D8.1, November 2020

Technology bias in technology-neutral renewable energy auctions

Scenario analysis conducted through LCOE simulation

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Executive Summary

This report identifies technology bias between renewable power plants in technology neutral auctions, caused by different auction design elements. We evaluate our technologies (PV, onshore wind, offshore wind, and biomass) using a quantitative model, with which we determine LCOEs, bid prices, and social values of the technologies are calculated. Based on these calculations, we calculate bias between two technologies, by taking the difference of differences between the bid prices of the auction, and the unit social values of the power plants, which are the total social revenue minus the total social cost in per unit terms.

With respect to bias, two efficiency concepts are used in the report: allocative and general efficiency. An auction is allocatively efficient if the technology with the highest associated unit social value, would emerge victorious from a multi-technology auction. The concept of general efficiency in terms of bias, is based on the average bias between all technologies, which we determine as the unweighted average of pairwise biases. Comparing two designs, we deem the design that leads to lower average bias as more efficient.

In the model, inputs from different sources are used for the technologies and other important parameters. As a result, the cases are not a representation of a given country or energy system, instead they serve as basis for scenario comparison in archetypical technology/market situations. The main approach of the analysis is to compare various cases with differing input parameters and auction design elements. Seven different auction design elements are evaluated, which are remuneration scheme, support period, granted realisation period, timing of the auction within a year, balancing cost payment responsibility, grid integration cost compensation payment and environmental harm compensation payment (i.e. internalisation of environmental effects into the auction).

In the model, three main scenarios are defined. In the “laboratory scenario”, all technologies face equal market prices and no externalities are considered. The “no externality scenario” is very similar, but in this case, price cannibalisation is introduced, so renewable deployment influences the achieved market prices for all technologies. Finally, in the “baseline scenario”, grid integration costs and environmental harm are introduced – here, they are considered as influencing the societal value of the technology, but are still regarded as externalities for producers. The separation of these three cases is important, because the different setups lead to quite different results even when base cases are considered. In the “laboratory scenario”, PV proved to be socially the most beneficial, while in the “no externality” and “baseline” cases, it was onshore wind. The laboratory scenario is allocatively efficient for sliding and fixed premium remuneration schemes when the same auction rules are implemented for all technologies, while the “no externality” and “baseline”, this is only the case for fixed premiums. Average bias between all technologies is lower in fixed premium schemes in the “laboratory” and “no externality” setups, while in the “baseline scenario”, sliding premium schemes lead to lower bias, because the hierarchy between the technologies is completely different in terms of bias compared to the other two cases. Because of these differences, all three main scenarios are being used by the evaluation of the different auction design elements.

With respect to the different design elements, it is impossible to formulate a rule of thumb type policy conclusions. The main reason behind this is that that when a different setup is assumed, it can change the hierarchy between renewable technologies in terms of bias. This can result in the fact that the same change in the design (for example increasing support period from 15 years to 20), may increase the average bias in one setup and decrease it in another. We term this as “starting point effect”, as the effect of a design element change is heavily influenced by the extent of biases present in the originally assumed setup. Therefore, case-by-case analysis is required to determine the effect of a design element change, on bias.

Our model results enable us to formulate conclusions relating to the extent different design elements influence technology bias. The outcomes show that while change of support period, or the introduction of grid integration costs and environmental harm compensation may heavily influence average bias between technologies, the effects are more moderate when changes in granted realisation period or in balancing payment responsibility are applied, and almost negligible if changes in timing of the auction within a year occur. Remuneration scheme design is a very important determinant as well, but there is no clear hierarchy identifiable comparing two-sided sliding premiums and fixed premiums. Both schemes are though clearly leading to lower risk of technology bias than one-sided sliding premiums, as in several setups where a technology is mature enough to survive without support, one-sided premiums may result in very high biases.

An additional very important conclusion of the report is that allocative and general efficiency do not necessarily occur simultaneously. By comparing two designs, it is often the case that a given setup results in allocative efficiency, but in terms of general efficiency it fares worse than another allocatively inefficient auction setup. The reason behind this phenomenon is that allocative efficiency in practice mainly consider the differences between the most mature technologies (and check which of them is being awarded), in our case (based on the assumed input values), these technologies are typically PV and onshore wind, while general efficiency takes into account all the biases, that is including toward biomass and offshore wind, which are the technologies that have smaller chances of winning in the auction due to their currently higher technology cost.

To conclude, this report provides a useful theoretical concept and practical tool to analyse the effect of design element changes on technology bias, which can be used by policymakers or other interested actors. The quantification of technology bias enables policy makers to make informed decision about implementing multi-technology auctions, about which technologies to include, about if differentiation of rules may be an appropriate decision, and it so, at what level potential bonus or malus should be set.

Contents

1 Introduction

Different technologies have different value to society, and not all the values are fully reflected in the market. What seems to be a technology-neutral auction with the same rules for all, will often implicitly favour one or the other technology through market bias and externalities. For assessing the efficiency of an auction scheme, it is important to have an approximate idea of value differences and implicit biases thus the "fairness" of the competition. This report sets out to quantify the differences in socio-economic value by orders of magnitude. The main aim of the analysis is to evaluate different auction setups, and to identify how changes of important auction design elements may lead to the increase or decrease of technology bias between renewables in different market environments. The results presented in this report should help policy makers, by providing a theoretical framework and a practical tool to analyse technology biases and help to strategically employ auction design elements in regard to their impact on technology bias.

Similar work was done by Haelg (2020) with a slightly different focus. Building upon this work, our report uses a novel approach in terms of calculating the bias and defining efficiency. Technology bias is defined as the difference between the bid prices submitted by project promoters of a technology neutral auction, and the average value provided to society by that technologies.

This novel bias definition makes it possible to test the general and allocative efficiency of several auction setups. An auction is considered allocatively efficient if, based on the bid prices, the winning technology produces the highest value for society. In terms of general efficiency, those auction designs faring better which are leading to the lowest average bias across all participating technologies.

Based on these definitions an LCOE model was built, with which it is possible to calculate technology bias between renewables and evaluate different market design elements through scenario analysis. It is important to highlight that as the main tool of this report is scenario comparison, it only makes sense to draw conclusions based on the differences of selected estimations, not based on the raw results. This conclusion is strengthened by the fact, that not actual countries or energy systems were modelled, instead hypothetical auction setups and system were compared using a large variation of input variables and design elements. Also, it is important to note that the model does not consider strategic behaviour of bidders, instead consider a state where bids are made to fully cover the arising costs.

The results of the estimations show that it is difficult to draw universal conclusions about the evolution of technology bias, under different circumstances. Therefore, it is also not possible to create general rules of thumb for policy solutions. In order to design renewable auctions that reduce the bias between the participating technologies, case-by-case evaluation is necessary.

The report is structured as follows. Section 2 presents the methodology that was used for analysing technology bias. First, it introduces the LCOE model on which the estimations of this report are based, then it gives a formal definition of the most important output variables, including technology bias. The second part of this section introduces the concept of general and allocative efficiency, the two most important criteria based on, the calculated model scenarios can be evaluated. Also, it presents the most relevant auction design elements which are investigated in the report and lists the main input values for the reference and sensitivity estimations. Section 3 presents the result of the three reference scenarios which are analysed throughout this report and also shows the robustness of these result for various input variables. Section 4 analyses the effect of several important auction design elements on technology bias, in the three highlighted scenarios. As a final point, Section 5 collects the main conclusions of the report.

2 Methodology

This section presents the modelling framework that was used for calculating the results on which this report is based. First the general model structure is introduced, then definitions for the levelized cost of electricity, bid price and unit social values are presented, which are the most important elements in the calculation of technology bias. As a final step a formal definition of technology bias is given, which is used throughout this report.

2.1 General structure of the model

To calculate the bias between the technologies, a hypothetical renewable auction was modelled. The model allows the calculation of the levelised cost of electricity (LCOE) and the corresponding bid prices, for different renewable technologies, which values are important elements of the bias calculation. In general, four different technologies were investigated, utility scale solar PV, onshore wind, offshore wind, and woodchips fuelled biomass.

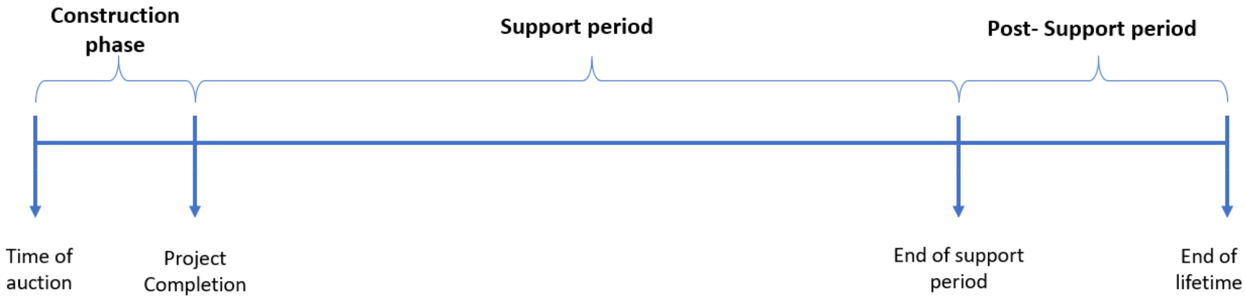
The model itself is organized on a monthly basis. The time periods that the model covers can be split into four different phases. The first phase is the 0th month where the auction takes place, and the bids are submitted by the project promoters. The second phase is the construction phase. This lasts from the 1st month, until the time the given technology must be realised. The model allows different granted realisation periods for the different technologies, so it is possible that PV promoters only have 18 months to complete the project, while onshore wind promoters have 24 months. On the other hand, the model assumes in all cases that promoters scoop the granted realisation period, and do not finish their projects earlier. It was assumed that the granted realisation period is always equal to the actual completion time. During the realisation period, the power plants are not able to generate income as the projects are not yet finished, they pay their investment costs within this timeframe. The third phase is the support period. In the model three different remuneration schemes were considered, which determines how the support is paid for the different technologies. The three investigated schemes are the one-sided feed in premium (*1s*), two-sided feed in premium (*2s*) and fixed premium (*fixed*). The unit revenue of the different power plants depends on the remuneration scheme during the support period. Equation (1) shows the unit revenues in all three support cases. In the equations r represents that the given variable is technology dependent so it differs when different technologies are considered, while t stands for the different time periods (months), while P is the market price.

(1)
$$Unit\_revenue\_1s_{r,t} = \max(Bid\ price\_1s_r; P_{r,t})$$
$$Unit\_revenue\_2s_{r,t} = Bid\ price\_2s_r$$
$$Unit\_revenue\_fixed_{r,t} = P_{r,t} + Bid\ price\_fixed_r$$

In the one-sided feed in premium case, producers always receive their bid price, if it is lower than the market price. In any other cases they receive the market price. The two-sided feed in premium system is very similar to the one-sided case, the only difference is that in this setup, if the market price is higher than the bid price, producers are not allowed to keep their excess revenues, they have to pay it back to the system. As a result, in a two-sided feed in premium case the unit revenue in the support period is always the bid price itself. Finally, in the fixed premium case, promoters bid for only the premium, so in all time periods they receive a bonus on top of the market price they face. In the model all technologies are receiving support for the same length of time, after completion.

The final phase of the model is post-support period. If in a given setup, the lifetime of the project is longer than the support period, the power plant always continues to operate until the end of its lifetime. In this period, it receives the market price, for the electricity it produces. The lifetime may differ between technologies. The four phases of the model are summarized by Figure 1.

Figure 1: The phases of the used model



2.1.1 LCOE calculation

To determine the bias between technologies, two values need to be calculated, the levelized cost of electricity (LCOE) of the four analysed technologies, and the bid price set, in the three investigated remuneration schemes. In this subsection the calculation of LCOE will be described in more detail.

One of the most important outputs of the model is the social LCOE ($sLCOE$), which is defined as the sum of the individual LCOE, and the external unit cost, in Equation (2).

(2) $$sLCOE_r = LCOE_r + unit\ externality_r$$

The $sLCOE$ is denominated in EUR/MWh, and shows the level of unit revenue, which is required by the power plant throughout its lifetime production to cover for its own costs, and the social externalities associated with its operation. Hence, it can be considered as unit social cost of electricity production of the selected technology, or as a constant revenue which makes the social welfare of the project 0.

The two components of $sLCOE$ are $LCOE$ and $unit\ externality$. $LCOE$ is the individual levelized cost of electricity, which is defined by the following formula, where ∂ is the nominal discount factor, l is the lifetime and c is the construction time, q is the produced energy, while TC represents the total cost of the project.

(3) $$LCOE_r = \frac{\sum_{t=1}^{l_r} TC_{r,t} * \frac{1}{(1+\partial)^t}}{\sum_{t=1}^{l_r} q_{r,t} * \frac{1}{(1+\partial)^t}}$$

So $LCOE$ is the amount of unit revenue which is needed to cover the costs the promoters facing. In the model the total cost of the project (TC) consist of several different cost elements. The exact value assumptions that were used in the modelling will be described in more detail in Section 2.3.

(4) $$TC_{r,t} = Capex_{r,t} + Opex_{r,t} + Balancing\ cost^*_{r,t} + Grid\ integration\ costs^*_{r,t} + Enviromental\ harm^*_{r,t}$$

The two most important pillars of the costs are the investments cost ($Capex$) and the operation costs ($Opex$). Investment cost is a fixed amount of money which needs to be paid, throughout the construction phase. The model is designed in a way that nominally equal amount of Capex has to be paid by the project promoters, in every time period of the construction phase. The Opex consists of two elements, a fixed amount, which has to be paid in all months of the support and post-support period until the end of operation, and a variable part which is expressed in EUR/MWh, which is the per unit cost of produced energy.

Three other cost elements are included in total costs, which are the balancing costs, grid integration costs, and environmental harm. All these cost elements are defined in EUR/MWh terms, so paid after every unit of produced energy. These cost factors however are marked with a * as they are only part of total costs of the promoter if the auction design is created in a way that producers bears the cost of balancing/grid integration/environmental harm. For this reason, these cost elements are only contributing to individual LCOE in some of the investigated scenarios.

The other important element of $LCOE$ is the monthly produced energy (q) which is calculated by the following formula:

(5) $$q_{r,t} = Capacity_r * \left(Capacity\ factor_r * \frac{24*365}{12}\right) * Seasonality\ multiplier_{r,t}$$

The participating capacity, the capacity factor and the seasonality multiplierserve as an input of the model.

On top of the individual LCOE, the unit externality of the selected technology has to be calculated as well for social LCOE, by Equation (6). Externalities are those social costs and benefits, which are associated with the operation of power plant, but as the project promoters do not need to cover these costs, or receive its benefits, these elements have no effect on the promoters' market behaviour. Throughout this report only external costs are investigated in more detail. In the model unit externality is defined in the following way,

(6) $$unit\ externality_r = \frac{\sum_{t=1}^{l_r} externality_{r,t} * \frac{1}{(1+\emptyset)^t}}{\sum_{t=1}^{l_r} q_{r,t} * \frac{1}{(1+\emptyset)^t}}$$

where $\emptyset$ is the social discount factor. So, unit externality is the value what a given producer has to pay after each unit of produced energy, in order to compensate for the external harm which was caused by the operation of the power plant.

In the model three different type of potential social externalities were included.

(7) $$externality_{r,t} = Balancing\ cost^*_{r,t} + Grid\ integration\ costs^*_{r,t} + Enviromental\ harm^*_{r,t}$$

These are the balancing costs, if the auction is designed in a way that producers are not responsible for balancing. Grid integration costs and environmental harm are also part of this category if producers are not obliged to pay for these elements. Similarly to total costs, all three factors are marked with a star (*) as it is dependent on the analysed scenario, whether these elements contribute to total individual costs, or social externalities. It is important to note, that depending on the scenario these cost elements either arising as externalities or as costs for producers (also a shared setup is possible), but there is no double count of these costs.

2.1.2 Bid price calculation

In an ideal setup the bid price in the sliding premium case, and the bid price plus the market price in the fixed premium case should be equal to the individual LCOE of the power plant, under certain conditions. On the other hand, it is not the case in the model, based on two reasons. First, that the support period may differ from the lifetime of the projects, so in the post-support phase power plants have to survive in the market without further support. Second, that wholesale market price varies over time. Because of these two "distorting" factors present, the LCOE does not equal the bid price, or the bid price plus the market price depending on the remuneration scheme.

In the model highly competitive auctions were assumed, which lead to the fact that promoters bid the lowest possible value, which does not lead to negative rent. With this assumption in mind, the optimal bid for the promoters will be the value, which leads to zero individual net present value. So, the optimal bid in each remuneration scheme is the $Unit\_revenue$ value that solves the following equation, where s is the support period:

(8) $$0 = \sum_{t=c_r+1}^{s}\left[(Unit\_revenue\_X_{r,t} - LCOE_r) * q_{r,t} * \frac{1}{(1+\partial)^t}\right] + \sum_{t=c_r+s}^{l_r}\left[(P_{r,t} - LCOE_r) * q_{r,t} * \frac{1}{(1+\partial)^t}\right]$$

The unit revenues for the different remuneration schemes were defined in Equation (1).

