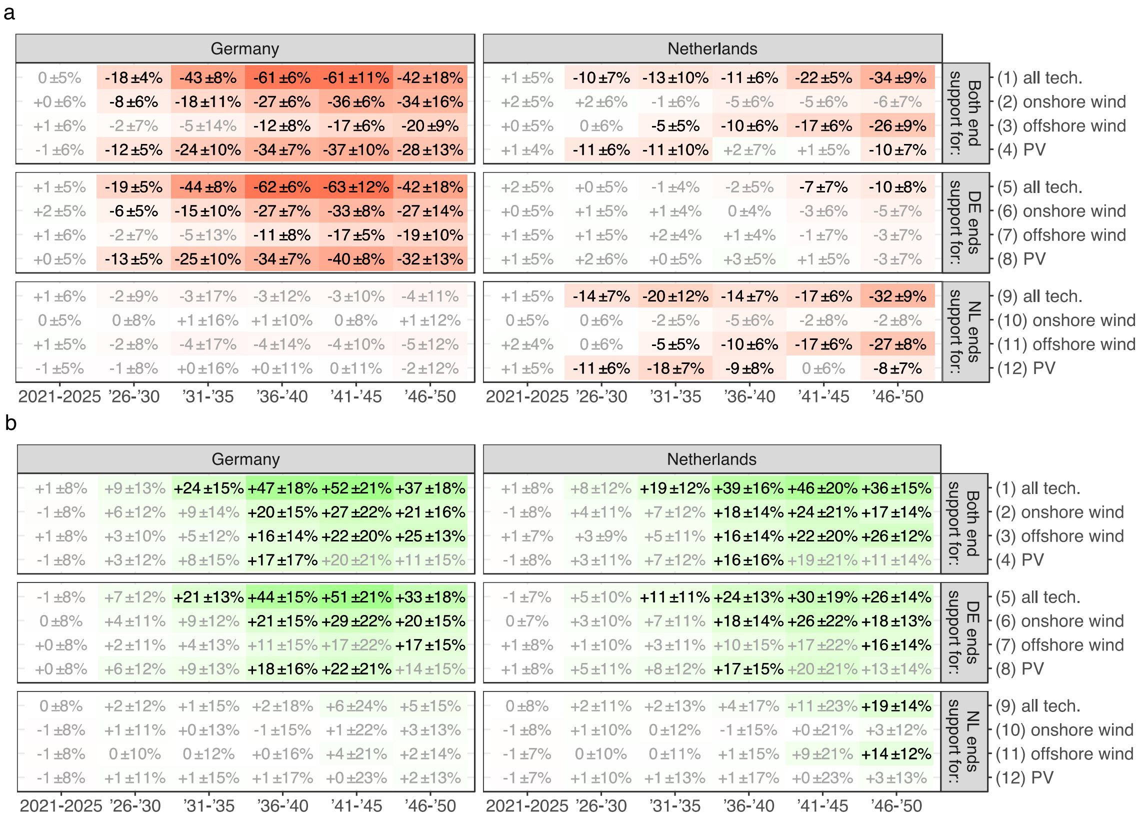

Figure 6: Capacity and price changes in the phase-out scenarios. Figures show percentage changes in (a) renewables capacity and (b) average electricity prices following the phase-out of auctions in 2025. Percentages (±SD) are mean averages over 30 model iterations and depict the differences between the auction scenario and the 12 phase-out scenarios. Darker colours signify stronger effects, and greyed-out numbers are of low significance.

While capacity changes mainly occur in the country that phases out support, scenario 5 is a notable exception: if *solely* Germany ends support for all technologies, cross-border effects cause an increase in Dutch prices and new renewable capacity in the Netherlands declines by 7–10%. This seems counterintuitive, as increasing prices should lead to more investment activity. The observed decline can be explained by a shift from auctions to the free market, and in the Netherlands, the decline in auction-based investment outweighs the increase in the free market (compare Figure 4 to Figure 7). The underlying reason is the (simulated) government's expectation: because of more (expected) free market activity, the quantity targets of auctions are lowered. However, as future developments are uncertain, the required quantity is underestimated, triggering a departure from the target pathway (Section 3.1.4).

Cross-border effects also influence the deployment of renewables if *both* countries phase out support. Prices are 16–19% higher if Germany and the

Netherlands end support for PV, compared to a 1–3% (non-significant) change if only the Netherlands discontinues support (Figure 6b, Scenario 4 vs 12). These higher prices then incentivise 7–9% more investments in the Dutch free market (at least until 2040).

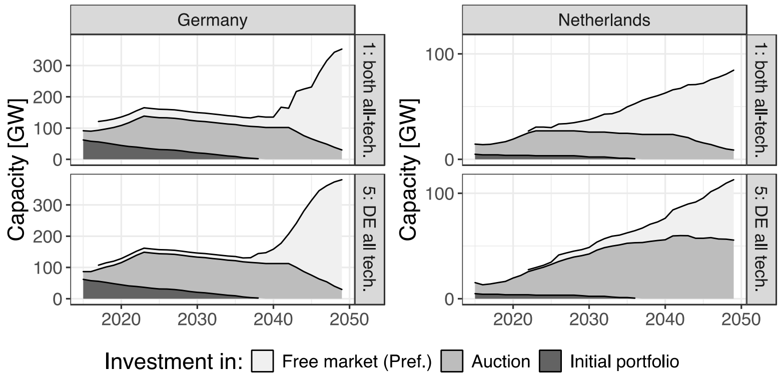

Figure 7: Origin of renewable capacity in scenarios 1 & 5. Pref. = with preference-algorithm. Areas depict averages over 30 model iterations.

