

Research paper

Beyond LCOE – Economic performance of renewable auctions

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ABSTRACT

This study analyses how different types of remuneration schemes in renewable auctions can lead to economically efficient or inefficient outcomes in technology-specific and multi-technology settings. The main metric in this assessment is the Extended Support Need (ESN) indicator – defined as the balance between social costs and benefits of variable renewable energy source (vRES) technologies – incorporating not only the costs of vRES development through their LCOE values but also their market benefits for society measured by the market value of these technologies. Depending on the level of the ESN and the technology set-up, the analysed three remuneration schemes (one-sided, two-sided or fixed premium scheme) perform very differently from an economic efficiency point of view. In the negative ESN range (meaning technologies require support) fixed premium schemes are the most advantageous, but in case of positive ESNs two-sided schemes may outperform the others. However, sliding premium systems may present technology selection bias in a multi-technology setup applied in many EU countries, meaning that suboptimal technology is selected in the auction. The findings show that fixed premium schemes should be the preferred option if adjusted to accommodate positive ESN projects by introducing the option of negative bids.

1. Introduction

This paper analyses how renewable technologies are selected in three widely applied RES auction remuneration schemes; fixed premium, one-sided and two-sided premiums also known as Contract for Differences (CfDs) and under varying market conditions: declining leveled cost of electricity (LCOE), increasing variable renewable energy source (vRES) deployment, and rising wholesale prices. The main interest of the research is to determine which remuneration design leads to the selection of economically optimal renewable technologies. This takes into account the technology bias of the three auction designs under a multi-technology setup and also assesses how these schemes perform in an environment where technologies no longer require support. The technology bias means that specific auction designs tend to prefer certain technologies in their selection procedure, even though the selected technology is not economically optimal. The analysis focuses on the following two interlinked problems. The modelling-based assessment checks whether the most widely applied renewable support design in the EU – the two-sided premium scheme (CfD) – is the most efficient design of the auctions in economic terms. Second, it analyses whether multi-

technology auctions – in which PV and wind technologies compete in the same auction – result in an economically efficient outcome. These are important auction design questions, as other design options (e.g., fixed premium and technology-specific auctions) could correct the resulting bias in auctions. Renewable auctions are expected to gain higher importance in the future, either as government or corporate auctions resulting in long-term Power Purchasing Agreements (PPAs). As PPAs create a long-term commitment for the participants, which could extend to 15–20 years, it is important to select the auction design that uses public or corporate financing in the most efficient way. Our results demonstrate that specific auction designs will be efficient in case of PV and wind technologies in the various EU member states, and the results also show that multi-technology auctions can result in technology selection bias in many countries. Technology bias, measured by the Unit Social Value (USV) indicator, as introduced by Diallo and Kitzing (2020), reflects the difference between the social benefits of a technology (market price + external benefits) and its social costs (individual costs + external costs) per unit of electricity generated. Comparing unit social costs with bid prices at an auction reveals the technology bias, as, in an ideal world, bid prices should reflect the social value difference

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between two technologies.

Our study applies the above-mentioned USV concept in a simplified manner. Our indicator - called Extended Support Need ESN - is calculated as the market value of the RES technology subtracting its LCOE, so it is not a full social value indicator as we disregard externality costs and benefits. We omit externalities for two reasons. First, because we compare only wind and PV technologies, not conventional ones (such as lignite, coal, and gas-fired plants), therefore the difference in externalities between these two technologies is much smaller. Samadi (2017) estimated the externality cost for PV and onshore wind generation to be 0.3–0.6 ¢cents/KWh for both technologies compared to the 10.4 ¢cents/KWh value of lignite generation in Europe. Second, the externality values in the literature exhibit substantial variation. Sovacool et al. (2021) analysed 83 studies on externalities of power generation technologies and come up with estimates in a range of 0.007–42 ¢cent/KWh for wind and 0.08–74 ¢cent/KWh for PV technologies, depending on the methodology of the study. Such a high range shows that incorporating externalities in the USV calculation is a difficult task and brings high uncertainties to the indicator. Although ESN is a more simplified measure than the USV value applied in (Diallo and Kitzing, 2020), the resulting indicator is still suitable for capturing the technology bias across different EU countries and avoiding the high uncertainties of the externality values.

The following example illustrates the logic of ESN.

In Country-B there is a higher PV deployment, reducing the Market value of PV, while in country-A PV still produces in high price hours (e.g. increased cooling demand hours) and its market value remains higher. This is reflected in the difference in ESN, as illustrated by the last columns in Figs. 1-2.

The novelty of this paper lies in being the first to quantify technology bias and selection distortions in RES auctions using actual country-specific data from the EU. It is also novel in presenting that technology bias can occur even in a higher carbon pricing environment and stronger deployment of storage technologies, two prevailing tendencies with the increasing RES targets of the EU.

The paper focuses on two technologies, PV and onshore wind, as they

are the ones that, based on existing auction experience, are competitive in a multi-technology auction without any further measures (such as technology quotas). The assessment also considers the issue of price cannibalisation, a process by which PV technology (and to smaller extent wind) reduces the price of electricity during main production hours, leading to lower market values for vRES, which reduces the profitability of these technologies.

The power market unit commitment model (EPMM) is applied for the assessment, where the performance of the auctions is analysed under technology-specific and multi-technology designs. A sensitivity assessment is also carried out to evaluate the effects of higher carbon prices and higher levels of storage technology, and different risk levels associated with the three remuneration schemes in future energy markets of Europe. Future renewable deployment in energy markets is based on National Energy and Climate Plans (NECPs). It is assumed that the 2030 target set by the countries will be met in the case of PV, while for wind capacities in most of the countries, only 80% of the target will be reached, taking into consideration the past 3–4 years' trends in wind deployment. The following subsections review the literature on the economic assessments of the various auction design schemes and the impacts of the cannibalisation effect.

2. Review of RES support scheme designs, financing and applications

2.1. Support scheme design (FiT, FiP, CfD)

Well-designed renewable support schemes should reduce the financing costs for RES developers and prices to consumers while minimizing overall integration costs for the power system. Auctions have the potential to deliver these benefits effectively and are used quite extensively. More than 130 countries used renewable energy auctions in 2022, enabling the achievement of RES targets in a cost-efficient manner (CESEC, 2021). Global awarded capacity reached 160 MW in 2023, out of the overall RES power capacity installation of 484 GW, meaning that one-third of the capacity is procured in this way (IEA, 2025; EMBER,

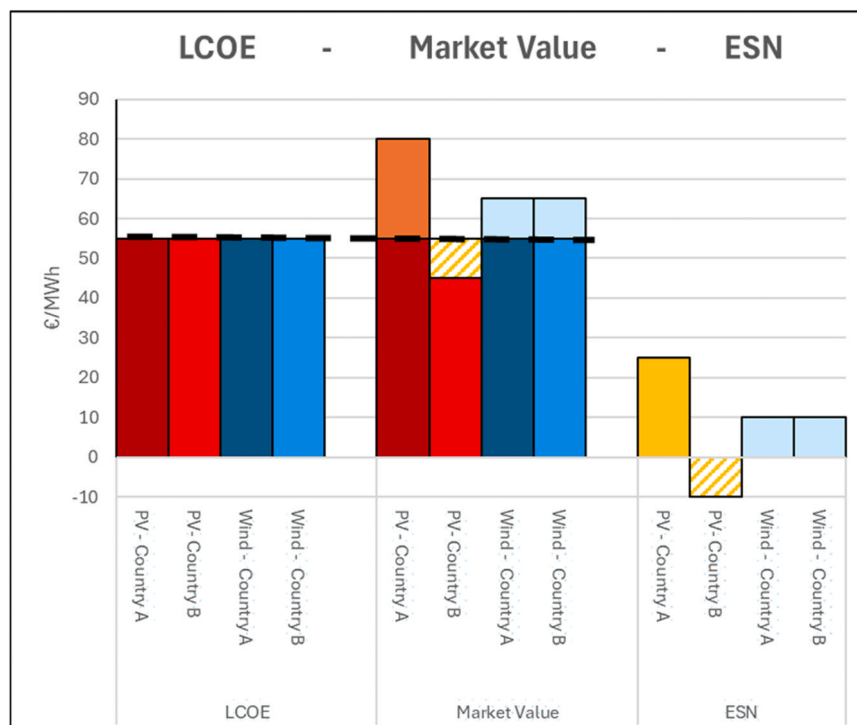


Fig. 1. Calculating ESN in a hypothetical multi-technology auction.

