Addressing Market Issues in Electrical Power Systems with Large Shares of Variable Renewable Energy

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***Abstract*— This paper reports recent findings from IEA Wind TCP Task 25, which compiles international experiences and research related to large-scale integration of wind and other renewable energy. In the paper, we address the main challenges for market integration of variable renewable energy, relating to price formation, cost recovery, balancing and other grid services. The paper gives an overview of recent scenario studies on electricity price impacts of (1) various generation, energy storage and demand types in different markets, and (2) different market designs and energy/climate policies. Studying markets with very high shares of variable renewable energy requires an improved set of analysis tools for forecasting market outcomes, estimating flexibility needs and sources, and assessing resource adequacy. Key market features need to be investigated within these improved analytical capabilities for systems transitioning to high shares of variable renewable energy, storage and flexible demand. System services that can be supported by markets will likely need to be revisited. Finally, this paper identifies open questions and suggested future market design work for supporting systems with very high shares of variable renewable energy, which are to be addressed in follow-up work of Task 25 collaborative research.**

***Index Terms*-- Variable renewable energy, market design, cost recovery, electricity prices**

I. Introduction

As Variable Renewable Energy (VRE) and various types of Electrical Energy Storage (EES) become more competitive, it is necessary to revisit the foundations of market designs, typically developed on the premise of fuel-based generation. Previously, market studies of VRE often considered support schemes and how subsidy-driven investments impacted the market and conventional generators. The focus is now shifting to VRE technologies, which in many places are the cheapest available source on a €/kWh basis [1][2][3]. This trend is foreseen to continue, supported by national and international targets for power system decarbonization. Two key challenges for achieving decarbonized systems are related to (1) economically balancing supply with demand, and (2) designing systems with inverter-based resources that ensure reliability and stability. The former contains additional concerns related to the design of efficient competitive wholesale electricity markets that support cost recovery for resources needed to ensure reliability [4][5]. Therefore, market designs and studies must consider VRE as a driving force in the power system and consider how other technologies can play a supportive role at lowest possible system cost.

All central scenarios by IPCC, EC, IEA and EIA agree that VRE will dominate electricity supply towards 2050 [6][7][8][9]. Moreover, increased electrification of heat and transport, new technologies for Demand-Side Management (DSM), and the development of Power-to-X (P2X), give rise to new active consumers in the electric power market. Together, VRE, EES and active consumers will likely impact wholesale price formation, cost recovery of all power plants, as well as balancing prices and costs for different grid services. A key question looking to the future is, therefore, whether current market designs and market products are economically efficient and can suitably incentivize investments needed for reliability, particularly when VRE technologies are dominating the power mix. On top of that, the zero-marginal-cost resources necessitates a new approach to the governing economics of power systems [10].

This paper reports recent findings from IEA Wind TCP Task 25, which compiles international experience and research related to large-scale integration of renewable energy. In the paper, we address the main challenges for market integration of VRE related to price formation, cost recovery, balancing and other grid services. The paper will give an overview of recent scenario studies on the impact on price outcomes of (1) various generation, energy storage and demand types in different markets, and (2) different market designs and energy/climate policies. Finally, we highlight open questions and potential future work that can support the evolution towards energy systems with very high shares of VRE.

II. Technology Impacts on Markets

A. Generation

Newer wind turbines tend to be larger, both in terms of rated power and rotor diameter, and often installed at higher hub heights compared to existing installations [11]. In Europe, modern onshore turbines can provide up to around double the capacity factor (CF) compared to existing fleets [12], leading to lower variability in wind generation output [13]. In energy system optimization, high CF turbines (low specific power and high hub height) may be favored even more than would be indicated by simple Levelized Cost of Electricity (LCOE) analysis, driven by highly variable future electricity market prices [14]. This highlights the importance of price signals, not only in operational decisions, but also in planning of new investments. From a producer perspective, the “self-cannibalization” effect (electricity prices tend to fall when VRE generation is high) can reduce revenues. However, VRE technology development can also mitigate it. An example is the LowWind technology, which has a very low cut-out wind speed (around 13 m/s), allowing the blades to be lighter, cheaper, and more efficient at low wind speeds [14]. Market prices at times of high wind speeds are often low since all traditional turbines will tend to be generating at around rated power. Reduced generation at these times of low prices is compensated by increased generation at low wind hours when prices tend to be highest.