Deployment changes occur for all technologies but to varying degrees. For instance, ending support for German offshore wind projects leads to only a 20% decline in new capacity, whereas ending support for Dutch onshore wind and PV projects does not substantially impact growth between 2036–2045 (Figure 6a, Scenarios 2–4). Specifically, the Dutch development suggests a high maturity of onshore wind and PV. Further, these technologies can temporarily compensate for reduced Dutch offshore capacity (Figure 8, Scenarios 1 & 3), while in the other scenarios, supported technologies just continue along their auction trajectories. This compensation is possible due to increased free market activity in the Netherlands, allowing for more technology shifts (**Figure 7**, Scenario 1).

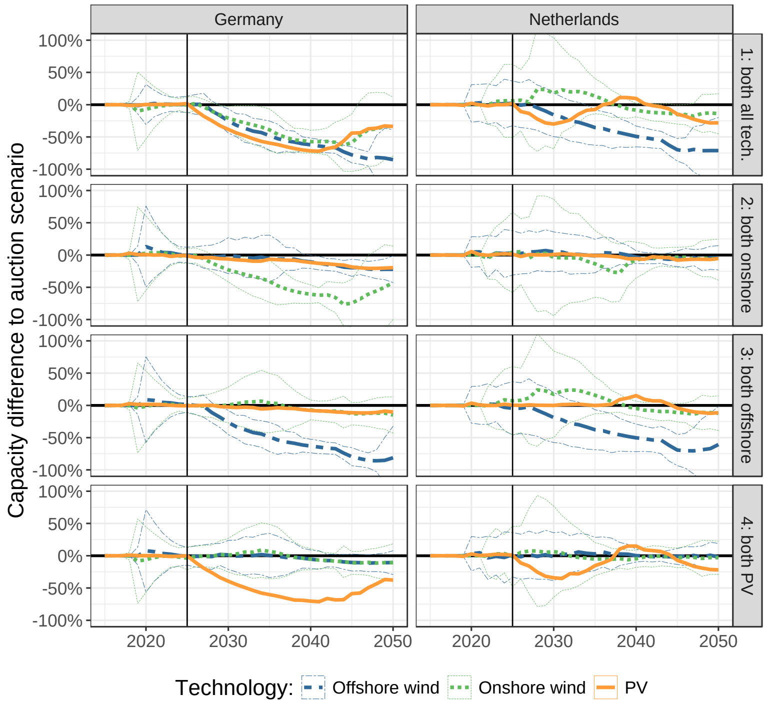

Figure 8: Capacity developments of different technologies. Percentage changes are mean averages over 30 model iterations and depict the differences between the auction scenario and the 4 phase-out scenarios. The vertical line marks the phase-out of auctions in both countries in 2025. Shaded areas depict 95%-CIs.

4.3 Impact of the investment algorithm

The main results in the previous section were simulated using the preference-algorithm. In this section, the development of renewable capacity (Figure 9a) and average electricity prices (Figure 9b) using the original NPV-algorithm is shown. Like in the main results, most targets are missed without support[11], but here, the deployment changes are smaller. This is particularly the case in Germany, whereas results for the Netherlands are very similar with both algorithms unless cross-border effects play a more decisive role (e.g., Scenarios 4 and 5). Smaller deployment changes in Germany also cause fewer domestic/cross-border price effects.

[11] However, the significance of NPV-algorithm results is low, specifically in Germany.

a

	Germany 2021-2025	Germany '26-'30	Germany '31-'35	Germany '36-'40	Germany '41-'45	Germany '46-'50	Netherlands 2021-2025	Netherlands '26-'30	Netherlands '31-'35	Netherlands '36-'40	Netherlands '41-'45	Netherlands '46-'50
Both end support for: (1) all tech.	+2 ±7%	-10 ±11%	-17 ±17%	-19 ±12%	-8 ±14%	-21 ±23%	+0 ±5%	-14 ±9%	-21 ±10%	-17 ±8%	-16 ±5%	-32 ±8%
(2) onshore wind	+2 ±8%	-7 ±14%	-14 ±20%	-15 ±12%	-12 ±16%	-18 ±26%	+1 ±5%	-2 ±7%	-2 ±7%	-4 ±7%	-3 ±7%	-4 ±6%
(3) offshore wind	+1 ±7%	-2 ±14%	-5 ±22%	-5 ±12%	-1 ±15%	-5 ±25%	+1 ±5%	-1 ±6%	-3 ±6%	-10 ±5%	-15 ±5%	-24 ±7%
(4) PV	+3 ±7%	-10 ±11%	-13 ±19%	-9 ±13%	-9 ±16%	-22 ±25%	+1 ±6%	-12 ±6%	-17 ±6%	-9 ±9%	-2 ±7%	-9 ±7%
DE ends support for: (5) all tech.	+2 ±8%	-13 ±12%	-20 ±18%	-16 ±13%	-9 ±17%	-24 ±25%	+0 ±5%	-2 ±6%	+1 ±6%	-1 ±5%	-1 ±7%	-2 ±6%
(6) onshore wind	+4 ±7%	-9 ±12%	-19 ±19%	-16 ±11%	-13 ±15%	-22 ±25%	+0 ±5%	0 ±6%	+1 ±5%	-1 ±4%	-1 ±6%	-2 ±6%
(7) offshore wind	+4 ±7%	-4 ±14%	-7 ±23%	-6 ±12%	-3 ±16%	-12 ±26%	+0 ±5%	0 ±6%	+2 ±5%	+0 ±4%	-1 ±6%	-3 ±6%
(8) PV	+2 ±7%	-11 ±11%	-17 ±19%	-11 ±12%	-6 ±17%	-15 ±26%	+1 ±5%	0 ±5%	-1 ±5%	+1 ±5%	-1 ±6%	-3 ±7%
NL ends support for: (9) all tech.	+3 ±7%	-8 ±14%	-15 ±25%	-8 ±17%	-9 ±18%	-15 ±29%	+0 ±5%	-15 ±7%	-18 ±9%	-12 ±7%	-17 ±6%	-33 ±7%
(10) onshore wind	+2 ±6%	-5 ±13%	-9 ±22%	-4 ±14%	-2 ±18%	-9 ±30%	+0 ±5%	-4 ±6%	-4 ±6%	-4 ±7%	-2 ±8%	-3 ±6%
(11) offshore wind	+3 ±7%	-7 ±14%	-12 ±23%	-6 ±13%	-6 ±16%	-11 ±27%	0 ±5%	-2 ±6%	-3 ±5%	-9 ±5%	-16 ±5%	-26 ±8%
(12) PV	+1 ±7%	-2 ±13%	-1 ±22%	0 ±13%	0 ±18%	-2 ±29%	0 ±5%	-13 ±6%	-17 ±7%	-11 ±10%	-3 ±9%	-8 ±7%