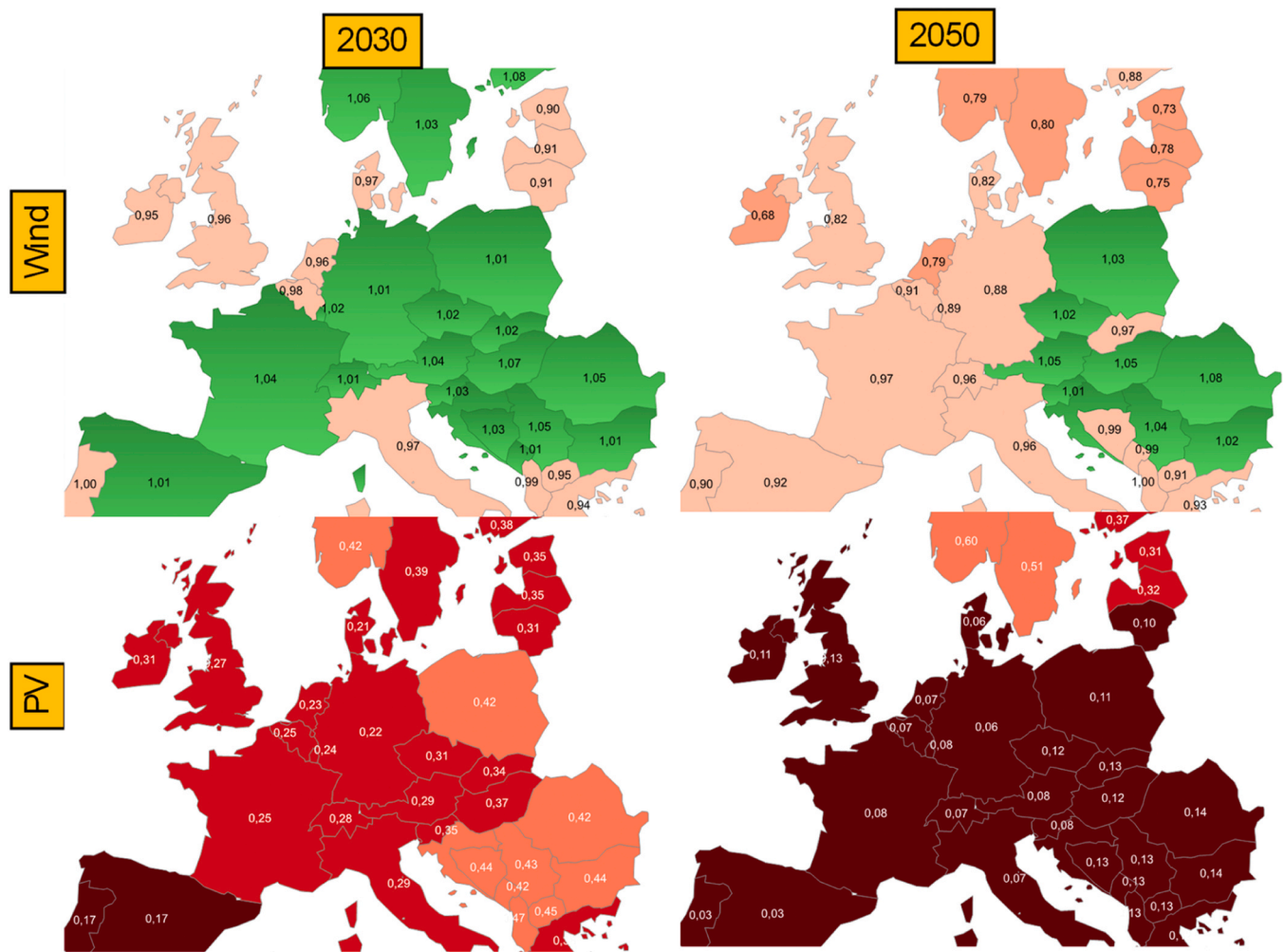


Fig. 2. PV (bottom) and wind (upper) market value compared to the baseload price in 2030 and 2050 in EU countries, %. Source: Own calculation based on EPMM modelling.

2026). The EU and India had a share of 40–40 GW out of this auction quantity, while the Rest of the World had 40 GW. In China, India, and Europe, auctions accounted for more than 50% of the overall RES capacity procurement over the last three years, whereas in other regions (Africa, the Americas, and other Asia), their share is below that level. Technology-wise, 45% of the auctions targeted PV, and 20–20% were onshore and offshore wind in 2021–2024. According to IEA (IEA, 2025), more than 60% of the RES capacity procurement will come from auctions in the period of 2025–2030. Auctions are followed by merchant contracting, which mainly focuses on corporate-based PPAs. Pricewise, the auctions achieved significant cost reductions, following the LCOE development of the technologies. Auction prices for PV were reduced from 60 to 50 USD/MWh during 2016–2024, with some fluctuations, while in the case of wind generation, prices increased from 45 to 75 USD/MWh (IEA, 2025). Most EU Member States and China opted for the Contract for Difference (CfD) type of remuneration schemes, also called two-sided premiums, and it is expected that this type of scheme will become more widespread in the future, replacing FIT and one-sided schemes. A new trend in the auctioning of firm RES capacity, meaning procuring intermittent RES and storage, or mixed RES capacities together, that can sell more firm and adjustable RES production. Their level was 8 GW in 2023, rising to 45 GW in 2024, but uptake shows signs of cooling in 2025, as these capacity procurements resulted in a 20–40 USD/MWh markup compared to stand-alone PV auctions.

In the initial phase of RES uptake, governments sought to attract investors by establishing the most predictable support system, which

was the Feed-in tariff (FiT) scheme (Held et al., 2006; Haas et al., 2011). The next phase aimed to capitalize on the steep cost reduction in vRES technologies (PV and wind), and with their broader deployment, more attention was given to consumer costs and system integration-related issues (Winkler et al., 2016).

In this respect, one of the most important milestones for Europe was the introduction of the EU state aid guidelines (European Commission, 2014), which requires Member States to treat RES producers on equal footing with other generators in the field of balancing responsibilities. According to the guideline, electricity generated from vRES is to be sold directly on the power markets, with competitive mechanisms applied for remuneration from 2017. This process led to the widespread application of Feed-in Premium systems (FiP) across several EU Member States, exposing the growing pool of RES producers to market forces, leading to more competitive price-setting procedures (CEER, 2021, 2018). There is an emerging debate if production-based support mechanisms like FiT and FiP are best suited for mature RES markets compared with investment or capacity-based support mechanisms (Huntington et al., 2017; Newbery, 2021).

Kitzing (2014) using a mean-variance portfolio assessment on Denmark concluded that FiTs reduce risk for project developers more than FiPs, resulting in lower support costs. The author estimated that around 40% higher support is needed for a fixed FiP scheme for the developers to cover the higher market risks. In a subsequent paper, Kitzing and Weber (2015) used the Capital Asset Pricing Model (CAPM) to incorporate unsystematic risks for a selected offshore German wind

development, estimating the FiT support costs to be 4–10% lower than FiP due to lower risk levels.

However, recent research papers that include RES system integration costs find the opposite results. [Meus et al. \(2021\)](#) demonstrated that FiT underperforms FiP from a system operation point of view, even with lower RES investment costs. Other characteristics, such as additional system costs, deteriorate the economic performance of FiT. The authors conclude that fixed FiP systems outperform slightly sliding FiP support schemes.

[Neuhoff et al. \(2022\)](#) use a German case study to illustrate the differences between the three types of Feed-in Premium systems. They show that contract-for-difference (CfD) premiums result in the lowest cost to consumers, since in a high wholesale price environment, support levels are effectively capped, followed by one-sided and fixed premiums. At the same time, the CfD results in the highest strike price in a bidding procedure since producers cannot count on extra revenues when electricity prices are high.

The key takeaway for CfD schemes is the asymmetry of risk levels between RES producers and consumers. In CfD premium systems, uncertainty is largely hedged to reduce vRES financing costs and policy risks ([Anatolitis et al., 2021](#)). Furthermore, CfD also mitigates consumer risks even during high electricity price periods, when producers pay back the excessive revenues over their required LCOE. Declining technology costs have adversely impacted sliding and fixed premium systems, with market revenues making up relatively larger shares of producer income, increasing revenue volatility, and thus the financing cost. In contrast, CfD internalizes the risk of declining technology costs ([Roth et al., 2021](#); [Amazo et al., 2021](#)). [Newbery \(2023\)](#) goes a step further, and recommends a yardstick CfD with a life specified renewable output MWh/MW, which would assure efficient dispatch of variable RES production. With this financial CfD optimal level of subsidisation of RES production is expected. The study by [Finck et al. \(2025\)](#) identifies the CfD strike price as a key parameter determining the profitability for producers and the cost-effectiveness of the instrument for the public counterparty and resulting strike price levels per technology indicate the importance of competitive auctions to allocate the CfDs.