2.1.3 Calculation of technology bias

The calculation steps presented in the previous subsections however are just a prerequisite to calculate technology bias between different renewables. The main goal of this report is to identify potential factors which may distort the level of playing field, for renewables. To quantify these distortions however a proper definition of bias is required.

This report uses the following definition. An auction is unbiased across two technologies if the social, unit net present value difference between the two technologies is equal to the difference between the bid prices of the two technologies in the auction. In more simple terms, if the unit social values of two technologies are the same, they should bid the same in a renewable auction in order to consider the auction unbiased. This definition is formalised by Equation (9).

$$(9) \qquad Unit\ social\ value_{\overline{r_1}} - Unit\ social\ value_{\overline{r_2}} = Bid\ price\_X_{\overline{r_1}} - Bid\ price\_X_{\overline{r_2}}$$

Thus, the bias of the auction between the two technologies is the difference of these two differences.

$$(10) \qquad Bias_{\overline{r_1,r_2}} = (Unit\ social\ value_{\overline{r_1}} - Unit\ social\ value_{\overline{r_2}}) - (Bid\ price_{X_{\overline{r_1}}} - Bid\ price_{X_{\overline{r_2}}})$$

Bid prices of the different remuneration schemes were defined in Equation (1), so as a final step only a definition is needed for $\boldsymbol{Unit\ social\ value}$, in order to calculate the technology bias.

$\boldsymbol{Unit\ social\ value}$ is defined by Equation (11) the following way, where Q is the total produced energy over the lifetime.

$$(11) \qquad Unit\ social\ value_r = (Total\ social\ benefit_r - Total\ socal\ external\ costs_r - TC_r)/Q_r = \frac{\sum_{t=c_r+1}^{l_r}[\ (P_{r,t} - LCOE_r - unit\ externality_r) * q_{r,t} * \frac{1}{(1+\emptyset)^t}]}{\sum_{t=c_r+1}^{l_r}[\ q_{r,t} * \frac{1}{(1+\emptyset)^t}]}$$

First the total social NPV of the technology must be calculated, which is the difference of total social revenues and total social costs, which must be divided with the amount of produced energy. Total social revenue is the aggregated sum of market price multiplied with the amount of produced energy in the given month, while social cost consists of two parts, the investment and operation costs of the power plant and social externalities. After some simplification, a new formula can be created which is presented after the second equal sign in Equation (11). All the included elements can be derived from the model, so based on Equation (10), it is possible to calculate technology bias between any two technologies.

2.2 Concept of efficiency and technology bias

After providing an exact definition for technology bias between two renewable technologies in Equation (10), it is important to cover two topics, first, how it is possible to relate this bias definition to the efficiency of different auction setups and second, to identify what factors may act as a source of the defined bias. Also, those design elements need to be introduced that were analysed by the model.

2.2.1 Definition of allocative and general efficiency

In terms of efficiency with respect to technology bias this report uses two main concepts. The first is allocative efficiency and the second is general efficiency. The main aim of an auction on top of reducing support payments through competition is to select the best power plants. This aspect is even more relevant if different technologies are competing against each other in a technology neutral auction.

Equation (9) defined the unit social value of all analysed technologies. This indicator shows on average how much value, one unit of produced energy by the selected technology generates for the whole society. This means that the technology with the highest unit social value is the most beneficial to the society. As a result, those action settings can be considered good which select the technology as the winner of the tender, which is associated with the highest unit social value. If this criterion is fulfilled, it is possible to mark the analysed setup as allocatively efficient.

It is also interesting, however, at what extent a given setup is biased between all participating technologies. Pairwise biases between two technologies can be calculated based on Equation (10). From the pairwise biases it is possible to create an indicator which shows the general bias of a given auction setup, by calculating the simple unweighted average of all pairwise biases for all participating technologies. This indicator is called the average bias between all technologies. Based on its value it is possible to rank two auction setups relative to each other. In this paper that auction setup is considered more efficient in terms of general efficiency, which is associated with the lower average bias between all technologies.

2.2.2 Sources of potential bias in technology neutral auctions

After introducing the main efficiency concepts, it is also important to identify the most important factors that may result in bias between technologies. In general, the reason behind biases that renewable technologies differ from each other in many aspects and therefore, different auction design elements affect them significantly differently.

In their research, Kreiss (2019) identified several factors that may result in a bias between technologies. We supplemented this list with our own collection in Table 1. The second column of the table shows whether the given factor is incorporated in the modelling approach that was used for the creation of this report.

Table 1: Potential differences that may cause bias between the technologies, evaluated on the basis of their inclusion in the model approach

POTENTIAL DIFFERENCES IN TECHNOLOGIES THAT MAY CAUSE BIAS	COVERED IN THE MODEL
DIFFERENT COSTS	Included
DIFFERENT COST UNCERTANTIES	Not included
DIFFERENT PREQUALIFICATION REQUIREMENTS	Not included
DIFFERENT DISPACHIBILITY	Included
DIFFERENT CAPACITY FACTORS	Included
DIFFERENT INTEGRATION COSTS	Included
DIFFERENT TYPICAL PROJECT SIZE	Included
DIFFERENT OWNERSHIP STRUCTURE	Not included
DIFERENT FUTURE COST PATTERNS	Included
DIFFERENT MARKET VALUES THROUGH DIFFERENT PRODUCTION PROFILES	Included
PARTIALLY OR FULLY VEILED THROUGH SUPPORT TYPE (PREMIUMS) *	Included
DIFFERENT IMPACT ON SYSTEM INFRASTRUCTURE *	Included
DIFFERENT REALISATION PERIODS *	Included
DIFFERENT REALISATION PROBABILITES *	Not included
DIFFERENT NON-MONETARY IMPACTS (ENVIRONMENTAL & SOCIAL) *	Included

Source: Kreiss (2019) & own collection (marked with *)

Most of the identified potential factors that may cause bias between technologies were incorporated in the model. There are only four elements which are not covered by our evaluation. Out of these four elements, two are connected to uncertainty. The model on which this report is based is deterministic, so does not account for uncertainty measures. As a possible future improvement, the model may be supplemented with stochastic features, but for this analysis, uncertainty was out of scope. The other two elements (prequalification criteria and ownership structure) are not appropriately captured by an LCOE based approach.

More detail about how the factors of Table 1 are incorporated in the model are presented in Section 2.2.3 and Section 2.3.

2.2.3 Modelled design elements

After introducing the potential sources of technology bias this subsection presents a list of auction design elements which may affect the magnitude of technology biases and possible to evaluate with an LCOE type of model. Those design elements that are listed here, were evaluated with the model. It is important to note, that this is not a complete list of possible design elements that may affect technology bias. It is possible to identify additional relevant factors. However, this list only includes those which are analysed in more detail in this report.

Remuneration scheme

Throughout the report three main remuneration types are investigated, one-sided sliding feed in premium, two-sided sliding feed in premium and fixed premium. The calculation of unit revenue for all three schemes were already introduced by Equation (1). The effect of the remuneration scheme is treated specially in this report, as all examined scenarios were estimated for all three schemes.

Support period

Based on the AURES 2 auction database[1], the general length of the support period in renewable tenders are 15-20 years, depending on many factors. In the model, for the reference case a 20-year long support period was assumed, however the effects of several different support period lengths on the bias were investigated. Based on this design element four different scenarios were made, with a support period of 10 years, 15 years, 20 years, and 25 years. For all cases, the same support length was assumed for all four investigated technologies.

Granted realisation period

An important design element of all renewable auctions, is how much time is available for promoters to complete their projects. In the modelling it was assumed that project promoters take the exact time granted to realise their projects, so no early finishes and delays were allowed. Several different scenarios were created with respect to granted realisation periods, mostly based on the data of the AURES II auction database. The different scenarios are summarised in Table 2.

Table 2: Granted realisation periods in the different scenarios for all investigated technologies, Months.

	PV	Onshore wind	Offshore wind	Biomass
Reference	24	36	48	48
Equal low	24	24	24	24
Equal high	60	60	60	60
Fastest possible	12	16	36	36
Long for one technology	48	72	96	96

Source: Own calculation based on AURESII auction database[2]

The reference case consists of likely realisation periods for the four technologies. In the equal low and equal high cases, the granted realisation period was assumed to be equal at a low and high value, respectively. In the fastest possible case, the lowest realisation period was assumed for all technologies based on the AURES II auction database. The long for one case consist of 4 different scenarios. In each scenario the reference value was used for all technologies except one, for which a significantly higher realisation period was granted. The last line of Table 2 presents the non-reference values for each technology in these setups.

Timing of the auction

The different renewables have quite different production profile, as PV tend to produce more in summer, while wind is more efficient in winter. For this reason, the timing of the auction may favour or disfavour some technology relative to the other. As a result, the timing of the auction was investigated as well in the model. In the reference setup, the tender was assumed to take place in March (0^{th} months), so the first modelled month was April. However, three different cases were also estimated when the auction was organised in June, September, and December.

1 http://aures2project.eu/auction-database/
2 http://aures2project.eu/auction-database/

Balancing responsibility

In newly designed European auction, it is required by the European Commission that balancing costs should be paid by the renewable producer. However, considering earlier support schemes or outside Europe cases, it often occurs that renewable producers are not required to pay for balancing.

In the model two different setups were tested. First when producers pay balancing costs, for the whole lifetime of the project. The second when the "system" is responsible for covering balancing related costs. In the latter scenario, as long as the support period lasts, there is no balancing cost payment responsibility for producers, so these costs only occur as social externalities. Even in this scenario however producers cover balancing cost between the end of the support period and the end of the project's lifetime. More detailed description of the balancing cost values used for modelling can be found in Section 2.3.

In the reference case it was assumed that producers are responsible for paying for balancing.

Grid integration cost compensation

With the completion of a renewable project significant grid integration costs occur in the energy system. These costs mostly do not affect renewable electricity producers, as mainly the transmission and distribution system operators are responsible for covering these expenses. Although there are some auction designs where grid integration contribution is required by the promoters like in Portugal (del Rió et al., 2019). More detailed description of the grid integration cost values used for modelling can be found in Section 2.3.

With respect to grid integration costs three different setups were tested. The first where producers do not have to pay for grid integration, the second where they must cover half the cost of grid integration and the third where these costs are totally internalised by the producers.

In the reference case it was assumed that producers are not required to pay for grid integration.

Environmental harm compensation

The building and operation of a renewable power plant is associated with several different types of negative externalities. For a more detailed description of these potential externalities and the assumed values in the modelling see Section 2.3. In theory, it is possible to design an auction scheme in which compensation payment is required in order to cover the social costs of these external harms.

In the analysis three different cases were considered. In the reference case, no compensation is required by the promoters. Also, there is a scenario where producers have to cover half of these social externalities, and another where the total external costs must be paid in form of a compensation. Additionally, some scenarios were investigated in which producers must pay both the environmental cost compensation and grid integration costs.

2.3 Main inputs of the model

This section provides a general summary about the input values used in the model and the sensitivity scenarios. It is important to highlight that the reference value by the different variables does not necessarily mean that it is the possible best estimate, more like as a starting point of a comparative scenario analysis, which was conducted with the used modelling approach.

Discount rate

Two types of discount rates are included in the model, the nominal social discount rate ($\emptyset$), and the nominal individual discount rate (∂). In the modelling process it was always assumed, that a given discount rate (social or individual) is the same for all technologies, however the individual and social rates may differ from each other. The following yearly average discount rate values were assumed in the different modelling scenarios.

Table 3: Value assumptions for individual and social discount rates

Variable	Reference case	low	high
∂ (individual)	5%	2.5%	10%
∅ (social)	6%	3%	12%

Source: Own calculation

Participating capacity

The participating capacity is used to calculate produced energy in each month. The exact calculation is presented in Equation (5). A capacity of 5 MW was assumed for all technologies, and no sensitivities were made with respect to this variable, since the results are not significantly impacted by this assumption.

Capacity factor

Capacity factors are used for the calculation of monthly energy produced. For more details see Equation (5). The reference capacity values are based on the IRENA renewable energy database[3], and it was calculated as the unweighted average of the capacity factors of the European countries where data was available. The reference case and the sensitivities are summarized in Table 4.

Table 4: Value assumptions of capacity factors used in the model for all investigated technologies.

Technology	Reference case	low	high
PV	18.00%	13.50%	22.50%
Onshore wind	34.57%	25.93%	43.21%
Offshore wind	47.30%	35.48%	59.13%
Biomass	80.00%	-	-

Source: Own calculation based on IRENA renewable energy database[4]

Lifetime

Lifetime of the project assumptions were made, based on Danish Energy Agency & Energinet (2016). In the model the lifetime of PV power plants is set for 30 years, while for all other technologies 25 years. No sensitivity was conducted for different possible lifespans.

Seasonality multiplier of energy generation

In the model the average monthly production is calculated from the participating capacity and the capacity factor based on Equation (5). This value however is adjusted with a seasonality multiplier, in order to account for the non-homogeneous production profile of renewables in time. The multipliers are calculated from the EIA's data[5] about the USA. First the average monthly production was calculated from the database for 2018 and 2019. Then the monthly actual production value was divided with this average for all months to get monthly multipliers for 2018 and 2019 separately. The multipliers were averaged out across the years for the same months, for the final values that were used in the modelling. These values are listed in Table 5.

[3] https://www.irena.org/Statistics/Download-Data
[4] https://www.irena.org/Statistics/Download-Data
[5] https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_1_01_a

Table 5: Value assumptions for seasonality multipliers of production that were used in the model for all investigated technologies

	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
PV	0.63	0.69	0.97	1.14	1.24	1.34	1.31	1.28	1.11	0.97	0.72	0.60
Wind[6]	1.07	0.97	1.10	1.18	1.05	1.00	0.80	0.83	0.90	1.03	1.00	1.08
Biomass	1.07	0.95	1.01	0.91	1.00	1.01	1.09	1.09	0.98	0.94	0.95	1.01

Source: Own calculation based on EIA[7]

In some scenarios heavy seasonality was assumed, by taking the square root of the difference of the multiplier form one, then adding or subtracting this value from one depending on whether the multiplier is smaller or larger than one originally. The result of this mathematical transformation is that those values which were originally larger than one became even larger, while those smaller, became even smaller resulting in significantly stronger seasonality.

Operation costs (OPEX)

Operation costs consist of two parts for all technologies. There is a variable part which is dependent on the amount of produced energy and a fixed part which must be paid, in each year independently of the amount of generated electricity. These costs need to be paid in every time period, between the commencement and the end of the operation of the power plant. First year of production values of operation costs are based on Danish Energy Agency & Energinet (2016). In addition to the reference setup, higher and lower OPEX values were considered in the sensitivity cases.

Table 6: Value assumptions for the 1st operation year OPEX in the model for all investigated technologies

	PV		Onshore wind		Offshore wind		Biomass	
	Variable (EUR/MWh)	Fixed (EUR/year)	Variable (EUR/MWh)	Fixed (EUR/year)	Variable (EUR/MWh)	Fixed (EUR/year)	Variable (EUR/MWh)	Fixed (EUR/year)
reference	2.02	12800	2.80	25600	4.30	57300	40.00	110000
low	1.35	8533	1.87	17067	2.87	38200	26.67	73333
high	3.03	19200	4.20	38400	6.45	85950	60.00	165000

Source: Danish Energy Agency & Energinet (2016)

On top of the starting values of Table 6, ageing of the infrastructure was considered as well. For this reason, a yearly 0.5% cost increase was introduced, for both the variable and fixed OPEX.

Investment costs (CAPEX)

The modelled investment cost values are European wide averages of IRENA's renewable energy data base[8]. Only a slight adjustment was made with respect to offshore wind as the IRENA value seemed unrealistically high, so the cost estimated by Windpower Monthly[9] was used. Similarly, to OPEX, sensitivity estimates of low and high Capex cases were also investigated.

6 The same values were used for onshore and offshore wind seasonality.
7 https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_1_01_a
8 https://www.irena.org/Statistics/Download-Data
9 https://www.windpowermonthly.com/article/1582464/wind-represents-61-european-investments-2018

Table 7: Value assumptions for the CAPEX of all investigated technologies, million EUR per MW of installed capacity

Technology	reference	low	high
PV	0.76	0.51	1.14
Onshore wind	1.42	0.95	2.13
Offshore wind	2.50	1.67	3.75
Biomass	4.39	2.93	6.59

Source: IRENA renewable energy database[10], Windpower Monthly[11]

In the model investment cost payments are nominally equal in all time periods between the 1st month and the realisation date. The undiscounted sum of these payments equals the values of Table 7.

<u>Market price & technology penetration</u>

Market price is an important element of determining both the bid-prices in the different remuneration schemes and the social value of the technologies.

In order to create price assumptions for the model three theoretical price patterns were formed (reference, low, high) for yearly average prices for 40 years. The model however operates on a monthly basis, so monthly seasonality in prices were introduced as well. The monthly seasonality factors were determined based on EEX prices[12] of 2018 and 2019. First, the average monthly prices were calculated from the data for 2018 and 2019. Then the monthly actual prices were divided, with the average for all months in a year, to get monthly multipliers for 2018 and 2019 separately. The multipliers were averaged out across the years for the same months, for the final values that were used in the model. These values are listed in Table 8.