b

	Germany 2021-2025	Germany '26-'30	Germany '31-'35	Germany '36-'40	Germany '41-'45	Germany '46-'50	Netherlands 2021-2025	Netherlands '26-'30	Netherlands '31-'35	Netherlands '36-'40	Netherlands '41-'45	Netherlands '46-'50
Both end support for: (1) all tech.	+1 ±8%	+5 ±12%	+10 ±14%	+18 ±17%	+17 ±25%	+20 ±20%	+1 ±8%	+5 ±11%	+11 ±12%	+19 ±17%	+17 ±25%	+22 ±17%
(2) onshore wind	+0 ±8%	+3 ±12%	+7 ±15%	+11 ±16%	+11 ±26%	+11 ±25%	+0 ±8%	+3 ±10%	+5 ±11%	+10 ±15%	+11 ±26%	+7 ±20%
(3) offshore wind	0 ±9%	+0 ±12%	+2 ±16%	+8 ±17%	+12 ±24%	+11 ±21%	-1 ±8%	+0 ±10%	+2 ±13%	+8 ±16%	+14 ±24%	+14 ±16%
(4) PV	-2 ±9%	+3 ±11%	+7 ±15%	+7 ±18%	+10 ±28%	+15 ±23%	-2 ±8%	+3 ±10%	+6 ±12%	+7 ±17%	+9 ±27%	+13 ±20%
DE ends support for: (5) all tech.	0 ±8%	+4 ±11%	+9 ±14%	+13 ±16%	+13 ±27%	+18 ±27%	0 ±8%	+3 ±9%	+5 ±10%	+11 ±15%	+12 ±26%	+13 ±19%
(6) onshore wind	0 ±8%	+4 ±12%	+8 ±15%	+11 ±16%	+13 ±27%	+12 ±22%	0 ±7%	+3 ±10%	+4 ±11%	+10 ±15%	+12 ±26%	+9 ±19%
(7) offshore wind	+2 ±8%	+4 ±11%	+6 ±14%	+8 ±16%	+10 ±25%	+11 ±24%	+2 ±8%	+4 ±10%	+4 ±11%	+7 ±15%	+10 ±25%	+8 ±19%
(8) PV	+0 ±8%	+3 ±10%	+4 ±13%	+4 ±18%	+3 ±26%	+6 ±22%	+0 ±7%	+2 ±9%	+3 ±11%	+3 ±17%	+3 ±26%	+4 ±18%
NL ends support for: (9) all tech.	-2 ±8%	+3 ±11%	+6 ±15%	+6 ±18%	+14 ±27%	+14 ±25%	-1 ±7%	+4 ±10%	+6 ±12%	+7 ±17%	+17 ±26%	+21 ±17%
(10) onshore wind	+1 ±8%	+2 ±11%	+4 ±15%	+4 ±18%	+4 ±26%	+5 ±20%	+1 ±8%	+2 ±10%	+3 ±11%	+3 ±17%	+4 ±26%	+4 ±18%
(11) offshore wind	-2 ±8%	+1 ±12%	+4 ±15%	+5 ±18%	+10 ±26%	+11 ±23%	-2 ±7%	+0 ±10%	+3 ±12%	+6 ±17%	+12 ±26%	+17 ±18%
(12) PV	+1 ±8%	+3 ±12%	+5 ±16%	+2 ±19%	+4 ±27%	+4 ±20%	+0 ±8%	+3 ±11%	+4 ±13%	+3 ±18%	+4 ±27%	+4 ±19%

Figure 9: Capacity and price changes using the alternative NPV-algorithm. Figures show percentage changes in (a) renewables capacity and (b) average electricity prices following the phase-out of auctions in 2025. Percentages (±SD) are mean averages over 30 model iterations and depict the differences between the auction scenario and the 12 phase-out scenarios. Darker colours signify stronger effects, and greyed-out numbers are of low significance.