The designs of support schemes directly affect the risks of RES technologies, which in turn affect the related financial costs and the associated investment decisions discussed in the following chapters.

2.2. Risks, WACC and cost of capital for RES

[Szabó et al. \(2010\)](#) showed that the capital costs of energy technologies are determined by dynamic interactions within the assessed financial scheme, support mechanism, and industry cost reduction, and proposed using a range of WACC values with the related risks.

[Steffen \(2020\)](#) assessed the costs of capital for renewable technologies based on varying financial market data, auction results, expert estimates, and ranked them in different geographical locations for PV and wind technologies. [Steffen et al. \(2025\)](#) also compiled a recent WACC dataset for renewable projects. [Wilson et al. \(2025\)](#) have shown that renewable electricity technologies are more sensitive to the cost of capital than fossil fuel-based technologies, and that solar and wind are associated with lower spreads than fossil fuels, reflecting lower risks for investors.

The conclusion is that WACC and capital costs play a central role in cross-competitiveness between power technologies, and it is important to use the most recent capital cost values in technology assessments. This analysis used 2024 WACC data ([EUROBSERVER, 2025](#)) in the model set-up and consequent calculations.

2.3. Auction and technology bias

The AURES research project provides a critical analysis of recent renewable auctions by assessing the impacts of various design elements on economic efficiency. The paper by [Anatolitis et al. \(2022\)](#) analysed

with a panel regression model the impact of auction design on the support cost efficiency. Designs enabling high competition rates would be the most powerful tools to reduce support costs, while many restrictions, e.g. technology quotas or limiting auctions to small-scale projects would have a contrary effect. Applying financial prequalification requirements and multi-technology setup could also increase the efficiency of auctions. [Kitzing et al. \(2019\)](#) summarised the role of auction formats, pricing rules, and technology focus of auctions based on the AURES project results. Their main finding was that policymakers should focus on supporting the competition of bidders through well-functioning price formation and avoiding market distortions, while treating the risks of low realisation rates, mainly through financial and material prequalification criteria. [del Río and Kiefer \(2023\)](#) showed that auctions generally support cost-efficient allocations, although their performance in terms of effectiveness is more mixed. Their impact on promoting actor diversity is clearly negative. Nevertheless, the literature shows that the success of auctions strongly depends on their design. [Kiefer and del Río \(2024\)](#) found that auctions generally increase the concentration of participants. Technology-specific auctions are likely to offer more opportunities to a broader set of actors than technology-neutral ones, because the stronger price competition (and lower average bids) in the latter would be detrimental for smaller actors. In these auctions, investment risks, and consequently lower capital costs help actor diversity.

The remuneration type of the support schemes in the RES auctions will be increasingly important in the future, as RES operators' income, and consequently, their returns will be more market price driven, and consequently, more volatile. In recent literature, several authors identify that auction-based revenue is only a part of the power plants' total revenue; therefore comparing auction prices does not result in a valid comparison between different schemes or projects. Such an argument is made for example by [Beiter et al. \(2021\)](#), where the authors apply the concept of the levelized revenue and value of electricity LRVe. A similar comparison concept was developed previously by [Jansen et al. \(2020\)](#), with harmonised levelized revenue (HER).

The present analysis arrives one step further than previous studies in the field. It shows that if a more holistic social benefit evaluation framework is applied - by evaluating the unit social value of vRES projects - the efficiency of the remuneration schemes can change drastically in the changing economic environment of the power markets. With the substantially increasing deployment levels accompanied by the reducing market values for PV, the selection of the remuneration schemes can lead to a distorted selection of the awarded technologies from a social point of view.

Technology bias exists in multi-technology auctions where more technologies compete in the same auction, for example PV and wind technologies. In general, one technology has cost or realisation advantages compared to the other due to the auction design or to technology characteristics. Usually, single technology auctions do not face this problem, the multi-technology auctions have the advantage to make the competition stronger between the technologies, and therefore price reductions are expected to more closely follow the technology learning rates. [Jerrentrup et al. \(2019\)](#), [Fleck and Anatolitis \(2023\)](#) highlights the advantages of multi-technology auctions as having higher static efficiency, higher participation rates and higher probability to reach the desired capacity targets at a low cost. However, as [Ehrhart et al. \(2018\)](#) points to this fact, in this situation the auction design becomes more complex to provide level playing field for all participating technologies. Even in single technology auctions, like in the German reference yield wind auctions could present technology bias between units within the same technology, but different characteristics e.g. low or high wind locations, [Kröger et al., 2022](#)). [Buschle et al. \(2024\)](#) characterises these auction distortions as explicit and implicit discriminatory effects. In the explicit case, the design features discriminate amongst the technologies e.g. realisation time or prequalification requirements). [Kreiss \(2018\)](#) provided a first overview on the possible discriminations in multi-

technology auctions. [Kost et al. \(2021\)](#). points to the fact that a similar sized utility PV has much lower maintenance costs, and it has less burdensome permitting process in most countries e.g. more simplifies environmental permits) [Haelg \(2020\)](#) and [Kreiss \(2018\)](#)). Implicit distortions are those where the design elements are the same, but due to inherent technology characteristics, one or more technologies are negatively discriminated. In this latter category the most important factors are the differing learning rates of the various technologies, the future market value of the technologies and the impacts of the remuneration set-up. This latter two are the focus of our assessment following the concept of [Diallo and Kitzing \(2024\)](#) on unit social cost. [Melliger \(2023\)](#) showed in his assessment based on the AURES II auction database, that 80% of the multi-technology auctions were favouring one technology within the competing ones, but he was not able to identify which auction design factors were the most influential ones in this distortion, but country and auction-external factors could explain these impacts.

2.4. Price cannibalisation, market value and capture prices

A recent stream of literature focuses on the market value and its forecasted value of PV and wind. A group of these studies assess and estimate the effect of price cannibalization of vRES technologies. Cannibalization means that at higher penetration rates the market value - the market price the RES producer can receive in each hour it produces averaged over a year- of vRES production decreases, therefore it is also called market value reduction effect ([Sensfuß et al., 2008](#)). [Hirth \(2013\)](#) applied the European Electricity Market Model EMMA to Germany, France, Belgium, the Netherlands, and Poland, demonstrating the market value effect of high wind and/or PV penetration rates. According to their modelling results, the market value of wind decreases to half of its original value at a wind penetration rate of 30%. For PV, the effect is even stronger, claiming half of the original market value at a 15% penetration rate. The study also concludes that at a higher baseload production share (like in France), there is a higher reduction in the market values. The same model was applied by [Brown and Reichenberg \(2021\)](#), investigating the effect of various policy options on the market value of vRES technologies, comparing the FiP with CO₂ taxation of fossil-based power generators. Combining PV and wind under the FiP scheme, the market value falls to zero when the penetration rate is above 50%. In this situation, only a relatively high level of carbon pricing could keep the vRES market value within a positive range, given higher electricity prices.

[Prol et al. \(2020\)](#). assess the impact of wind and PV penetration rates on Californian electricity prices using the 'value factor' indicator, defined as the revenue of solar/wind production divided by the baseload price. Assessing the historical data on California, they found that the wind value factor is fairly resilient to higher deployment, while the PV value factor is more vulnerable.

[Mills and Wiser \(2015\)](#) assessed the options to maintain the market value of wind and solar energy using an electricity market dispatch model for California. The study concluded that PV market value fell by 75% when PV deployment reaches 30%. Although the market value of wind similarly falls with growing penetration, the effect is more limited. The market value of wind generation falls by slightly over 35% at 30% penetration rate, so the size of effect is only half compared to the PV deployment. They assess different policy options to limit the erosion of market value, including geographic or technological diversity, higher penetration of energy storage and real-time pricing, concluding that sizeable loss in vRES market value is inevitable with rising deployment.

More recent studies on the merit order and revenue cannibalisation effect of vRES is carried out by [Halttunen et al. \(2020\)](#). comparing 37 EU and non-EU countries. According to their results, the revenue reduction effect cannibalization) is smaller for wind (0.23%) and higher for PV (1.93%) for each percentage point increase in their deployment. Another assessment by [Blume-Werry et al. \(2021\)](#). explores wind and PV capture

prices in European countries. Their research concludes that higher natural gas and carbon prices result in lower wind and PV value factors (ratio of hourly wind and PV -weighted average wholesale price and the base price), and they also found substantial merit order effects in wind and PV capture prices.

A recent study by [Stiewe et al. \(2025\)](#). assessed whether the cannibalization effects can impact larger geographic areas even at cross-border levels. They found that solar and wind market values are depressed by higher deployment, not only in domestic, but in neighbouring markets as well. At the same time, the cannibalization showed larger impact for solar than for wind penetrations. They also pointed out that greater interconnectivity in the EU electricity market could mitigate domestic impacts but increase cross-border cannibalization. The findings of the analysis by [Tselika et al. \(2025\)](#). also indicate that solar is more vulnerable to cannibalization than wind power and confirm that the policy support design remains essential to ensure the viability of renewable investment.