Table 8: Value assumptions of seasonality multipliers for market prices

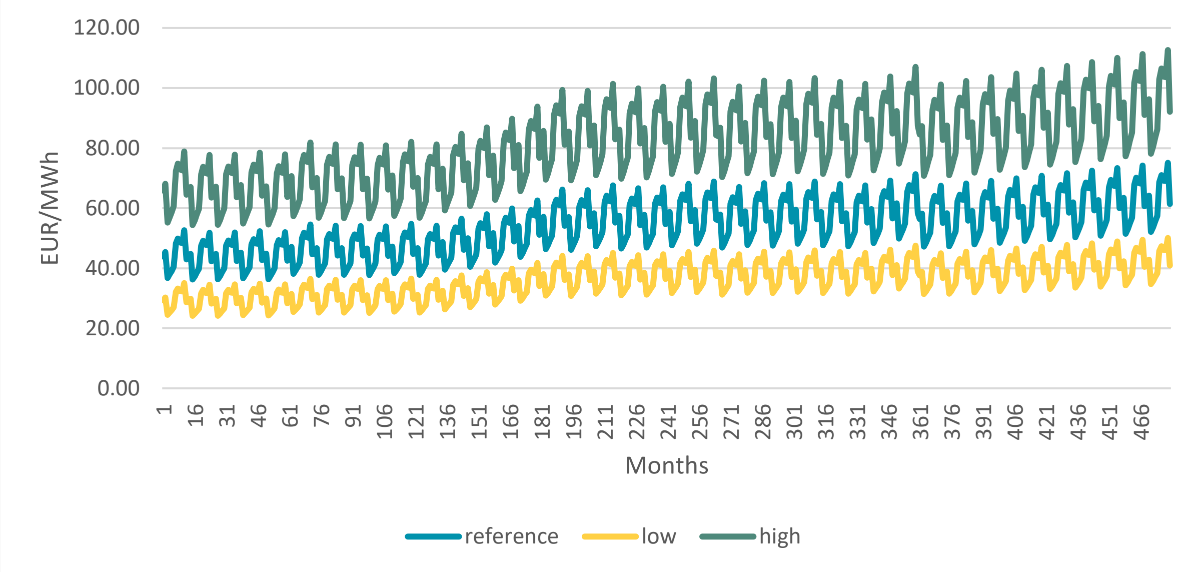
	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
Seasonality multipliers	0.99	1.02	0.83	0.85	0.88	0.91	1.08	1.12	1.09	1.09	1.18	0.97

Source: Own calculation based on EEX

By multiplying the yearly average prices with the seasonality multipliers, the three main price patterns were created.

10 https://www.irena.org/Statistics/Download-Data
11 https://www.windpowermonthly.com/article/1582464/wind-represents-61-european-investments-2018
12 https://www.epexspot.com/en/market-data

Figure 2: Three main price patterns that were used in the model



Source: Own estimations

Prol et al. (2020) highlight however that different technologies may face different market prices, depending on their penetration. Because solar PV and wind power plants can only produce, when the weather conditions are appropriate, , a possible outcome if the penetration of a given technology is high is, that in the time periods of their production, electricity oversupply will be on the market. This would reduce market price. In this sense higher penetration of the technology can reduce its market value. This effect is referred as cannibalisation throughout this report.

Prol et al. (2020) quantify this effect for California with regression analysis for PV and wind[13]. They establish a connection between the penetration of the technology and its market value factor, which is the portion of the market price the given technology receives for its production. Based on their research the following cannibalisation rates were used in the model.

Table 9: Value assumptions for same- and cross-technology cannibalisation effects for market value factor based on the penetration of the technology

	Effect on PV market value factor (% point)	Effect on Wind market value factor (% point)
1 percentage point increase of PV share	- 2.01	0.73
1 percentage point increase of wind share	- 0.96	- 0.58

Source: Prol et al. (2020)

These values, based on Prol et al. (2020)'s research, mean, that self-cannibalisation effect is present for both PV and wind, however the extent of price reduction is stronger for PV. An additional interesting conclusion is that while the increasing share of wind reduces the market value factor of PV, however a ceteris paribus increase in PV penetration would increase the market value of wind. They argue that the reason behind these cross-cannibalisation effects is the opposite daily pattern of wind and solar power production, and the fact that solar production is much more concentrated around noon. This results in a larger drop in sunny periods and thus a larger increase of prices in the not sunny daytime, when wind produces more.

[13] They only calculated cannibalisation rate for onshore wind. Same value was assumed for offshore.

Using the cannibalisation rates of Table 9 it is possible to calculate the technology specific market prices, for different penetration assumptions. In the model, several renewable penetrations were tested. The share of different technologies, in the beginning of the 1st modelled year and at the end of the 40th year are summarized in Table 10.

Table 10: Value assumptions for renewable penetration scenarios in the electricity mix that were used in the model in the 1st and 40th (last) year, %

	PV		Onshore wind		Offshore wind	
Scenario name	First year	Last year	First year	Last year	First year	Last year
low-low	0%	5%	0%	5%	0%	5%
low-high	0%	20%	0%	30%	0%	10%
high-high	10%	20%	20%	30%	5%	10%
PV dominant	10%	20%	0%	5%	0%	5%
Wind dominant	0%	5%	20%	30%	5%	10%
No renewable	0%	0%	0%	0%	0%	0%

Source: Own estimations

As electricity production based on biomass is a flexibly dispatchable power source, for biomass there is no connection between the market value factor and its penetration within the model. Because of the flexible dispatchability it was assumed, that the biomass power plant will produce when price is generally higher, so in the modelling a constant market value factor of 1.1 were used for the whole period in every penetration scenario for this technology.

Balancing costs

A great challenge for weather dependent renewable technologies is to prepare an accurate schedule of their production. When deviation occurs, the cost of balancing must be covered either by the producer or another energy market participant depending on the given country's renewable regulation.

The balancing cost of the different renewable technologies in the reference case was estimated based on Fürstenwerth et al. (2015). Because the production of a biomass power plant is much more predictable, a significantly lower value was used for the balancing costs of biomass.

The values of the study however are more relevant for more mature electricity markets. In Hungary for example the balancing costs of solar PV is about 8-10 EUR/MWh (Bartek-Lesi et al., 2020), which is significantly higher than the proposed 1-2 EUR/MWh of the reference case. Also, the report of Gorenstein and Dedecca et al. (2020) on network costs shows that in many European countries balancing costs can reach 5-10 EUR/MWh. For these reasons, such sensitivities were estimated too, where higher balancing costs were assumed. The following balancing cost values were used in the model:

Table 11: Value assumptions for balancing costs that were used in the model for all investigated technologies, EUR/MWh

Technology	reference	high
PV	1.00	10.00
Onshore wind	2.00	10.00
Offshore wind	2.00	10.00
Biomass	0.10	-

Source: Fürsthenwert et al. (2020) & Bartek-Lesi et al. (2020)

Because of the ageing of the equipment and the potential increase of renewable share in all estimated scenarios a yearly 2% increase of the balancing cost was assumed.

System integration costs

The completion of renewable power plants is associated with integration cost both at the transmission and the distribution grid level. These costs are difficult to estimate, however a study from Fürstenwerth et al. (2015) provides some cost estimation for both cost elements in Europe, based on a set of other studies. In the model these values were used as reference.

On top of the study values, several artificial scenarios were created for the sensitivity estimations. These artificial scenarios are not based on real integration cost values and only serve the purpose to show, how the calculated technology bias between the different renewables are affected if the grid integration cost structure changes. In the "same" case, the averages of the reference values were used for all technologies, in the "half the difference", the lowest integration cost value was held constant, and for all other technologies the cost were reduced to a level, where the difference was halved relative to lowest value, compared to the reference setup, while in "no cost" case, system integration costs were assumed to be zero for all technologies. Table 12 summarises the above described cases:

Table 12: Value assumptions for grid integration costs that were used in the model for all investigated technologies, EUR/MWh

Technology	reference	same	half the difference	no cost
PV	7.00	14.50	6.00	0.00
Onshore wind	11.00	14.50	8.00	0.00
Offshore wind	35.00	14.50	20.00	0.00
Biomass	5.00	14.50	5.00	0.00

Source: Fürsthenwert et al. (2020) & Own estimations

Environmental harm

The building and the operation of power plants is in many cases associated with significant external costs to the society. Of course, because these costs are mostly arising as externalities and no real monetary transaction is associated with them, it may prove difficult to give a valid estimation about the extent of these externalities. Streimikiene & Alisauskaite-Seskiene (2013) however, gave an estimation for many relevant external factors for Lithuania. They categorised these costs into three groups, climate change related cost, environmental harm and healthcare related harm. In our model the estimation of Streimikiene & Alisauskaite-Seskiene (2013) was aggregated for the three category and were used as a reference case for environmental harm. The same artificial sensitivity scenarios were engineered for environmental harm as for system integration costs. Table 13 shows all the estimated scenarios.

Table 13: Value assumptions for environmental harm that were used in the model for all investigated technologies, EUR/MWh

Technology	reference	same	half the difference	no cost
PV	11.05	16.90	6.20	0.00
Onshore wind	1.35	16.90	1.35	0.00
Offshore wind	1.50	16.90	1.43	0.00
Biomass	53.68	16.90	27.52	0.00

Source: Streimikiene & Alisauskaite-Seskiene (2013) & Own estimations

3 Main results of the modelling

In this section the results of three different model specification are presented, which serve as benchmark for further calculations and thus considered as references. It is important to note that the three described cases are possibly not the "most realistic" or the "best" scenarios, that could have been engineered. It is more like a starting point of the bias evaluation. Through these three scenarios it is possible to conduct a ceteris paribus analysis for the different design elements, and compare the change of the technology bias, caused by the investigated factors. Also, to provide a deeper understanding of the results, several sensitivity scenarios were estimated, which are also presented in this section.

The first analysed scenario is called "laboratory scenario". For this case, based on sections 2.2.3 and 2.3 the reference values were inputted into the model. The scenario however is called "laboratory", as a 0 percent renewable penetration was used for all technologies, thus all technologies face the same market price in all time periods. In the model cannibalisation can affect mostly solar, but at some extent onshore and offshore wind too, so it was important to analyse the magnitude of technology bias, if cannibalisation is not present. Additionally, in the "laboratory scenario", grid integration costs and environmental harm were set to 0, for all technologies, which means that all externalities were excluded from the model. Having scenarios without externalities is important, as those values are not easy to properly estimate, so it is meaningful to have scenarios, where their effect on bias is not considered. Balancing cost in the "laboratory scenario" (similarly to the "no externality" and "baseline"), are paid by the producers.

The "no externality" scenario is very similar in its assumptions to the "laboratory". The only difference is that in the "no externality" case, scenario "low-high" is considered for renewable penetration, so it is assumed that the small renewable share at the time of the auction will increase significantly until the end of the model period. In this sense the "no externality" scenario considers cannibalisation but excludes external costs. Finally, the third reference scenario is called "baseline", where the same assumptions apply, as in "no externality" except, that reference values of grid integrations costs (paid by the system), and environmental costs (not internalised) are present.

The differences of the three main scenarios are highlighted in Table 14.

Table 14.: The differences between the three main scenarios used in the modelling

	Laboratory	No externality	Baseline
Different market price for technologies (cannibalisation)	No	Yes	Yes
Externalities considered	No	No	Yes

3.1 Laboratory scenario

Table 15 summarises the basic results of the model estimation, of the "laboratory scenario" for all technologies.

Table 15: Main results of the laboratory scenario for reference values, EUR/MWh

	PV	Onshore Wind	Offshore Wind	Biomass
LCOE	56.03	61.78	87.46	129.50
Unit externality	0.00	0.00	0.00	0.00
Bid price 1s	54.50	62.22	91.39	138.10
Bid price 2s	55.65	62.38	91.39	138.10
Bid price fixed	6.78	13.04	41.37	82.58
Unit social value	-5.21	-10.50	-32.37	-64.36
Winning technology	yes	no	no	no

Source: Own calculation

The levelised cost of electricity (LCOE) was calculated based on Equation (3). As in the laboratory scenario no externality was considered, the unit externality values are 0 for all technologies. The third to fifth rows show the optimal bid price in one-sided feed in premium (bid price 1s), in two-sided feed in premium (bid price 2s) and in fixed premium (bid price fixed). The difference between the LCOE and the bid price in the sliding premium systems arises from the fact that the support periods for all technologies are shorter than their lifetimes, so in their last years of operation they will receive the market price. The last but one column shows the unit social value calculated based on Equation (11). This is negative for all technologies which means, that an average unit of produced energy costs more than the average market price, so the technologies require support.

Based on the results, in the presented setup PV is the cheapest technology comparing LCOEs and as the market price is the same for all technologies this technology should win in a technology neutral auction, as it has the highest unit social value. PV is followed by onshore wind with around a modest 5 EUR/MWh margin, while there is a large cost difference present with respect to offshore wind, and an even larger relative to biomass. In all three remuneration schemes, PV would win the auction, which is in line with the technologies cost structure, so a technology neutral auction would be allocatively efficient.

Even though PV is the winner in all remuneration schemes, there are technology bias present in the auction. As it was introduced in Equation (10) technology bias between two selected technologies can be calculated as a difference between the difference of their bid price, and their unit social value. Figure 3 summarizes the pairwise technology bias, in all remuneration schemes.

Figure 3: Pairwise and average biases between technologies in the laboratory scenario with reference values in 1s sliding premium (up), in 2s sliding premium (middle) and in fixed premium (down) schemes, EUR/MWh

1s sliding premium

	PV	Onshore wind	Offshore wind	Biomass	
PV		-2.43	-9.73	-24.44	
Onshore wind			-7.30	-22.02	
Offshore wind				-14.72	
Biomass					
Average					13.44

2s sliding premium

	PV	Onshore wind	Offshore wind	Biomass	
PV		-1.44	-8.58	-23.30	
Onshore wind			-7.14	-21.86	
Offshore wind				-14.72	
Biomass					
Average					12.84

fixed premium

	PV	Onshore wind	Offshore wind	Biomass	
PV		-0.97	-7.43	-16.65	
Onshore wind			-6.46	-15.68	
Offshore wind				-9.22	
Biomass					
Average					9.40

Source: Own calculation

In the one-sided feed in premium in the "laboratory scenario", the technology bias between PV and onshore wind is 2.43 EUR/MWh in favour of PV, which is the first value of the bias table. The unit value difference between PV and onshore wind, were estimated to be 5.29 EUR/MWh (10.5-5.21), while the difference in their optimal bid is more 7.72 EUR/MWh in favour of PV. This shows that PV faces a price advantage of 2.43 EUR/MWh in the auction. All other values in the three tables can be interpreted the same way.

Based on the pairwise comparison it is possible to identify the hierarchy between technologies with respect to technology bias. Based on the results in the laboratory scenario in all three remuneration schemes the auction is biased mostly toward PV, followed by onshore wind, offshore wind and biomass. The differences between the technologies however are not the same across the schemes. For example, the advantage of PV over onshore wind is only 0.97 EUR/MWh in the fixed premium, while 1.44 EUR/MWh in the two-sided sliding premium scheme.

The green number for all remuneration schemes is the average of all pairwise technology biases, which serves as the main indicator of technology bias of a given auction setup. In the report this value is referred as "average bias" or "average bias between all technologies". Figure 3 shows that the average bias is almost the same for the two types of sliding premium systems, as the bid prices of the two systems are very close to each other. On average two-sided sliding premium performs better than its one-sided counterpart comparing the average biases. On the other hand, in the fixed premium system the average bias is around 3.5-4 EUR/MWh lower, than in the sliding premium schemes, which is the result of the fact that in the fixed premium scheme all pairwise biases are lower. This means that fixed premium scheme would lead to an outcome which is better in terms of general efficiency than sliding premium.

3.2 No externality scenario

In the "no externality scenario" cannibalisation effects were introduced so technologies face different prices based on their penetration in the energy system. The results of the model estimations are summarized in Table 16. The LCOE values are the same as in the "laboratory scenario", as there were no changes in the cost structure, while externalities are still not present.

Table 16: Main results of the no externality scenario for reference values, EUR/MWh

	PV	Onshore Wind	Offshore Wind	Biomass
LCOE	56.03	61.78	87.46	129.50
Unit externality	0.00	0.00	0.00	0.00
Bid price 1s	62.24	62.63	91.68	138.10
Bid price 2s	62.24	62.67	91.68	138.10
Bid price fixed	23.77	14.57	43.01	82.58
Unit social value	-16.76	-11.66	-33.60	-64.36
Winning technology (1s, 2s)	yes	no	no	no
Winning technology (fixed)	no	yes	no	no

Source: Own calculation

Because cannibalisation affects PV the most, in the "no externality scenario" a bid price increase is observable for PV in all remuneration scheme relative to "laboratory" case. The bid price of onshore and offshore wind is also higher, but the increase is significantly smaller. Based on the unit social value of the different technologies with cannibalisation effect considered onshore wind should be the winning technology on the technology neutral auction despite the fact the PV has the smallest LCOE. This occurs because the social benefit resulting from higher market price for wind compensate for the cost advantage of PV.

