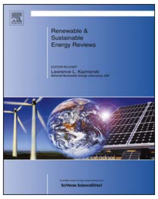
Renewable and Sustainable Energy Reviews xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



Identifying barriers to large-scale integration of variable renewable electricity into the electricity market: A literature review of market design

Jing Hu*, Robert Harmsen, Wina Crijns-Graus, Ernst Worrell, Machteld van den Broek

Copernicus Institute of Sustainable Development, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands

ARTICLE INFO

Keywords:
Market integration
Barrier
Integration costs
Electricity market
Variable renewable electricity

ABSTRACT

For reaching the 2 °C climate target, the robust growth of electricity generation from variable renewable energy sources (VRE) in the power sector is expected to continue. Accommodation of the power system to the variable, uncertain and locational-dependent outputs of VRE causes integration costs. Integrating VRE into a well-functioning electricity market can minimize integration costs and drive investments in VRE and complementary flexible resources. However, the electricity market in the European Union (EU), as currently designed, seems incapable to deliver this end. This paper aims to provide a comprehensive literature review of barriers to the large-scale market integration of VRE in the EU electricity market design. Based on the set-up of the EU electricity market, a framework was developed to incorporate the most pertinent market integration barriers and resulting market inefficiencies.

This paper concludes that an overhaul is needed for the current EU electricity market to address all barriers identified. Firstly, a discrete auction intraday market, a marginal pricing balancing market, a two-price imbalance settlement and a nodal pricing locational marginal pricing mechanism seem more promising in limiting integration costs. Secondly, to support business cases of VRE and complementary flexible resources in the electricity market, a level playing field should be established and the price cap should be lifted up to the value of lost load (VOLL). Meanwhile, to fit VRE's market participation, a higher time resolution of trading products and later gate closure time in different submarkets would be required. Lastly, feed-in support schemes currently widely used for VRE investments might be inconsistent with market integration, as they increase integration costs and lock VRE investments in a subsidy-dependent pathway. To avoid such lock-in, further investigation of alternative capacity-based support schemes is recommended.

1. Introduction

The Paris Agreement aims to limit the increase of the global average surface temperature to 1.5–2 °C above pre-industrial level to avoid the worst impacts of climate change [119]. Keeping the temperature increase well below 2 °C through cost-effective strategies requires the decarbonization of the power sector, which accounted for 38% of global energy-related CO_2 emissions in 2013 [74,80]. Variable renewable electricity (VRE), which is electricity generation from stochastic energy flows (e.g. wind and solar), plays an indispensable role in replacing fossil-fired electricity production that, next to climate change, cause other negative externalities including air pollution and energy insecurity [103,13,81,89]. According to the 2 °C scenario of the International Energy Agency (IEA), the contribution of VRE to global electricity supply has to increase from 4% in 2013 to 25% in 2040 [75]. Similar figures are found for the European Union (EU) that should increase the share of VRE in gross electricity generation from 11% in 2014 [50] to at least 36% by 2050 to contribute to its long-term emission reduction target [36]. VRE, characterized by variability, uncertainty and locational-dependence, however, interacts with the non-VRE part of the power system (hereafter referred to as the residual system). This results in technological, institutional and managerial challenges associated with grid operation, such as the increased need for flexible resources (e.g. flexible plants, storage, demand response, grid infrastructure) and power quality control, better inter-regional coordination and sophisticated method to size reserve. They often cause extra

---

[*] Corresponding author.
E-mail address: j.hu@uu.nl (J. Hu).

http://dx.doi.org/10.1016/j.rser.2017.06.028
Received 5 September 2016; Received in revised form 28 March 2017; Accepted 9 June 2017

Please cite this article as: Hu, J., Renewable and Sustainable Energy Reviews (2017), http://dx.doi.org/10.1016/j.rser.2017.06.028

operational and investment costs in the residual system to accommodate VRE ([113,61,65,72,5,17]). These costs are often labelled as integration costs,[1] which increase with the rising penetration of VRE. They inevitably become notable when VRE penetration reaches 10%. Various sources [68,118,72,113] indicate that at 10% penetration, integration costs are 9–13 €/MWh for onshore-wind and 26.5–32 €/MWh for solar PV. Integration costs can act as an economic barrier for the continuous growth of VRE [118]. Integration costs reduction becomes increasingly prominent in today's energy policy agenda [107]. Despite an emphasis on "cost-effectiveness" and "cost-efficiency" in the EU's official *Roadmap for Moving to a Competitive Low Carbon Economy* [34] and *Framework Strategy for a Resilient Energy Union with a Forward-looking Climate Change Policy* [38], few efforts have been made yet by policy-makers and regulators for the minimization of integration costs [107,93].

