Market Designs, Actor Decisions and Market Values: Assessment of Remuneration Mechanisms for Future Electricity System Scenarios

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***Abstract*—For reasons of climate protection requirements, future energy systems will have to comprise very high shares of variable Renewable Energy Sources (vRES). Yet, it is still unclear whether the necessary investments into vRES can recover their costs on an Energy-only Market (EoM). Financial support instruments may be necessary for de-risking according decisions. If it appears that support is required, appropriate instruments must be selected and well designed. This study conducts a case study for Germany in order to assess market-based cost recovery of vRES for a scenario with two variants in model-endogenous flexibilities, investigating market performance indicators (MPIs) for different support schemes. In terms of market-based cost recovery, results reveal a strong sensitivity towards hydrogen prices as well as the model-endogenous flexibility representation. We find some cases where market-based cost recovery rates are not sufficient with an average of 70% for photovoltaic systems (PV) and nearly 90% for offshore wind. In other cases, recovery rates exceed the costs by far with more than 200% for onshore wind. For the studied cases, all support schemes under consideration contribute to full cost recovery, thereby de-risking investments. However, we find some differences among the studied support instruments. Most notably, we find two-way Contracts for Differences (CfD) to increase renewable curtailment compared to one-way CfDs. Furthermore, our results reveal that instruments that do not distort dispatch lead to systematically higher wind offshore curtailments, thus also increase prices as well as market-based cost recovery rates.**

***Index Terms*—agent-based modeling, agent-based simulation, power market, renewable generation, policy support**

I. Introduction

To contribute to the decarbonization of economies around the globe, future energy systems have to comprise very high shares of variable Renewable Energy Sources (vRES). The power sector plays a major role in the energy transition [1] and accordingly, large vRES investments are required in this sector [2]. Possible development pathways have been widely studied for energy systems [3]–[5] as well as for the power sector in particular [6], [7]. For the latter, it is still unclear if all necessary investments will recover their costs within Energy-only Markets (EoM). It is also unclear which market designs could best support the necessary investments without overcompensation. These challenges also concern policymakers in the course of European power market redesign [8]. Research of the TradeRES project [9] aims to contribute to these discussions by assessing market designs for energy systems with high renewable shares. The German case study of TradeRES focuses on the assessment of vRES remuneration policy options to better understand their impact on future electricity market dynamics. Therefore, different support schemes are compared to each other and to an EoM benchmark without support. The studied instruments comprise both, well-established support schemes already in place such as a variable market premium or simple Contracts for Differences (CfD) schemes, as well as recent proposals in the course of European power market redesign process, such as the Financial CfD proposed by [10] which have not yet been assessed by means of a model-based approach. Thus, compared to existing literature, we contribute as follows: (1) We assess refinancing of vRES in an EoM for highly decarbonized energy systems. (2) We apply agent-based simulation which allows us to explicitly consider actor's dispatch decision making and model the financial flows. (3) We systematically assess state-of-the-art vRES support schemes for highly renewable systems, also studying their market implications.

The remainder of the paper is structured as follows. Section II outlines existing works assessing the need for renewable support as well as proposing or studying different renewable support instruments. The methodology we apply for our case study is described in III. An overview on the applied agent-based simulation model AMIRIS [11] is given. The modelling of policy support within AMIRIS as well as the case study design applied to study different policy designs are set out. Results are presented and discussed in IV. Conclusions on the necessity of renewables support as well as on the analyzed support instruments are drawn in V.

II. Related Work

There are some existing works on the necessity of renewable support. [12, p. 30–34] and [13] derive the necessity for support instruments from declining market values of vRES, also empirically found by [14]. Newer studies from [15] and [16] imply, that the cannibalization issues [17] resulting from the merit-order effect of vRES [18] could be tackled with carbon pricing resp. market-value stabilization effects from flexibility sources in the power system. Yet, the mentioned studies consider a cost-minimal system configuration under a social planner paradigm. Thus, an evaluation taking a business-oriented perspective and accounting for market imperfections is still lacking, and yet, the question regarding the necessity of support policies for vRES remains unanswered.