Interestingly however, this fact is not represented in all remuneration schemes as in the sliding premiums solar PV bids lower than onshore wind, only in the fixed premium scheme onshore wind would emerge as winner. This means only fixed premium is allocatively efficient. The reason behind this phenomenon is that fix premium scheme relies more heavily on the market price, while sliding premium scheme eliminates the differences between the market values of the technologies at significantly greater extent, by providing a fixed unit-revenue for producers.

The above described finding leads to a very important conclusion. If cannibalisation is present, or for some other reason technologies are facing different market prices, it is possible that a sliding premium remuneration would favour a different technology than fixed premium scheme.

By analysing the pairwise biases between technologies of Figure 4, it is also visible that the hierarchy between the technologies in terms of bias is different in sliding premium than in fixed premium. In the former schemes the hierarchy between the technologies, is the same as in the "laboratory scenario", in the latter however the position of onshore wind and PV changes. In more exact terms with the same input values assumed, the sliding schemes provide an approximately 5.5 EUR/MWh advantage to solar PV, while in the fixed premium action it is onshore wind which has a 4 EUR/MWh advantage over PV.

Figure 4: Pairwise and average biases between technologies in the no externality scenario with reference values in 1s sliding premium (up), in 2s sliding premium (middle) and in fixed premium (down) schemes, EUR/MWh

1s sliding premium

	PV	Onshore wind	Offshore wind	Biomass	
PV		-5.48	-12.59	-28.25	
Onshore wind			-7.11	-22.77	
Offshore wind				-15.66	
Biomass					
Average					15.31

2s sliding premium

	PV	Onshore wind	Offshore wind	Biomass	
PV		-5.52	-12.59	-28.25	
Onshore wind			-7.07	-22.73	
Offshore wind				-15.66	
Biomass					
Average					15.30

fixed premium

	PV	Onshore wind	Offshore wind	Biomass	
PV		4.11	-2.39	-11.20	
Onshore wind			-6.49	-15.31	
Offshore wind				-8.81	
Biomass					
Average					8.05

Source: Own calculation

By looking at the average biases, the main conclusion is very similar to the “laboratory scenario”, as fixed premium outperforms the sliding premium schemes, which are similar, with the two-sided scheme having a smaller average bias. An additional interesting conclusion is that average bias increases relative to the “laboratory scenario” in the sliding premium schemes, while decreases in the fixed premium.

3.3 Baseline scenario

As a final step, the “baseline scenario” was estimated, by introducing grid integration costs and environmental harm as external cost. The definition of externality that it does not affect the investment decision of the project promoters, thus the LCOE and the bid prices in all remuneration schemes are the same as in the “no externality scenario”. The unit social value however changes, as society experience these externalities as social costs. In Table 17, the main results of the “baseline scenario” are presented.

Table 17: Main results of the baseline scenario for reference values, EUR/MWh

	PV	Onshore Wind	Offshore Wind	Biomass
LCOE	56.03	61.78	87.46	129.50
Unit externality	18.05	12.35	36.50	58.68
Bid price 1s	62.24	62.63	91.68	138.10
Bid price 2s	62.24	62.67	91.68	138.10
Bid price fixed	23.77	14.57	43.01	82.58
Unit social value	-32.69	-22.60	-65.62	-115.83
Winning technology (1s, 2s)	yes	no	no	no
Winning technology (fixed)	no	yes	no	no

Source: Own calculation

The ordering of the unit social values did not change with the introduction of externalities in the model, but the differences between the technologies have increased relative to the “no externality scenario”. Because there were no changes in the bid, in the "baseline scenario" if a technology neutral auction is held PV would win in a sliding premium scheme and onshore wind would dominate a fixed premium auction, which means that only the latter is allocatively efficient.

The biases between the analysed technologies are shown in Figure 5.

Figure 5: Pairwise and average biases between technologies in the baseline scenario with reference values in 1s sliding premium (up), in 2s sliding premium (middle) and in fixed premium (down) schemes, EUR/MWh

1s sliding premium

	PV	Onshore wind	Offshore wind	Biomass	
PV		-10.48	3.49	7.29	
Onshore wind			13.97	17.76	
Offshore wind				3.80	
Biomass					
Average					9.46

2s sliding premium

	PV	Onshore wind	Offshore wind	Biomass	
PV		-10.52	3.49	7.29	
Onshore wind			14.01	17.81	
Offshore wind				3.80	
Biomass					
Average					9.49

fixed premium

	PV	Onshore wind	Offshore wind	Biomass	
PV		-0.90	13.69	24.33	
Onshore wind			14.58	25.23	
Offshore wind				10.64	
Biomass					
Average					14.89

Source: Own calculation

Interestingly, with the introduction of the external costs the hierarchy between different technologies in terms of bias changed drastically. In all remuneration schemes biomass enjoys the largest relative advantage, followed by offshore wind, PV and onshore wind. This ordering is the exact opposite that was observed in "laboratory" and "no externality" scenarios which proves that externalities are a very important determinants of technology bias. It is also important to highlight that in fixed premium onshore wind wins the auction despite the fact, being the most disadvantaged technology.

In the "baseline" case the average bias between all technologies is higher in the fixed premium case, than in the sliding premium schemes, mainly because of the larger difference between solar PV and onshore wind, solar PV and biomass, onshore wind and biomass, and offshore wind and biomass. On the other hand, the bias between PV and onshore wind is significantly lower in the fixed premium scheme. Because of the larger average bias, with respect to general efficiency, sliding premium scheme performs better than fixed premium.

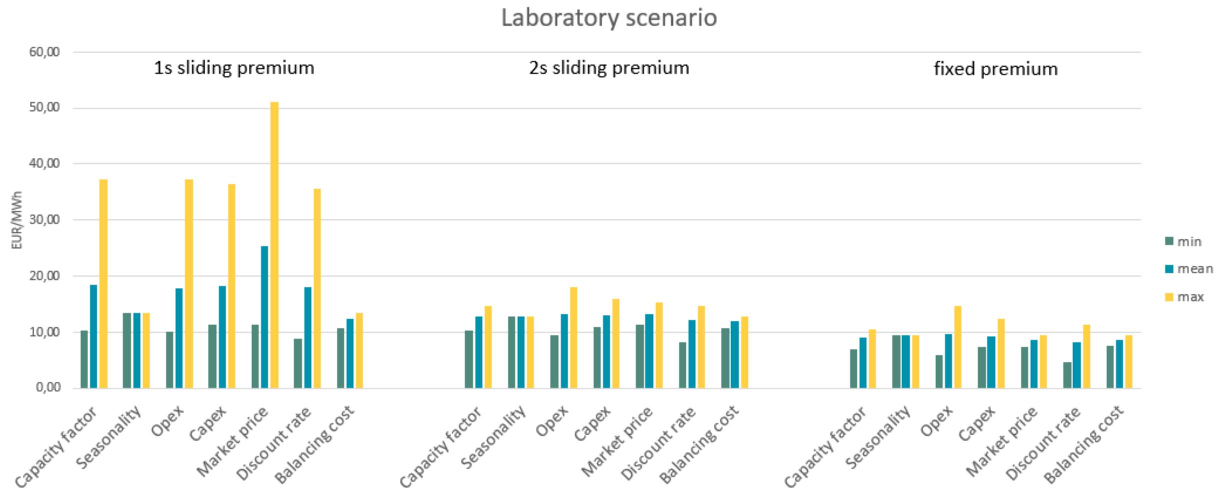
From these results another important conclusion can be drawn. Even though in the "baseline scenario" sliding premium leads to on average smaller biases between the technologies, it is fixed premium which results in socially optimal selection. Note that this result not necessarily means, even in this setup, that fixed premium should be the preferred auction format if the policymaker's aim is to reduce technology bias, as if significant cost reduction occurs for offshore wind, it is highly likely that fixed premium would underperform relative to sliding premium. However, from these results it is evident that general and allocative efficiency do not evidently go hand in hand.

3.4 Sensitivity estimations

In Section 2.3 of the report the most important input values of the model were introduced, but also some sensitivity values were presented. This section summarises the results of the sensitivity model runs based on those values, with no change in the auction design itself. These results show how different inputs influence the calculated biases of Section 3.1-3.3.

Figure 6 is a general summary graph about the input sensitivities based on the average bias between all technologies, in all three of the introduced scenarios. The left-hand side of each graph shows the results in a one-sided sliding feed in premium scheme, the middle stands for the two-sided, while the right-hand side for fixed premium scheme.

Figure 6: The minimum, average and maximum values of average bias between all technologies in the three investigated remuneration schemes for the laboratory (up), no externality (middle) and baseline scenarios (down)



Source: Own calculations

For each remuneration scheme the variables that were tested are listed on the horizontal axis. In case of the capacity factor for example all setups were estimated that included the capacity values for the different technologies listed in Section 2.3 and holding all other general input variables and design elements constant. For all the estimated scenarios the average technology bias between all technologies were calculated, similarly to Figure 5 (green value). Figure 6 shows three values for each input, the mean, which is the mean of all average technology biases, and the minimum and the maximum of the same values.

By looking at the result the same pattern is identifiable, that was concluded based only on the three main scenarios with reference values. In the "laboratory" and "no externality scenarios", the average bias is in general lower for fixed premium, while in the "baseline scenario" for sliding premium. By analysing the range of the values, it is also identifiable that in almost all cases the bias is robust to the different inputs, there are no large differences observable between the maximum and minimum values for most of the model estimations.

There are some cases however, where larger differences are present. In the one-sided sliding premium, for some inputs, spikes up to 40-50 EUR/MWh are observable for maximum bias values, mostly at the "laboratory scenario", but at same instances for the "no externality scenario" as well. The explanation for these spikes originates from the fact that in many scenarios (mainly in laboratory case), with the investigated input values, a given technology (in our case only PV or wind), were able to operate on the market without financial support. In the one-sided feed-in premium case if a technology is mature enough to operate without support than the optimal bid would be 0 EUR/MWh (assuming perfect knowledge of future market prices), as all bid-prices between 0 and the breakeven point result in the same revenue, but the 0 bid maximises that chance of winning. As a result, it can happen that one technology only needs a little support, while the other none, but despite this fact there is 30-40 EUR/MWh difference between the bid prices of the two technologies, thus resulting in a large bias (on a per unit bases), between them.

Similar barriers occur in the fixed premium case as well. There is no such "jump" as in the one-sided feed in premium scheme, so no such spikes are present, however, when technologies reach the zero support phase, the fixed premium scheme is also not able to differentiate any more between them, which may be necessary because of the different social values. The only system which is not affected by the described market maturity effect at all, is the two-sided sliding feed in premium, where bid price decreases gradually even after zero support point is reached. One can argue, that auction is not necessary when technologies need no support, however for example in Portugal, PV auctions are organised because of the scarce grid connection capacities, and promoters bid well below the expected market price (del Rió et al., 2019), that is why those cases are also relevant.

Also, there are some input variables which can cause large differences in the average bias, based on the sensitivity cases. These variables are mainly the discount rates, the market price, and the environmental harm. Table 18 contains a more detailed analysis about the relevance of the different input variables. Sensitiveness of the results to the variation of different input variables were categorised based on the difference between maximum and minimum values of the average bias presented in Figure 6, for each variable. Where the difference between the maximum and the minimum were less than 1 EUR/MWh, its sensitivity was categorized as marginal, between 1 and 5 EUR/MWh as low, between 5 and 10 EUR/MWh as moderate, and for more than 10 EUR/MWh as high. In all cases, the remuneration scheme is marked with a *, which is the most robust to the variation of the investigated input variable.

Table 18: Sensitivity of model results to variation of different inputs in the different remuneration schemes and scenarios (lowest values marked with *)

	Laboratory			No externality			Baseline		
	1s sliding	2s sliding	fixed	1s sliding	2s sliding	fixed	1s sliding	2s sliding	fixed
Capacity factor	high	low	low*	moderate	low	low*	moderate	low*	low
Seasonality of production	marginal	marginal	marginal*	marginal	marginal	marginal*	marginal*	marginal	marginal
OPEX	high	moderate*	moderate*	moderate*	moderate*	moderate*	moderate*	moderate	moderate
CAPEX	high	moderate*	moderate	moderate	moderate	moderate*	moderate	low*	moderate
Market price	high	low	low*	moderate	moderate	low*	high	low*	moderate
Discount rate	high	moderate*	moderate	moderate*	moderate	moderate	high*	high	high
Balancing costs	low*	low	low	low	low	low*	low	low*	low
Res penetration	-	-	-	moderate	moderate	low*	low	low	low*
Grid connection costs	-	-	-	-	-	-	moderate	moderate	moderate*
Environmental harm	-	-	-	-	-	-	high	high	moderate*

Source: Own calculations

From the table several important conclusions can be drawn. First, that there are only a few numbers of cases where the range of the bias is larger than 10 EUR/MWh, and most of them is associated with the one-sided sliding premium scheme, because of mature technology scenarios described earlier. The only exceptions are the discount rate in all remuneration scheme in the "baseline scenario", and the environmental harm variable, for sliding premium in the "baseline" too. This means, that even if different input values are used, it is expected that the average bias between all technologies will not vary drastically.

On the other hand, the sensitivity of a given input is in most of the cases dependent on the fact, whether the laboratory, no externality or baseline scenario is used. Such variation is observable by market price, discount rate, or renewable penetration. However, there are some inputs variables where the range of bias is relatively constant across the three scenarios such as CAPEX, OPEX, balancing costs or capacity factor.

By looking at the comparison of the different remuneration schemes, it is also difficult to identify strong patterns, whether two-sided sliding or fixed premium is less vulnerable to the changes of the analysed input variables. For most of the variables different remuneration schemes provide less variation in "Laboratory", "No externality" and "Baseline scenarios". The only exceptions are capacity factor, RES penetration, grid connection costs and environmental harm, as in all those cases fixed premium leads to lower variation of the bias.

4 Effect of different auction design elements on technology bias

Several important auction design elements were highlighted which may contribute to the bias between technologies in Section 2.2.3. In this section the separate effects of these features are analysed in more detail.

4.1 Length of support period

With respect to the length of support period, four different cases were tested, when support is paid for 10 (very short), 15 (short), 20 (reference) and 25 (long) years. Similarly to the previous sections, results of the "laboratory", "no externality" and "baseline scenarios" are presented separately. Several sensitivity runs were also made, where the result for different market prices and RES penetration were tested.

4.1.1 Laboratory scenario

Table 19 summarises the bid prices and the unit social values for all remuneration schemes and all technologies, in the laboratory scenario, assuming different support period lengths.

Table 19: Bid-prices and unit social values of all technologies when reference values were considered for different support period lengths, EUR/MWh

	PV				Onshore wind				Offshore wind				Biomass			
	Ref.	short	long	very short	Ref.	short	long	very short	Ref.	short	long	very short	Ref.	short	long	very short
Bid price 1-sided	54.5	54.9	54.2	56.3	62.2	63.5	61.5	66.7	91.4	98.3	87.5	113.1	138.1	153.1	129.5	184.7
Bid price 2-sided	55.7	55.4	55.9	56.3	62.4	63.5	61.8	66.7	91.4	98.3	87.5	113.1	138.1	153.1	129.5	184.7
Bid price fixed premium	6.8	8.1	6.0	10.9	13.0	15.7	11.5	21.0	41.4	49.7	36.6	66.8	82.6	99.2	73.0	133.3
Unit social value	-5.2	-5.2	-5.2	-5.2	-10.5	-10.5	-10.5	-10.5	-32.4	-32.4	-32.4	-32.4	-64.4	-64.4	-64.4	-64.4

Source: Own calculations

It can be observed, that the unit social value is the same for all support lengths as in the reference, because change in support length does not influence social costs and benefits. The only difference between the cases occurs through the change of the bid prices. In the analysed scenarios there is a negative relationship between the length of the support period and the bid price. The reason behind this connection is that with shorter support period, power plants have smaller time frame to cover their costs from support, so promoters bid higher. Similarly to the reference case, all investigated setup in the "laboratory scenario" are allocatively effective, as PV is the most beneficial technology and the winner of the auction in every setup.

In Table 20 the average bias between all technologies for different support periods are shown.

Table 20: The average bias between all technologies when reference values were considered for different support period lengths, EUR/MWh

	Reference case	short	long	very short
Average bias 1s	13.4	21.7	8.7	38.7
Average bias 2s	12.8	21.4	7.9	38.7
Average bias fixed	9.4	18.0	4.5	35.6

Source: Own calculations

In general, all pairwise biases become larger if the support period shortens in all remuneration schemes. Consequently, the average bias between all four technologies is the smallest when long (25 years) support period is considered and becomes larger with shorter support periods. Based on the results the average biases between the technologies are very sensitive to changes of support period, there is a more than 25 EUR/MWh difference between the average bias if 10 years or 25 years of support is assumed both in sliding and fixed premium schemes.

Also, several sensitivities were estimated with varying market prices[14]. The results of these calculations are summarised in Table 21. In the table average biases of different scenarios are compared.