In a similar direction in analysing the sensitivity of solar and wind market values, [Brown and Reichenberg \(2021\)](#) showed that the cannibalization effects on wind and solar can be mitigated by CO₂ pricing but can be exacerbated by direct subsidies.

As renewable energy gains importance within electricity generation portfolios, their negative impact on wind and solar market values has become more significant in many EU Member States. However, market sensitivity also depends on technology shares, support schemes and market designs. Therefore, it is important to closely examine the design and technology coverage of auctions and market schemes for solar and wind.

2.5. Externalities, emissions and grid costs

Following the work of [Pearce \(2003\)](#) on externalities of energy technologies, analysing the incremental damage caused by emitting greenhouse gases, there has been a wealth of analyses, empirical studies, and measurements in the area. In Europe, the ExternE project ([European Commission, 2003](#)) by the European Commission has produced measurements and projections of human health and other pollution-related damages for the sector. The overview by [Sovacool et al. \(2021\)](#). provides a recent comprehensive analysis of externalities in the energy sector, although it does not specify the externality values specifically for Europe. [Samadi \(2017\)](#) not only provides externality values for Europe, but also assesses the grid costs of RES technologies, which are evaluated to be much higher than the externality costs.

[Denholm and Hand \(2011\)](#) emphasised that without grid flexibility, no high penetration of wind and solar energy can be achieved, as a large fraction of wind and solar may be curtailed. However, they point out that energy storage can enable wind and solar penetration above 80%. Among the enabling factors, [Szabo et al. \(2024\)](#). showed that diversified solar deployment can increase the market value of solar, decrease curtailment, and reduce the cannibalisation effects of large solar penetration compared to business-as-usual investment in solar technologies. This underlines the importance of influencing investor decisions through market auctions and supporting designs to achieve longer-term impacts.

3. Methodology

This study uses the European Power Market Model (EPMM) to conduct a scenario-based assessment of the impact of growing vRES deployment on market value. The model and its predecessor (EEMM) have been used in several past studies, notably the SEERMAP ([Szabó et al., 2019](#)) project (in combination with TU Wien's Green-X model) and TEN-E regulation ([European Commission, 2020](#)). A more detailed description of the model can be found in [Mezösi et al. \(2020\)](#). EPMM models the cost-optimal dispatch within the ENTSO-E region, taking into account cross-border trading opportunities. Based on the hourly production pattern and wholesale electricity prices

estimated by EPMM, the market value of the vRES technologies can be calculated. Knowing the vRES market values, it is possible to estimate how efficient the different remuneration schemes are, through a welfare measure called the Unit Social Value.

3.1. Market modelling

The European Power Market Model (EPMM) is a unit commitment and economic dispatch optimisation model, satisfying the electricity consumption needs of the modeled countries at minimum system cost according to characteristics of the available power plants and cross-border transmission capacities. The model selects the lowest-cost power plants to meet electricity demand at minimum cost, including start-up and shut-down, production costs (fuel and CO₂), and RES curtailment. The latter one is an option for the model. It is used when the equilibrium price without curtailment would be negative, or when it is a cheaper option to reduce RES production, than shut down a large power plant, with high start-up cost. The model simultaneously optimises all 168 h of a modeled week to determine the hours of the week in which power plants operate and their production level. The model is executed for each week of the given year, with a representative weather pattern. EPMM endogenously models 42 countries across the ENTSO-E network. The capacities are exogenously determined. The electricity price is based on the marginal cost pricing method, determined by the merit order curve, the demand curve, and the cross-border opportunities in a given modeling hour.

EPMM falls under the general logic of Operation Decision Support tool according to the typology of Després et al. (2015), applied to classify numerous energy and power sector models by Ringkjøb et al. (2018). It follows a bottom-up approach, in its technological coverage including conventional and renewable generation and energy storage. The grid representation uses a reduced approach of Net Transfer Capacity, enabling it to capture commercial electricity trade amongst the covered European countries.

It is important to note that the reference scenario for this study assumes a high level of RES deployment reflecting the EU Green Deal decarbonisation targets: 67% in 2030 and nearly 90% by 2050

3.2. Market value forecast of PV and wind technologies in Europe

Fig. 3 illustrates the ‘market value factor’ indicator for PV and wind in 2030 and 2050 calculated as the market value divided by the baseload price for all European countries. Although only the 2030 and 2050 market values are illustrated, nevertheless all the market values between 2026 and 2050 are calculated.

In 2030, the market value indicator for PV is 20–45% in most EU countries. More isolated (less interconnected) countries and northern countries with lower PV penetration (e.g. Poland, the Nordic countries) have higher ratios and consequently lower levels of market value factor

reduction. In the longer term to 2050, the indicators mostly fall across EU countries to the 10–50% range, but in most of the continent, it is between 10% and 20%. The lowest figures, representing the highest rate of market value reduction, are found in the southern EU countries with high PV deployment levels and in those countries with high inter-connectivity. In this latter case, neighbouring countries can export their market value reduction effect to countries through PV deployment. These results are in line with (Stiewe et al., 2025).

The indicator for wind is much higher than for PV technology. In 2030, the indicator for wind generation is relatively constant, between 90% and 107%, meaning wind effectively receives the baseload price. There is more variation in 2050, but the indicator never falls below 65% in any country and for most of the countries it is still above 90%. This indicates a minimal presence of the market-value-reduction effect, even with a deployment rate of 44%. In many countries, mainly in the well-connected CEE region, wind market value and the baseload price are almost identical, with very minor differences even in 2050. Inter-connectivity and the higher wholesale price environment in wintertime, when wind technology has higher utilisation rates, help the region to keep the market value of wind at the market prices, supported by its ‘baseload’ profile spread across a wider geographical area.

3.3. Definition of extended support need

ESN compares the costs and benefits of the per unit production of vRES to the power sector actors (represented in the model as electricity consumers, power producers and grid operators) to quantify which technology generates the highest benefits for these actors.

The comparison of different renewable technologies is often conducted by comparing the levelized-cost of electricity (LCOE) values. The ESN, however, is novel in the sense that it broadens the scope of the analysis by considering not only the costs of the power plant operation (LCOE) but also the benefits, measured by the market value. Market value deviates from the average wholesale electricity price, as it reflects market participants' valuations of the real value of the energy produced during the given production hours.

Based on these considerations, ESN can be defined as the difference between the potential market benefits and the costs of the project as represented in the market value of the given technology over time and its LCOE(1).

$$ESN_r = \text{Market Value}_r - LCOE \quad (1)$$

In the equation, r represents the various renewable technologies. LCOE is calculated as follows (2).

$$LCOE_r = \frac{\sum_{t=1}^{t_r} TC_{r,t} * \frac{1}{(1+\theta)^t}}{\sum_{t=1}^{t_r} q_{r,t} * \frac{1}{(1+\theta)^t}} \quad (2)$$

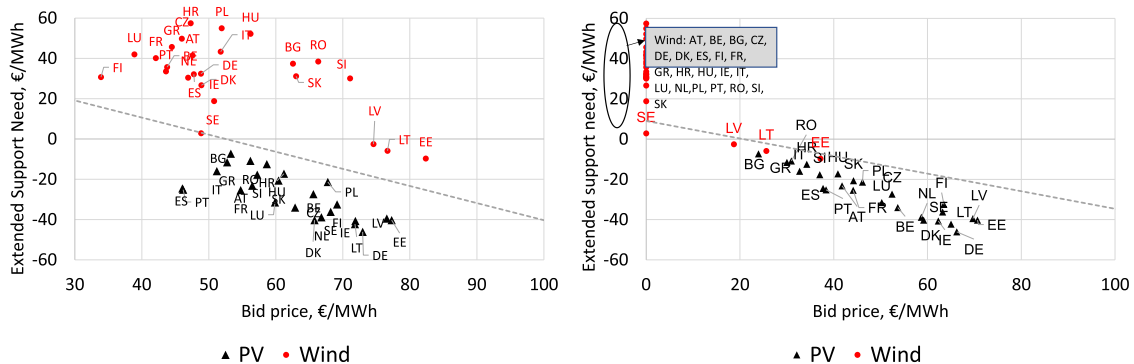


Fig. 3. Bid price and ESN comparison in two-sided (left) and one-sided (right) technology-neutral auction.

where l is the total lifetime of the given project, t represents the different time periods (hours), TC is the total cost of the project, including the investment costs (CAPEX) and the operation costs (OPEX), q is the produced energy, and ϑ is the discount rate. Thus, LCOE represents the required level of constant benefit throughout the project lifetime to break even.

