# D6.5 – Recommendations for market trading in a ~100% power system

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| Author(s) information (alphabetical) | | |
|---|---|---|
| **Name** | **Organisation** | **Email** |
| Hugo Algarvio | LNEG | hugo.algarvio@lneg.pt |
| Antonio Couto | LNEG | Antonio.couto@lneg.pt |
| Niina Helisto | VTT | Niina.helisto@vtt.fi |
| Silke Johanndeiter | EnBW | s.johanndeiter@netze-bw.de |
| Juha Kiviluoma | VTT | juha.kiviluoma@vtt.fi |
| Johannes Kochems | DLR | johannes.kochems@dlr.de |
| Kristina Nienhaus | DLR | Kristina.nienhaus@dlr.de |
| Ingrid Sanchez Jimenez | TU Delft | i.j.sanchezjimenez@tudelft.nl |
| Gabriel Santos | ISEP | gjs@isep.ipp.pt |
| Christoph Schimeczek | DLR | Christoph.schimeczek@dlr.de |
| Jos Sijm | TNO | Jos.sijm@tno.nl |
| Helleik Syse | bU | Helleik@bitunitor.com |
| Russel Wolff | bU | russel@bitunitor.com |



| Acknowledgements/Contributions | | |
|---|---|---|
| **Name** | **Organisation** | **Email** |
| Fernando Lezama | ISEP | flz@isep.ipp.pt |
| Evelyn Sperber | DLR | Evelyn.sperber@dlr.de |
| Zita Vale | ISEP | zav@isep.ipp.pt |


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| Review and approval | |
|---|---|
| **Prepared by** | **Reviewed and approved by** |
| Russel Wolff (bU) | Ana Estanqueiro |

## Disclaimer

# Executive Summary

The present deliverable, as part of Task 6.4, covers recommendations regarding the evolution of the market design considering a ~100% renewable power system, and reflect lessons learned throughout the project, detailed in a number of project deliverables including the experiments and validation of case studies as well as the feedback of the stakeholders enrolled in TradeRES activities. Based on the models developed, respective analyses were carried out within the case studies in work package 5 that focused on complementary aspects of national and regional markets, and different spatial scales, from local markets to pan-European trade. The derived recommendations for market designs were summarised and compared with the stakeholders' feedback.

The main recommendations for future electricity market trading in a near 100% renewable power system emphasize the need for various changes. First, **enabling closer-to-real-time trading by transitioning from a traditional Day-Ahead Market (DAM) to a 6-hour Period-Ahead Market (PAM)** could minimize power forecast errors, market distortions, real-time balancing needs, and penalties. **Reconsidering the current Intraday Market (IDM) design** is necessary to reduce the uncertainty associated with variable Renewable Energy Sources (vRES). If properly implemented, **active participation of market players can enhance vRES market-based renumeration through diversified revenue streams**. Bidding strategies can be applied from any perspectives, e.g., by using different types of wholesale bids such as block orders in EPEX and Nord Pool or complex bids in MIBEL. However, more active and strategic participation of vRES market players should be studied before implementation to enhance their market-based remuneration through diversified revenue streams.

Enhancing the accuracy of vRES power forecasts requires the **inclusion of tailored and non-conventional data** rather than relying solely on generalized models. Given the high penetration of vRES, electrification, and increasing demand-side flexibility, the risks in retail markets may rise significantly, making local markets crucial for adjusting consumption to local production. **Fully indexed tariffs** should be implemented to provide the right local price signals closer to real-time, indexed to local generation and grid costs, with appropriate weight on congestion management prices to avoid local congestion.

Ancillary services need to be adapted to allow participation from vRES. The **procurement of secondary power should be dynamically assessed** according to expected net loads and deviations. Opening these services to smaller and aggregated players can incentivize more participation from vRES and consumers, thereby reducing imbalances. An **imbalance settlement mechanism** that fairly reflects the true costs of these services is necessary.

**Support schemes to de-risk vRES investments must be properly designed**, with Contracts for Difference (CfDs) offering a balanced approach by ensuring stable revenues for investors while controlling support costs for end consumers. However, the design of these CfDs requires careful attention to avoid dispatch distortions, such as increased market-based curtailment of vRES if investors anticipate production-based payments.

**Capacity Remuneration Mechanisms (CRM) are needed both during and after the energy transition**, based on the demand for capacity by final consumers including households and SMEs, providing them with a price hedge (insurance). Increasing the transmission capacity of tie-

lines or using dynamic line rating is important to reduce vRES curtailments and market splitting between zones, promoting price harmonization. New electric loads from sector coupling can support energy flexibility if they are exposed to real-time pricing. During congestions, network tariffs should also signal limited availability in a cost-effective manner while respecting grid limitations.

**Dynamic Line Rating assessing** in real-time of overhead power lines **can contribute to reduce vRES curtailments** and integrate new renewable generators without the need for constructing new lines. Cross-border trading could also benefit from the potential increase in capacity, which may help reduce market-splitting events. This, in turn, would facilitate the convergence of market price between different countries. Distribution System Operators (DSOs) may develop products to incentivize consumers to avoid local congestion. Effective markets are essential across all energy networks to balance supply and demand and utilize flexibility correctly.

Market structures should **prioritize seamless integration between Local Energy Markets (LEMs) and wholesale markets**, utilizing aggregators to effectively represent smaller energy communities. Expanding dynamic pricing mechanisms to include all market participants, from large consumers to small consumers and prosumers, is essential. Such an approach would incentivize demand response and align local energy use with real-time market signals, enhancing the overall efficiency of the energy system.

Strategic investment in renewable energy generation and energy storage must be actively promoted through **targeted regulatory measures**. Revising ancillary service market rules to facilitate the participation of variable vRES, distributed energy resources, and energy storage is critical.

In conclusion, these recommendations aim to create a resilient, efficient, and balanced future electricity market capable of integrating a near 100% renewable power system, enhancing investment security, market participation, and system reliability.

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# List of Acronyms

| | |
|---|---|
| aFRR | automatic Frequency Restoration Reserve |
| AMIRIS | Agent-based Market model for the Investigation of Renewable and Integrated energy Systems |
| BRP | Balancing responsible party |
| CfD | Contracts for difference |
| COMPETES | Competition and Market Power in Electric Transmission and Energy Simulator |
| CRM | Capacity renumeration mechanisms |
| DAM | Day ahead market |
| DLR | Dynamic Line Rating |
| DSO | Distribution system operator |
| EM | Electricity Market |
| EMLAB | Energy Modelling Laboratory |
| ENTSO-E | European Network of Transmission System Operators for Electricity |
| EOM | Energy only market |
| EU | European Union |
| GET | Grid enhanced technologies |
| HPP | hybrid/hybridised power plants |
| IDM | Intra-day market |
| LEC | Local Energy Communities |
| LEM | Local Energy Markets |
| LMPI | Local market performance indicators |
| MASCEM | Multi-Agent Simulator of Competitive Electricity Markets |
| MIBEL | Iberian Electricity market |
| MPI | Market Performance Indicators |
| NWP | numerical weather prediction |
| P2P | Peer-to-peer |
| PAM | Period ahead market |
| PPA | Power Purchase Agreement |
| PV | Photovoltaic |
| RES | Renewable energy sources |
| SIDC | Single intra-day coupling |
| SR | System reserves |
| TSO | Transmission system operator |
| vRES | Variable renewable energy sources |

## 1. Introduction

TradeRES seeks to find new market design(s) for a 100% renewable energy sources electricity system. Such a system will be characterized by large fluctuations of generation from variable renewable energy sources (vRES), thus demanding for respective investments and de-risking mechanisms, a high amount of power system flexibility and fast reactions of power system elements to balance out these fluctuations.