Table 21: The average, minimum and maximum of the average biases, when sensitivities for different market prices were considered, for different support period lengths, EUR/MWh

	1s sliding				**2s sliding**				**fixed**			
	Ref.	**short**	**long**	**very short**	**Ref.**	**short**	**long**	**very short**	**Ref.**	**short**	**long**	**very short**
average bias	25.31	32.25	18.53	46.73	13.18	21.71	8.29	38.94	8.64	14.79	5.97	29.20
min bias	11.33	19.80	6.54	37.31	11.33	19.80	6.54	37.31	7.37	8.95	4.35	16.81
max bias	51.17	55.27	40.31	64.19	15.36	23.90	10.45	40.81	9.40	17.95	9.08	35.57
Range (max-min)	39.84	35.47	33.77	26.88	4.03	4.10	3.91	3.51	2.03	9.01	4.73	18.76

Source: Own calculations

The sensitivities show that two-sided sliding premium and fixed premium schemes are more robust to sensitivities with respect to average bias, than one-sided premium, because of the maturity effect described in Section 3.4. However, an important difference is identifiable between fixed premium and two-sided sliding feed in premium as well. The robustness of bias in the latter schemes is relatively constant for the different support lengths, the range of the min-max biases are in all cases around 3.5-4.1 EUR/MWh. In the fixed premium setup however, the range of min-max bias is highly dependent on the support period as with 20 years it is only 2 EUR/MWh, while with 10 years it increases to almost 19 EUR/MWh. The possible explanation for this that bid price thus the bias is more affected by the market price in the fixed setup, than for sliding premiums thus it is more sensitive for changes of it.

[14] In the laboratory scenario the RES penetration is always 0, so it is not possible to conduct sensitivities for it.

4.1.2 No externality scenario

The results of the same calculation for the "no externality" scenario is presented in Table 22.

Table 22: Bid-prices and unit social values of all technologies when reference values were considered for different support period lengths, EUR/MWh

	PV				Onshore wind				Offshore wind				Biomass			
	Ref.	**short**	**long**	**very short**	**Ref.**	**short**	**long**	**very short**	**Ref.**	**short**	**long**	**very short**	**Ref.**	**short**	**long**	**very short**
Bid price 1s	62.2	67.6	58.6	77.9	62.6	64.3	61.7	68.4	91.7	99.1	87.5	114.9	138.1	153.1	129.5	184.7
Bid price 2s	62.2	67.6	58.6	77.9	62.7	64.3	61.8	68.4	91.7	99.1	87.5	114.9	138.1	153.1	129.5	184.7
Bid price fixed	23.8	28.5	21.0	38.4	14.6	17.5	12.9	23.5	43.0	51.6	38.0	69.4	82.6	99.2	73.0	133.3
Unit social value	-16.8				-11.7				-33.6				-64.4			

Source: Own calculations

The bid-prices in the "no externality scenario" are behaving similarly to the "laboratory scenario" as they are higher for all technologies if the support period is shorter. Because of the introduced cannibalisation effect in the no externality scenario onshore wind is the most beneficial technology. It was already concluded, that in the reference setup only fixed premium scheme leads to efficient allocation as in sliding premium PV would emerge victorious in Section 3.2. This selection efficiency however is not independent of the support period length. If support length is short, or very short, even in the sliding premium schemes onshore wind would dominate the auction. The winner of the fixed premium scheme is independent of support length, always onshore wind.

With respect to average bias the dynamics are the exact same as in the "laboratory scenario", that a decrease in support period decreases the average bias.

Table 23: The average bias between all technologies when reference values were considered for different support period lengths, EUR/MWh

	reference	short	long	very short
Average bias 1s	15.3	21.1	12.3	15.3
Average bias 2s	15.3	21.1	12.3	15.3
Average bias fixed	8.1	15.5	3.7	8.1

Source: Own calculations

This finding is even more interesting in this "no externality scenario", as it was already shown that allocative efficiency occurs in the sliding premium systems only when support period is short or very short, but in these cases average technology bias is significantly higher, relative to the setups where longer support periods are assumed. This means that for sliding premium schemes shorter support periods are allocatively more efficient, however in terms of general efficiency schemes with longer support lengths fair better.

The results considering sensitivities for RES penetration and market prices are summarised in

Table 24.

Table 24: The average, minimum and maximum of the average biases, when sensitivities for different market prices and RES penetration were considered, for different support period lengths, EUR/MWh

	1s sliding				2s sliding				fixed			
	Ref.	short	long	very short	Ref.	short	long	very short	Ref.	short	long	very short
average bias	19.13	24.09	15.66	39.14	15.67	20.68	12.13	36.14	8.12	13.87	5.22	30.55
min bias	12.80	12.80	8.74	35.13	12.80	12.80	7.88	34.78	6.23	6.23	3.68	20.70
max bias	46.00	46.00	44.03	58.70	19.06	24.21	16.99	38.71	9.40	17.95	5.27	35.57
Range (max-min)	33.21	33.21	35.29	23.57	6.26	11.41	9.11	3.93	3.17	11.72	1.58	14.87

Source: Own calculations

In the "laboratory scenario" it was concluded that bias of the fixed premium case is much more sensitive to alternative scenarios, than in the two-sided sliding premium case. This is however not true in the "No externality scenario" as in that setup, larger variation occurs in the two-sided scheme as well, so the identified difference between the two schemes disappear.

4.1.3 Baseline scenario

Table 25 present the general results for different support lengths in the "baseline scenario", where grid integration costs and environmental harm were also considered as externalities. As a result, the bid prices are the exact same as in the "No externality" scenario, however the unit social values are different, thus the biases as well between the technologies.

Table 25: Bid-prices and unit social values of all technologies when reference values were considered for different support period lengths, EUR/MWh

	PV				Onshore wind				Offshore wind				Biomass			
	Ref.	short	long	very short	Ref.	short	long	very short	Ref.	short	long	very short	Ref.	short	long	very short
Bid price 1s	62.2	67.6	58.6	77.9	62.6	64.3	61.7	68.4	91.7	99.1	87.5	114.9	138.1	153.1	129.5	184.7
Bid price 2s	62.2	67.6	58.6	77.9	62.7	64.3	61.8	68.4	91.7	99.1	87.5	114.9	138.1	153.1	129.5	184.7
Bid price fixed	23.8	28.5	21.0	38.4	14.6	17.5	12.9	23.5	43.0	51.6	38.0	69.4	82.6	99.2	73.0	133.3
Unit social value	-32.7	-32.7	-32.7	-32.7	-22.6	-22.6	-22.6	-22.6	-65.6	-65.6	-65.6	-65.6	-115.8	-115.8	-115.8	-115.83

Source: Own calculations

The results for average biases of the "baseline scenario" are different in many aspects form the "no externality" and the "laboratory" cases.

Table 26: The average bias between all technologies when reference values were considered for different support period lengths, EUR/MWh

	Reference case	short	long	very short
Average bias 1s	9.5	4.5	13.4	12.4
Average bias 2s	9.5	4.5	13.5	12.4
Average bias fixed	14.9	7.8	19.2	8.6

Source: Own calculations

In the previous two setups, for all cases when reference values were assumed and the variation of different support period lengths were tested, the average bias was lower for the fixed premium, than for sliding premium. In the "baseline scenario" however this is not any more the case as only when very short support periods are assumed, fixed premium performs better, for all other scenarios than sliding.

Also, the direct relationship between support period and average bias are broken as well, which can be seen in Table 26. The smallest bias occurs in the short support period in all remuneration schemes, both very short and long support times result in higher on average bias. This means that the relationship between the two factors is not monotonic anymore. The reason behind this phenomenon is that the general structure of the pairwise biases changes, as support periods shortens. In the long support period case biomass and offshore wind enjoy a relatively large advantage over onshore wind and PV, which decreases with shorter support periods, resulting in smaller average bias. Between short, and very short support period there is a drastic change, as bias shifts toward to benefit PV and onshore wind, relative to offshore wind and biomass in sliding premium, and toward biomass as well in fixed premium. This shift results in an increase in the average bias.

These results highlight a very important conclusion. It is visible that in the "baseline scenario" the effect of longer support period is quite the opposite on general efficiency compared to the "Laboratory" and "No externality scenarios". In the "baseline case" the average biases are smaller if supports are shorter, while in the "laboratory" and "no externality" cases the biases are higher. These results are the consequence of the starting point effect. In the first two auction setups the design granted and advantage for PV and onshore wind relative to offshore wind and biomass, which is the exact opposite of the "baseline scenario". Because the starting point in terms of bias is different, the same change of the support length results in completely different outcomes for average bias, in the "baseline scenario". These results highlight the importance of this starting point effect, as a given policy change is only evaluable if the biases of the starting point setup are evaluated as well.

The allocative efficiency is not affected by the introduction of externalities relative to "no externality" case, as in the "baseline scenario" still onshore wind is the most beneficial, and as bid prices are the same, so are the results of the auction. It is interesting to note however, that the contradictory nature of allocative efficiency and general efficiency ceases to exist in the "baseline scenario" for sliding premium too, as a 15-year long support period leads to efficient selection, but on top of that it is also associated with the lowest average bias in all remuneration schemes.

As a final point in Table 27, the sensitivities for RES penetration and market prices are presented.

Table 27: The average, minimum and maximum of the average biases, when sensitivities for different market prices and RES penetration were considered, for different support period lengths, EUR/MWh

	1s sliding				**2s sliding**				**fixed**			
	Ref.	**short**	**long**	**very short**	**Ref.**	**short**	**long**	**very short**	**Ref.**	**short**	**long**	**very short**
average bias	11.48	8.25	14.99	14.57	9.66	6.34	13.79	14.57	15.61	10.20	19.80	10.29
min bias	8.15	4.51	12.14	12.41	7.98	4.51	11.61	12.41	13.87	5.73	18.56	6.90
max bias	23.33	23.33	22.52	17.43	10.88	10.88	15.28	17.43	22.05	22.05	25.25	14.29
Range (max-min)	11.48	8.25	14.99	14.57	9.66	6.34	13.79	14.57	15.61	10.20	19.80	10.29

Source: Own calculations

The sensitivity cases also show that short support period is associated with the lowest bias on average, but in the fixed premium case the difference is very small between the short and very short setup.

For all remuneration schemes short support period is the most robust to different electricity market characteristics, as the range of biases are only 6-10 EUR/MWh depending on the scheme. Similarly, to the no externality the range of biases are not independent of the support length as for some support periods 15-20 EUR/MWh ranges are observable. In general, it can be concluded, that market characteristics matter a lot a when average bias is investigated for different support periods.

As a final conclusion for the "baseline scenario" it is important to highlight that the robustness pattern is different for the fixed premium schemes and sliding premiums. In all cases short support period is the most robust, but the highest range occurs when very short support period is assumed for the latter scheme, and in the case of long support in the former.

To summarise, with respect to support period several important conclusions can be drawn. Based on the results support period seems to be an important determinant of technology bias as if different support lengths are considered more than 10 EUR/MWh differences can be observable between the average biases. It was also showed that shorter support lengths favour PV and onshore wind more than offshore wind and biomass. As a result, in the "laboratory" and "no externality" scenarios longer support periods led to better general efficiency, while in the "baseline" shorter. The difference between the effects are the results of the starting point effect, which is a very important point to consider, when a design element is evaluated. In the "baseline" scenario, when externalities as well are considered, the modelling results show, that in all remuneration schemes a 15-year long support period is allocatively efficient, and the best performing in terms of general efficiency. However, it is important to highlight that with different input or design assumptions this finding does not necessarily hold.

4.2 Granted realisation period

The second analysed auction design element is the granted realisation period of the project. Please note that in the model it was assumed that granted realisation is always equal with the actual realisation, so there is no early completion or delay. With respect to project completion, numerous scenarios were considered. There are two in which all technologies have equal granted realisation periods (equal long, equal short), one where the fastest possible realisation was assumed for all technologies (fastest) and four scenarios where three technologies faces the reference realisation period but it is allowed for one technology to take significantly longer time for completion (PV long, Onh. wind long, Offsh. wind long, biomass long). On top of the reference results several sensitivities were estimated with varying RES penetration and market prices.

4.2.1 Laboratory Scenario

First the results of the “laboratory scenario are presented in Table 28.

Table 28: Bid-prices and unit social values of all technologies when reference values were considered for different granted realisation periods, EUR/MWh

	PV								Onshore Wind							
	Ref.	Equ-ally short	Equ-ally long	Fast-est	PV long	Onsh. wind long	Offsh. wind long	Bio-mass long	Ref.	Equ-ally short	Equ-ally long	Fast-est	PV long	Onsh. wind long	Offsh. wind long	Bio-mass long
Bid price 1s	54.5	54.5	57.8	53.5	56.6	54.5	54.5	54.5	62.2	61.2	64.4	58.6	62.2	65.6	62.2	62.2
Bid price 2s	55.7	55.7	58.7	54.6	57.7	55.7	55.7	55.7	62.4	61.4	64.5	59.0	62.4	65.6	62.4	62.4
Fixed	6.8	6.8	7.8	6.4	7.5	6.8	6.8	6.8	13.0	12.7	13.8	10.2	13.0	14.3	13.0	13.0
Unit social value	-5.2	-5.2	-5.8	-5.0	-5.6	-5.2	-5.2	-5.2	-10.5	-10.3	-10.8	-8.4	-10.5	-11.2	-10.5	-10.5
	Offshore wind								Biomass							
	Ref.	Equ-ally short	Equ-ally long	Fast-est	PV long	Onsh. wind long	Offsh. wind long	Bio-mass long	Ref.	Equ-ally short	Equ-ally long	Fast-est	PV long	Onsh. wind long	Offsh. wind long	Bio-mass long
Bid price 1s	91.4	88.7	92.7	90.2	91.4	91.4	97.4	91.4	138.1	135.5	139.4	136.8	138.1	138.1	138.1	143.9
Bid price 2s	91.4	88.7	92.7	90.2	91.4	91.4	97.4	91.4	138.1	135.5	139.4	136.8	138.1	138.1	138.1	143.9
Fixed	41.4	40.0	42.0	40.8	41.4	41.4	44.8	41.4	82.6	81.5	83.2	82.0	82.6	82.6	82.6	85.4
Unit social value	-32.4	-32.0	-32.5	-32.3	-32.4	-32.4	-33.7	-32.4	-64.4	-64.7	-64.2	-64.5	-64.4	-64.4	-64.4	-64.1

Source: Own calculations

In general, the change of the realisation period shifts the projects in time, thus resulting in simultaneous bid price and unit social value change. Based on the assumed price pattern in the investigated setup if the realisation period become shorter, a decrease of the bid prices can be observed in all remuneration schemes. The changes are moderate, as for solar PV for example bid prices range between 53.5 EUR/MWh and 57.8 EUR/MWh. The differences in the unit social values are somewhat smaller, around 1 EUR/MWh.

The dynamics of these changes are relatively similar across the technologies, which results in the fact that in all remuneration schemes and in all setup, PV bids the lowest, so the investigated cases are allocatively efficient.

Based on the bid prices and unit social values Table 29 presents the average bias between all technologies.

Table 29: The average bias between all technologies when reference values were considered for different granted realisation periods, EUR/MWh

	Reference case	equal short	equal long	fastest	PV long	owind long	offwind long	biomass long
Average bias 1s	13.44	11.74	12.72	13.16	12.57	12.98	14.23	16.48
Average bias 1s	12.84	11.13	12.23	12.52	12.08	12.4	13.63	15.88
Average bias fixed	9.4	8.55	9.54	9.16	9.24	9.29	9.76	10.99

Source: Own calculations

By shortening the realisation period, the results show that the advantage of PV relative to other technologies in the auction becomes smaller. This effect is less relevant with respect to onshore wind, however stronger for offshore wind and biomass. Also, the bias between the other technologies decreases as well. Because of that, those results are faring better in terms of general efficiency with respect to bias, where realisation periods are shorter. Of course, the dynamics between the technologies are not that simple as also the differences of realisation periods matter. To give an example the lowest average bias is achieved in the equal short scenario, even though the realisation periods for solar PV and onshore wind are smaller in the fastest case. The variation of biases however is not large, only around 3.5 EUR/MWh. For all estimated scenarios fixed premium result in lower average bias. It is also interesting to highlight that highest biases are reached when offshore wind, or biomass is allowed for significantly longer realisation period.

4.2.2 No externality scenario

In the "no externality scenario" cannibalisation of prices for PV and Wind were allowed. Table 30 summarises the results with respect to bid prices and unit social value in this setup.