Market Values (the benefit side) is defined in (3) as follows:

$$\text{Market Value}_r = \frac{\sum_{t=1}^l P_{r,t} * q_{r,t} * \frac{1}{(1+\vartheta)^t}}{\sum_{t=1}^l q_{r,t} * \frac{1}{(1+\vartheta)^t}} \quad (3)$$

where P is the wholesale market price for the produced electricity. With respect to the Market Value, two important elements need to be highlighted. First, the market-value reduction can cause wholesale prices to differ markedly across technologies in each period. For example, for a system with high level of PV capacities production profiles can be expected to be uniform, causing an oversupply during period of operation and resulting in lower-than-average electricity prices. Second, individual benefits to the producer may differ from the potential market benefit of electricity production. When renewable power plants participate in RES auctions, they not only receive the actual wholesale price but also a support part, based on their bid at the tender. For example, if in a given period, a power plant can sell one unit of electricity for 20 EUR/MWh, but support would increase its earnings to 30 EUR/MWh, then the potential market benefit is still based on the 20 EUR/MWh market price.

3.3.1. Determination of LCOE values

The Market Values can be calculated with EPMM projected electricity prices, but ESN calculations require the LCOE levels for the vRES technologies as defined in Eq. (2). Thus, CAPEX, OPEX, the discount rate and produced electricity levels must be defined for onshore wind and solar PV technologies.

Investment cost data as well as country specific WACC information is based on (EUROSERVER, 2025; IRENA, 2025). Therefore, country

variation in LCOE is driven mainly by the country-specific capacity factors and the WACCs.

With limited country-specific OPEX data, mainly the same values based on Danish Energy Agency & Energinet (Mezösi et al., 2020) were used in the LCOE calculations for all countries. For solar PV the variable OPEX is assumed to be 0 EUR/MWh with a fixed OPEX of 7000 EUR/MW/year. For onshore wind the variable OPEX is assumed to be 5 EUR/MWh with a fixed OPEX of 30000 EUR/MW/year.

The WACC, serving as a discount rate for solar PV is based on (EUROSERVER, 2025)

In the final dataset, the solar PV WACC ranges between 4.7% (France) and 6.9% (Hungary). For onshore wind, the lowest discount rate is Germany (3.9%) and the highest is Lithuania (6.0%).

LCOE values - presented in 2025 real terms - were calculated based on the above data according to Eq. (2) and summarised in Table 1.

3.4. Calculation of optimal bids

The three remuneration schemes assessed in this analysis are the following:

- One-sided sliding premium: Producers receive the market price and a premium equivalent to the difference between the auction strike price and the wholesale market price. If the wholesale market price is higher than the auction strike price, producers retain the excess market revenues.
- Two-sided sliding premium or CfD: Same as the above, except if the market price is higher than the auction strike price, producers must pay back the excess revenues to the system.
- Fixed premium: Producers receive the strike price on top of the market price, independent of the actual price level.

By incorporating target shares of vRES, the EPMM model projects power market developments and wholesale prices (both hourly and baseload) that determine the market values of PV and wind generation, which are fed into ESN calculations. Then, based on the LCOE and

Table 1
Input data used for calculating LCOE (€2025, real term).

	Wind					LCOE, €/MWh	PV					LCOE, €/MWh
	Investment cost, m€/MW	Variable OPEX, €/MWh	FIX OPEX, EUR/MW/year	WACC	Capacity factor (%) - model		Investment cost, m€/MW	Variable OPEX, €/MWh	FIX OPEX, EUR/MW/year	WACC	Capacity factor (%) - model	
AT	1.35	5	30000	4.70%	25.8%	57.6	0.80	0	7000	4.0%	13.7%	46.5
BE	1.35	5	30000	4.80%	28.0%	53.8	0.80	0	7000	4.1%	12.1%	52.9
BG	1.35	5	30000	5.80%	21.6%	72.6	0.80	0	7000	5.2%	15.6%	45.1
CZ	1.35	5	30000	5.90%	28.8%	56.0	0.80	0	7000	5.2%	12.7%	55.6
DE	1.35	5	30000	4.50%	25.6%	57.2	0.80	0	7000	3.9%	10.0%	62.9
DK	1.35	5	30000	4.80%	29.1%	51.9	0.80	0	7000	4.2%	11.6%	55.8
EE	1.35	5	30000	6.40%	21.5%	75.6	0.80	0	7000	5.9%	11.1%	67.3
ES	1.35	5	30000	4.80%	26.1%	57.3	0.80	0	7000	4.1%	17.8%	36.0
FI	1.35	5	30000	4.90%	35.3%	43.9	0.80	0	7000	4.2%	10.6%	61.0
FR	1.35	5	30000	4.70%	28.8%	52.1	0.80	0	7000	4.0%	14.2%	44.8
GR	1.35	5	30000	5.50%	28.9%	54.5	0.80	0	7000	4.7%	15.6%	43.1
HR	1.35	5	30000	5.30%	27.0%	57.3	0.80	0	7000	4.6%	13.8%	48.6
HU	1.35	5	30000	6.90%	25.6%	66.2	0.80	0	7000	6.0%	14.6%	51.2
IE	1.35	5	30000	5.60%	33.9%	47.5	0.80	0	7000	5.0%	11.2%	61.9
IT	1.35	5	30000	5.30%	24.9%	61.8	0.80	0	7000	4.5%	16.1%	41.2
LT	1.35	5	30000	5.70%	22.9%	68.5	0.80	0	7000	5.1%	11.3%	61.8
LU	1.35	5	30000	4.40%	30.2%	48.9	0.80	0	7000	3.6%	12.3%	49.9
LV	1.35	5	30000	6.10%	22.9%	70.2	0.80	0	7000	5.6%	10.9%	66.6
NL	1.35	5	30000	4.60%	27.5%	53.9	0.80	0	7000	4.0%	11.2%	56.8
PL	1.35	5	30000	6.20%	26.3%	61.9	0.80	0	7000	5.3%	12.3%	57.7
PT	1.35	5	30000	5.10%	29.4%	52.4	0.80	0	7000	4.3%	18.0%	36.2
RO	1.35	5	30000	6.40%	21.3%	76.3	0.80	0	7000	5.3%	15.0%	47.0
SE	1.35	5	30000	4.80%	27.9%	53.9	0.80	0	7000	4.2%	11.1%	58.2
SI	1.35	5	30000	5.10%	18.3%	81.1	0.80	0	7000	4.4%	13.9%	47.2
SK	1.35	5	30000	5.40%	20.9%	73.0	0.80	0	7000	4.8%	13.5%	50.4

Sources: (EUROSERVER, 2025; Mezösi et al., 2020; IRENA, 2025)

wholesale prices, the corresponding auction bids are calculated considering the specific design of the auction (one-sided, two-sided sliding or fix premium).

It is assumed that in all countries the selection procedure is pay-as-bid and price only. The following equations show the exact calculation of the bid prices, where $bidprice1s$, $bidprice2s$, $bidpricefix$ are the optimal bids of producers in the selected remuneration scheme of a given country:

1-sided sliding feed-in premium:

$$0 = \sum_{t=2025}^s [(\max(bidprice1s_r; P_{r,t}) - LCOE_r) * q_{r,t} * \frac{1}{(1+\delta)^t}] + \sum_{t=s}^l [(P_{r,t} - LCOE_r) * q_{r,t} * \frac{1}{(1+\delta)^t}] \quad (4)$$

2-sided sliding feed-in premium (CfD):

$$0 = \sum_{t=2025}^s [(bidprice2s_r - LCOE_r) * q_{r,t} * \frac{1}{(1+\delta)^t}] + \sum_{t=s}^l [(P_{r,t} - LCOE_r) * q_{r,t} * \frac{1}{(1+\delta)^t}] \quad (5)$$

fixed feed-in premium:

$$0 = \sum_{t=2025}^s [(bidpricefix_r + P_{r,t} - LCOE_r) * q_{r,t} * \frac{1}{(1+\delta)^t}] + \sum_{t=s}^l [(P_{r,t} - LCOE_r) * q_{r,t} * \frac{1}{(1+\delta)^t}] \quad (6)$$

In the equations s shows the length of the support period, uniformly considered 15 years, for all technologies and countries, while the l stands for the lifetime of the projects, which is 20 years for both solar PV and onshore wind.

The calculations assume that in all three remuneration schemes producers receive support for 15 years and then operate purely under market conditions for the last 5 years of their lifetime. The first year of operation is assumed to be 2026.

In all cases, assuming intense competition, the optimal bid for the lifetime balance of cost and revenues associated with the building and operation of the power plants is 0. This means that all participants offer bid prices that cover costs, assuming perfect investor foresight of future electricity prices. Cost coverage also means that financial cost, e.g., normal profit rates of power producers, is also covered by the effective bids.