The differences found between the algorithms are rooted in the preferences used and in the remapping function of the preference-algorithm. First, technology preferences affect the evaluation of projects and change the technology mix, e.g., onshore versus offshore wind projects of medium investors in Germany (**Figure 10**). Preferences also change the ratio between PV and onshore wind projects, e.g., in small, large, and very large investors with higher preferences for PV. Second, the mapping of simulated to actual ROEs (see Section 3.1.3) limits high return values and leads to fewer (seemingly) profitable projects. In EMLab, this can occur in early simulation years when producers expect too many hours of lost load, and hence, high returns[12].

Finally, there are similarities between the algorithms: both represent the actual competitiveness of PV and onshore wind adequately. These are the

[12] This can be an issue if balancing capacity from a small market is limited.

most mature and deployed technologies in algorithms and reality. In summary, taking away support is risky regardless of the applied algorithm, but more so for Germany than for the Netherlands.

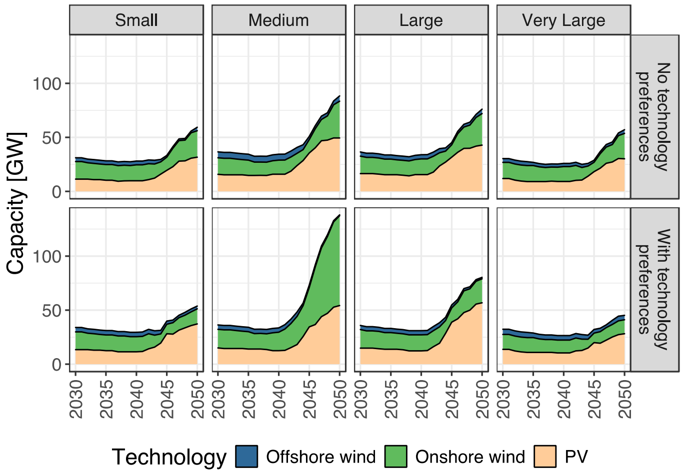

Figure 10: Impact of preferences on technology mixes. The figure depicts the capacity development in Germany and in scenario 1 without (top row) and with preferences (bottom row). Columns are different types of renewables-investors. Colours are different technologies. Areas are mean averages over 30 model iterations.

4.4 Model sensitivity for risks, initial capital, and carbon prices

Sensitivity analyses are performed for risks, carbon prices and the initial capital. These parameters are varied in both the auction and phase-out scenarios. The differences between these adjusted scenarios are then compared to the differences depicted throughout the previous two sections. Overall, the model is sensitive to risks.

First, risk represented by the discount rate, here WACC, differs between investors and changes over time, and thus, it is an important parameter to consider for the correct interpretation of our results. An adjusted WACC for renewables-investors leads to a parameter sensitivity in the Netherlands and Germany (Figure 11). With higher risks, reaching targets becomes harder, i.e., less new renewable capacity is deployed in later years.

	Germany						Netherlands					
1: both all tech.	2021-2025	'26-'30	'31-'35	'36-'40	'41-'45	'46-'50	2021-2025	'26-'30	'31-'35	'36-'40	'41-'45	'46-'50
5% WACC	+1 ±10%	0 ±6%	+3 ±14%	+17 ±17%	+39 ±20%	+28 ±24%	-2 ±11%	+14 ±12%	+15 ±13%	+5 ±8%	+10 ±11%	+41 ±14%
8% WACC	0 ±8%	+1 ±9%	+2 ±17%	+2 ±12%	+12 ±20%	+9 ±26%	-2 ±7%	+5 ±12%	+12 ±13%	+5 ±9%	+1 ±8%	+13 ±15%
12% WACC	+0 ±7%	+0 ±10%	+0 ±16%	-1 ±10%	-7 ±15%	-14 ±28%	-3 ±7%	+3 ±16%	+13 ±14%	+3 ±8%	+4 ±8%	+11 ±13%
15% WACC	-2 ±6%	-3 ±9%	-2 ±14%	-3 ±10%	-12 ±14%	-19 ±29%	+0 ±9%	+1 ±13%	+8 ±16%	+2 ±7%	+5 ±10%	+3 ±12%

Figure 11: Model sensitivity of WACCs. The figure shows percentage changes of renewable capacity in scenario 1 if WACCs are 5%, 8%, 12% or 15 % and auctions are phased out in 2025. Percentages (±SD) are mean averages over 30 model iterations and depict the differences between the auction scenario and the adjusted scenarios. Darker colours signify stronger effects, and greyed-out numbers are of low significance.

Second, initial capital levels of single investors in a country have no considerable effects on investments (see Appendix C), even if the German renewables-investors' initial capital is varied by ±25%. To avoid potential interaction effects, only the capital of a single investor type was adjusted. Finally, carbon prices do not considerably affect capacity, even if the baseline increase of €1.50 per year is varied by ±10% and ±20% (see Appendix C). While higher carbon prices do translate into decreased deployment, these effects are less significant.

5 Discussion and conclusion

This paper first investigated how the phase-out of support for renewables in Germany and the Netherlands affects capacity pathways and average electricity prices. In a second step, the role of cross-border effects following these phase-outs was explored. In conclusion, continued support is needed to reach national targets, and policy changes in a large country like Germany affect its own energy transition and the development in the neighbouring Netherlands, even if Dutch policymakers maintain support. Two findings from our simulations and their underlying mechanisms support this conclusion.