Table 30: Bid-prices and unit social values of all technologies when reference values were considered for different granted realisation periods, EUR/MWh

	PV								Onshore Wind							
	Ref.	**Equ-ally short**	**Equ-ally long**	**Fast-est**	**PV long**	**Onsh. wind long**	**Offsh. wind long**	**Bio-mass long**	**Ref.**	**Equ-ally short**	**Equ-ally long**	**Fast-est**	**PV long**	**Onsh. wind long**	**Offsh. wind long**	**Bio-mass long**
Bid price 1s	62.2	62.2	66.0	61.0	64.7	62.2	62.2	62.2	62.6	61.6	64.7	59.2	62.6	65.9	62.6	62.6
Bid price 2s	62.2	62.2	66.0	61.0	64.7	62.2	62.2	62.2	62.7	61.7	64.7	59.3	62.7	65.9	62.7	62.7
Fixed	23.8	23.8	28.8	22.1	27.1	23.8	23.8	23.8	14.6	14.1	15.5	11.5	14.6	16.1	14.6	14.6
Unit social value	-16.8	-16.8	-19.8	-15.7	-18.8	-16.8	-16.8	-16.8	-11.7	-11.4	-12.1	-9.4	-11.7	-12.5	-11.7	-11.7
	Offshore wind								**Biomass**							
	Ref.	**Equ-ally short**	**Equ-ally long**	**Fast-est**	**PV long**	**Onsh. wind long**	**Offsh. wind long**	**Bio-mass long**	**Ref.**	**Equ-ally short**	**Equ-ally long**	**Fast-est**	**PV long**	**Onsh. wind long**	**Offsh. wind long**	**Bio-mass long**
Bid price 1s	91.7	89.0	92.9	90.5	91.7	91.7	97.7	91.7	138.1	135.5	139.4	136.8	138.1	138.1	138.1	143.9
Bid price 2s	91.7	89.0	92.9	90.5	91.7	91.7	97.7	91.7	138.1	135.5	139.4	136.8	138.1	138.1	138.1	143.9
Fixed	43.0	41.5	43.7	42.4	43.0	43.0	46.8	43.0	82.6	81.5	83.2	82.0	82.6	82.6	82.6	85.4
Unit social value	-33.6	-33.0	-33.8	-33.4	-33.6	-33.6	-35.1	-33.6	-64.4	-64.7	-64.2	-64.5	-64.4	-64.4	-64.4	-64.1

Source: Own calculations

The main dynamics of bid prices are similar as in the "laboratory scenario" that shorter realisation periods are associated with lower bid prices. One important difference to identify that the variation in unit social values is larger in this scenario reaching 3 EUR/MWh for solar PV.

It was already concluded in Section 3.2 that in the reference setup only fixed premium is allocatively efficient as in the sliding premium schemes PV would win a mixed technology auction. The allocative efficiency of fixed premium does not vary between the different realisation periods, as in all cases onshore wind wins the auction. The situation however is completely different for sliding premium. There are several scenarios which turns out as allocative efficient, such as equal short, equal long, fastest and PV long, however in other case PV remains the winner, which are the reference, onsh. wind long, offsh. wind long and biomass.

In order to evaluate general efficiency average bias values are needed which are shown in Table 31.

Table 31: The average bias between all technologies when reference values were considered for different granted realisation periods, EUR/MWh

	Reference case	equal short	equal long	fastest	PV long	owind long	offwind long	biomass long
Average bias 1s	15.31	13.62	15.6	14.68	15.08	14.9	16.06	18.35
Average bias 1s	15.3	13.61	15.6	14.66	15.08	14.9	16.05	18.43
Average bias fixed	8.05	7.26	7.95	8.11	7.83	7.69	8.42	9.64

Source: Own calculations

The average biases of the fixed premium scheme are lower than in the "laboratory scenario" while for sliding premium the values became higher. This means, that the difference in terms of general efficiency between the two types of remuneration schemes increases in the "no externality scenario". On the other hand, the dynamics between the different setups are very similar to the "laboratory scenario" the smallest average bias is associated with the equal short case, while the highest when offshore wind and biomass were granted significantly longer realisation periods than other technologies.

4.2.3 Baseline scenario

In the "baseline scenario" grid integration costs and environmental harm were introduced as externalities. The main results of these scenario are summarised in Table 32.

Table 32: Bid-prices and unit social values of all technologies when reference values were considered for different realisation periods, EUR/MWh

	PV								Onshore Wind							
	Ref.	**Equ-ally short**	**Equ-ally long**	**Fast-est**	**PV long**	**Onsh. wind long**	**Offsh. wind long**	**Bio-mass long**	**Ref.**	**Equ-ally short**	**Equ-ally long**	**Fast-est**	**PV long**	**Onsh. wind long**	**Offsh. wind long**	**Bio-mass long**
Bid price 1s	62.24	62.24	65.98	61.04	64.70	62.24	62.24	62.24	62.63	61.60	64.74	59.18	62.63	65.90	62.63	62.63
Bid price 2s	62.24	62.24	65.98	61.04	64.70	62.24	62.24	62.24	62.67	61.66	64.75	59.33	62.67	65.90	62.67	62.67
Fixed	23.77	23.77	28.81	22.13	27.11	23.77	23.77	23.77	14.57	14.10	15.49	11.54	14.57	16.13	14.57	14.57
Unit social value	-32.69	-32.69	-35.25	-31.83	-34.41	-32.69	-32.69	-32.69	-22.60	-22.44	-22.87	-20.54	-22.60	-23.14	-22.60	-22.60
	Offshore wind								**Biomass**							
	Ref.	**Equ-ally short**	**Equ-ally long**	**Fast-est**	**PV long**	**Onsh. wind long**	**Offsh. wind long**	**Bio-mass long**	**Ref.**	**Equ-ally short**	**Equ-ally long**	**Fast-est**	**PV long**	**Onsh. wind long**	**Offsh. wind long**	**Bio-mass long**
Bid price 1s	91.68	89.04	92.94	90.48	91.68	91.49	97.71	91.68	138.10	135.51	139.43	136.79	138.10	138.10	138.10	143.87
Bid price 2s	91.68	89.04	92.94	90.48	91.68	91.49	97.71	91.68	138.10	135.51	139.43	136.79	138.10	138.10	138.10	143.87
Fixed	43.01	41.48	43.69	42.38	43.01	42.82	46.79	43.01	82.58	81.46	83.15	82.03	82.58	82.58	82.58	85.44
Unit social value	-65.62	-65.67	-65.51	-65.75	-65.62	-65.47	-65.97	-65.62	-115.83	-117.17	-115.17	-116.50	-115.83	-115.83	-115.83	-113.61

Source: Own calculations

Because grid integration costs and environmental harm arises as externalities, the bid prices are the same in the "no externality scenario" and the "baseline scenario", only the unit social values changed. However, in all setups onshore wind has the highest unit social value so that technology should win the auction. Because of the unchanged bid prices the same setups are allocatively efficient which were in the "no externality scenario."

Because of the changes of the unit social value however changes occur in the average biases which are presented in Table 33.

Table 33: The average bias between all technologies when reference values were considered for different granted realisation periods, EUR/MWh

	Reference case	equal short	equal long	fastest	PV long	owind long	offwind long	biomass long
Average bias 1s	9.46	11.44	9.35	9.92	9.59	10.84	9.25	7.1
Average bias 1s	9.49	11.47	9.36	10	9.61	10.84	9.27	7.12
Average bias fixed	14.89	16.23	15.2	15.02	15.4	15.41	14.32	12.35

Source: Own calculations

Remember that in the "baseline scenario" the ordering of pairwise biases change, resulting in the setup that biomass is the relatively most favoured technology. The ordering of the biases is quite the opposite as in the "laboratory" and "no externality scenarios". Because of these relative changes, for the different realisation periods the opposite results are observable than in the two previously presented scenarios. In Section 4.1 this was identified as the starting point effect, which plays a significant role for realisation period as well. Based on the results the lowest average bias occurs, when biomass has long realisation period, while the highest for equal short setup. Please note that these results lead to a state where in the sliding premium setup the most efficient scenario in terms of average bias is allocatively not efficient.

By summarising the results with respect to realisation period the following conclusions can be drawn. It was identified that changing realisation period results in change of both bid prices and unit social value. With our assumptions an increase of the bid price was identified when the realisation period became longer for a given technology. This result may seem to be a little counter intuitive, however note, that model is not able to deal with uncertainty, so all projects are always finished in time, which means that realisation period change only acts as a shift in time. The model results showed that in general shorter realisation period favours other technologies compared to PV and decreases the bias between the technologies in the "laboratory" and "no externality scenarios". In the baseline scenario however the same changes act toward increasing the bias, which means that the starting point effect is a very important concept for analysing efficiency for this case as well. When all elements are included in the "baseline scenario" it was identified that those setup leads to the lowest average bias which grants excess realisation time for biomass. This setup however is only allocatively efficient if the remuneration scheme is fixed premium. Finally, it is important to highlight, that realisation period is not an important determinant of technology bias in our model setup, as lower than 5 EUR/MWh difference were measured between the different cases.

4.3 Timing of the auction

As the production of many renewable technologies are highly dependent on weather, it was estimated with the model, whether the level of technology bias faced in a technology neutral auction is dependent on the timing of the auction within a year. In all scenarios investigated so far, the auction was timed in March, however other scenarios were tested where the tender was held in June, September, and December. The timing was tested in the "laboratory", "no externality" and "baseline scenarios" as well, but because the results are very identical across the three scenarios only the "baseline" case is presented in this report.

4.3.1 Baseline scenario

The main results of the reference setup are summarised in Table 34.

Table 34: Bid-prices and unit social values of all technologies when reference values were considered, for auctions organised at different times in a year, EUR/MWh

	PV				Onshore wind				Offshore wind				Biomass			
	MAR	JUN	SEPT	DEC	MAR	JUN	SEPT	DEC	MAR	JUN	SEPT	DEC	MAR	JUN	SEPT	DEC
Bid price 1s	62.24	62.42	62.62	62.45	62.63	62.67	62.55	62.60	91.68	91.74	91.55	91.65	138.10	138.04	138.09	138.11
Bid price 2s	62.24	62.42	62.62	62.45	62.67	62.71	62.60	62.64	91.68	91.74	91.55	91.65	138.10	138.04	138.09	138.11
Bid price fixed	23.77	23.77	23.95	24.16	14.57	14.39	14.17	14.74	43.01	42.82	42.53	43.18	82.58	82.27	82.16	82.82
Unit social value	-32.69	-32.66	-32.78	-32.96	-22.60	-22.44	-22.28	-22.73	-65.62	-65.45	-65.25	-65.76	-115.83	-115.58	-115.49	-116.02
Average bias 1s	9.46	9.47	9.43	9.49	9.46	9.47	9.43	9.49	9.46	9.47	9.43	9.49	9.46	9.47	9.43	9.49
Average bias 2s	9.49	9.49	9.45	9.52	9.49	9.49	9.45	9.52	9.49	9.49	9.45	9.52	9.49	9.49	9.45	9.52
Average bias fixed	14.89	14.92	14.93	14.90	14.89	14.92	14.93	14.90	14.89	14.92	14.93	14.90	14.89	14.92	14.93	14.90

Source: Own calculations

From the data it is visible that changing the time of the auction within the year influences the bid-prices and the unit social values simultaneously. This effect however differs between the technologies. Solar PV bids the lowest in March, onshore and offshore wind in September, while biomass in June. However, it is also evident that differences between the scenarios are very small, for all cases less than 0.5 EUR/MWh.

From the bid prices and unit values it is possible to calculate average biases between all technologies, which calculation is summarised in Table 35.

Table 35: The average bias between all technologies when reference values were considered, for auctions organised at different times in a year, EUR/MWh

	MAR	JUN	SEPT	DEC
Average bias 1s	9.46	9.47	9.43	9.49
Average bias 2s	9.49	9.49	9.45	9.52
Average bias fixed	14.89	14.92	14.93	14.90

The results show that the variation of biases is even smaller than the variation of bid prices, the average bias in the four evaluated cases can be considered as equal. Because the very small effects associated with timing, no sensitivity scenarios were estimated for this design element.

Based on the above results this report concludes that variation in timing only marginally changes unit social value and bid prices (less than 0.1 EUR/MWh in general), thus the average bias between all technologies. For these reasons it can be stated that timing of the auction is not an important determinant of technology bias.

4.4 Balancing cost payment responsibility

The next design element to investigate is the balancing cost payment responsibility. There are two main options analysed, first when balancing costs are totally paid by producers, and second when there is no balancing responsibility for renewable power plants, so these costs occur as externalities. With respect to balancing only the results of the "no externality" and baseline" results are discussed as there is no meaningful difference in the structure of results between the "laboratory" and "no externality scenarios". Also, sensitivities for different balancing cost values were also tested.

4.4.1 No externality scenario

Table 36 shows the main modelling results, based on balancing cost payment responsibility in all remuneration schemes in the "no externality scenario".

Table 36: Bid-prices and unit social values of all technologies when reference values were considered, with different actors responsible for balancing payments, EUR/MWh

	PV		Onshore Wind		Offshore wind		Biomass	
	Producer	**System**	**Producer**	**System**	**Producer**	**System**	**Producer**	**System**
Bid price 1s	62.24	61.02	62.63	60.04	91.68	89.77	138.10	138.00
Bid price 2s	62.24	61.02	62.67	60.18	91.68	89.77	138.10	138.00
Bid price fixed	23.77	22.55	14.57	12.08	43.01	41.10	82.58	82.48
Unit social value	-16.76	-16.76	-11.66	-11.66	-33.60	-33.60	-64.36	-64.36

Source: Own calculations

When producers are not required to pay for balancing, their costs decrease which result in lower bid prices. This general mechanism is observable in the results as in all remuneration schemes the bid prices are lower when the system is responsible for balancing.

As the unit social value is highest for onshore wind, this technology should win on the auction. It was already concluded, in Section 3.2, that when producers pay balancing costs, in the sliding premium scheme, PV would emerge victorious. This is not the case however when system is responsible for balancing. In the investigated setup, when producers have no balancing payment obligations, then also in the sliding premium cases onshore wind would win the auction. The reason for the change, that balancing costs of PV were assumed to be lower than for wind in the reference, so the bid price for wind decreases with a larger amount than of PV's.

Table 37 shows, that for all remuneration schemes, the average bias between all four technologies is larger when system is responsible for balancing. Note however that differences between the two cases are very small, less than 1 EUR/MWh for the sliding premiums and around 1 EUR/MWh for fixed premium. Also note that the average bias is significantly lower when fixed premium scheme is assumed in all cases.

Table 37: The average bias between all technologies when reference values were considered with different actors responsible for balancing payments, EUR/MWh

	Producer	System
Average bias 1s	15.31	15.95
Average bias 2s	15.30	15.92
Average bias fixed	8.05	9.10

Source: Own calculations

In general, the reference values for balancing costs were relatively low, and mostly relevant for mature European electricity markets. Because of this, several sensitivity scenarios were investigated, where 10 EUR/MWh balancing costs were assumed for different technologies. With these large differences, it is especially important to analyse the robustness of the above presented results to the changes. Table 38 shows the results of the sensitivity analysis when different balancing cost values were assumed.

Table 38: The average, minimum and maximum of the average biases, when sensitivities for different balancing costs were considered, with different actors responsible for balancing payments, EUR/MWh

	1s sliding		2s sliding		fixed	
	producer	**system**	**producer**	**system**	**producer**	**system**
average bias	14.23	18.04	14.22	18.02	7.39	11.59
min bias	13.15	15.95	13.15	15.92	6.43	9.10
max bias	15.31	19.59	15.30	19.57	8.05	13.51
range (max-min)	2.16	3.64	2.15	3.65	1.62	4.41

Source: Own calculations

The sensitivities lead to similar results as the reference case. For all remuneration schemes the average of the average biases is lower if producers pay for balancing. It is also visible that despite that fact that in some scenarios large balancing costs are assumed, the bias between the technologies remains mostly unaffected, the largest range between minimum and maximum bias is less than 4.5 EUR/MWh. It can be also concluded that the robustness of bias is mostly independent from the fact whether the producer or the system pays for the balancing in the sliding premium scheme as the difference between the range of biases is only 1.5 EUR/MWh. The difference is larger, almost 3 EUR/MWh for fixed premium. For all schemes, the range of values is smaller, when producers are responsible for balancing.

4.4.2 Baseline scenario

In the baseline scenario grid integration costs and environmental harm were also considered as externalities when the effect of balancing cost payment responsibility was investigated. The main results are summarised in Table 39. Similarly to the earlier presented results, the bid prices are the same as in the "no externalities" scenario, as those are unaffected when the externalities are introduced, and changes occur only in the unit social values, thus in the biases as well.

Table 39: Bid-prices and unit social values of all technologies when reference values were considered, with different actors responsible for balancing payments, EUR/MWh

	PV		Onshore Wind		Offshore wind		Biomass	
	Producer	**System**	**Producer**	**System**	**Producer**	**System**	**Producer**	**System**
Bid price 1s	62.24	61.02	62.63	60.04	91.68	89.77	138.10	138.00
Bid price 2s	62.24	61.02	62.67	60.18	91.68	89.77	138.10	138.00
Bid price Fixed	23.77	22.55	14.57	12.08	43.01	41.10	82.58	82.48
Unit social value	-32.69	-32.69	-22.60	-22.60	-65.62	-65.62	-115.83	-115.83

Source: Own calculations

When externalities are present the highest unit social value is associated with onshore wind. As a result, the allocative efficiency is the exact same as in the "no externality" scenario as the bid prices remained unchanged.

With respect to average bias between the four technologies some differences observable relative to the "no externality scenario" in Table 40.

Table 40: The average bias between all technologies when reference values were considered with different actors responsible for balancing payments, EUR/MWh

	Producer	**System**
Average bias 1s	9.46	8.37
Average bias 2s	9.49	8.44
Average bias fixed	14.89	13.97

Source: Own calculations

In the "baseline scenario" the setup where system pays for balancing dominates the setup where balancing costs are internalised, so the opposite of the "no externality setup". This is the result of the starting point effect. In all three remuneration schemes, the average bias is lower with approximately 1 EUR/MWh, when system is responsible. This leads to the interesting conclusion, that assuming the reference values as inputs, in the "baseline scenario" the outcome where system is responsible for balancing cots payments is more efficient in general terms and allocatively as well than the setup where producers. Also sliding premium results in lower biases than fixed premium.