The present deliverable was developed as part of the research activities of the TradeRES project's Task 6.4 – Recommendations for market design in a ~100% power system. This report constitutes the capture of feedback and recommendations that were gathered throughout the project. It incorporates recommendations and lessons learned from the different spatial-scale market case studies, as depicted in Figure 1, performed as part of work package 5, market design options identified in D3.5 [11], and stakeholder feedback gathered primarily in the context of D6.4 [1].

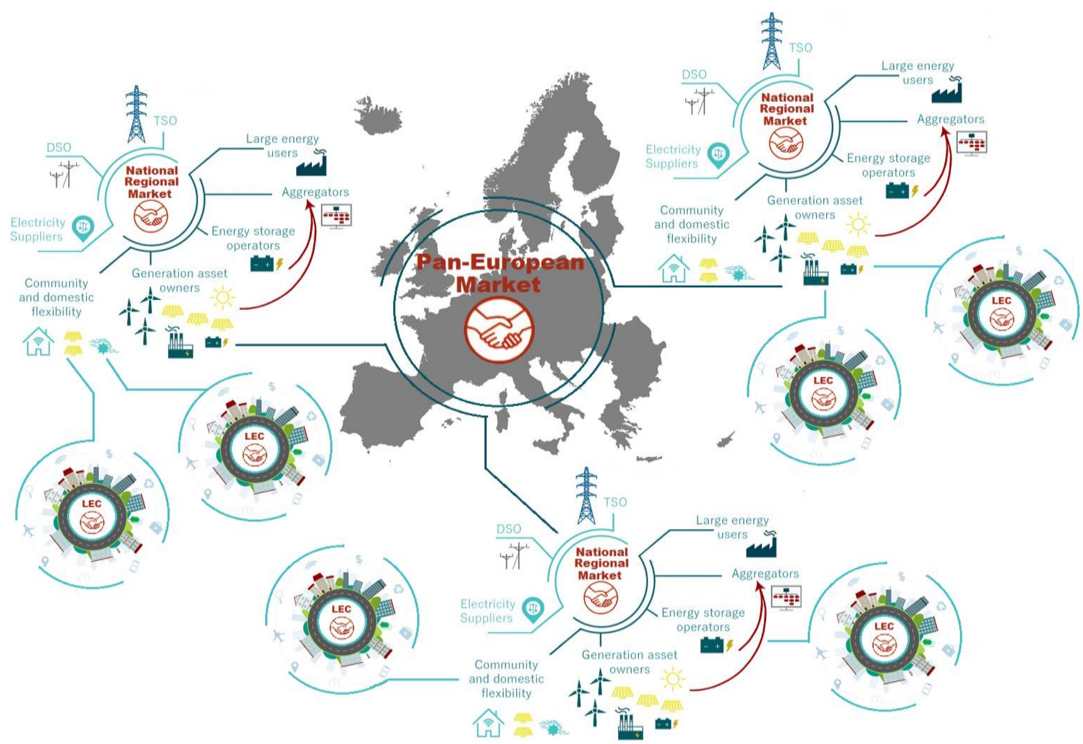


Figure 1 - Different scales of electricity markets in TradeRES project.

### 1.1 Structure of the deliverable

The deliverable is structured with Chapter 2 providing a brief outline of the feedback collection process and then details the recommendations gathered during publicly available workshops and webinars, both in person and remote and explains how the feedback and recommendations received were fed back into the project. Chapter 3 then looks at the case studies from WP5, first looking at the individual case studies, then summarizing the recommendations for market design in a ~100% power system. Chapter 4 provides a summary of recommendations from the TradeRES project for market design in a ~100% power system in a bulletized fashion by thematic area and with regard to the stakeholders' perspective. Chapter 5 concludes the deliverable, offering considerations and alignment towards D3.5 and D5.5 along with overall summary recommendations.

## 1.2 Link with other deliverables and tasks

This deliverable is closely aligned with several project deliverables and represents a final summarization of the market design recommendations identified based on project results. D6.4 (syntheses of the stakeholder experience with TradeRES testing and benchmarking) [1] provides much of the model feedback gathered during workshops with tool demonstration. Additionally, this deliverable complements the recommendations resulting from the case studies in WP5 drawing on recommendations and lessons learned. Finally, this deliverable balances against D3.5, Market design for a reliable ~100% renewable electricity system [11]. A list of aligned tasks and deliverables include:

D3.2 – Characterization of new flexible players [23]

D3.5 Market design for a reliable ~100% renewable electricity system [11]

D5.2 Performance assessment of current and new market designs and trading mechanisms for Local Energy Communities (Case Study A) [3]

D5.3 Performance assessment of current and new market designs and trading mechanisms for national and regional markets [4]

D5.4 Pan-European Wholesale Electricity Market [5]

D6.1 Stakeholder Engagement Plan [6]

D6.4 Syntheses of the stakeholders experience with TradeRES testing and benchmarking [1]

D6.2 User guide for TradeRES models and tools [9]

D8.1 and D8.2 as part of WP8 Ethics Requirements [7,8]

# 2. Feedback collection process

To maximize the project results while ensuring that TradeRES' recommendations regarding the new design and products of the electricity market are realistic and socially acceptable, the engagement of key stakeholders was identified as a crucial supplementation to the project work. Thus, important contributions from the stakeholders were collected from the beginning of the project and during the development of the reference electricity system and market design assessment.

The project provided several avenues and dissemination activities for the stakeholders' engagement where stakeholders were able to provide recommendations. Some of the more prominent activities were publicly available workshops, webinars, and tutorials on the Internet (e.g. on YouTube presented in Deliverables 6.2 [9] and 6.3 [10]).

Additionally, media outlets such as the project website and newsletter were used to keep interested parties afloat of the latest activities of the project. For detailed feedback, the project hosted several workshops. These workshops were area-specific and aligned towards the case studies in WP5. Details of the tool presentation and feedback can be found in Deliverable 6.4, while this deliverable looks into project results and recommendations.