Some studies evaluate dedicated existing or proposed support policies and, in some cases, compare multiple instruments among each other. Frey et al. [19] studied the German market premium model. They found the thread of a self-reinforcing downwards price trend in case vRES become price setting with their opportunity costs incurring from the market premium model. While this general finding still holds, a countermeasure taken by politics is to phase out support in times of negative prices [20]. Kitzing et al. [21] compare a feed-in tariff and a feed-in premium using a cash flow model and find a higher risk premium to be applied in the case of a feed-in premium leading to higher financing costs. May et al. [22] conduct similar research and empirically compare countries with fixed feed-in tariffs, variable market premia as well as tradable green certificates. They find significantly higher risks and thus financing costs for tradable green certificates, where a strong imposure to market price signals is prevalent. Building on this, Neuhoff et al. [23] compare a variable market premium, a fixed premium as well as a CfD for which they do not further specify the design, for the case of falling technology costs. They conclude, that one-sided regimes, such as a variable or fixed premium, lead to higher technology costs through the increased risk exposure which is especially true when technology costs approach market price levels. Nonetheless, using a stylized model, dispatch effects are not analyzed.

A very recent strand of literature focuses on the design of CfDs in particular. Schlecht et al. [10] review current designs and design flaws and introduce what they call Financial CfD. Effectively, it combines two revenue streams: a capacity premium payment from the government and a payback obligation for the producer for revenues of a reference plant, thus making the instrument production-independent. Newbery [24] introduces a similar instrument, the Yardstick CfD, that also addresses the distortions caused by production-dependence. In contrast, payments shall be granted not for a dedicated time horizon, but a lifetime specified in MWh/MW as well as dependent on site specific potential measurements. The latter is according to [10] also immanent to a Capacity-Based CfD proposed by the Belgian TSO Elia, but yet unpublished. Favre et al. [25] analyze CfD designs differing in the degree of coverage and correlation to the plant production and find a trade-off between greater dispatch incentives by exposure to short-term market signals and higher revenue risks incurred by revenue volatility.

Winkler et al. [26] conduct similar analyses to the prevalent by incorporating different kinds of support schemes into a module of the power market simulation model PowerACE. They find an impact of support instruments regarding market prices and their volatility and also an effect of different degrees of system flexibility. Also, they state the trade-off between smaller market distortions in the case of a capacity premium payment and higher support costs that might occur compared to a variable market premium regime. However, compared to our analysis, they do neither account for CfD schemes, nor do they study the effects in a system that is dominated by vRES.

III. Methodology

The model AMIRIS

AMIRIS (the open Agent-based Market model for the Investigation of Renewable and Integrated energy Systems) is an open agent-based electricity market model. It enables modelling of business-oriented decisions in the energy sector [11]. Hereby, AMIRIS represents real world power market actors by prototypical agents. Each of the agents is attributed with a dedicated decision making rule.

In technical terms, AMIRIS builds upon the framework FAME (the open Framework for distributed Agent-based Modelling of Energy systems). FAME again consists of the actual core framework to manage the simulation [27] as well as comprehensive complementary tools for input- and output data management [28].

Modelling of policy support

AMIRIS comprises an explicit modelling of the bidding behaviour taking into account financial flows resulting from policy support instruments for vRES. The support instruments considered for the prevalent analysis are:

- No support (*NONE*): vRES operators only receive revenues from the EoM but no state-administered support that serves as a benchmark setting.
- Fixed market premium (*MPFIX*): A fixed top up that is paid on a per MWh basis additionally to market revenues. Defined ex ante.
- One-way CfD (*1-WAY-CFD*): An ex post determined payment on a per MWh basis that serves to fill up market revenues below a certain strike price. The strike price equals the levelized cost of electricity of a given plant.
- Two-way CfD (*2-WAY-CFD*): A payment on a per MWh basis that serves to fill up market revenues below a certain strike price and to cut payments above the strike price. In case the market value exceeds the strike price for that clawback period the producer has to pay back.