In contrast, the support received differs across the three investigated schemes. For one-sided schemes, the revenue of the project is the maximum of the bid price and the market price for a given hour. In the two-sided system, the revenue is always the bid itself. In the fixed premium scheme, a bonus is paid on top of the market price. Thus, the optimal bid will differ according to the scheme for the same project in the same country. By construction, the one-sided and two-sided premium schemes do not provide the producer with an incentive to stop generation if the wholesale price becomes negative. Only administrative limitations prevent these RES generators from producing during negative price hours in the European power markets.

4. Results

This section presents the results of the scenario-based assessment of the various support schemes, presenting the optimal bids in the three types of remuneration settings, followed by a sensitivity assessment of the key model parameters. The performance is evaluated for both technology-specific (PV and onshore wind) and multi-technology auction settings.

4.1. Optimal bids for PV

Table 2 presents the LCOE, market value, and ESNs for PV technology-specific auctions, along with optimal bid levels for each of the three remuneration schemes in the investigated European countries. LCOE figures and average discounted market values are shown in the table for the period of 2026–2050 in 2026 real terms. This means that for every year, the market value is discounted back to year 2026, and then their average is calculated.

Spain and Portugal have the lowest LCOE values, at 36.0 and 36.1 EUR/MWh, largely due to relatively high capacity factors and low WACC values reported in the literature. The two highest LCOEs are above 65 EUR/MWh, in Latvia (66.5 EUR/MWh) and Estonia (67 EUR/MWh). The unweighted LCOE average is 52.23 EUR/MWh.

All countries have negative ESNs for PV, meaning monetary support is needed for the projects to break even over the long term (shown in red colours). The reason that standalone PVs are not any more profitable lies in the extreme cannibalisation present in the European markets for that technology. The highest support level required is in Germany (46.1 EUR/MWh), Lithuania (42.3 EUR/MWh), Denmark, Estonia and Ireland (40.2–40.7 EUR/MWh), with the remainder ranging between 7 and 35 EUR/MWh.

4.2. Optimal bids for onshore wind

Table 3 shows the corresponding data for the onshore wind technology.

Average onshore wind LCOE is 15% higher than PV technology, with an unweighted average unit cost of 60.2 EUR/MWh, meaning production costs of the two most mature variable renewable technologies are close, with PV holding a slight advantage. At the same time, onshore wind has slightly higher LCOE variation than solar PV.

The mostly positive ESNs (in green colour) indicate that wind generation does not require additional support, mainly due to the lower market value effect observed for wind. Estonia and Lithuania have the highest negative ESNs, while Latvia and Sweden are more manageable, with required support ranging between −2.6–2.8 EUR/MWh. For all other countries, the results indicate that onshore wind can operate profitably without financial support. Price uncertainty of electricity markets, also amplified by the market value reduction effect and site differences, might lead to situations where developers still bid for support, even if theoretically wind producers could operate without support.

If we compare the two technologies a clear distinction could be made. Based on the modelling results none of the countries have a positive ESN for PV in 2025, considering full lifetime and modelled market prices. In contrast, most countries carry a positive ESN for onshore wind except the Baltic countries. Therefore, the above-described effects distort the outcome for most of the onshore wind technology, positioning the two-sided sliding premium as the most efficient for wind.

For negative ESNs, when support is required, the conclusions are more straightforward: the fixed premium clearly outperforms one-sided and two-sided sliding premium schemes for both technologies. This is because the two-sided sliding scheme incentivises market participants to set their bids based on their LCOE, while the full market value is an external factor for producers. In this setup, projects with lower lifetime costs will win the auction. On the other hand, fixed premium scheme bids are based on the ESNs with producer benefits calculated relative to market prices, when lower prices and higher support lead to higher bids to cover costs. The one-sided sliding premium is a special mixture of the above two considerations, in which market value is only partially externalized.

Table 2

LCOE, 2025–2049 average market value, ESN, and bid prices of the investigated countries – PV (EUR(2026)/MWh).

	LCOE	Market value	Extended Support Need	Bid price		
				1s	2s	fix
AT	46.5	23.3	-23.2	41.8	56.5	27.7
BE	52.9	18.9	-34.0	53.7	62.9	40.1
BG	45.1	37.8	-7.3	24.0	53.3	9.9
CZ	55.6	28.2	-27.4	52.4	65.6	33.1
DE	62.9	16.9	-46.1	66.2	73.0	51.9
DK	55.8	15.5	-40.3	59.2	65.8	46.3
EE	67.3	27.0	-40.2	70.6	77.3	48.1
ES	36.0	11.5	-24.5	37.7	46.0	31.5
FI	61.0	28.5	-32.5	63.5	69.1	45.4
FR	44.8	19.4	-25.4	44.1	54.8	31.9
GR	43.1	31.6	-11.5	30.0	52.7	15.8
HR	48.6	36.2	-12.5	34.3	58.6	16.4
HU	51.2	34.0	-17.2	40.9	61.2	22.4
IE	61.9	21.2	-40.7	62.3	71.9	45.6
IT	41.2	25.2	-16.0	32.7	51.2	20.8
LT	61.8	19.6	-42.3	65.0	71.8	47.5
LU	49.9	18.3	-31.5	50.3	59.9	37.2
LV	66.6	27.1	-39.5	69.7	76.6	47.2
NL	56.8	17.9	-38.9	58.7	66.8	44.6
PL	57.7	36.4	-21.3	46.1	67.8	24.7
PT	36.2	11.0	-25.2	38.4	46.2	32.2
RO	47.0	36.1	-10.9	30.9	56.2	14.6
SE	58.2	22.0	-36.2	63.2	68.2	49.5
SI	47.2	29.5	-17.7	37.0	57.2	21.3
SK	50.4	29.8	-20.6	44.2	60.4	26.0

Source: Own calculation based on EPMM modelling

4.3. Technology-specific comparison

To analyse the allocation efficiency of the different remuneration schemes, the correlation between the bid-prices and the support need were investigated further. In an efficient scheme, projects are expected to bid the lowest value, representing the highest aggregated ESNs; thus, a strong negative correlation is expected between the two values. The reason for this negative correlation is the following: ESN is an aggregated measure which captures the benefits of the project for the producers and consumers, while in price-only auctions bid price exclusively determines which project is the winner of the tender. In an efficient setup, the projects with the largest benefit should perform best at the auction; therefore, the correlation between the bid price and ESN is a good measure of allocation efficiency.

Table 4 shows the cross-country correlation for all European countries, which can be interpreted as an efficiency measure if a European-wide technology-specific auction was organised for onshore wind and solar.

Based on economic theory, a negative correlation is expected between ESN and bid prices in an efficient scheme, meaning that projects with higher benefits for the society are associated with higher ESN. In this simplified theoretical setup these bidders are the ones requiring less support on average, they should bid lower prices on the auctions.

The remuneration scheme design also determines the correlation between bid prices and ESNs, which should be higher for fixed premiums than for sliding premium schemes. In the CfD scheme, optimal bids are only dependent on the LCOE rather than the market value, because producers receive supplementary payments until the strike price, as shown in Eq. (5). Under fixed premium schemes, however, support is paid on top of the market price, meaning higher bids are required from producers with lower market value to cover their costs. In this case, the main determinants of ESN aside from externalities are market value and LCOE. The one-sided sliding premium can be considered a hybrid scheme in which LCOE plays an important role in determining the optimal bid, but it is also influenced by excess market gains when the market price exceeds the strike price.

Table 4 summarises the results of the correlation analysis. PV shows a strong (negative) connection between the various bid levels and ESNs in all three schemes, meaning bids follow ESN development more closely. For onshore wind, the correlation between the two values is weaker, indicating a wider gap between the ESN and the bid price. For all technologies and for all remuneration schemes, however, the correlation is at least 0.7 in absolute terms, suggesting a strong co-movement. This means that all schemes for all technologies appear to be efficient tools for selection in case of technology-specific auctions.

In the technology-specific PV auction, the fixed-premium scheme

Table 3

LCOE, average market value, ESN, and bid prices – Onshore Wind.