## 2.1 Stakeholder groups and informed consent

The project comprised different stakeholders to closely follow the work developed providing feedback and recommendations on the modelling methodology and scope, on market design options, and on research results.

The stakeholders were categorized based on D6.1 - Stakeholder Engagement Plan. Additionally, informed consent as described in several deliverables such as D6.1, D8.1, and D8.2, was gathered from the stakeholders in the project. Briefing the participants on information about the project and ensuring they knew their participation was voluntary were just a few of the procedures taken to ensure informed consent. The full description can be found in the deliverables named above.

## 2.2 Insights from the European Commission Market Design Consultation

The original idea of TradeRES was to collect comprehensive feedback on market design issues and recommendations by dedicated requests towards stakeholders. However, during the project, the 2022 energy crisis vastly pushed a power market redesign process, with a respective very comprehensive stakeholder consultation and ultimately important reforms on the European level that were not foreseeable when the project first started. Hence, in the course of the project, it was decided to very carefully study these consultation results which touch most market design aspects analysed within TradeRES as this provides a valuable and representative data set. A more detailed summary of the EC consultation can be found in chapter 6.2 of D3.5 [11]. In the prevalent deliverable, we account for our main recommendations with this stakeholder feedback as well as with feedback we obtained in our workshops and case studies.

## 2.3 Recommendations from stakeholder workshops on market models

Recommendations were also gained from stakeholders during the workshops held. The stakeholder feedback was gathered for all project components, to include tool updates and Case Study design during the workshops. At times there was overlap, but where possible, the recommendations were separated between those for market's simulation tool design and those for those for market trading in a ~100% RES power system. This deliverable focuses on the latter, although some tool recommendations are touched upon here. D6.4 *Syntheses of the stakeholders experience with TradeRES testing and benchmarking* provides greater detail of the stakeholder workshops and tool feedback. The main feedback aspects from the workshops are summarized in the following chapters 2.3.1 to 2.3.3 and was incorporated in the case studies conducted in WP5.

### 2.3.1. AMIRIS and Backbone Models

A) Feedback received

During the course of the project, stakeholders from academia requested inclusion of hydrogen technologies to better model future electricity markets. Due to the energy crisis in the years 2022 and 2023 and associated high (and very volatile) electricity prices, governmental representatives publicly announced interest for market instruments that avoid overly high profits for market actors in times of price shocks. In the workshop on tools AMIRIS and Backbone, stakeholders asked to also include Newbery's Yardstick Contract for Difference (CfD) (Newbery 2023) [19] and Elia's Capability-based CfD (Elia 2022) [18]. During several workshops and presentations, stakeholders asked to explicitly include the modelling of competing flexibility options in AMIRIS. This workshop covered the application of the mentioned tools to the case studies of German electricity market (Task 5.2) and Pan-European (Task 5.4).

B) Results and steps taken

To reflect the impact of hydrogen prices on the electricity market, electrolysis units and hydrogen-fuelled power plants were introduced to AMIRIS. Also, new CfD support schemes were introduced to this tool, i.e. a two-way CfD with a monthly or annual reference period and a financial CfD as proposed by Schlecht et al. (2024) [20]. Further CfD variants, however, were not included in AMIRIS due to the argumentation laid down in Schlecht et al. (2024) [20] showing advantages of the financial CfD compared to other regimes as well as the massive parameterisation effort and a lack in data of per plant production potentials necessary for modelling a Capability-based CfD. Nonetheless, a thorough CfD design as well as addressing open design questions of the proposed schemes was identified as a relevant research question that shall be further investigated beyond the project.

The explicit modelling of competing flexibility options in AMIRIS was identified as a pressing issue with the model. A first bidding strategy to address competition between electricity storage agents was published. However, this strategy shows only a limited performance. Further research shall lead to improved bidding strategies for flexibility options with upcoming releases of AMIRIS.

The recommendations for the tools highlighted the importance of providing easy installation methods, clear installation instructions and good troubleshooting sections, all for different operating systems. In that way, Spine Toolbox installation instructions have been updated and improved and included in the updated tutorials as part of deliverable D6.2.2.

Future tool development should also pay attention to the importance of fully open-source software. Running the open-source Backbone tool with a large dataset requires a costly GAMS licence. For wider exploitation of the tools, it is not enough that the model code is open source, also the solving system behind it needs to be open source. Steps have been taken to develop an interoperable energy system data specification, which will also allow a dataset created for Backbone to be converted to a format that can be run using a fully open-source energy system optimisation software.

### 2.3.2. COMPETES-TNO and EMLAB Models

A) Feedback received

The workshop held focused on the application and results from the COMPETES and EMLab-AMIRIS model runs. The specific feedback to the COMPETES-TNO and EMLAB models is detailed in D6.4 while general recommendations from the joint presentation on the Dutch case study are provided here.

Uncertainties, mainly weather variability, cause risks to investors for supplying the necessary generation capacity. In principle, the weather uncertainty is "known" by everyone, so it should be hedged, but climate change may make this difficult.

Other risks that are not quantifiable cannot be resolved by hedging. There is additional concern about other types of risks and uncertainties, e.g. from energy policies and the stakeholders recommended that the impact of these should be researched further.

The sector experts expressed scepticism with respect to demand flexibility. They recommended research on additional revenues that could influence the results. For example, is there enough flexibility for consumers to pay for the optionality for the plants to reach their desired load levels?

Lastly, the capacity market was mentioned not to be technology-neutral and that there are biases for all technologies due to the support mechanisms. They would like to develop a mechanism that plays a joint effect while being careful to avoid lock-in with policies that won’t work later on during, or after, the transition phase.

B) Results and steps taken

As a result of the recommendations, there was no reason to adapt the COMPETES-TNO model and/or the (underlying) assumptions of the NL case study. However, the recommendations gathered drove TNO to further explain and clarify the key characteristics of the COMPETES-TNO model as well as the assumptions of the NL case study in D5.3. In addition, recommendations resulted in reducing the number of market performance indicators (MPIs) used within TradeRES project from the initial 48 to 10.

### 2.3.3. MASCEM - RESTrade models

A) Feedback received

The main feedback on the MASCEM-RESTrade tools were obtained during the MIBEL stakeholder workshop and from the meetings with the Advisory Board of the project. The issues and comments gathered are included in D6.4 while recommendations are summarized below.

Stakeholders recommended to put focus on the aggregation of local renewable generation with storage, such as batteries and pumped storage, as it will grow in the near future and that should be addressed for wholesale, reserves, and intraday market participation.

Stakeholders recommended increased focus on active/strategic participation of vRES in different markets, and not using (near zero) marginal costs to define bid prices, as in the real world's electricity markets, the price makers technologies tend to "monopolize" the system. Stakeholders emphasize that the tools being developed in the project should enable an active and strategic business design for vRES, taking into account different markets to diversify the revenue streams.