The results of a North European study on electricity price sensitivities [15] showed that the amount of base load (coal and gas) generation capacity has a very high impact on electricity prices. In the reference scenarios with a fixed large amount of base load generation capacity, the average electricity price decreased by 16–21 €/MWh when increasing the VRE share from 40 % to 60 %. In contrast, for those scenarios where the rest of the capacity mix, including thermal generation, was adjusted according to the increase in VRE share, average electricity price decreased only by 4–5 €/MWh when increasing the VRE share from 40 % to 60 %. Other work in the United States has similarly observed strong price suppression effects from adding large quantities of VRE without adjusting the underlying system [16].

A study of the North European power market analyzed the effect of increased VRE shares on the profits of conventional generators, using 75 historical weather years to capture annual variations in wind, solar, hydro inflow and temperature-dependent load [17]. The study found that wind power output and profits of conventional generators were highly negatively correlated, ranging from -0.65 to -0.79 (TWh wind vs €/kW installed conventional capacity). It also found that the annual profit of conventional generators varied between -30% to +70 % of the 75-year average, highlighting the potential financial risk of conventional generation incurred by natural variations in weather.

A study in Sweden performed by the TSO Svenska Kraftnät considered possible future scenarios for assessing transmission expansion needs [18]. In the “Electrification renewable” scenario, Sweden has 43 % higher consumption in 2035 than today. The load increase is assumed to be mainly covered with wind power, but also some solar PV, with a total share of wind and PV (yearly production) of 52 %. The power system is simulated for 31 weather years (wind, solar, load, hydro) as a part of the Northern European power system. The obtained price for wind power was found to be lower than the yearly mean price, varying between -8 % and -25 % depending on the area. A lower obtained price for wind power in surplus areas may be mitigated by increased flexible hydrogen production in the same area [19].

B. Forecasting

New market designs for energy systems with high shares of VRE require innovative tools to forecast the uncertain behavior of VRE power generation, demand and prices. There are several reliable and high-quality forecasting methods available for PV and wind power [20][21][22]. The main challenges are extreme weather events, such as cyclones or spontaneous cloud formation, that are difficult to forecast accurately both in time and space [23][24]. In recent years, the main developments in wind and PV forecasting have been to improve the prediction of aggregated generation in selected grid regions, or for single wind farms and large ground-mounted PV plants. The development of price forecasts can also be seen as an established research field and a commercial product [25]. However, the increasing price volatility observed, and projected in spot markets [26], creates new challenges for forecasting prices; volatility is triggered by weather dependent power production, flexibility needs, and market share of many differently sized active consumer loads.

Regarding optimization of forecast systems in the near future, we see two main areas where further developments are required with respect to trading activities. First, demand forecasts will become increasingly important [27]. The large-scale electrification of transport, heat and industry leads to a more complex, user-based and hence dynamic characteristic of demand profiles. The increasing presence of smart metering and consumers becoming more exposed to time-of-day or real-time prices also means that load profiles may become less predictable, particularly contrasting high-VRE days when prices may be notably reduced. Accurate demand forecasts are also crucial for estimating the available flexibility at different aggregation levels. Second, forecast systems must be further developed to estimate VRE generation, demand and market prices, for horizons of several weeks to months. It is well known that forecast quality decreases with increasing forecast horizon. Probabilistic methods should be adapted to forecast long-term assured capacities.