- Capacity premium (*CP*): A per installed MW payment that is equally spread in monthly chunks among the operation period of the plant.
- Financial CfD (*FIN-CFD*): A production-independent support instrument as proposed by [10]. The reference plant is chosen to be the country average of all infeeds for the same technology.

It is assumed that we have a competitive day-ahead power market without any market participant having significant market power[1]. In such a setting, supply-side bids can generally be derived from their marginal costs [29], [30]. For vRES in turn, opportunity costs reflect the support of respective instruments imposed, too. This can result in bids deviating from the marginal costs [10], [26].

For MPFIX, 1-WAY-CFD or 2-WAY-CFD, the bid price is given by equation (1).

$$c_{\text{var}} - MP \tag{1}$$

Here, c_{var} depicts the variable operational costs and MP the market premium. The market premium for 1-WAY-CFD in turn is defined according to equation (2) with the strike price p_{strike} and the energy-carrier specific market value MV_k for energy carrier k determined according to equation (3). For 2-WAY-CFD, the market premium is calculated analogously, but not capped at 0.

$$MP = \max(0, p_{\text{strike}} - MV_k) \tag{2}$$

$$MV_k = \frac{\sum_{t=1}^{m} p_t \cdot E_{k,t}}{\sum_{t=1}^{m} \cdot E_{k,t}} \tag{3}$$

Where t is the respective hour, m is the number of hours of the considered month, p_t is the day-ahead power price at EPEX Spot in hour t and $E_{k,t}$ is the total generation of the respective energy carrier k in hour t.

For 1-WAY-CFD, the actual market outcome is only known ex post. To account for this, we iteratively adjust the premium until refinancing is achieved. For 2-WAY-CFD, the situation where the market value is below the strike price is alike. In case the market value exceeds the strike price, the premium effectively becomes negative, thus bids above marginal costs occur as pointed out in [10].

If support is not paid out on a per MWh basis, but decoupled from the plants production, no dispatch distortion exists. Thus, plants will bid at their variable operation costs.

The policy agent calculates the monthly market values required to determine the support payment. The vRES traders receive the support payments from the support policy agent on a monthly basis and pass it on to the vRES plant operators.

[1]Note a deviation from this assumption in the scenario variant on the maximizing-profits strategy for the largest storage unit.

Case study design

We conduct a case study for the power sector of Germany and consider a scenario with $\sim$100% RES share. The scenario data is obtained from optimization results of the model Backbone [31], [32] which serve to derive the reference scenarios in TradeRES [33]. Tab. I shows the installed capacities for different technologies in Germany under scenario S1, which will be examined in this study in detail.

TABLE I
INSTALLED CAPACITIES FOR GERMANY IN THE SCENARIO S1

	Capacity in GW
Hydrogen turbines	52
Photovoltaics	260
Wind Onshore	110
Wind Offshore	30
Other renewables	28
Storage	62

In order to parameterize policy support, we proceed as follows. First, we run AMIRIS multiple times and iteratively adjust the premia for the MPFIX instrument until all vRES agents are able to recover their full costs within a $\pm 0.1\%$ tolerance band, thus ending up with a nearly perfectly parameterized support instrument. Though in reality, premia would be either administratively determined or defined in auctions, we neglect the resulting imperfect outcome of such procedures as we would like to focus on the general effects of the different support instruments. We choose the MPFIX instrument for the initial parameterization since it does not require an initial premium prognosis. In the next step, we align all other support instruments studied such that they also lead to a full cost recovery as closely as possible by extracting the MPFIX premium payments and adjusting the respective premium parameters for the other instruments individually.

We run AMIRIS for all support instruments as well as two variants differing in the degree of model-endogenous flexibility. For the first variant, we extract the storage dispatch from Backbone. For the second, we explicitly model storage dispatch using a profit maximizing strategy. Furthermore, we study the sensitivity of an altered (higher) hydrogen price. Since AMIRIS currently faces some limitations in terms of modelling competing flexibility options, we extract the dispatch of the remaining flexibility sources, i.e. further storages, flexibile electric vehicles as well as heat pumps from Backbone and apply it to our simulation. In addition, we apply imports and exports with the respective power prices associated from Backbone. Though these could be endogenized in principle, this way, we stay consistent with the remaining scenario setting. We explicitly model the dispatch of hydrogen electrolyzers as well as demand-side response, i.e. load shedding.