First, phasing out support in Germany slows down its deployment of new renewables by 61%, while a phase-out in the Netherlands reduces new capacity by up to 34%. The reason is that most investors, acting according to their financial and technological preferences, will not find appealing investment opportunities in the free market if support ends, and thus, require continued support. Investments in onshore wind and photovoltaics in the Netherlands are exceptions: these technologies are deployed without support but to a lesser extent than under support. The primary driver[13] of the decline in investment activity following the phase-out of support is each investor's low-income expectation. This makes sense because renewables depress prices precisely when they produce most: this cannibalisation effect is in line with previous research findings [62,63,64].

Second, phasing out support in Germany affects average electricity prices in both countries. The observed price-increase leads to higher activity in the free markets. The advantage is that some investments in the Dutch market become more lucrative, notably photovoltaics. However, the increased market activity is insufficient to compensate for the reduced amount of tendered capacity if governments underestimate future support needs. The primary requirement for these cross-border price effects is a sufficiently large power interconnection between the two countries.

5.1 Policy contribution

Our findings are relevant for Dutch and German policymakers specifically, and more generally, for policymakers in similar countries with interconnected markets[14]. If these countries wish to reach their national decarbonisation targets, continued support beyond 2025 is essential for most technologies and in most years. In Germany and the Netherlands, this particularly applies to photovoltaics and onshore wind, which contribute over 80% to their targets. Although the generation cost developments of these technologies suggest cost competitiveness with conventional power generation, it may be risky to focus the political discourse on this single factor. Other factors that affect income

[13] Costs and risks are other potential drivers. However, we keep them constant between auction and phase-out scenarios, thus they cannot be drivers of differences.
[14] Similar in respect to size and power system as discussed in Section 5.3.

must be considered, notably cannibalisation and cross-border effects because both depress free market revenues when renewables expand. Conversely, a phase-out of support in Germany increases prices, and therefore, the market competitiveness of photovoltaics in the Netherlands.

If policymakers from countries like Germany decide to phase out support, policymakers from the smaller country, here the Netherlands, must consider the side-effects on electricity prices, investment structure and deployment. We suggest that governments communicate policy changes well in advance to coordinate their reform plans and consider both the negative and positive spillover effects. As Germany and the Netherlands are interconnected with further states, interactions may even be more complex in reality. Therefore, we recommend developing a shared European vision for tackling the challenges of support policy changes and reducing costly deployment delays.

5.2 Methodological contribution

We have developed a new decision algorithm to better consider the heterogeneity of agents and match modelled returns to the empirical context. The addition of technology and return preferences, as well as the mapping of simulated to observed returns alters results and pathways. Hence, financial and behavioural assumptions in investment algorithms strongly influence simulation results, confirming the importance of reporting and reflecting on such assumptions in energy policy analyses. Our work is particularly relevant for agent-based models because their system behaviours and side-effects emerge from heterogeneous and myopic decisions [39].

While our qualitative result—that it is not feasible to fully phase out support in 2025 *and* reach all targets—was also found with the original algorithm, the new algorithm delivers empirically grounded and quantitatively refined results. Namely, it leads to a larger variation between the investors' portfolios and causes stronger effects following a policy change. Although gathering accurate and appropriate preference and return data may be time-intensive, there are clear effects on results. Hence, these social parameters add additional value to similar studies.

5.3 Limitations and outlook

Our study comes with some limitations, leaving opportunities for future research. First, auctions are designed without barriers[15]. This assumption allows most (renewables-)investors to participate in all auctions and maximises auction subscription. Therefore, our results are valid in a context where auctions have a high subscription status. While this is fundamental for auctions to work well, not all auctions in Germany and the Netherlands have been fully subscribed in the past, e.g., onshore wind auctions in Germany due to administrative barriers.

[15] Like pre-qualification criteria, geographical constraints, or societal resistance.

Second, the deployment of renewables is not explicitly limited with country-specific potentials. Nonetheless, technology potentials are indirectly considered through the quantity targets of auctions. These are based on actual national targets and have been shown to be physically possible by the underlying studies. As our deployment results hardly exceed these targets, this omission is very unlikely to affect our findings.

Third, investments are only possible within an investor's domicile. However, if policies change in different countries at different times, investors might shift their activity to other countries, as shown by previous research [6]. Future extensions of agent-based models like EMLab should thus add options for cross-border investments and incorporate investors' country preferences. For this, multiple large and independent markets outside the home market are needed to provide sufficient investment opportunities and avoid a bias towards the home market.

Finally, future policy changes may affect our results. Germany and the Netherlands could introduce phase-out policies for conventional technologies like gas, coal, and oil power, and they may decide to support deploying carbon-neutral flexibility and storage options. Such technologies will then affect general electricity prices through the merit order. However, our finding—phasing out support increases domestic/cross-border prices—will likely remain valid because both gas-powered generation and carbon-neutral flexibility options are expensive and increase prices [65,66].

While this paper has focused on the case of investors, policy changes and the deployment of renewables in Germany and the Netherlands, our methodological contribution is valid for any country context if behaviour and financial data are available. We also expect that our policy contribution is valid for other case studies, at least qualitatively[16]. First, the need to continue support in different countries has been recognised by other studies [5]. Second, fundamental elements of the electricity system are similar in many countries. Although technology and policy mixes vary, the effects of renewables on domestic/cross-border prices, the increasing technological maturity and the need for stringent targets are often similar. Examples of interconnected markets of differing size, similar to our case, are Spain & Portugal, France & Belgium or Brazil & Bolivia. With the increasing interconnection of electricity grids worldwide, good policy coordination is important for any country to expand renewables efficiently and effectively in their energy systems.