Additionally, stakeholders also suggested to perform an analysis of the cost benefit between investing in the transmission grid versus including a fee in the consumers' electricity bills to pay for curtailment.

Some Iberian stakeholders indicated they do not consider Power Purchase Agreement (PPAs) and CfDs to be the best solution for competitive liberalised market trading as those benefit/discriminate different types of generation players.

B) Results and steps taken

As a result of the feedback received from the stakeholders, the approach developed within the scope of the project already considered the most relevant concerns raised by the stakeholders. The current version of RESTrade system already enables simulation of the balancing markets and supports shorter bid and negotiation periods. MASCEM's current version includes MIBEL's original single intraday coupling (SIDC), as well as the proposed variation (see D5.3) which prioritizes vRES orders (instead of a "first in first out" approach) to increase the market's liquidity.

Stakeholder recommendations also contributed to work on the development of a strategic participation of vRES stakeholders in the day-ahead market (and subsequent markets), i.e., the active participation of vRES, to assess the economic benefit for the market players along the time.

For wind and solar power plants, the work conducted after the stakeholder meeting focused on a business strategy based on the probabilistic forecasts of vRES production developed within the project. Specifically, this involved identifying the percentage of time that the observed power exceeds the quantile forecast and the corresponding average power. This information is then used to determine appropriate bids in day-ahead markets and to participate in ancillary services with a high degree of confidence.

# 3. Market recommendations based on design options and TradeRES case studies

This section will review the market design options researched in the applications of the project developed market models and tools to the different case studies designed (work package WP5) with summary recommendations gathered from the case studies.

## 3.1 Insights from Local energy communities

The analysis of market designs for Local Energy Communities (LECs) investigated the optimisation of local energy markets (LEMs) through modelling. In this case study the modelling was performed at three levels: i) Local-wide models; ii) aggregation-wide models; and iii) Wholesale-wide models. Through the modelling, different pathways for supporting a nearly 100% renewable electricity system was investigated.

Local-wide models investigated trading and community-focused energy solutions, enhancing the participation of consumers and producers. Aggregation-wide models emphasize collective strategies that promote cost-effective energy management across communities. Wholesale-wide models operate on a regional or European scale, ensuring system adequacy and stability through structured trading mechanisms. The local energy communities case study also investigated novel ways to facilitate trading at a decentralized level by demonstrating a blockchain-based platform running on the Ethereum network.

Market structures should prioritize seamless integration between LEMs and wholesale markets, employing aggregators to effectively represent smaller energy communities. Aggregated bidding strategies can bridge local generation and demand with wholesale markets, enhancing both participation and economic viability for Local Energy Communities (LECs). Case studies demonstrate that LECs engaged in day-ahead and intraday markets can achieve significant operational cost reductions, supporting broader system flexibility and sustainability.

Dynamic pricing mechanisms should be expanded to include all market participants, from large consumers to small consumers and prosumers. Such an approach would incentivize demand response and align local energy use with real-time market signals. Local-wide models have shown that optimized tariff selection and P2P trading can lead to cost reductions for prosumers while improving overall system responsiveness. Extending dynamic pricing across different market levels can facilitate more balanced load management and better integration of vRES.

Incorporating the tailored defined Local Market Performance Indicators (LMPIs) [3] into market assessments is crucial for accurately evaluating the effectiveness of local energy initiatives. Unlike standard MPIs developed within TradeRES project [24], LMPIs such as Local Energy Neutrality, Import-Export Ratios, and Levelized Local Costs provide a clearer picture of localized performance, reflecting the unique dynamics of local energy production and consumption. This approach ensures that policy and market adjustments are aligned with the specific needs and capabilities of LECs, fostering their contribution to decarbonization efforts.

Strategic investment in renewable energy generation and energy storage should be actively promoted through regulatory measures. Aggregation-wide models highlight that coordinated investments across communities not only reduce dependency on external energy sources but also enhance local carbon neutrality and economic resilience. Such strategic cooperation allows LECs to optimize their energy systems and maintain economic viability in the face of changing energy demands.

Revising ancillary service market rules to facilitate the participation of vRES, distributed energy resources, and energy storage is essential. This would support a more balanced and robust system, allowing diverse actors to contribute services such as frequency control and inertia. Insights from deliverable D3.5 [11] underscore the importance of including non-fossil-based flexibility services to ensure system adequacy, an aspect that becomes increasingly relevant in a renewable-centric energy system.

## 3.2 National and regional markets

Recommendations for national and regional markets were presented in the second edition of deliverable 5.3 [4], which provided a final assessment of the market designs and products developed in the TradeRES project. Three computational case studies were analysed: study B (Netherlands); study C (Germany); and study D - MIBEL (Portugal/Spain).

### 3.2.1. Energy Only Markets vs Capacity Remuneration Mechanisms

The Netherlands is part of the EPEX SPOT market (together with twelve other countries) [22]. The large-scale potential of wind offshore in the North Sea puts the Netherlands in a privileged position to accommodate large shares of vRES to meet both domestic and foreign electricity demand. This case study focused on the energy-only market with a vRES capacity target and on the performance of capacity remuneration mechanisms (CRMs) with respect to enhancing the adequacy and security of supply in a decarbonized electricity market.

In the Dutch market simulation of a steady-state scenario for a fully decarbonized energy system in which demand, fuel prices, and CO2 prices were stable, investment cost recovery was uncertain due to the large impact of inter-annual weather variability. In this study it was compared the impact of weather uncertainty with the uncertainty from stochastic demand growth and observed that even in a very flexible system, shortages were higher in scenarios with weather variability. In these simulations, the inter-annual variability of cost recovery increased more than three-fold, and the annual variability of weighted-average electricity prices more than ten-fold, in comparison with a scenario without weather uncertainty.

An interesting finding of this research was the impact of the weather year that investors use for deciding upon new generation capacity. It was demonstrated that, if investors based their investments on a weather year with very low vRES, thereby ensuring the reliability of the system for the worst weather years, they would be unable to recover their investments. On the other hand, if they would base their investment decisions on a more optimistic vRES yield, they would invest less and receive excessive returns, but this would come at the cost of lower system reliability and higher electricity prices. It was concluded that in a system with variable and weather-dependent supply, investors have insufficient incentive to ensure reliability, and therefore a capacity remuneration mechanism will be needed to ensure enough backup capacities.

Following that result, the Dutch market case studied the performance capacity remuneration mechanisms (CRM) such as: i) a capacity market; ii) a strategic reserve; and iii) capacity subscription in a climate-neutral, high vRES version of the Dutch electricity system. The first two options have been implemented in other countries; capacity subscription is an instrument that promises to involve consumers (both household and industrial ones) better, but this instrument has not been tried in practice. All three of the reviewed mechanisms can reduce the cost to society in a low-carbon power system with a high reliance on vRES as solar and wind energy. Capacity markets and capacity subscription schemes offer a choice of whether to remunerate all or only dispatchable generation technologies. The latter appears to be the better choice, because imperfectly estimated derating factors of vRES and batteries can distort the market, and remunerating for capacity could reduce the exposure of these technologies to market signals, depending on the CRM design. Total costs to consumers remained at similar levels as in an energy only market (EOM), while reducing shortfalls in volume and duration, thus reducing the total system costs.