In order to assess the effects of the studied support instruments towards the electricity market, we use the concept of so-called market performance indicators (MPIs) that has been developed in the course of TradeRES [34]. For the prevalent analysis, we put special emphasis on average market prices, cost recovery rates, both market- and support-based, as well as curtailment of renewable energy sources. Here, cost recovery rates define the relation between the revenues from markets resp. markets and support payments $R_{k,t}$ for each hour t of the year y and the annualised full costs C_k for technology k as stated in equation (4).

$$CR_k = \frac{\sum_{t=1}^{y} R_{k,t}}{C_k} \tag{4}$$

Using the described setup, we conduct an ex-post assessment of profitability.

IV. Results

The following section presents the results for the TradeRES scenario S1. Firstly, the reference case is shown, assuming all input data and storage dispatch as in Backbone. Secondly, the results of sensitivity analyses concerning hydrogen prices and model-endogenous flexibility are presented.

Results for the reference case

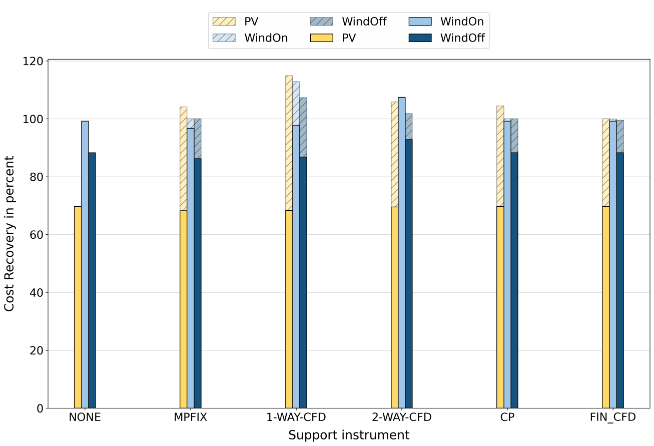

Fig. 1. Average cost recovery rates for vRES technologies, reference case (REF)

Fig. 1 displays the cost recovery rates for vRES technologies. The figure presents the average results per technology, aggregating the results for different sub-types (e.g. rooftop PV and ground-mounted PV). Solid bars represent the cost recovery rates from market revenues, while hatched bars represent cost recovery from support payments. It is evident that, in the considered scenario, the market revenues generated by PV and offshore wind are on average insufficient to cover their total costs, irrespective of deviations induced by the support instrument. Particularly, PV suffers from low market-based refinancing of around 70% on average. The reason for this is that the energy carrier exhibits a high level of simultaneity, and thus has comparatively lower market values [14, cf.]. However, there are differences in the types of PV. Rooftop PV, which is more expensive, is at a disadvantage, while cheaper ground-mounted PV is able to cover its costs via the market.

In contrast, for wind, especially for onshore wind, market revenues are almost sufficient to cover costs. The market-based cost recovery rates are between 88% and 99% in case of no support (NONE). If a 2-WAY-CFD is used, market revenues even exceed total costs for onshore wind. This is because the 2-WAY-CFD may become negative in clawback periods when average market values are high in some months (compare section III). As a result, vRES traders bid above their marginal costs, and average prices rise, ultimately also increasing market incomes.

Note that for the FIN-CFD case, we assume the feed-in potentials for the reference plant to equal those of the actual plant in this study. Therefore, this support instrument always results in 100% refinancing for all vRES technologies.

The variations in the impact of support instruments are more evident when examining market-based curtailment, as shown in Fig. 2. Offshore wind is heavily curtailed - to more than 15% - in the NONE case and in cases with support instruments that do not cause any dispatch distortions, i.e. CP and FIN-CFD. This is due to its higher variable cost compared to other vRES technologies. When using MPFIX or 1-WAY-CFD, all vRES technologies that receive support in a period bid at zero cost in the underlying scenario setup due to the opportunity cost of the market premium[2]. As a result, all vRES technologies are awarded the same shares when they are price-setting on the day-ahead market. This leads to the displacement of onshore wind and PV electricity by offshore wind.