While we suggest keeping most support to reach overarching targets, policymakers may rank cost-effectiveness considerations higher than the deployment speed, stronger integrate renewables in the market and eventually abandon support completely. Therefore, we also encourage researchers and

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[16] To derive country-specific results using our model, it is simple to adjust power plant portfolios, targets, demand and return values (for the decision algorithm). Moreover, investment behaviours in countries tend to resemble each other (see Section 3.2.3) unless socio-economic factors and risks differ strongly from the German context.

policymakers to explore how support can become more market-based or be abandoned without jeopardising cost-effectiveness or deployment targets.

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Appendix A Technology and trend assumptions

Technology assumptions including lifetime, capacities, running hours and viability for investment are depicted in Table 6. Assumptions for demand and fuel price variations are depicted in Table 7.

Table 6: Technology assumptions. The bottom four renewable technologies are only available for renewables-investors. Column "viable investment" indicates if investors can invest in new capacity of this type after 2015.

Technology	Lifetime	Capacity of one plant in model	Minimal running hours	Viable investment
available to incumbent-investors only				
Hard coal	40 y	750 MW	5000 h	No
Lignite	40 y	1000 MW	5000 h	No
Biomass	30 y	500 MW	0 h	Yes
Gas (CCGT)	30 y	775 MW	0 h	Yes
Gas (OCGT)	30 y	150 MW	0 h	Yes
Fuel oil	30 y	50 MW	0 h	Yes
Nuclear	40 y	1000 MW	5000 h	No
Hydro	50 y	250 MW	0 h	No
available to renewables-investors only				
PV	25 y	500 MW	0 h	Yes
Onshore wind	25 y	600 MW	0 h	Yes
Offshore wind	25 y	600 MW	0 h	Yes

Table 7: Demand and fuel price start values and growth trends per year. Shown are the most relevant fuels. Converted to MWh from typical energy units used in the model.

	Start value	Minimum growth	Expected growth	Maximum growth
Demand DE	N/A	0.99	1.00	1.05
Demand NL	N/A	0.98	1.02	1.03
Fuel oil price	56.9 €/MWh	0.96	1.01	1.04
Hard coal price	7.4 €/MWh	0.97	1.00	1.04
Natural gas price	36.3 €/MWh	0.95	1.01	1.06

Appendix B Additional results

As shown in **Figure 12**, differences in *conventional* technologies in the phase-out scenarios are negligible and of low significance (all numbers are greyed-out numbers due to low significance). Hence, these numbers are not reported in the text.

	Germany						Netherlands						
	2021-2025	'26-'30	'31-'35	'36-'40	'41-'45	'46-'50	2021-2025	'26-'30	'31-'35	'36-'40	'41-'45	'46-'50	
Both end support for:	+1 ±7%	+0 ±9%	0 ±9%	+1 ±10%	+1 ±11%	+5 ±16%	+1 ±3%	+2 ±5%	+1 ±8%	+0 ±9%	+1 ±9%	+5 ±11%	(1) all tech.
	+0 ±7%	-2 ±9%	-1 ±10%	0 ±12%	+1 ±12%	+4 ±15%	0 ±3%	-1 ±6%	+1 ±7%	-1 ±8%	-2 ±8%	-1 ±10%	(2) onshore wind
	+2 ±8%	+0 ±10%	+1 ±10%	0 ±11%	+1 ±12%	+4 ±15%	+1 ±3%	+1 ±6%	+0 ±7%	+0 ±8%	+2 ±9%	+2 ±10%	(3) offshore wind
	+0 ±8%	-1 ±10%	-2 ±10%	-2 ±12%	-1 ±12%	-1 ±13%	+1 ±3%	+1 ±6%	0 ±8%	+1 ±8%	0 ±9%	+0 ±12%	(4) PV
DE ends support for:	+1 ±7%	-1 ±10%	0 ±11%	+4 ±12%	+3 ±11%	+5 ±16%	+1 ±3%	0 ±5%	-1 ±7%	-2 ±8%	-3 ±10%	-1 ±12%	(5) all tech.
	+2 ±7%	0 ±10%	+2 ±10%	+3 ±11%	+3 ±10%	+3 ±15%	+1 ±3%	-1 ±6%	0 ±7%	-1 ±8%	-1 ±10%	+1 ±12%	(6) onshore wind
	+1 ±8%	-2 ±10%	0 ±10%	+0 ±11%	+2 ±11%	+4 ±15%	+0 ±3%	+1 ±6%	+0 ±7%	0 ±8%	0 ±9%	+1 ±10%	(7) offshore wind
	-1 ±6%	-3 ±10%	-1 ±9%	-2 ±12%	0 ±13%	+3 ±16%	+0 ±3%	+1 ±5%	+1 ±7%	+0 ±9%	-1 ±9%	+0 ±11%	(8) PV
NL ends support for:	+2 ±8%	-1 ±10%	-2 ±10%	-2 ±12%	0 ±13%	+1 ±16%	+1 ±3%	-1 ±6%	0 ±7%	-1 ±8%	+0 ±9%	+2 ±13%	(9) all tech.
	+0 ±7%	+1 ±9%	+1 ±10%	-1 ±11%	-2 ±11%	-2 ±14%	+1 ±3%	+1 ±6%	+2 ±7%	+0 ±7%	0 ±9%	0 ±12%	(10) onshore wind
	+1 ±8%	+1 ±11%	0 ±10%	-1 ±12%	-1 ±12%	-2 ±15%	+1 ±3%	+1 ±6%	+1 ±7%	+1 ±8%	+1 ±10%	+2 ±12%	(11) offshore wind
	-1 ±7%	-1 ±9%	-1 ±10%	-2 ±12%	-2 ±12%	0 ±15%	+0 ±2%	+1 ±5%	+1 ±7%	0 ±8%	0 ±10%	0 ±13%	(12) PV