C. Diversification

A possible countermeasure against large electricity price fluctuations and reduced revenues is diversification of the electricity mix. While wind and solar PV generation have dominated recent developments due to lowest LCOE, other sources might gain importance in the future. A recent case study of a wave power plant off the Portuguese coast in 2030 has shown improved market performance (as compared to wind and solar) [28]. Similar studies have also been investigated for wave power off the Irish coast [29]. Even though measurable, the identified benefits tend to be small (a few percent) and insufficient to assure profitability of the wave power plant in the given scenario. However, the mentioned revenue reduction effects grow with increasing shares of VRE, making the relative long-term outlook for alternative sources potentially more favorable. Thus, as pointed out in section II.A, a portfolio of different renewable technologies would likely benefit the system and markets.

D. Transmission

The benefit of transmission in supporting multi-regional wind and other renewable deployment is well documented in the literature [30][31][32][33]. In Denmark, a study demonstrated that without the developments in power plant flexibility and transmission capacity with neighboring countries, it would be extremely challenging to integrate VRE to the level Denmark has today. In cases without flexible power plants (Scenario 2), with reduced interconnector capacity (Scenario 3), and with combined flexibility reductions (Scenario 4 = Scenario 2 + Scenario 3), the market prices are lower compared to the present flexible system. For example, market prices obtained by wind decreased by 30 % and 34 % in Scenarios 3 and 4, respectively, see Figure 1. [31].

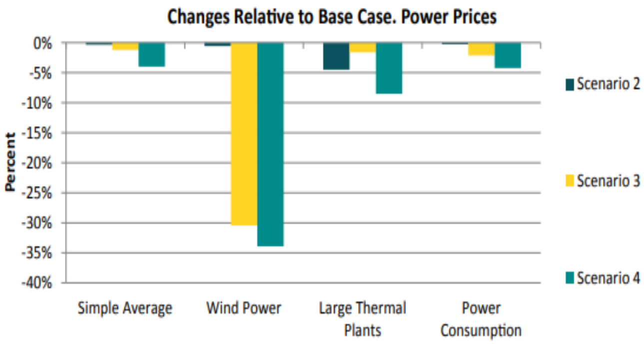

Figure 1. Changes in market prices in the case of the non-flexible system in Denmark [34].

The impact of aggregation benefits of wind power forecast errors also influences reserve requirements. A Nordic study showed that reserve requirements, reflected as an increase in existing hourly imbalances due to adding wind power, are twice as high for Finland forecast errors than for Nordic-wide forecast errors [35]. In Germany, the amount of activated operating reserves were found to drastically decrease after creating a joint balancing area for the four system operators, despite increasing amounts of wind and solar [36]. The development of a meshed offshore grid, connecting offshore wind energy hubs to multiple countries, shows benefits compared to connecting each offshore wind power individually [37], especially in highly sector-coupled scenarios [38].

The study on electricity price sensitivities referred to in section II.A [15] also explored the impact of reducing transmission capacities from the optimized values. The results showed that impacts in a certain area depend on whether the area is more dominantly exporting or importing electricity. In an importing area, reduced transmission capacity increased the number of hours of high electricity price, whereas in an exporting area, reduced transmission capacity increased the number of hours of very low prices. In an area that uses its interconnections more equally for both export and import, the number of hours of both high price and low price increased when transmission capacity was reduced.

In the United States, recent work has highlighted a complex set of technical and regulatory issues that create barriers in the transmission planning process, specifically with how transmission costs are allocated to wind and other VRE resources in interconnection queue processes [39][40][41]. Declining technology costs and policy goals have led to an exponential VRE growth in these queues [42][43]. Because transmission is required to transport much of this VRE to the load centers, some proposed projects are being assigned the full (or near-full) cost of new transmission, despite the fact that the benefits are being realized by the broader system, including neighboring regions in some cases [43]. Wind has been particularly disadvantaged by current transmission cost allocation structures: the resulting cost burden and time in the queue have led to only 19 % of wind projects successfully making it through the queue to operations [44]. The current (at the time of writing) Federal Energy Regulatory Commission Advance Notice of Proposed Rulemaking (NOPR) on transmission cost allocation is yet another indicator of the pressing need to improve transmission expansion practices [45].