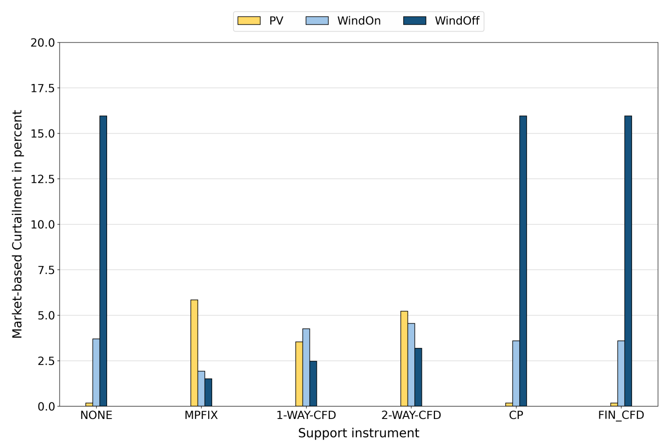

Fig. 2. Market-based curtailment for vRES technologies, reference case (REF)

There are differences in the curtailment between MPFIX and 1-WAY-CFD. In the latter case, the premium and bid vary throughout the year, and so does the curtailment. Differences are even more pronounced in the 2-WAY-CFD case with its clawback regulations.

Sensitivity analysis

As a first scenario variant, the hydrogen price has been replaced due to its assumed high impact on market prices

[2]Note that we do not consider support at negative prices, thus supply bids are capped at 0 €/MWh.

(H2). In the reference case for S1 (REF), the price was 45 €/MWh, for H2 it is replaced with 150 €/MWh.

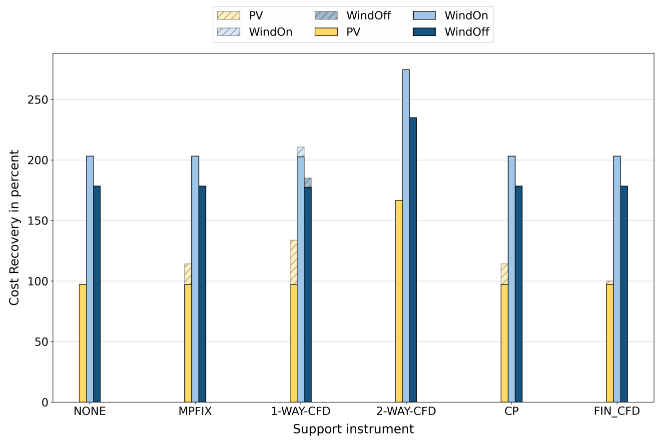

Fig. 3. Average cost recovery rates for vRES technologies, with higher hydrogen price (H2)

As shown in Fig. 3, a higher hydrogen price significantly increases refinancing rates for all vRES technologies. Support is mainly required for rooftop PV. For onshore wind, refinancing rates can reach over 200%. In the case of 1-WAY-CFD, offshore wind plants receive additional support payments during months when market incomes do not cover costs. Cost recovery is highest among all vRES technologies in the case of 2-WAY-CFD. This again is because of the higher prices resulting from negative premia during clawback periods and corresponding bidding.

The second scenario variant focuses on the dispatch strategy of the largest storage unit. In the reference case, the storage dispatch was directly taken from Backbone, resulting in a system cost-minimizing dispatch. We now depict the largest storage as a profit-maximizing unit with market power. This may overestimate the market power of storage facilities in reality, but serves to study trends in different market strategies for flexibility.

Fig. 4 displays the cost recovery rates for the scenario variant with a profit-maximizing storage (STO). In this case, the storage can increase price spreads in the day-ahead market by purchasing electricity at lower prices and selling it at higher prices compared to the reference case. This is achieved by holding back charge power and discharge power compared to the reference. Specifically, it charges during low-price periods by purchasing cheap electricity from PV, not more than to prevent prices from increasing. It then discharges at high-price periods, but to a lower degree compared to the reference in order to stipulate that backup units set the price. As a consequence, PV operators are worse off, with market-based refinancing rates being 6-9 percentage points lower compared to the reference. Wind, on the other hand, profits from this storage strategy, with market revenues that exceed total cost.