	LCOE	Market value	Extended Support Need	Bid price		
				1s	2s	fix
AT	57.6	99.1	41.5	0.0	47.6	0.0
BE	53.8	89.5	35.7	0.0	43.8	0.0
BG	72.6	109.9	37.4	0.0	62.5	0.0
CZ	56.0	105.8	49.8	0.0	46.0	0.0
DE	57.2	89.6	32.4	0.0	48.8	0.0
DK	51.9	78.6	26.7	0.0	48.9	0.0
EE	75.6	65.9	-9.7	37.2	82.4	12.7
ES	57.3	89.4	32.1	0.0	47.8	0.0
FI	43.9	74.6	30.7	0.0	33.9	0.0
FR	52.1	92.2	40.1	0.0	42.1	0.0
GR	54.5	100.1	45.7	0.0	44.5	0.0
HR	57.3	114.8	57.5	0.0	47.3	0.0
HU	66.2	118.4	52.2	0.0	56.2	0.0
IE	47.5	66.3	18.8	0.0	50.8	0.0
IT	61.8	105.2	43.4	0.0	51.8	0.0
LT	68.5	62.6	-5.9	25.6	76.7	7.8
LU	48.9	90.9	42.0	0.0	38.9	0.0
LV	70.2	67.6	-2.6	18.7	74.6	3.5
NL	53.9	84.3	30.4	0.0	46.9	0.0
PL	61.9	116.9	55.0	0.0	51.9	0.0
PT	52.4	85.9	33.5	0.0	43.6	0.0
RO	76.3	114.8	38.5	0.0	66.3	0.0
SE	53.9	56.8	2.8	0.0	48.8	0.0
SI	81.1	111.2	30.1	0.0	71.1	0.0
SK	73.0	104.2	31.2	0.0	63.0	0.0

Source: Own calculation based on EPMM modeling

Table 4

The correlation coefficients between bid prices and ESN for the three remuneration schemes.

Technology	PV	Onshore wind
1-sided	-0.9472	-0.76086
2-sided	-0.73894	-0.5945
fixed	-0.98513	-0.72008
Number of relevant observations	26	26

Source: Own calculation based on EPMM modelling

results in the highest correlation values (0.985), whereas for onshore wind, the 1-sided sliding feed-in-premium (0.76) shows the highest value. Based on these results, it can be hypothesized that the relative underperformance of onshore wind in terms of efficiency, measured through correlation, and strong performance under the one-sided sliding premium, can be explained by the low number of countries requiring support.

The fixed premium scheme cannot differentiate between projects

that do not require support, as negative values are not allowed in most applied schemes. One exception is the general remuneration scheme for PVs in Portugal, which requires producers to pay a fixed “premium” to the system (Diallo and Kitzing, 2024). The situation is similar to the one-sided feed-in premium: with negative support needs the optimal bid for producers is 0, as this bid maximises the probability of winning the auction. However, since the producer can retain excess market revenue, it would also lead to a financially preferred outcome for developers. The only support scheme that meaningfully differentiates between projects that do not require financial support is the two-sided sliding premium, under which the payback requirement strongly incentivises producers not to bid 0 and lose revenue.

4.4. Multi-technology comparison

After analysing the technologies separately, this subsection investigates whether there are additional distorting elements under a multi-technology setup, when onshore wind competes directly with PV. This type of auction design has recently emerged in several EU countries,

including Germany, Denmark, Italy and Poland. This section focuses on the cross-technology bias in auction designs, selecting the technology with lower social value outcomes.

The ESNs in Table 5 represent the best performing technologies from market benefit perspective (column 'optimal winner') and the selected winners of the auction under the three types of remuneration schemes. Red cells represent auction outcomes that are not optimal, indicating technology bias, while green cells indicate that no bias can be measured in the given country.

The winning bid does not lead to the market optimum in several countries. Under multi-technology auctions, 8 out of the 75 cases are suboptimal; the results indicate a technology bias toward PV technology in case of two-sided premium scheme. Two-sided support schemes, which are most common today, have the highest error and are outperformed by both one-sided and the fixed premium schemes.

One weakness of the presented assessment is the assumption of perfect foresight, meaning decisions are made based on perfect knowledge of future wholesale prices and costs. If this assumption does not hold, a two-sided premium would provide greater safeguards for consumers, when wholesale energy prices increase. This happens as two-sided premium promises payback in a high-price environment (and assuming vRES operators are not allowed to opt out from the two-sided scheme). This area should be investigated further in future research.

Fig. 3 illustrates the relationship between the ESN, bid prices and technologies more intuitively. For PV technology, the relationship between the ESN and bid price is linear, whereas for onshore wind, a higher variation could be observed. The figures showing the one-sided and fixed premium schemes present particular characteristics: due to technology cost reductions, many countries reach zero bids as early as 2026. The majority of the countries are in this situation for wind technology. The downside is that the one-sided and fixed premium schemes do not differentiate between the zero bids, while the two-sided schemes can differentiate between bidders in this 'price zone' and remedy the situation.

It is challenging to relate the calculated results to other studies, as quantifying technology bias is uncommon in the literature. The same bias concept is applied in Diallo and Kitzing (2020) (2024), but they do not apply country specific LCOE values, only European averages. The latter paper applies a case study to Italy, yielding similar results; however, the wholesale price assumptions of the two papers are not comparable. Thus, it is only possible to compare the sub-results of the paper with other works, analysing LCOE of market value factor developments. Our findings on the market value reduction effects come to a similar range as those of (Halttunen et al., 2020) and (Blume-Werry et al., 2021) concerning the PV deployment, but our estimates on the wind capture price reduction effect are smaller than the other two studies. This is an

Table 5
Cross-technology bias in European countries.

	Extended Support Need- PV	Extended Support Need - Wind	Optimal winner	1 sided winner	2 sided winner	fixed winner
AT	-23.2	41.5	Wind	Wind	Wind	Wind
BE	-34.0	35.7	Wind	Wind	Wind	Wind
BG	-7.3	37.4	Wind	Wind	PV	Wind
CZ	-27.4	49.8	Wind	Wind	Wind	Wind
DE	-46.1	32.4	Wind	Wind	Wind	Wind
DK	-40.3	26.7	Wind	Wind	Wind	Wind
EE	-40.2	-9.7	Wind	Wind	PV	Wind
ES	-24.5	32.1	Wind	Wind	PV	Wind
FI	-32.5	30.7	Wind	Wind	Wind	Wind
FR	-25.4	40.1	Wind	Wind	Wind	Wind
GR	-11.5	45.7	Wind	Wind	Wind	Wind
HR	-12.5	57.5	Wind	Wind	Wind	Wind
HU	-17.2	52.2	Wind	Wind	Wind	Wind
IE	-40.7	18.8	Wind	Wind	Wind	Wind
IT	-16.0	43.4	Wind	Wind	PV	Wind
LT	-42.3	-5.9	Wind	Wind	PV	Wind
LU	-31.5	42.0	Wind	Wind	Wind	Wind
LV	-39.5	-2.6	Wind	Wind	Wind	Wind
NL	-38.9	30.4	Wind	Wind	Wind	Wind
PL	-21.3	55.0	Wind	Wind	Wind	Wind
PT	-25.2	33.5	Wind	Wind	Wind	Wind
RO	-10.9	38.5	Wind	Wind	PV	Wind
SE	-36.2	2.8	Wind	Wind	Wind	Wind
SI	-17.7	30.1	Wind	Wind	PV	Wind
SK	-20.6	31.2	Wind	Wind	PV	Wind

Source: Own calculation based on EPMM modelling

important outcome, meaning that wind generation has a higher value both from the individual developer and from societal point of view, due to its more baseload production pattern, once its production is aggregated over a larger geographical area. This has an important impact on technology neutral auctions in the longer term, as it means competitive advantage to wind generation over PV that will appear in their future bidding prices,

4.5. Sensitivity analysis

The final step of the analysis tests the robustness of the results with three sensitivity scenarios, assessing the impacts of varying assumptions.

The first scenario applies higher ETS prices to the baseline scenario. In the baseline, CO₂ prices reach 100 EUR/tonne by 2030 and to 250 EUR/tonne by 2050. The high CO₂ price scenario assumes 150 EUR/t for 2030 and 470 EUR/t for 2050. In general, higher ETS prices lead to higher wholesale prices, increasing the viability of renewable investments and reducing support requirements.

In the second scenario (High storage), it is assumed that storage capacities (including battery and pump storage) increase considerably. In the baseline scenario, European storage capacity reaches 88 GW by 2030, which increases to 180 GW by 2050. The High storage scenario reaches 126 GW storage capacity by 2030 while 307 GW by 2050.

The third sensitivity scenario applies different WACCs to the remuneration schemes to account for varying levels of risk and financing costs across Europe. This illustrates the impacts in a higher interest-rate environment, an important research direction. Based on the work of Roth et al. (2021). and Breitschopf and Alexander-Haw (2022) a WACC premium of 0.78% point was incorporated in the modelling for two-sided sliding premium relative to one-sided sliding premium, and 1.07% point for fixed premium, also relative to sliding premium. As a result, LCOEs in CfD and fixed premium increased relative to the baseline estimations.

The correlations between ESNs and bid prices are presented in Table 6 for the sensitivity test.