Sensitivities for different balancing costs were also estimated, with results in Table 41.

Table 41: The average bias between all technologies when reference values were considered with different actors responsible for balancing payments, EUR/MWh

	1s sliding		2s sliding		fixed	
	producer	**system**	**producer**	**system**	**producer**	**system**
average bias	10.29	7.70	10.30	7.75	16.03	12.70
min bias	9.46	6.60	9.49	6.63	14.89	10.32
max bias	11.11	8.37	11.11	8.44	16.75	13.97
range (max-min)	1.65	1.77	1.62	1.81	1.86	3.65

Source: Own calculations

Similarly to the reference setup, with the sensitivities considered, the average bias is significantly lower when the system is responsible for balancing instead of producers. The difference is around 3 EUR/MWh in both the sliding premium and fixed premium schemes. The differences between the ranges are almost zero in the sliding premium schemes, between the setup when the system and the producers are responsible for balancing. This difference is also very small in the fixed premium case, less than 2 EUR/MWh, with internalised balancing cost framework being more robust. The results of the "baseline scenario" in this sense is more robust across the two payment types, than the "no externality scenario".

To conclude the analysis of balancing payment responsibilities, the main finding is that if low balancing costs are assumed, then changing the party responsible for balancing costs payments only leads to small change of the average bias. If balancing cost are reaching very high values (10 EUR/MWh) for some technologies, then this effect increases to 4-5 EUR/MWh. Based on these findings balancing cost payment responsibility is not a very important determinant of average technology bias thus general efficiency. Additionally, the results show that fixed premium is allocatively efficient in every setup, while sliding premium if the system is responsible for balancing. With respect to general efficiency, as a result of the starting point effect, in the "no externality scenario" those setup leads to lower biases, when producers are responsible, while in the "baseline scenario" when the system is responsible for balancing payments.

4.5 Grid integration cost compensation

Grid integration is associated with significant grid development costs, which in many cases can be considered as negative externalities, because producers are often not required to cover these costs. The next design element this report investigates is, whether the internalisation of these costs (by paying compensation after every unit of produced energy) would increase or decrease technology bias between renewables. Three different cases were analysed, when no grid integrations costs need to be paid by producers, when half of it should be covered by them and when all the grid integration cost must be covered. Because grid integration cost is only relevant factor in the "baseline scenario", only this scenario was analysed. Also, several sensitivities were estimated with different grid integration cost profiles.

4.5.1 Baseline scenario

The results with the reference values are summarized in Table 42.

Table 42: Bid-prices and unit social values of all technologies when reference values were considered, for different grid integration cost compensation payment requirements, EUR/MWh

	PV			**Onshore wind**			**Offshore wind**			**Biomass**		
	0%	**50%**	**100%**	**0%**	**50%**	**100%**	**0%**	**50%**	**100%**	**0%**	**50%**	**100%**
Bid price 1s	62.2	66.6	70.9	62.6	68.9	75.1	91.7	111.5	131.3	138.1	140.9	143.8
Bid price 2s	62.2	66.6	70.9	62.7	68.9	75.1	91.7	111.5	131.3	138.1	140.9	143.8
Bid price fixed	23.8	28.1	32.4	14.6	20.8	27.0	43.0	62.8	82.6	82.6	85.4	88.2
Unit social value	-32.7	-32.7	-32.7	-22.6	-22.6	-22.6	-65.6	-65.6	-65.6	-115.8	-115.8	-115.8

Source: Own calculations

By internalising grid integration costs, the bid prices of all technologies become higher. However, the grid integration costs are different across technologies, so the extent of bid price increase differ. In the 0% case, when grid costs are present, in the sliding premium auctions PV would emerge victorious even though onshore wind has the highest unit social value. The difference however between solar PV and onshore wind increases as grid connection costs became internalised. When 50% has to be paid, the bid price difference increase form 0.4 EUR/MWh to 2 EUR/MWh, and when 100% of the costs are covered by the producers than to 4 EUR/MWh between the two technologies. This means, that the sliding premium system would lead to inefficient selection with increasing advantage of PV in all three cases.

In the fixed premium scheme, the advantage of onshore wind decreases, but remains over PV. In the 0% case it is 9 EUR/MWh, in 50% case 7 EUR/MWh, and 5,5 EUR/MWh in the 100% setup. In fixed premium scheme the internalisation of grid connection costs also favours PV over wind, but it does not affect selection, the winner of the auction is always onshore wind.

By looking at Table 43, it is identifiable that when more of the grid connection cost is internalised, the average bias between the four technologies increases in the sliding premium schemes. In fixed premium there is no major difference between the 0% and 50% setups, but if the total costs are internalised it leads to significantly higher bias as well. Based on the modelling results the most unbiased auction with the assumed inputs when grid integration costs are present in the system as externalities for the producers in the sliding scheme and when 50% of the costs needs to be covered by the producers in the fixed scheme. By comparing the remuneration schemes, it can be concluded that sliding premium leads to lower average biases, however efficient selection of technologies only occurs in the fixed premium scheme. This means that like in many examined cases, the most efficient outcome in terms of general efficiency, is allocatively not efficient.

Table 43: The average bias between all technologies when reference values were considered, for different grid integration cost compensation payment requirements, EUR/MWh

	0%	50%	100%
Average bias 1s	9.5	12.6	21.3
Average bias 2s	9.5	12.6	21.3
Average bias fixed	14.9	14.6	23.1

Source: Own calculations

Similarly, to the other design elements, several sensitivities were estimated with respect to grid integration cost payment responsibility. In the different sensitivities, alternative values for grid integration costs were assumed. Before presenting the results, it is important to highlight however, that these alternative scenarios are more artificial than in the earlier cases, as such situations were tested, when the grid integration costs are equal, or the costs differences are half of the reference between technologies. In this sense these alternative estimations only serve the purpose to show, how different grid integration cost structures affect the bias. The results of the sensitivities are summarised in Table 44.

Table 44: The average bias between all technologies when reference values were considered for different grid integration cost compensation payment requirements, EUR/MWh

	1s sliding			**2s sliding**			**fixed**		
	0%	**50%**	**100%**	**0%**	**50%**	**100%**	**0%**	**50%**	**100%**
average bias	13.98	15.54	18.77	13.99	15.54	18.77	16.88	17.41	20.59
min bias	9.46	12.60	17.15	9.49	12.60	17.15	14.18	14.61	18.97
max bias	17.39	17.39	21.25	17.40	17.40	21.25	19.22	19.22	23.07
range (max-min)	7.93	4.80	4.10	7.92	4.80	4.10	5.04	4.61	4.10

Source: Own calculations

The analysed sensitivities lead to a slightly different conclusion than the reference case. With the different grid connection costs considered, on average, the smallest bias occurs if none of the grid integration cost is internalised, which increases with the extent of internalisation, in all three remuneration schemes. Remember that with reference values in fixed premium scheme the setup with 50% internalisation rate was slightly more efficient with respect to average bias than the 0% setup.

The range of biases are not independent from which market participant is responsible for the payment of grid integration costs. In the 0% case the range is relatively high, 8 EUR/MW in the sliding premium and 5 EUR/MWh in the fixed premium. If compensation payments are introduced for grid integration however, the biases become more robust. In the sliding premium scheme, the range of biases reduces to a little less than 5 EUR/MWh, while in the fixed premium to 4 EUR/MWh. This means that the range of biases varies more in the sliding premium system.

To conclude the first important finding is that as grid integration costs are higher for wind than for PV in our data, the internalisation of these costs leads to the relative advantage of PV over wind compared to the reference case. As a result, all analysed cases in the sliding premium schemes are allocatively inefficient as PV would emerge as winner from the auction. This dynamic occurs in fixed premium as well, but the effect is not large enough to allow PV to bid lower than onshore wind so even the 100% case is allocatively efficient. In terms of general efficiency if more payment is required by the producers the average bias increases in the sliding premium. General efficiency of 0% and 50% is almost equal in fixed premium but 100% cost integration is faring worse in this setup as well. In general, it can be concluded that grid integration costs compensation payment is an important determinant of bias as a difference of 7-12 EUR/MWh is identifiable between the analysed setups.

4.6 Environmental harm compensation

The completion and operation of a renewable power plant bears several external costs to the society. These external costs (excluding grid connection costs) are summarised in the environmental harm variable. One theoretically possible auction design element is that producers have to pay a compensation for the harm the powerplant is causing to the society. Similarly, to the grid integration costs 3 separate cases were tested, when 0%, 50%, or 100% of the environmental harm needs to be covered by the producers. Also, as the environmental harm is only non-zero in the "baseline scenario", only this case was modelled. Sensitivity scenarios were also run for different environmental harm values.

4.6.1 Baseline scenario

The results of the main estimation are summarised in Table 45.

Table 45: Bid-prices and unit social values of all technologies when reference values were considered, for different environmental harm compensation payment requirements, EUR/MWh

	PV			Onshore wind			Offshore wind			Biomass		
	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%
Bid price 1s	62.2	69.1	75.9	62.6	63.4	64.2	91.7	92.5	93.4	138.1	168.5	198.8
Bid price 2s	62.2	69.1	75.9	62.7	63.4	64.2	91.7	92.5	93.4	138.1	168.5	198.8
Bid price fixed	23.8	30.6	37.4	14.6	15.3	16.1	43.0	43.9	44.7	82.6	112.9	143.3
Unit social value	-32.7	-32.7	-32.7	-22.6	-22.6	-22.6	-65.6	-65.6	-65.6	-115.8	-115.8	-115.8

Source: Own calculations

The results show that when more compensation is required from the producers, the bid price for different technologies increases, however the rate of increase is not equal between them. As based on the inputs PV is associated with a larger environmental harm than onshore wind, the bid price of the former grows at a larger extent if environmental harm is partly or fully internalised. This evolution is behind the fact that in the 0% case PV would win in the sliding premium auction, but in the 50% and 100% cases onshore wind would emerge victorious. Because onshore wind has the largest unit social value, the auction becomes allocatively efficient if environmental harm is at least partly internalised in the sliding premium schemes. In the fixed premium setup onshore wind would always dominate the auction independently of the harm internalisation rate.

Table 46: The average bias between all technologies when reference values were considered, for different environmental harm compensation payment requirements, EUR/MWh

	0%	50%	100%
Average bias 1s	9.5	13.6	27.9
Average bias 2s	9.5	13.6	27.9
Average bias fixed	14.9	10.6	26.1

Source: Own calculations

The evolution of average bias between the four technologies is very different between the remuneration schemes, which can be seen in Table 46. If the 0% and 50% setup is compared, the average bias increases if half of the harm is internalised by the producer, in the sliding premium scheme and decreases in the fixed premium. The reason behind these phenomena is that in the 0% case the auction is heavily biased toward biomass in all schemes compared to PV and onshore wind. The internalisation of environmental harm relatively disfavours biomass, in the fixed premium scheme with 50% internalisation, the difference between PV, onshore wind and biomass moves close to zero, which result in low average bias. The similar dynamics are present for the sliding premium however at larger magnitude, leading to a state where PV and onshore wind enjoy a relative advantage over biomass, which results in higher bias. These dynamics even lead to the case that when 50% of the environmental harm is internalised by producers, then fixed premium is more efficient in terms of average bias than sliding premium.

When 100% of the environmental harm is required to pay by the producers, then average bias between all technologies is the highest in all remuneration schemes as the above-described relative changes continue, so the auction starts to favour PV and wind relative to biomass. However, the average bias remains less in the fixed premium setup even in the 100% case.

Similarly to the other design elements, several sensitivities were estimated with respect to environmental harm compensation. In the different sensitivities, alternative values for environmental harm were assumed. Before presenting the results, it is important to highlight however, that these alternative scenarios are more artificial than in the earlier cases, as such situations were tested, when environmental harms are equal, or the costs differences are half of the reference between technologies. In this sense these alternative estimations only serve the purpose to show how different environmental harm values affect the bias in the technology neutral auctions. The results of the sensitivities are summarised in Table 47.

Table 47: The average bias between all technologies when reference values were considered for different environmental harm compensation payment requirements, EUR/MWh

	1s sliding			**2s sliding**			**fixed**		
	0%	**50%**	**100%**	**0%**	**50%**	**100%**	**0%**	**50%**	**100%**
average bias	15.66	18.38	23.63	15.67	18.38	23.63	15.48	15.74	21.62
min bias	9.46	13.60	21.02	9.49	13.60	21.02	9.33	10.56	18.84
max bias	21.30	21.30	27.87	21.31	21.31	27.87	18.85	18.99	26.05
range (max-min)	11.84	7.71	6.86	11.83	7.71	6.86	9.51	8.44	7.21

Source: Own calculations

The sensitivities show, that on average in the sliding premium schemes there is a clear hierarchy between the three cases, as lower environmental harm compensation leads to smaller bias between the technologies. With fixed premium the dominance of 50% internalisation is not as clear as when only the reference setup was considered, as the average value of the 0% and 50% cases are nearly equal.

The range of biases are in general high, in all cases larger than 5 EUR/MWh, but larger than 10 EUR/MWh values also occur. A general pattern, that the largest range is associated with the 0% percent case in all schemes, with increasing robustness for large compensation setups.

Summarising the report's findings about environmental harm compensation it can be concluded that this design element is an important determinant of technology bias. The range of the values in the different setups may reach 12-16 EUR/MWh. The main dynamics when larger share of environmental harm is internalised by the producer that wind start to fare better relative to PV and all technologies relative to biomass. As a result, when 50% of environmental harm is internalised sliding premium becomes allocatively efficient. However, it is important the note the 0% case is the most efficient in this scheme in terms of average bias, with the values that were used for modelling. Fixed premium is always allocatively efficient, reaching the lowest average bias if 50% of environmental harm is internalised. In this setup this scheme is even more efficient than sliding premium.

4.6.2 Simultaneous effect of grid integration cost and environmental harm compensation

As final point, two additional scenarios were estimated. In the first, producers are required to cover 50% of both grid integration costs and environmental harm, while in the second 100% of these two elements. In this sense these scenarios analyse the simultaneous effect of grid integration cost payment, and environmental harm compensation payment. For these special setups only the results for the reference scenario will be presented.

Table 48 presents the reference case of the "baseline scenario" and the two alternative specifications.

Table 48: Bid-prices and unit social values of all technologies when reference values were considered, for different environmental harm and grid integration cost compensation payment requirements, EUR/MWh

	PV			Onshore Wind			Offshore wind			Biomass		
	0% / 0%	50% / 50%	100% / 100%	0% / 0%	50% / 50%	100% / 100%	0% / 0%	50% / 50%	100% / 100%	0% / 0%	50% / 50%	100% / 100%
Bid price 1s	62.2	73.4	84.5	62.6	69.7	76.6	91.7	112.3	133.0	138.1	171.3	204.5
Bid price 2s	62.2	73.4	84.5	62.7	69.7	76.6	91.7	112.3	133.0	138.1	171.3	204.5
Bid price Fixed	23.8	34.9	46.0	14.6	21.6	28.5	43.0	63.6	84.3	82.6	115.8	148.9
Unit social value	-32.7	-32.7	-32.7	-22.6	-22.6	-22.6	-65.6	-65.6	-65.6	-115.8	-115.8	-115.8

Source: Own calculations

With the simultaneous internalisation of both grid integration costs end environmental harm a drastic increase in the bid price is observable in all technologies. The least affected however are onshore wind, where the sum of the two factors are the lowest based on our input data. As a result, in both mixed setups the selection is efficient as onshore win would win the auction, independently of the remuneration scheme.

Table 49: The average bias between all technologies when reference values were considered, for different environmental harm and grid integration cost compensation payment requirements, EUR/MWh

	0% / 0%	**50% / 50%**	**100% / 100%**
Average bias 1s	9.5	7.4	20.6
Average bias 2s	9.5	7.4	20.6
Average bias fixed	14.9	2.3	14.5

Source: Own calculations

Earlier in this report it was shown that 50% internalisation is the most beneficial in terms of general efficiency in fixed premium and 0% in sliding for both environmental harm and grid integration cost compensation. Table 49 shows that if there is a simultaneous 50-50% payment requirement present for all producers, that would lead to the lowest average bias observed, with even all original case compared. In the 50-50% setup the average bias in the sliding premium cases is 7.44 EUR/MWh, while for fixed premium it is only 2.25 EUR/MWh, which is the lowest shown value for average bias in the whole report. This also means that in terms of average bias, fixed premium performs significantly better than sliding premium.

Originally, in both setups when only the payment requirement of one factor was analysed, led to the conclusion, that 100% internalisation increases the average bias drastically. Therefore, it is not surprising to observe, that average bias in the 100%-100% setup is significantly higher than both in the 50-50%, and 0-0% setups. However, it is also important to note that in the 100%-100% setup fixed premium performs better than sliding premium.

4.7 Comparison of the auction design elements

In the final subsection the aim of this report is to provide a meaningful comparison between the six analysed auction design elements. It was already shown for several cases that because of the starting point effect there are no rule of thumbs, that how a change of a given design element would affect the bias thus general efficiency. For these types of conclusions, case by case analysis are required.