Figure 12: Conventional capacity changes. The figure shows percentage changes in conventional capacity following the phase-out of auctions in 2025. Percentages (±SD) are mean averages over 30 model iterations and depict the differences between the auction scenario and the 12 phase-out scenarios. Darker colours signify stronger effects, and greyed-out numbers are of low significance.

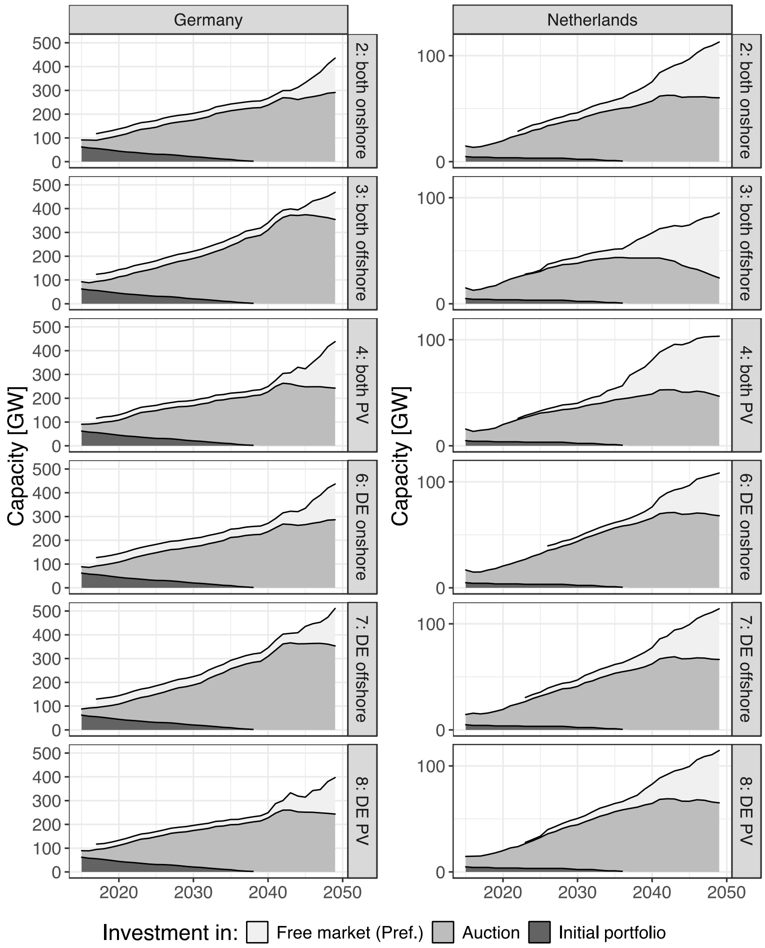

Figure 13: Origin of renewable capacity in different scenarios. Pref. = with preference-algorithm. Areas depict averages over 30 iterations.

Appendix C Results of sensitivity analyses

Figure **14** and

Figure **15** show sensitivity analyses for the initial capital and carbon prices, respectively. Both figures depict differences to the unadjusted scenario results in Section 4.2 (these are not differences to the auction scenarios). In both figures, all numbers are greyed-out numbers due to low significance.

a

	Germany 2021-2025	Germany '26-'30	Germany '31-'35	Germany '36-'40	Germany '41-'45	Germany '46-'50	Netherlands 2021-2025	Netherlands '26-'30	Netherlands '31-'35	Netherlands '36-'40	Netherlands '41-'45	Netherlands '46-'50
Both end support for: (1) all tech.	-1 ±7%	-2 ±6%	-2 ±13%	-1 ±10%	0 ±18%	+0 ±27%	-1 ±6%	-3 ±10%	-4 ±16%	-3 ±8%	-1 ±8%	+1 ±13%
Both end support for: (2) onshore wind	0 ±9%	+2 ±8%	+0 ±15%	0 ±10%	+1 ±9%	+3 ±22%	-1 ±6%	-3 ±9%	-2 ±9%	-1 ±8%	-2 ±9%	+2 ±10%
Both end support for: (3) offshore wind	-1 ±8%	+1 ±9%	+0 ±18%	0 ±11%	+0 ±8%	+1 ±14%	+0 ±6%	+0 ±9%	-1 ±8%	-1 ±8%	0 ±9%	+2 ±12%
Both end support for: (4) PV	+1 ±9%	+0 ±7%	-1 ±14%	-1 ±10%	-1 ±13%	+0 ±20%	-2 ±6%	+1 ±9%	+1 ±16%	-3 ±11%	-3 ±7%	+2 ±9%
DE ends support for: (5) all tech.	-1 ±8%	0 ±7%	-1 ±13%	+0 ±10%	+1 ±17%	+3 ±24%	-1 ±6%	+1 ±8%	0 ±6%	+0 ±7%	-1 ±8%	+4 ±10%
DE ends support for: (6) onshore wind	-2 ±8%	0 ±7%	-2 ±14%	-1 ±10%	-1 ±10%	-2 ±21%	-2 ±6%	-1 ±7%	-1 ±6%	-1 ±6%	-1 ±9%	+3 ±9%
DE ends support for: (7) offshore wind	-1 ±9%	+1 ±8%	+0 ±16%	-1 ±11%	+1 ±8%	+1 ±15%	0 ±6%	+0 ±7%	-1 ±6%	-2 ±7%	-1 ±9%	+2 ±9%
DE ends support for: (8) PV	-1 ±8%	+0 ±7%	+0 ±14%	+0 ±10%	0 ±11%	+4 ±20%	-1 ±7%	-1 ±8%	-1 ±7%	-1 ±7%	-2 ±7%	+2 ±9%