A strategic reserve incentivized more investments in hydrogen-fuelled thermal power plants than the other CRMs in the Dutch model. It also caused volatile and high day-ahead/short-term electricity prices, mainly due to the dispatch of the reserve at the price cap. Its benefits appear to be limited to cases in which unprofitable plants need to be kept available for a period, e.g., gas plants that would need to remain available until replacements would have been built. Both a capacity market and capacity subscription are able to provide system adequacy/ security of supply and stable electricity bills to consumers. In a capacity market, a central entity determines the capacity demand curve and other parameters. With capacity subscription, consumers purchase yearly subscriptions that ensure that their electricity supply will not be limited below the subscribed level during periods of scarcity. In the Dutch model of capacity subscription, consumers base their willingness to pay on experienced shortages, and generators base their investments on the capacity subscription price. Because the contract duration was one year and the assumed limited "memory" of consumers and generators, periodic scarcity events caused investment cycles. Larger investment cycles were observed, when consumers and generators do not have any "memory" regarding past shortages, ignoring the risk of extreme weather events. Capacity subscription could limit investment cycles by offering long-term contracts for capacity. During the energy transition, an intermediary agent (regulated entity on behalf of the government) could contract capacity long-term from generators and sell it in annual contracts to consumers. The advantage over a capacity market remains the incentive for consumers to develop flexible solutions behind the meter, and the fact that the net demand for dispatchable capacity is revealed.

### 3.2.2. vRES support and investment derisk

Germany is the country with the highest absolute vRES electricity generation in Europe and has ambitious goals for the expansion of these renewable technologies [12]. The German case study addressed the question on the necessity for vRES remuneration schemes and analysed different kinds of support instruments. The considered instruments comprised production-dependent forms, such as a fixed market premium, a 1-way CfD or a 2-way CfD and production-independent ones, such as a capacity premium or a financial CfD.

One major finding was a strong cross-scenario variation of market-based cost recovery rates for vRES. A strong dependency on the underlying uncertain scenario assumptions was found. Particularly, the price of hydrogen as well as the flexibility of the demand side, were found to have a large impact on prices and on cost-recovery rates. Among the vRES technologies, differences were observed: Compared to wind, it is more challenging for solar photovoltaic (PV), especially rooftop plants, to recover their costs on the electricity market across all scenarios. For wind onshore and offshore, scenarios with a high vRES share and comparatively low hydrogen prices, as well as little demand-side flexibility, a purely market-based cost recovery was not possible. Thus, without energy-policy intervention, investors might face significant risks, which can in turn hamper vRES expansion. Hence, to de-risk investments in vRES technologies, robust support policy designs are recommended that can adapt to different future developments.

The German case study further showed that provided their correct parameterization, the examined support instruments result in full cost recovery in all cases investigated (with regard to the analysis conducted on the basis of aggregated capacities), thereby reducing the risk associated with investments. For some production-dependent CfD designs, most notably one-way and two-way CfD, slightly excessive support payments were observed. This could be traced back to two reasons: (i) the selection of a monthly reference period with strong inter-monthly variations of market values, which was chosen to showcase the effect of inter-annual variations, as well as (ii) a discrepancy between the ex-ante anticipated market value and the ex-post realized one after curtailment.

For one-way CfD, both the highest support costs as well as the highest rates of excessive support were found. This is due to the one-sided risk hedging which also is not in line with future EU regulations, but from an investor's point of view allows for the maximum degree of risk hedging. Furthermore, it is notable that two-way CfD result in a greater level of vRES curtailment when compared to other support instruments. This can be explained by an anticipation of clawback obligations and resulting bids above marginal costs for clawback periods. One mechanism to address this design flaw that was not yet explicitly studied is dynamically limiting the clawback obligation to retain production incentives for prices above marginal costs [13]. The high curtailments led to elevated prices and enhanced market-based cost recovery rates. However, in terms of costs to society, 2-way CfD were found to perform worse when compared to production-independent CfD.

Moreover, the findings indicate that production-independent instruments that do not distort dispatch (capacity premium and financial CfD) result in a consistently higher level of wind offshore curtailment, which can be directly traced back to higher marginal costs of this technology [14]. Concerning costs for society, production-independent financial CfD were found to perform best in nearly all scenarios.

An aspect that also requires further attention are the differences in the risks in prognosing the parameters determining support rates: While for instruments like production-dependent 2-way CfD, it is comparatively easy to predict the levelized costs of electricity which ultimately determine the strike price, for other instruments such as a fixed capacity premium, it is very hard to anticipate the cumulated market revenues over a plants' lifetime in order to determine the need for support.

Concluding, the necessity for vRES support as a measure to de-risk investments has been pointed out. Concerning the choice of the support instrument, there is no silver bullet as each instrument comes with advantages and disadvantages. Production-independent support instruments seem to be a promising option. However, these instruments introduce a new base risk for investors for which the implications still need to be studied further.

**Contrast with stakeholder feedback:** Overall, stakeholders positively responded to support for vRES in the form of CfDs. Design elements such as exposure to market signals and decoupling the dispatched volumes were deemed important factors. Some scholars opted for financial CfDs. This is widely in line with findings from TradeRES, though the preference is not as explicit due to the new base risk that needs further attention. Most stakeholders opted to make CfDs an optional, not a mandatory element and facilitate the uptake of PPAs. Though those were not explicitly studied, this would also be backed by TradeRES findings.

### 3.2.3. Short-term markets

The countries in the MIBEL market, *i.e.,* Portugal and Spain, are among the European countries with a higher penetration of vRES in their power systems. The Iberian case study focused on new market designs and rules aimed at making short-term markets more effective at handling the fluctuations of vRES. In this sense, the MIBEL case study explored i) market designs that enable closer-to-real-time trading, and/or ii) business strategies that allow them a diversification of the revenue streams. This case study addressed the day-ahead market (DAM), Intraday Continuous market (using the single intraday coupling – SIDC model), and balancing markets considering existing mechanisms and some improvements developed during the project based on the results and stakeholders' feedback.

Currently, the existing market design limits vRES participation and cause market distortions. Contrary to conventional dispatchable technologies, vRES cannot easily regulate their generation. Most of the European day-ahead markets (DAM) require power forecasts 12-36 hours ahead, which often results in significant vRES forecast errors. Consequently, the market prices reflect true wholesale electricity costs including both DAM prices and high balancing penalties for these variable renewable technologies. In response, a 6-hour Period-Ahead Market (PAM) has been introduced. This design benefits from more accurate power forecasts due to shorter intervals before trading, with revenues improvements of over 7% for wind power and 4% for solar PV at the national level in both Portugal and Spain. The outcomes of this new market design suggest it can effectively reduce market distortions, minimize real-time balancing needs, and lower penalties for vRES participants.