E. Demand Side Management and Sector Coupling

Driven by the electrification of the heat and transportation sectors, electricity consumption is expected to increase significantly. Projections in Europe towards 2050 show electricity consumption doubling or even tripling compared to today [9][46], with electricity generation dominated by VRE. Sector coupling can also provide significant flexibility to the system, e.g., through P2X, as exemplified in Figure 2. , and through the heat sector [46][47]. Individual heating loads are likely to be highly correlated, and highly seasonal in nature, but thermal storage, for example in the form of underfloor heating or larger storage connected to district heating schemes, potentially presents opportunities for demand shaping and participation in flexibility-oriented markets, and with the potential to reduce peak demand (and peak price) periods. In [48], a capacity expansion model with sector coupling between electricity and hydrogen was used to study decarbonization scenarios for the energy system in Texas. By utilizing electrolyzers as flexible load coupled with hydrogen storage, the study showed that fewer stationary batteries and flexible gas power plants were needed for balancing power. It was also shown that flexible hydrogen production contributed to stabilizing the electricity price.

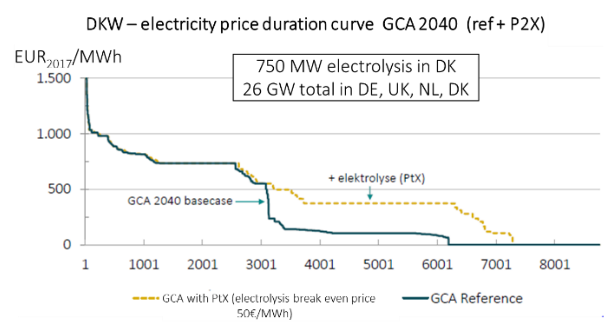

Figure 2. Example from the price area of Denmark West (DKW) on how future Power-to-X electrolyzers can improve the low prices during surplus hours. The averal annual settlement price for wind and PV inDKW increases from about 20 to 40 €/MWh in the P2X scenario. (Source: Energinet).

Growth in the number of EVs will also tend to increase annual electricity consumption, but vehicle charging is flexible to some extent, with the possibility of bidirectional power flow through "Vehicle-to-Grid" technology (V2G) [49][50]. In general, increased access to a range of flexibility options may reduce the need for renewables curtailment and the need for conventional generation sources for system support needs, particularly for smaller systems, which may further push down electricity prices and system services prices [51][52]. For scenarios with very high amounts of wind and solar power, hybrid cross-sectoral demand will limit the number of hours with zero or negative prices. Ref. [53] highlights the importance of explicitly modelling cross-sectoral demand bidding to achieve a better picture of price formation in those systems with limited numbers of conventional generators. The results reveal that extreme prices in both directions can be avoided to a high degree in the presence of flexible, cross-sectoral demands and interconnections in the European power system towards 2040. Similar trends have been found for studies in the United States, where the presence of demand side flexibility in potential futures with widespread electrification (up to 36 % of 2050 final United States energy demand met by electricity) saw reduced electricity price variability and volatility [54].

Higher electricity demand due to electrification would itself increase electricity prices, and new flexible loads could benefit from and smooth out extreme prices. In [52], higher system flexibility due to electrification further increased the share of VRE, which is beneficial from an environmental point of view. However, this caused electricity price volatility to increase. The result highlights the importance of considering the market impacts of combined changes in the system.

F. *Energy Storage*

Energy storage has been investigated as a crucial element of renewable energy systems for decades [55]. In addition to well-established pumped hydropower, stationary batteries have received much attention in recent years. Many other storage technologies exist, but they are generally further away from commercialization. For systems with high shares of wind and solar power, it is required to study how different storage technologies will optimally be used for balancing net load [55], better support grid infrastructure utilization [56][57] and counteract forecast errors [57][58]. In wholesale power markets, energy storage is typically used for price arbitrage, which leads to levelling out price variations over different timescales. However, it is also well known that the marginal value of storage in the market diminishes as a function of installed capacity [59]. It is shown in [60] that there exists a competitive market equilibrium with optimal generation and storage capacities where all units in the system recover their costs from spot prices, However, this result is subject to simplifications regarding the representation of storage (kWh) capacity, which requires further theoretical and numerical investigations. In a recent capacity expansion study [61], all technologies except storage were found to be profitable from the resulting spot prices in a scenario with 75 % VRE.