Table II presents a comparison of the volume-weighted average electricity prices at the day-ahead market in different scenario variants. It is evident that prices are highly dependent

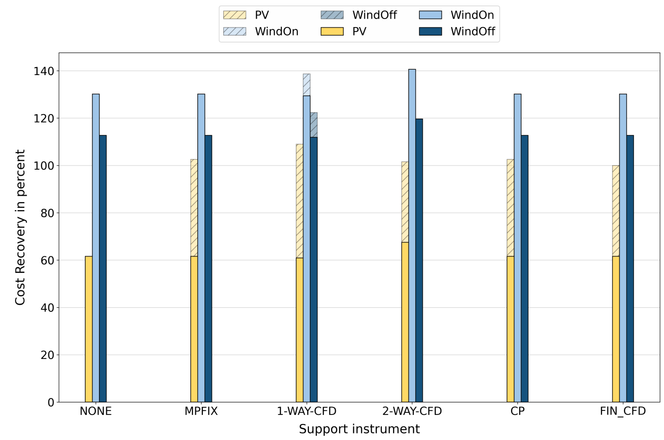

Fig. 4. Average cost recovery rates for vRES technologies, with profit-maximizing storage (STO)

on the scenario setup, particularly on price assumptions such as the hydrogen price. Additionally, the 2-WAY-CFD scheme has a significant impact on prices. This is because vRES traders bid at higher prices due to the payback obligation in clawback periods, which results in an increase in electricity prices. Thirdly, the impact of the other support instruments considered is relatively low. MPFIX and 1-WAY-CFD have a slight decreasing effect on prices, as vRES traders take into account the opportunity cost of the premium in their supply bids. For CP and FIN-CFD, support is separated from production, and therefore, there is no impact on bidding behaviour and, consequently, prices.

TABLE II
VOLUME-WEIGHTED AVERAGE DAY-AHEAD ELECTRICITY PRICES

Case	*NONE / CP*	*MPFIX*	*1-WAY-CFD*	*2-WAY-CFD*	*FIN-CFD*
REF	63.0	62.2	62.4	65.1	63.0
H2	127.8	127.7	127.4	158.7	127.8
STO	88.0	88.0	87.7	91.9	88.0

V. Conclusion

Based on simulations with an agent-based electricity market model we study different financial support instruments for vRES in the course of a case study for Germany.

Our results indicate initial trends in the efficiency and effectiveness of support instruments. They reveal that support instruments are likely necessary to reduce the risk of vRES investments. This is particularly true for rooftop PV. All instruments considered guarantee at least 100% refinancing of vRES technologies. A significant finding is that two-way CfDs increase market-based curtailment and cost recovery rates for all vRES technologies, leading to higher market prices that benefit the refinancing of vRES.

However, we find large deviations among scenario variants. Especially prices for backup turbines, i.e. hydrogen, are found to have a significant impact on market prices, and in turn incomes. It is possible that a high hydrogen price could render support instruments obsolete for most vRES technologies. Furthermore, we show a strong sensitivity towards introducing flexibility to the scenario. A storage strategy focused on maximizing its profits results in higher market-based refinancing rates, especially for wind power, compared to a strategy that focuses on minimizing system costs. While both strategies are not entirely reflective of reality, they demonstrate the potential range of market outcomes.

In our scenarios, all support instruments are designed based on perfect information about the market performance of vRES, considering the simulation results. In contrast, ex-ante designed support instruments such as MPFIX lack the necessary information for support. Those deviating risk structures of the support instruments as well as strategic bidding behaviour in auctions for RES support require for future research. Ultimately, additional scenarios as well as the effect of multiple competing endogenous flexibility sources towards market value stabilization for vRES should be studied taking actors' behaviour into account.

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