While the continuous intraday market (SIDC) allows some corrections of forecast errors in DAM/PAM up to one hour before real-time, its continuous nature creates challenges. Forecast accuracy for vRES improves significantly with updates made closer to the SIDC gate closure; however, the current "first in, first out" mechanism will disadvantage these later vRES bids with lower forecast errors. To address this, the study recommends adjusting the SIDC to clear only at gate closure, similar to marginal markets and, eventually, implementing a rule that prioritizes vRES within the first in, first out framework. This simple change enables to increase liquidity and vRES trading opportunities, thereby reducing balancing needs and their associated penalties. The results recommend transitioning to a clearing process at the gate closure that prioritizes or, at least, doesn't strongly penalize vRES.

In balancing markets, it is crucial to differentiate between the procurement of upward and downward regulation. This approach would enhance competition and better reflect the dynamic value of these services. Research conducted within MIBEL case study suggest that both countries may improve the allocation of their secondary reserve capacity, as the results indicate more capacity is reserved than needed to balance the system, considering all ancillary services. As vRES increasingly replace traditional dispatchable technologies, adapting balancing mechanisms to their inherent variability is essential for maintaining system resilience. Developing dynamic strategies for procuring system reserves (SR) can optimize efficiency and ensure effective resource allocation in real time. Imbalance settlement mechanisms should account for the real-time balancing prices of energy used to balance BRPs. This incentivizes BRPs to self-balance when facing high balancing prices in their imbalance direction and encourages them to increase their imbalance if it benefits the overall power system (resulting in a negative penalty).

As wind and solar PV gain a larger share in the market, these power plants will need to actively participate in the different markets. This means they must be capable to strategically diversify the expected generation in the various market products, including day-ahead, intraday, and ancillary services. In TradeRES, a simplified strategy of vRES market participation was designed and applied in MIBEL studies. Therefore, vRES players submitted bids to the DAM/PAM based on their forecasted output in two ways: i) submitting their full hourly forecast, or ii) bidding 80% of their hourly forecast, reserving the remaining 20% for participation in balancing markets. If vRES are allowed to actively participate in ancillary services, this market strategy suggests that these players could achieve significantly higher market-based revenues by diversifying their income streams. Their involvement would also enhance competition, the replacement of other conventional technologies (usually fuel-based technologies) and reflect the value of ancillary services.

For short term markets, the role of demand flexibility and high-share of vRES in findings from S1-S4 highlighted:

- Demand flexibility adapts the consumption behavior to vRES production, reducing curtailments and, as a consequence, market prices.
- Demand flexibility makes demand to define the prices; electrification and electrolyzers increase the system's total costs and may increase the costs for society, being beneficial to accommodate vRES and potentially profit from H2 prices.

The following recommendations for market trading in a ~100% power system, in the perspective of short-term markets, shall be also considered:

- Improve the market design with shorter lead times between market closure and delivery time. In power systems dominated by variable renewable energy sources (vRES), this modification enables the use of more accurate power generation forecasts than those currently employed in the DAM. This will lead to a reduction in the need for balancing, lower overall system costs, and helps minimize the frequency of "virtual" market-splitting events among bidding zones.
- Consider a dynamic procurement of the secondary capacity according to the power system net load and balancing needs [15].
- Allow vRES and demand players' full access to the participation in the ancillary services to increase the reliability and adequacy of a power system with near 100% RES shares.
- Apply fairer imbalance settlement mechanisms to distribute balancing prices according to real-time balancing needs, considering that the energy costs to balance with a net zero are paid by BRPs to TSOs [16].
- Incentivize a market-participation strategy for vRES players. This active market participation revealed a potential high benefit of enhancing market-based remuneration through diversified revenue streams. [4]

To facilitate market trading in a ~100% power system the following recommendations are also important:

- Increasing effort in the power forecast systems: The combination of numerical weather prediction (NWP)-based model forecasts and historical production data has proven advantageous compared to approaches relying on only one type of forecast. The benefits are particularly noticeable for shorter forecast horizons, as is the case with the PAM design tested. Consequently, power producers should invest in enabling real-time access to observed power data for forecast providers, which would significantly improve forecast accuracy. Additionally, incorporating (non-conventional) meteorological variables, such as atmospheric boundary layer data, is crucial for enhancing the accuracy of wind and solar power forecasts. Tailored, market-specific power forecasts are necessary, rather than relying on single, generalized models.
- Applying GET, e.g. dynamic line rating can optimize the capacity of existing overhead power lines, reducing network congestion and the frequency of market splitting events. This contributes to greater harmonization within electricity markets.
- New market actors/players, such as the one based on hybrid/hybridised power plants (HPPs), can be important for trading in nearly 100 % renewable power systems. HPPs offer several advantages, including higher capacity factors compared to single-technology plants. This increase not only boosts their market value and remuneration for vRES power producers but also strongly reduces investor risk and supports diversified revenue streams

that can adapt to shifting market conditions an especially valuable benefit in future renewable-based power systems.

In conclusion, new market designs should avoid mechanisms that lead to market distortions, promote non-discriminatory practices, and rely on marginal pricing. They must also adapt to the variability and difficult predictability of vRES, which are set to become the dominant energy sources in future carbon-neutral power systems.

**Contrast with stakeholder feedback:** Overall, the Iberian case study results and recommendations are aligned with the Iberian stakeholders feedback and recommendations on short-term markets. Although the Iberian stakeholders never mentioned closer to delivery market closure, they have recommended to increase our focus on a strategy of market participation for vRES, instead of using only (near zero) marginal costs, emphasising that tools being developed should enable a strategy bidding, taking into account different markets to diversify the revenue streams. However, that strategy should be designed carefully to avoid compromising market efficiency or exploiting market power. Iberian stakeholders also recommended the investment in improving generation and consumption forecasts, while discouraging the use of current support instruments as they may discriminate/benefit different types of players. Consequently, further research is needed to address the risk associated with existing support instruments.

## 3.3 Pan-European wholesale electricity market

The focus of the Pan-European case study (D5.4) was to identify drivers of market prices and profitability of variable renewables (vRES) in different scenarios of the future European electricity wholesale market. D5.4 detailed several reasons why the analysis is not suitable to estimate total future system costs or to derive recommendations on optimal system design. While the Pan-European energy system model allowed the inclusion of technologies that are likely to affect markets in the future, namely, technologies capable of shifting load between sectors and time steps, such as heat pumps, electric vehicles, electrolyzers and long-term storages, several simplifications were made to keep it computationally tractable. In terms of electricity generation, the main scenarios only consider a single vRES time-profile and use uniform cost assumptions. Therefore, the results and subsequent recommendations are suitable to identify drivers of future market dynamics but should not be understood as a projection.