III. Policy and Market Designs

A. *Carbon Pricing*

The impact of carbon pricing on electricity prices naturally depends on the carbon intensity of power plants. In the North European study first referred to in section II.A [15], the effect on electricity price were quantified for different generation capacity scenarios. With a significant amount of base load coal in the system, increasing the CO_2 price relatively modestly from 29 €/t to 49 €/t increased the average electricity price by 7–12 €/MWh. Similar change in the CO_2 price increased the average electricity price by 5–6 €/MWh when base load coal was removed from the system and replaced by gas-fired power plants.

B. *System Adequacy and Cost Recovery*

A prominent concern for systems with large contribution levels of zero-marginal-cost VRE resources is revenue sufficiency, which is the opportunity to recover both fixed and variable costs of resources needed to ensure resource adequacy (also referred to as system adequacy) [5]. In the United States, this concern is supported by empirical price suppression effects from zero-marginal cost VRE resources, expanded access to low-cost natural gas, limited demand growth, large planning reserve margins, and a host of underlying inherent attributes that prevent electricity markets from functioning as perfectly competitive markets [5][62][63][64][65][66][67]. Options to address this concern typically involve some form of administrative or out-of-market actions, such as scarcity pricing, capacity payments, bilateral or other out-of-market contracts, or some hybrid combination [62]. Operating Reserve Demand Curves (ORDCs), such as those in ERCOT and PJM, are one form of scarcity pricing that utilizes price incentives in short-term markets for energy and reserves to ensure capacity adequacy and revenue sufficiency [68][5]. A second approach, taken by CAISO, relies on administrative and centralized planning procedures to ensure both the amount of future capacity and level of flexibility in the future resource mix [68]. Other options include multi-period pricing and settlement, carbon pricing, and price-responsive demand, the latter of which would address a core market failure referenced above [5][62]. Since traditional energy prices do not capture all costs incurred while dispatching resources, many operating areas in the United States are proposing and implementing alternative pricing methods to increase transparency and efficiency by reflecting additional operating costs (start-up and commitment/no-load costs) that systems incur during daily operations and by allowing resources to set prices during time periods that otherwise would be ineligible [69].

As consumers become increasingly aware of their energy consumption, costs, and alternative objectives, such as environmental impact, load flexibility becomes an important resource. As a result, a new resource adequacy paradigm would ideally be designed to increase cost transparency so that regulators, policymakers, and consumers understand the relative costs of different levels of, and approaches to, reliability and can make informed investment decisions. There needs to be a clear understanding among policymakers, regulators, and system planners of incremental reliability costs to consumers so that tradeoffs can be made between cost and risk. The increased role of wind, solar, storage, and load flexibility requires the industry to rethink reliability planning and resource adequacy methods and to reconsider analytical approaches. Ongoing work through the Energy Systems Integration Group [70] is investigating the data, methods and metrics used to determine resource adequacy with the changing generation mix.

C. Balancing and Grid Services

Balancing markets and payments for grid services need to be carefully designed to allow participation by a wide selection of flexible resources on the generation, storage and demand side. Inefficient utilization of existing flexibility—such as that caused by misaligned scheduling and settlement intervals—or unwillingness of resources to provide flexibility—such as through self-scheduling caused by contractual limitations—can compromise system reliability by not meeting the changing net load, and it can also lead to higher costs when an inefficient use of flexibility resources occurs [71]. Newer ancillary service market designs, such as pay-for-performance regulation, primary frequency response, fast frequency response, and ramping markets, provide additional incentives to support flexibility and reliability for resources that may not have offered those incentives in the past [71][72][73]. Other market mechanisms to provide flexibility include allowances for non-traditional resources, such as demand response, energy storage, and even VRE itself [71].