Many parts of the world (including the EU) have established liberalized electricity markets to facilitate the trade of electricity and boost economic efficiency. A well-functioning competitive electricity market can theoretically limit integration costs associated with a given penetration of VRE. This is the case because a theoretical long-run equilibrium exists to deliver the least-cost residual system, which minimizes integration costs. An electricity market functions well, if its price signals support efficient short-term operation and provide sufficient investment incentives for all generation capacity needed [33,69,51,6]. This means that it should be able to provide sufficient remunerations to recover capital costs and support business cases for investments in VRE and complementing low-carbon flexible resources, which are indispensable to adapt to the variable and uncertain outputs of VRE. Otherwise, the least-cost residual system will not be reached. However, in absence of a level playing field due to incomplete internalization of social costs of carbon (SCC) and (explicit and/or implicit) subsidies for fossil fuels, the electricity market cannot effectively promote VRE investments in line with the EU's deep decarbonization goal [35]. This justifies the adoption of various national support schemes, which has driven the rapid and large-scale capacity expansion of VRE in the EU. These schemes aim to financially secure capital-intensive VRE investments against market revenue risks[2] and thus reduce the cost of capital [76,98,101,128]. Their implementation has also contributed to significant costs reduction of VRE technologies, because of economies of scale and technological learning [29,90]. Nevertheless, support schemes, in particular the feed-in tariff, typically create market distortions in operational decisions, due to limited exposure and/or response of VRE generators to market signals [6,10,36,49]. Moreover, such schemes often grant priority dispatch[3] and, sometimes, exemption of balancing responsibilities[4] to VRE generators, regardless of price signals that reflect their negative impacts on system operation [19,30,31,49,85]. These all might contribute to increased residual system costs and thus increased integration costs [99,107,36,62,9,93].

The lack of alignment of VRE development with market price signals have gained increasing concerns, as the penetration of VRE continues to grow [128]. To reduce integration costs and improve economic efficiency,[5] many studies and most EU stakeholders (including the EC) suggest that as an increasingly-mature technology, VRE should be progressively integrated into the electricity market (hereafter referred to as "market integration") [1,18,40,46,49,62,128,6,35,37,39,106,71]. Despite the lack of a standard definition, two dimensions of market integration, with respect to different time horizons, can be drawn from existing literature:

- Firstly, in the short-run, VRE should be exposed and respond to short-time market price signals as much as possible via more market-compatible support schemes, in order to minimize distortions [34,36,41,18,128].

  To fulfill this dimension, the EC's ***Environmental and Energy State Aid Guidelines*** [37] has obliged direct market participation, balancing responsibilities and the removal of subsidies during negative price periods to new VRE installations from 2016 onwards. However, many scholars and stakeholders point out that this also requires the adaption and improvement of electricity market design [104,43,61,76]. As the current market design was historically selected for a power system dominated by dispatchable plants, it may not well suit a power system where VRE plays a growing important role [61]. Furthermore, due to design flaws, certain elements in the existing market design may be incapable of delivering price signals that reflect real market conditions and associated costs [121,20,31,62].

- The second dimension of market integration lies in that support levels should be degressive and eventually be phased out once VRE becomes fully commercially mature [37].

  This means that in the long-run, VRE investments should be mainly driven by market price signals to avoid lock-in into a subsidy-dependent pathway [20,76]. Many authors and stakeholders also stress their concern for a level playing field. They argue that the incomplete internalization of externalities and subsidies for fossil fuels place VRE at a competitive disadvantageous position. Even if VRE becomes fully commercially mature, support schemes may still be necessary in order to compensate for the unleveled playing field [39,5,51,75,128].

Synthesizing all these views, market integration can be defined as a dynamic transition of letting the investment and production of VRE be increasingly driven by market price signals via a well-functioning electricity market in order to minimize integration costs, which must be safeguarded by increased policy efforts to establish a level playing field, improve the electricity market design and adjust support schemes to minimize distortions. Many barriers to market integration still exist to date. Although they can relate to a broader context that covers multiple dimensions (e.g. technological, institutional, political, and societal) (see e.g. 72,73,77,78), barriers related to the market design *per se* are of particular importance. As "the set of arrangements which govern how market actors generate, trade, supply and consume electricity and use the electricity infrastructure" [39], the market design plays a central role in determining market functioning. Market functioning also depends on multiple policy and regulation schemes most relevant to the electrical power sector at EU and MS level, such as carbon pricing under the

---

[1] Integration costs (C_{int}) can be formally defined as additional costs in the residual system for serving the same amount of residual electricity demand ($E_{resid} = E_{tot}-E_{VRE}$) after VRE introduction, in comparison to a benchmarking conventional system without VRE: $C_{int} = C_{resid}-(C_{tot,conv}/E_{tot})*E_{resid}$. The residual system costs equal total system costs minus VRE generation costs: $C_{resid} = C_{tot}-C_{VRE}$, which include life-cycle (fixed and variable) costs for non-VRE plants, balancing services, grid infrastructure and storage [118]. The concept of integration costs and its decomposition will be further discussed in Chapter 4.

[2] Market revenue risks include price risk due to uncertain electricity price, volume risk due to uncertain sale volume and balancing risk due to penalty for deviations from schedule [128].

[3] Due to very low marginal costs, VRE is normally dispatched in priority based on the merit order. However, priority dispatch here refers to the situation of VRE being dispatched with no or less respect to its marginal costs and price signals. Priority dispatch can be distinguished into two types: explicit physical priority dispatch (i.e. obligations of system operators to dispatch VRE ahead of any other generators) and implicit financial priority dispatch (i.e. subsidies that enable VRE to bid and accept a price below its marginal costs). Both can undermine operational efficiency and exacerbate system stress events, e.g. negative price periods when minimum must-run generation level is reached [6].

[4] Balancing responsibilities for VRE can be fully exempted (e.g. under feed-in tariff schemes in Germany and Croatia) or largely exempted (e.g. a tolerance marginal for imbalances exists for offshore wind in Belgium) [31].

[5] "Efficiency" will appear many times in this paper in different terms, such as operational efficiency, allocative efficiency, efficiency of trading behaviors and price efficiency. It should be noted that they all relate to integration costs, because they reflect different aspects of the electricity market's ability in reducing integration costs.