The key findings indicate that the current electricity market design generally results in efficient price signals, given perfectly competitive markets for all energy carriers and a well-integrated flexible demand-side. Under these conditions, prices in future electricity markets are often determined by the opportunity costs of cross-sectoral demand technologies. Specifically, electrolyzers become a predominant price-setting technology in the presence of a high demand for hydrogen and abundant solar and wind power. Consequently, electricity prices frequently exceed variable renewables' low variable costs. However, average price levels vary substantially among scenarios. They are particularly driven by the hydrogen import price and the share of thermal power in electricity supply.

The results have the following implications: First, for investors in solar and wind power this implies that they can become profitable in future markets, even when they provide the large majority of electricity supply. A prerequisite is a price-responsive demand side. Hence, adequate instruments, such as real-time pricing should be implemented, as they were also shown to enable flexible consumers to adapt to varying price levels. Furthermore, flexibility is shown to reduce required electricity generation capacities. Second, investors also risk not to recover their costs, as revenues crucially depend on the realisation of this prerequisite and other uncertain parameters. Similarly, non price-responsive electricity consumers are shown to be exposed to significant price risks. Therefore, risk-mitigating instruments, such as adequate Contracts for Difference should be implemented.

The European case study also evaluated different design options of CfD. Similar to the findings of the German case study, dispatch distortions induced by production-dependent CfD types were shown to affect curtailment in the European market. Additionally, the Pan-European case study showed that curtailment is reduced under CfD types that expose investors to market price signals and therefore, incentivise more system-friendly investments. Since the financial CfD exposes investors to market price signals, while not distorting dispatch decisions, system costs including CfD expenditures are also lowest under this type of CfD in the particular scenario studied. However, due to the changes in market outcomes that were not anticipated when defining the CfD's underlying strike price, some investors fail to recover their costs under the financial CfD. As mentioned above, future research should further investigate risks associated with each type of CfD. The majority of wind power plants, however, over-recover their costs across bidding zones and CfD types, indicating that they are generally an adequate instrument to foster investments in renewables. Finally, while the case study did not study costs of the expansion of the transmission grid, it found a higher level of available cross-border capacities to reduce curtailment and the need for electricity generation capacities.

# 4. Summary of recommendations from TradeRES project for market trading in a ~100% power system

This chapter follows the categories of market design options detailed in D3.5. Resulting from the recommendations drawn from D3.5, case studies in WP5, and stakeholder feedback from WP6, this section identifies market design options and key recommendations for each. The goal of this chapter is to highlight the main recommendations of future electricity market trading in a near 100% power system.

Wholesale market

- *Enable closer-to-real-time trading*

  Moving from the traditional DAM to, e.g., 6-hour PAM, minimizes power forecast errors, market distortions, real-time balancing needs, and penalties. vRES' weather dependence may increase imbalances, but shorter market closure lead times would reduce this effect. However, units with low ramp rates may continue to require longer lead times (e.g., biomass, among others), and, therefore, a compromise will need to be found between the need to accommodate facilities with ramping constraints, which need longer lead times, and variable renewable energy sources, for which a short time between market clearing and delivery reduces weather uncertainty.

- *Include a more appropriate clearing mechanism in the continuous IDM*

  The current IDM design needs to be reconsidered aiming to reduce vRES' (weather) uncertainty and optimal consideration of all types of flexible resources. A possible solution is to reduce the time between trade and delivery [21]. Including the clearing at gate closure (instead of at order submission) in the "first in, first out" market mechanism while prioritising vRES, besides enabling improved power forecasts also increases market liquidity.

- *Incentivize the active and strategic participation of vRES market players*

  A careful study on the implications of the active and strategic participation of vRES players in markets should be performed before implementing it, as, if properly implemented, active participation of market players can enhance vRES market-based remuneration through diversified revenue streams. Bidding strategies can be applied from many perspectives, e.g.: i) by using different types of wholesale bids such as block orders in EPEX and Nord Pool or complex bids in MIBEL; ii) by strategically submitting different energy volumes of the total power amount in multiple tranches for the same hour and/or into different types of trading, i.e., day-ahead, intraday auctions, intraday continuous, etc: iii) strategically defines bid prices and energy volumes for the different trading periods; among others. Nevertheless, these strategies should not jeopardize the market's efficiency, e.g., through making use of market power.

- *Create conditions to improve power forecast systems*

  vRES power forecast systems are a key *enabler* for market trading in a nearly 100% renewable energy power system. Establishing common procedures and best practices, including investing in real-time power data access, can significantly improve forecast accuracy. Moreover, including tailored and non-conventional data, instead of relying on generalized models, is also critical to enhance the accuracy of vRES power forecasts.

Retail market design

- *Implement Fully Indexed Tariffs for Real-Time Local Price Signals*

  The high penetration of vRES, electrification, and demand-side flexibility may significantly increase the risk in retail markets. Locational marginal pricing increases the social welfare of the system. So, local markets may be critical in adjusting consumption to local production [3].

  Tariffs shall be fully indexed to provide the right local price signals closer to real-time. Local tariffs shall be indexed to local generation and local grid costs, being the weight of the congestion management price is important to avoid local congestion. [3].

  On the European scale, real-time pricing is also shown to be a key enabler of a functioning future wholesale market, where a high share of variable electricity generation with low operational costs meets a cross-sectoral, flexible demand-side [5].

Ancillary system services

- *Adapt Ancillary Services to enable the full participation of vRES players*

Ancillary services should be adapted and allow the participation of vRES, the future main energy providers. The separate procurement of secondary power between upward and downward regulation and trading it closer to real-time is important to increase competition and guarantee the participation of vRES [4].

- *Expand Participation to Aggregated and Smaller Players*
- *Implement Dynamic Procurement of Secondary Power*

With the increasing shares of vRES and demand flexibility, the procurement of secondary power should be dynamically assessed according to the expected net loads and deviations. Furthermore, opening the participation into these services to smaller and aggregated players is important to incentivize more participation from vRES and consumers and reduce imbalances.

- *Implement an imbalance settlement mechanism that fairly reflects the true costs of these services*

An imbalance settlement mechanism that reflects the exact costs of the services used to balance energy with a net zero cost to TSOs was considered. The proposed mechanism incentivizes self-balancing and self-deviation when it benefits the system according to balancing prices. Positive and negative balancing prices incentivize self-balancing and self-deviation, respectively [4].

vRES support schemes

- *Design Effective Support Schemes to de-risk vRES Investments*
- *CfDs seem to offer a balanced approach by securing stable revenues for investors while controlling support costs for end consumers.*

vRES support schemes are deemed necessary to de-risk vRES investments. CfDs seem to be a promising option as they address the trade-off between adequately securing investors' revenues as well as keeping support costs low for end consumers. However, their design requires careful attention.