Traditionally, electricity market participants have obtained most of their revenue through the supply of energy, with much lower revenues associated with the supply of system services, and/or capacity, if applicable. However, with increasing shares of renewables, the importance of a range of system services, e.g., fast reserve, ramping products, dynamic voltage support, grows significantly. For systems with very high renewable ambitions, or that are not inherently flexible, the lack of flexibility may impede their ability to achieve desired levels of renewable resource utilization. Consequently, future market designs may need to rebalance revenue streams between energy, system services, and capacity in order to incentivize investments which are low cost, but also can contribute towards flexibility needs.

In the United States, a study of an ERCOT-like test system showed that allowing wind and solar to provide operating reserves can contribute to economic and operational benefits (e.g., downward trending production costs and larger net revenues), as this open access to reserves markets enables greater access to the full set of capable resources at lowest cost [72]. ERCOT has good experience with well complying, fast responding wind power plants providing primary frequency control [30]. In Spain, most wind power plants have made compliance tests for frequency control and they are increasingly being used from the market – mainly for down regulation, and for the slower responding balancing [31]. In Sweden, a study [76] showed that an increase in profitability can be achieved by a wind farm operating in the ancillary service markets, such as Fast Frequency Reserve (FFR) and Frequency Containment Reserve (FCR). Periods with low spot prices represent especially good opportunities to increase profits, with downward regulation being the most profitable form of ancillary service for a wind farm, but upward regulation and symmetrical bids can be profitable in some situations.

D. Local Markets

Day(s)-ahead, intraday and short-term markets are typically well captured in modeling tools for exploring balancing and system services. Recent years have seen growing interest in local (or distribution-level) market designs, such as how electricity and flexibility can be traded between different end-users, e.g., peer-to-peer technologies. Many conceptual studies have been undertaken, and some local market designs show promising potential e.g., for reducing grid tariff costs in areas where flexible resources and VRE production can be traded between end users [77]. However, local trading may impact the grid significantly. In a study of 52 households in Norway [78], the use of batteries for local peer-to-peer trading was found to bring overall savings for the end-users, but also increased local grid losses by 14 %. How local markets will link to each other, and to bulk system markets, is a topic requiring more research, especially in areas which expect large growth in Distributed Energy Resources (DERs), such as energy storage and behind-the-meter PV. It is challenging to develop models for system-level studies which realistically account for resources connected at low voltage grid-levels. DER aggregation models are crucial to study the future interplay between bulk- and distribution-system VRE and flexible technologies.

IV. Conclusion and Further R&D

This paper addresses some of the major developments in the integration of renewable energy into electricity markets and identifies key remaining challenges for supporting future systems with very high shares of variable renewable energy. Several recent studies have been reported and classified into 1) Technology impacts on markets, and 2) Policy and market designs. Key findings from these studies includes:

- Price impacts of VRE is smoothed by building more transmission and diversify technology (e.g. wind turbine design) and energy sources (e.g. adding wave power to the mix).
- Demand forecasting and flexibility estimation and becomes increasingly important for markets due to electrification of transport, heat, and industry.
- Low-price periods can be utilized by storage, electrolysis and P2X, but long-term market impacts of these storage and demand types must be better understood.
- Cost recovery in markets with very high shares of VRE is challenging and may call for alternative pricing methods and targeted instruments to ensure system adequacy.
- With increasing shares of renewables, the importance of a range of system services grows significantly, impacting the revenue streams between energy, system services and capacity.

In general, there is likely to be a mismatch between current market designs and expected future power system needs. Studying systems with very high shares of VRE requires improved forecasting and modelling approaches, datasets, analysis, and integrated tools. Key market features, including proposed reforms, need to be critically investigated within these improved analytical capabilities for systems transitioning to high shares of VRE, storage and flexible demand. Key system services that can be supported by markets range from long-term cost recovery and resource adequacy to short-term balancing and stability, all of which will likely need to be revisited with new paradigms expected. Changes to market designs arising from increasing VRE and distributed flexibility will be addressed in follow-up work of IEA TCP Wind Task 25 collaborative research.

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