On the other hand, it is possible to evaluate the relevance of the different design elements in terms of bias. This is possible with the comparison of range of biases for all different cases when one design element was changed in the model. If the magnitude is high, it means that altering that design element may result in drastic average bias changes.

For the evaluation, a similar scale was used as for Table 18, that if the range of bias is less than 1 EUR/MWh the relevance of the given design element with respect to bias is marginal, if between 1 EUR/MWh and 5 EUR/MWh small, if between 5 EUR/MWh and 10 EUR/MWh moderate and if larger than 10 EUR/MWh than high. This evaluation was conducted for all three remuneration schemes, for the "baseline scenario" as that is the only scenario in which all six design elements were analysed. The results are summarised in Table 50.

Table 50: The relevance of the analysed design elements for technology bias in all three remuneration schemes, based on the reference values of the baseline scenario.

Relevance of design elements for technology bias in auctions	1-sided sliding premium	2-sided sliding premium (CfD)	Fixed premium
Support period	moderate	moderate	high
Granted realisation period	small	small	small
Timing of the auction	marginal	marginal	marginal
Balancing cost payment responsibility[15]	small	small	marginal
Grid integration cost compensation	high	high	moderate
Enviromental harm compensation	high	high	high

Source: Own calculations

Based on the model results, support period, grid integration cost and environmental harm compensation are the most important design elements which may influence technology bias, while the other three is associated with less influence.

With respect to the higher influence design elements the main conclusions of the model estimations were the following. In those cases when externalities were not considered the setups with higher support period resulted in lower bias, but after the introduction of externalities lower support times turned to be more beneficial. The reason behind this difference is the starting point effect. Using the reference values with externalities it was found that a 15-year long support period leads to the most efficient outcome.

For grid integration costs and environmental harm compensation, it is always possible to introduce such an internalisation rate that would minimise average bias between all technologies, however because of the starting point effect the optimal rate can only be determined on a case-by-case basis. Using reference values in the model it was found that the scenario when an 50% compensation is required for both grid integration costs and environmental harm simultaneously led to the most efficient outcome form the analysed cases.

It is important to note however, that these results are valid for the input values that were used in the modelling, several results proved that different outcomes may occur if the circumstances change. On the other hand, it is also important to note that this report provided a useful theoretical concept and practical tool as well, to analyse the effect of design element changes on technology bias, which can be used by policymakers.

[15] May reach moderate category if high balancing costs are considered.

5 Conclusion

The main aim of this report was to analyse how different renewable auction design elements in technology-neutral auctions favour different renewable technologies relative to each other. In a more formalised sense, to quantify technology bias between four selected technologies, which are solar PV, onshore wind, offshore wind and biomass.

Technology bias between two technologies was defined as the difference between the bid price of two technologies and the unit social value of two technologies. Bid prices are the values that project promoters would bid on the auction, while unit social value is the difference between the total social benefit and the total social costs of the project in per unit terms. To calculate the technology bias, an LCOE model was used. The model calculated the LCOE of different technologies, assuming various inputs, then based on the LCOE it was possible to estimate the bid prices and the unit social values, thus the technology bias as well.

The inputs of the model were based on different auction and market databases and values originating from relevant literature. It is important to highlight that the model was used for scenario analysis, which means that the input data that were used did not represent a selected country or energy system, instead the used modelling approach tried to show different types of general scenarios. In this sense this report does not provide answers to those type of question that what is the LCOE of PV, or what is the bias between PV and wind in the German auction. It focuses more on scenario comparison, like analysing the change in bias between two technologies in an assumed setup if for example the length of support period changes from 15 years to 20 years.

In this report, two types of efficiencies were analysed with respect to technology bias. These are general efficiency and allocative efficiency. Those setups were labelled more efficient based on general efficiency, where the average bias between all four technologies was lower. The average bias between all technologies were calculated as the unweighted average of pairwise technology biases. The concept of allocative efficiency is slightly different, as it is not associated with the bias between all technologies. Instead, it is about the question that when a technology neutral auction is held in an assumed setup, would the technology that is socially the most beneficial (having the largest social value), emerge victorious from the auction or not.

Three main scenarios were identified and evaluated, based on general and allocative efficiency. In all three scenarios, the same input values were used, which were labelled as reference case and described in more detail in Section 2.3. The first scenario was called the "laboratory scenario" in which externalities were assumed to be zero. Additionally, all technologies faced the same market price in this setup. In this sense the laboratory scenario is to some extent artificial, however, it provided a very good basis of our analysis. The second scenario was named "No externality", where externalities were also assumed to be zero, but price cannibalisation effects were introduced, which mean that if the share of PV or wind power plants increased in the energy system than it influenced the market value factor of these technologies, mainly reducing the market price of the respective technology. Finally, the third scenario was called "Baseline", where grid integration costs and environmental harm were introduced in the model, as externalities, based on literature values. In all scenarios a huge number of sensitivity cases were also estimated, with varying inputs.

In general, the effect of several auction design elements was investigated in the study. The main point of interest was the comparison of three different remuneration schemes, one-sided sliding feed in premium (when market price is higher than bid price, producer can keep the surplus), two-sided sliding premium (when market price is higher than bid price producer must pay back the surplus) and fixed premium. These three remuneration schemes were tested for all analysed setups. In addition to the remuneration, the effect of several additional design elements was investigated on technology bias, which were the length of support period, granted realisation period, timing of the auction within the year, balancing cost payment responsibility, grid integration cost compensation payment requirement and environmental harm compensation payment requirement.

First, the reference results for the three main scenarios were analysed in more detail. In the laboratory scenario solar PV was identified, as the most beneficial technology, and all three remuneration schemes were labelled as allocatively efficient, because solar PV producers were modelled with the lowest bid prices. The report identified that in the laboratory setup the ordering of technologies in terms of bias were PV>Onshore

Wind>Offshore Wind>Biomass, which means that PV would enjoy advantage over all technologies in a technology neutral auction. The average differences between the biases however turned to be significantly lower in the fixed premium scheme, which also resulted in lower average bias value for all technologies for this scheme.

With the introduction of cannibalisation effect, and different prices for technologies in the "no externality scenario" several important changes occurred. First that unit social value of onshore wind became larger than solar PV. This had important consequences on the allocative efficiency as in the "no externality scenario" in the fixed premium scheme onshore wind bid the lowest, however in the sliding premium schemes solar PV. As a result, in this setup only fixed premium turned to be allocatively efficient. The reason behind this finding is that with the introduction of cannibalisation, fixed premium scheme become biased toward onshore wind, while the sliding schemes remained biased toward PV. In terms of average biases and general efficiency fixed premium outperformed sliding premium in this setup as well.

As a final point the effect of introducing grid integration costs and environmental harm as externalities were investigated in the "baseline scenario". As in this setup the bid prices remained the same, and the ordering of the unit social values as well, still only fixed premium resulted in allocative efficiency. However, by introducing externalities the ordering of the technologies, in terms of technology bias, changed drastically to biomass > offshore wind > PV > onshore wind, in all remuneration schemes, which is the exact opposite of the ordering of the "laboratory" and "no externality scenarios". As a result, the average biases between all four technologies changed drastically resulting in the fact that in the "baseline scenario" sliding premium was associated with smaller average bias (higher general efficiency) than fixed premium.

From the above results two very important conclusions can be drawn. First, there is no clear hierarchy between the technologies in terms of bias in technology neutral auction, the ordering of technologies may be very dependent on the market setup and assumptions made. By introducing externalities into the system, the relative bias that the design offered to technologies changed drastically. The second important conclusion is that allocative efficiency and general efficiency are not complementary elements. The "baseline scenario" also showed that the fixed premium design is allocatively more efficient than the sliding premium design, however the latter schemes result on average lower bias between all technologies. This is the result of the fact that in the fixed premium setup the bias between solar PV and onshore wind were very small, which are the two technologies that have a real chance to win the auction (with their current maturity level). However, if all technologies are considered, the sliding premium scheme proved to be generally more efficient. This is an important insight, as this means that, if in the future offshore wind would become cheaper, it is possible that sliding premiums would be a more efficient system in terms of minimalizing technology bias, than fixed premium. Also, in many auction implementations it is the case that only onshore wind energy and solar PV energy are combined into the technology-neutral auction pool, meaning that this insight is already relevant in these cases.

On top of the reference case, several sensitivity scenarios for different inputs variables were tested. The list of the tested cases can be found in more detail in Section 2.3. Based on the sensitivity estimations this report concluded that in terms of general efficiency, two-sided sliding premium and fixed premium performs better than one sliding premium. In the one-sided scheme it often occurred that if one technology become mature (requires no support for operation) than its bid-price suddenly moved to 0, from a significantly higher level, resulting in very large biases in per unit terms.

By testing the robustness of all results to different input variables, it can be concluded that average bias between all technologies is relatively stable across all estimated cases. A more than 10 EUR/MWh variation in average bias only occurred for: 1) changes in discount factor in all schemes, 2) Changes in environmental harm in the sliding premium scheme only in the "baseline scenario", and 3) when the above-described maturity effect occurred in the one-sided feed in premium system. In terms of robustness, no clear conclusion can be drawn for the comparison of two-sided feed in premium and fixed premium. For some variable changes, the former was more robust, while for some other variable changes, it was the latter. The relative robustness often varied between the three main scenarios.

In the final section of the report, the effect of several different auction design elements on technology bias were investigated.

In terms of support period, a general pattern was identified that shorter support periods result in higher bid prices with the assumed inputs, as producers have less time to cover for the losses when the power plant operates on market basis after the support period ends. The results of the “laboratory scenario” showed that the average bias became lower when the support period increased in all schemes. The same dynamic was detectible in the “no externality scenario” however in this setup in the sliding premium schemes only those designs turned to be allocatively efficient when the support period was 10 or 15 years. Both in the “no externality” and “laboratory” case, the fixed premium scheme resulted in lower average bias than sliding premiums.

The results turned out to be more complicated in the “baseline scenario”. In this setup long support period led to the highest average bias, which became lower for shorter support lengths, however increased again when the support period shortened form 15 years to 10 years in all remuneration schemes. So, the general dynamic was the exact opposite of the “laboratory” and “no externality”, with a slightly different element when very short support period was considered. The main reason behind the opposite dynamic is the fact which were already described, that in the baseline case the ordering of technologies in terms of bias changed. The result, that 10-year support period led to higher bias comes from the fact that moving from long support period toward short, the advantage of biomass and offshore wind reduced relative to PV and onshore wind. In the 10-year case however, the latter two technologies enjoyed an advantage over the former two, which resulted in a higher on average bias. As a result of these two dynamics however in the “baseline scenario” a 15-year long support period led to allocative efficiency as well as to highest general efficiency, in all three schemes.

The results also show that the length of support period is an important determinant of technology bias, as depending on the scheme and analysed scenarios, the variation of average bias if support length is changed reached 9-11 EUR/MWh.

The analysis of the support period led to the general conclusion that “starting point” is a major determinant of how a change of the different design element affects technology bias. Assume that shorter support period would favour wind over PV within a given setup. If in the general auction design, PV enjoys an advantage over wind, then shortening the support period would decrease the bias, while in an auction setup where wind is favoured, a shorter support period would have the opposite effect. As a result, it is not possible to formulate such conclusions that a given design element would increase or decrease technology bias as it is always dependent on the starting point. This starting point effect resulted in the complete opposite dynamic in the “laboratory” and “no externality scenarios” relative to the “baseline” case.

The second analysed design element was the granted time for the completion of the project. Please note that in our model it was assumed, that producers always complete their project at the end of the granted realisation period, so there are no early finishes or delays. The results showed that bid prices are lower for shorter realisation periods, which is mainly the result of the market price assumptions used in the modelling.

As the starting point effect was explained in detail in the previous paragraphs, it shall suffice to highlight that the effect of granted realisation period on technology bias is heavily influenced by the starting point effect as well. In the “laboratory” and “no externality” scenarios, the setups that resulted in the lowest average biases were the ones in which realisation period was relatively short, for example when 24 months were allowed for all technologies, or when the fastest possible realisation was considered. On the other hand, in the “baseline scenario” in terms of general efficiency auction designs with longer realisation periods proved to be better. All the analysed cases turned out to be allocatively efficient for the fixed premium scheme, and many of the cases for the sliding premium scheme. Exceptions were the reference case, and when longer realisation period were granted for onshore wind, offshore wind or biomass in the “no externality” and “baseline scenarios”.

Despite similar dynamics, granted realisation period turned to be a less important determinant of technology bias than support period, as the variation between the different realisation setups only reached 3.5-4.5 EUR/MWh, depending on the scenario and remuneration scheme.

Also, the timing of the auction within the year was tested. This report concluded, that variation in timing only marginally changed unit social value and bid prices (less than 0.1 EUR/MWh in general), and hence the average bias between all technologies. For these reasons, it can be stated that timing of the auction is not an important determinant of technology bias.

For the last three design elements, the internalisation of different cost elements was investigated such as balancing costs, grid integration costs and environmental harm. For balancing cost, two separate setups were analysed: 1) when the system bears the balancing burden, and 2) when producers are responsible for paying balancing costs. A general pattern with respect to balancing was identified, that when producers are not responsible for balancing their costs reduces, resulting in lower bid prices. In the "no externality scenario" the average bias between all technologies was lower when producers were responsible for balancing, relative to the case when no payment were required from them. The situation changed, however, in the "baseline scenario" when grid integration costs and environmental harm were introduced as externalities, as in this setup bias was lower when producers were not responsible for balancing. The reason for the change is the already described starting point effect.

Note, however, that in both scenarios the difference between the average biases for all technologies was estimated small between the two payment responsibility types, reaching only 1 EUR/MWh. The main explanation behind this small effect was the low reference values (1-2 EUR/MWh), for the balancing costs of PV and wind. Because of that, such sensitivities were also investigated, when one or all weather dependent technologies faced a balancing cost of 10 EUR/MWh. In these setups, the effect of changing the party responsible for balancing on technology bias reached 5-6 EUR/MWh. Based on these results this report concluded, that balancing cost payment responsibility only influence technology bias, if balancing costs in the system are high, but even in such case only moderately.

Similar analysis was conducted for grid integration costs and environmental harm compensation. For both variables it was investigated how a compensation payment introduced for producers would affect bias. For both variables, three separate cases were compared, when 0%, 50% or 100% of the two cost elements were required to be paid by producers. As scenarios were defined such way, these designs elements were only analysed in the "baseline scenario". As the highest grid integration cost was associated with offshore wind, while highest environmental harm with biomass, the internalisation of grid integration costs and environmental harm would mostly reduce the advantage of those two technologies, relative to the others, in the auction respectively.

The results showed that the sole internalisation of grid integration costs does not help allocative efficiency, as it increased the bid price difference between onshore wind and solar PV relative to the 0% case. This means that the sliding premium scheme remained allocatively inefficient and the fixed premium scheme remained allocatively efficient even in the case when 100% of the grid connection costs were internalised. In terms of general efficiency sliding premium and fixed premium reacted differently to the internalisation of grid costs. In the sliding premium scheme, if more compensations were required by the producers, the average bias between all technologies increased, while in the fixed premium a slight decrease was observable from 0% to 50% and only if 100% was internalised the bias increased drastically. Grid integration costs compensation turned to be a significant determinant of technology bias as the range of biases between 0% and 100% cases reached 7-12 EUR/MWh.

For environmental harm, larger internalisation resulted in allocatively more efficient outcomes, as (based on our inputs) the costs internalised for PV were larger than those for onshore wind. As a result, even if only a 50% payment was required, the sliding premium scheme turned to be allocatively efficient, while fixed premium was already efficient in the 0% case. The average bias for all technologies was the lowest for all remuneration schemes when a 50% compensation was required. Environmental harm compensation turned to be a significant determinant of technology bias as the range of biases between 0% and 100% case reached 12-16 EUR/MWh.

The dynamics presented above lead to the conclusion that in terms of externalities, there should be an optimal level of compensation required for all schemes that would lead to the lowest average bias between the technologies. Unfortunately, this optimal level can only be determined on a case-by-case basis, and if all necessary inputs are known. It is, however, important to note that it is possible to combine these compensations. The results of the model estimations showed that the highest general efficiency of all modelled scenarios is achievable for all remuneration schemes when 50%-50% compensation was required for grid integration costs and environmental harm simultaneously.

To summarise, based on the findings of this report, two very important conclusions can be drawn for future policy makers. First, the effect of a change in a different design element on technology bias is highly dependent on the "starting point", that is on the extent of bias in the reference case. As a result, it is not possible to formulate general rules of thumb for policy solutions, as it is possible that a certain change would increase technology bias in one case but decrease it in another. For this reason, a case-by-case analysis is required if a policymaker's aim is to reduce bias between technologies. The second important conclusion is that aiming for allocative efficiency in terms of technology bias may result in completely different designs than aiming for general efficiency. It is necessary to separately analyse these two types of efficiency when comparing different auction designs. It was also found that internalisation of grid integration costs and environmental harm, alongside with the length of support period are those elements that possibly have the highest influence on technology bias.

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AURES II is a European research project on auction designs for renewable energy support (RES) in the EU Member States.

The general objective of the project is to promote an effective use and efficient implementation of auctions for RES to improve the performance of electricity from renewable energy sources in Europe.

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