The relative performance of the support schemes remains the same in the sensitivity analysis, as in the baseline case: fixed premium performs the best across the whole sample, while for onshore wind, one-sided sliding premium performs the best.

Still, it must be noted that the CO₂ and storage sensitivity scenarios tend to increase the profitability of renewable technologies, thus increasing the ESN value.

5. Conclusions

Creating an efficient auction design requires considering the costs and benefits of potential future projects in an extended way. The presented Extended Support Need (ESN) indicator, a preferred measure for comparing projects and technologies, goes beyond the traditional LCOE by incorporating associated market benefits. Thus, a key requirement for an economically optimal auction is a strong co-movement of bid prices determining the selection outcome with ESNs presenting the market benefits of the analysed technologies.

This study compared renewable electricity auctions across EU Member States within a schematic framework, considering potential

future solar PV and onshore wind deployment pathways. The aim was to determine which type of remuneration scheme leads to the most economically efficient outcome. In the auctions, fully competitive bidding was assumed, meaning that producers - to maximise their winning probability - bid at a level that sets their lifetime profit equal to zero. Both technology-specific and multi-technology settings were considered. The results differ if the ESN move from the negative to the positive range. In the former case, the auction's objective is to optimally allocate the necessary support. In the latter case, the power plants can operate on a market basis. In the second setup, renewable auctions will need to take alternative goals, for example, allocating scarce grid connection points or controlling the speed of vRES deployment.

If technology-specific tenders are assumed in Europe, the highest correlation between ESN and bid price is achievable with the fixed premium scheme for solar PV and two-sided sliding premium for onshore wind. The resulting correlations are influenced by several distinct factors, the most important one is whether the ESNs are positive or negative. A major disadvantage of both fixed and one-sided sliding premium schemes appears when two projects not requiring support compete for operation (ESN positive). In this case, remuneration schemes cannot differentiate between them, because the optimal bid is 0 even when there is positive social value. This distortion is avoided in the 2-sided sliding scheme, because the pay-back requirement incentivizes project promoters to bid 0, as this would result in much lower revenues relative to a bid based on their LCOEs.

Based on the scenario results, the ESNs for PV are mostly negative, whereas the ESNs for onshore wind are positive. This implies that for PV, the fixed premium, while for wind, the two-sided sliding premium performs better in the modelled period. It is important to note that if negative bids for fixed premiums were allowed, that would lead to the most efficient outcome, outperforming the two-sided sliding premium even when ESNs are mostly positive.

The situation is more complex for multi-technology auctions, where the relative performance of the technologies must be considered. The ESNs indicate that in eight countries, solar PV should optimally emerge as the winning technology in a multi-technology tender, namely Bulgaria, Estonia, Spain, Italy, Latvia, Romania, Slovenia and Slovakia. under the modelled market development. No cross-technology selection bias is present with respect to the one-sided and fixed premium schemes.

While sliding premium bids are mainly based on LCOE values, the fixed premium scheme is based on ESNs, leaving no space for cross-technology bias. At the same time, the LCOE of PVs is expected to be lower in the future, the market value reduction factor for PV is significantly higher in the long run than for onshore wind. This means that relative to an ESN based selection (fixed premium), a sliding premium system overvalues PV, creating an inefficient allocation of resources.

To conclude, multi-technology auctions share the same general mechanisms as technology-specific auctions. If power plants require support, the fixed premium scheme is the preferred design, leading to the most efficient outcome. This is distorted if no financial support is required, since only two-sided sliding premiums differentiate between projects and technologies. However, our analysis showed that sliding premium schemes are prone to cross-technology bias as it generally overvalues PV and can result in inefficient allocation. Thus, the multi-technology setup validates the conclusion that a fixed premium

Table 6
Correlation of bid prices and ESNs in the sensitivity scenarios.

	PV				Wind			
	Baseline	High storage	High CO ₂	Different market risk	Baseline	High storage	High CO ₂	Different market risk
1 s	-0.95	-0.97	-0.98	-0.95	-0.76	-0.86	-0.83	-0.76
2 s	-0.74	-0.90	-0.88	-0.75	-0.59	-0.64	-0.47	-0.59
fixed	-0.99	-1.00	-1.00	-0.99	-0.72	-0.85	-0.79	-0.70
N	25	25	25	25	25	25	25	25

Source: Own calculation based on EPMM modelling

scheme should be adjusted to accommodate positive ESN projects by introducing the option of negative bids. This, however, is not a common practice in Europe, as negative bids would mean that no support is required for the selected RES technologies. In this case, the need for auction diminishes, and opens the floor for other market instruments, such as corporate power purchasing agreements (corporate PPAs). In this situation, the auction is still rational, if e.g. grid connection opportunities are scarce, and developers are willing to pay for them. This was the situation in the 2019 Portugal auctions, where investors were willing to pay for connection from their expected revenues, executing a negative bidding procedure (del Río et al., 2019).

These results have important policy implications for the EU Member States concerning their renewable support policies and future auction design. If the multi-technology framework is followed by the Member States, as required by the present EU regulations, it would require the auctions to develop toward fixed premium schemes with the option to allow for negative bids. This is the form of remuneration that is not widely applied in many Member States, so less experience is gained in its application. On the other hand, CfDs are more frequently applied remuneration schemes, as more than 10 Member States already use them. In addition, the European Commission's new electricity market design (European Commission, 2023) promotes this type of support scheme to reduce the risk of overpayment to RES operators. Our results warn that inefficient allocation could be present, if CfD is applied in a multi-technology auction set-up. While it is true that in a highly volatile wholesale price environment, such as the 2021–2024 period in the European markets, CfDs provide higher certainty and more stable cash flows for investors. Therefore, the instrument should be applied in carefully designed auctions to avoid the aforementioned distortion. Wholesale price volatility increases the risks for investors, prompting them to apply higher risk premiums; however, its exact size has not yet been reliably analysed. Lazard's (Lazard's Levelised Cost of Energy Analysis, 2026) provides the most recent estimates of increased LCOE of wind and PV projects. But their assessment did not disaggregate the contributions of increased financial risks and of other factors, such as material shortages and supply chain bottlenecks.

The results underline that there is no 'one size fits all' solution in auction designs. Each country should tailor the design considering power market developments, deployment of vRES, interconnectivity of markets, and technology development (both RES and storage). Therefore, policymakers responsible for auction design should closely monitor technological and market developments to adjust their schemes to optimize support needs.

5.1. Caveats and future research directions

One weakness of the applied modelling approach is the lack of physical network modelling, meaning that grid integration costs are not quantified in our paper, even though they could be sizeable, as (Samadi, 2017) indicates. In future work, either location-specific connection costs or richer representations of the network and congestion modelling can help to capture these network effects. The model does not differentiate varying locations for wind and PV sites, meaning investors are treated homogeneously within a country. The arising market uncertainties, e.g. from the merchant risks are not treated by a stochastic approach; only the specified sensitivity assessments handle the prevailing uncertainties in three pre-defined areas – e.g. changing ETS price, WACC and storage levels. The assumed homogeneity of investors (bidders) does not allow for modelling strategic bidding. The bid calculation assumes perfect competition amongst bidders, forcing to reveal their true LCOEs, which might not be the case in many actual European auctions. The EPMM model has an overarching assumption of modelling competitive electricity markets in Europe, which is also a strong limitation, as this assumption is not met in European electricity markets.

In addition, the modelled scenario is deterministic, providing the best available reference estimates from the authors and the related

literature on the various driving factors of future power sector development, which are subject to sizeable uncertainties. Although these are partially tested in the sensitivity assessment of two important variables (carbon price and storage levels), indicating the size of the effects of uncertainties, a more systematic treatment of these uncertainties, including additional factors, should be an important future work in this area.

A further weakness of the approach is that it does not consider PPA contracts, which are gaining higher importance in the EU power markets. This means the analysis assumes all renewable production is remunerated at the spot market prices, without PPAs or bilateral contracts. This has implications for the results, as PPA contracts might use pricing formulas that differ markedly from spot prices, reducing the volatility of payments to project owners in the short run. However, over the long run, these pricing arrangements should reflect the long-term average market values of the technologies; otherwise, either the project owner or the purchaser of the PPA would foresee losses and would renegotiate the pricing agreement.

The deeper assessment of the abovementioned uncertainties, grid costs, strategic bidding and PPA arrangements are important future research dimensions.

CRedit authorship contribution statement

Sándor Szabó: Writing – review & editing, Writing – original draft. **László Paizs:** Software, Methodology. **László Szabó:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition. **Alfa Diallo:** Writing – original draft, Data curation, Conceptualization. **András Mezösi:** Writing – review & editing, Writing – original draft, Validation, Investigation, Formal analysis, Conceptualization.

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Data availability

Data will be made available on request.

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