A basic CfD that uses the hourly short-term market price eliminates the exposure of investors to price signals. Therefore, it causes inefficiencies in the design and siting phase of variable renewable power plants. This issue is addressed by production-dependent CfDs with a reference price that is constant over a certain period. However, the one-way CfD that does not include a payback obligation has the potential to result in over-support, particularly when a monthly reference period is used. The two-way CfD, on the other hand, is a more effective means of balancing support payments against investors' costs. However, both instruments may result in significant dispatch distortions, such as an increase in market-based curtailment of vRES, if investors anticipate production-based payments.

Production-independent instruments such as a financial CfD that still expose investors to price signals were found to be a promising option. However, they potentially expose investors to new base risks that require future analyses. In this regard, a general trade-off between effective risk hedging and system-friendliness incentives exists.

System adequacy

- *A CRM is needed, both during and after the energy transition.*

A CRM should be based on the demand for firm capacity by final consumers, including households and SMEs, and provide them with a price hedge (insurance).

During the energy transition, a government-backed intermediary could purchase generation capacity in long-term contracts and sell this to consumers in annual contracts.

Cross-border trade

- *Adopt GET, e.g. Dynamic Line Rating (DLR) as an enabler for enhance* electricity *markets harmonization*

Increasing the transmission capacity of overhead tie-lines or using a dynamic line rating approach is important to reduce vRES curtailments and market splitting events between market zones, increasing price harmonization. On the Pan-European scale, DLR was also found to reduce curtailment and the need for electricity generation capacities.

Sector coupling

- *Expose all end users to real-time wholesale market prices, with possibilities for protection against high prices.*
- *During congestions, signal the limited availability in network tariffs in a cost-effective way while respecting grid limitations.*
- *Create effective markets across all energy networks.*

Cost-efficient and reliable energy systems require coordinated market design and regulation across coupled infrastructures, including short-term markets, investment support instruments, tariffs, fuel markets and taxes. New electric loads from sector coupling, such as like electric vehicle charging, heating and cooling, and hydrogen production, can support energy flexibility if exposed to real-time pricing. In addition, during congestions (which may not coincide with peak loads), network tariffs should also signal the limited availability in a cost-effective way while respecting grid limitations. Automation and auxiliary systems, like fuel boilers, could further enhance flexibility provision. For hydrogen, sufficient infrastructure for storage and transmission, or alternatives like liquid hydrogen derivatives, could advance and enhance its role in reducing fossil fuel consumption. Effective markets are essential across all energy networks, including hydrogen as well as heating and cooling systems, for balanced supply and demand and utilising flexibility correctly.

Transmission networks and cross-border trade

- *Adopt GET, e.g. Dynamic Line Rating (DLR) as enabler to enhance electricity markets harmonization*

The adaptation of Dynamic Line Rating can be important to reduce curtailments and integrate new renewable generators without a lengthy process to construct new lines [17].

Distribution networks

- *DSOs and LECs may play a critical role with increasing decentralized vRES generation and electrification.*

The provision of LEC tariffs indexed to local generation incentivizes flexible consumers to adjust to local generation, reducing the net load and contributing to avoiding local congestion [3]. DSOs may develop products to incentivize consumers to avoid local congestion.

# 5. Conclusions

The concluding chapter revisits key takeaways for recommendations for market trading and modelling in a ~100% power system which are summarized in Table 1 at the end of this chapter. Feedback from stakeholders was gathered regarding the modelling work conducted in work package 4, covering each of the models applied. As this work was already aligned to the analyses of various market design options, the feedback addressed not only modelling but also content-related expectations.

Based on the models developed, respective analyses were carried out within the case studies in work package 5 that focused on complementary aspects of national and regional markets, and different spatial scales, from local markets to pan-European trade. The derived recommendations for market designs were summarised and compared with the stakeholders' feedback. With regard to wholesale markets, recommendations include a closer-to-real-time trading, a more appropriate and vRES-friendly clearing mechanism in the continuous intraday market, incentives for an active participation of vRES market players, and to create conditions to improve power forecast systems, Fully indexed tariffs for real-time local price signals were identified as a measure for adjusting consumption to local production in retail markets.

With regard to ensuring necessary investments in renewables, it was concluded that effective support schemes have to be designed to de-risk vRES investments. CfDs were found to be a promising option as they address the trade-off between securing revenues as well as keeping support costs low for end consumers. However, they have to be carefully designed to avoid dispatch distortions or new base risks, e.g. as favour over-support or promoting vRES curtailment.

TradeRES findings further demonstrated that strategic bidding allowed for better vRES integration but came with trade-offs, including higher market prices. It was noted vRES earned higher revenues from the market due to two key factors: i) an increase in DAM/PAM prices, and ii) participation in balancing services. Providing ancillary services (AS) can significantly enhance the value of vRES plants by diversifying their revenue streams across multiple markets. Furthermore, the results indicate that variations in CfD design impact both investment and dispatch, particularly curtailment. Finally, the period-ahead market with a rolling 6-hour window clearing has been proposed as a new market design and analysed proving to be superior in almost all categories when compared to the current day-ahead market design, allowing for a better vRES integration, an increase in system efficiency as well as improving pricing and transmission aspects [2].

Table 1. A summarized list of key recommendations by thematic area for market trading in a ~100% power system.

| Market design component | Recommendations |
|---|---|
| **Wholesale market** | • Enable closer-to-real-time trading<br>• Include a more vRES-friendly clearing mechanism in the continuous intraday market (IDM)<br>• Incentive the active participation of market players, e.g., using vRES strategic participation in different markets<br>• Create conditions to improve the accuracy of power forecast systems and synchronize timings of markets and weather inputs |
| **Retail market design** | • Implement fully indexed tariffs for real-time local price signals |
| **Ancillary system services** | • Adapt ancillary services for enabling the full participation of vRES players<br>• Expand participation to smaller and aggregated RES players<br>• Implement dynamic procurement of secondary reserve power<br>• Implement an imbalance settlement mechanism that fairly reflects the true costs of these services |
| **vREs support schemes** | • CfDs proved to offer a balanced approach by securing stable revenues for investors while controlling support costs for end consumers. However, the selection of CfD type and design must be carefully studied for each particular market.<br>• Design effective support schemes to de-risk vRES Investments |
| **System adequacy** | • A CRM is needed, both during and after the energy transition. |
| **Transmission networks and Cross-border trade** | • Adopt grid enhanced technologies (GET), e.g. dynamic line rating (DLR) as enablers to increase the transmission capacity of tie-lines. This can help reduce the occurrence of market splitting, thereby contributing to enhance the electricity markets harmonization. |
| **Sector coupling** | • Coordinated market design and regulation across coupled infrastructures and energy vectors. |
| **Distribution networks** | • DSOs and LECs may play a critical role with increasing decentralized vRES generation and electrification. |

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