b

	Germany 2021-2025	Germany '26-'30	Germany '31-'35	Germany '36-'40	Germany '41-'45	Germany '46-'50	Netherlands 2021-2025	Netherlands '26-'30	Netherlands '31-'35	Netherlands '36-'40	Netherlands '41-'45	Netherlands '46-'50
Both end support for: (1) all tech.	-1 ±7%	+5 ±14%	+5 ±19%	0 ±11%	+1 ±20%	+3 ±26%	-1 ±7%	-3 ±9%	-5 ±14%	-1 ±9%	+1 ±8%	0 ±12%
Both end support for: (2) onshore wind	+1 ±8%	+5 ±18%	+6 ±26%	+4 ±13%	+3 ±11%	+7 ±23%	-2 ±7%	-3 ±8%	-3 ±8%	+0 ±9%	+1 ±9%	+1 ±9%
Both end support for: (3) offshore wind	-1 ±8%	0 ±20%	+3 ±31%	+4 ±16%	+3 ±11%	+4 ±17%	-1 ±7%	+1 ±8%	+0 ±7%	+1 ±8%	+1 ±9%	+1 ±11%
Both end support for: (4) PV	+2 ±8%	+4 ±16%	+3 ±24%	+1 ±15%	+2 ±15%	+1 ±21%	0 ±6%	+1 ±8%	-2 ±14%	-3 ±11%	+1 ±8%	+1 ±9%
DE ends support for: (5) all tech.	-1 ±8%	+7 ±16%	+6 ±20%	+1 ±12%	+1 ±21%	0 ±28%	-2 ±7%	-1 ±8%	+0 ±6%	0 ±8%	+1 ±9%	+1 ±10%
DE ends support for: (6) onshore wind	-2 ±8%	+6 ±17%	+9 ±23%	+4 ±13%	+4 ±14%	+1 ±24%	-1 ±7%	-1 ±8%	-1 ±5%	0 ±6%	+1 ±9%	+3 ±9%
DE ends support for: (7) offshore wind	0 ±9%	+2 ±18%	+4 ±29%	+4 ±15%	+4 ±11%	+5 ±16%	-1 ±7%	+0 ±7%	-2 ±6%	-2 ±6%	+0 ±9%	+2 ±9%
DE ends support for: (8) PV	+0 ±8%	+5 ±15%	+5 ±23%	+3 ±13%	+2 ±13%	+3 ±20%	-2 ±7%	-1 ±8%	-1 ±7%	+1 ±7%	+1 ±8%	0 ±8%

Figure 14: Sensitivity of renewables-investors' initial capital if it is (a) high (€30 billion) or (b) low (€18 billion). Percentages (±SDs) depict the average differences of sensitivity scenarios to the main scenario results (with €24 billion initial capital). Darker colours signify stronger effects, and greyed-out numbers are of low significance.

1: both all tech.	Germany 2021-2025	Germany '26-'30	Germany '31-'35	Germany '36-'40	Germany '41-'45	Germany '46-'50	Netherlands 2021-2025	Netherlands '26-'30	Netherlands '31-'35	Netherlands '36-'40	Netherlands '41-'45	Netherlands '46-'50
CO2-price -20%	+1 ±8%	+1 ±9%	+0 ±16%	0 ±11%	-3 ±18%	-13 ±27%	-1 ±7%	-1 ±10%	-2 ±15%	-1 ±8%	+1 ±8%	-3 ±12%
CO2-price -10%	+2 ±7%	-2 ±6%	-3 ±12%	-1 ±9%	0 ±19%	-8 ±28%	-1 ±8%	-3 ±10%	-3 ±15%	-2 ±8%	+0 ±8%	-2 ±12%
CO2-price +10%	-2 ±7%	0 ±10%	+1 ±18%	+1 ±13%	+4 ±20%	+7 ±27%	-3 ±7%	-2 ±10%	-2 ±16%	-1 ±9%	+1 ±7%	+3 ±13%
CO2-price +20%	0 ±7%	-1 ±10%	0 ±19%	0 ±15%	+6 ±24%	+6 ±27%	0 ±6%	-2 ±9%	+2 ±14%	-2 ±9%	0 ±7%	+2 ±12%

Figure 15: Sensitivity of carbon prices. The figure shows percentage changes of renewable capacity in scenario 1 if carbon prices vary upwards and downwards by 10 or 20 percentage points and auctions are phased out in 2025. Percentages (±SD) are mean averages over 30 model iterations and depict the differences between the auction scenario and the adjusted scenarios. Darker colours signify stronger effects, and greyed-out numbers are of low significance.

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