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Institutional challenges caused by the integration of renewable energy sources in the European electricity sector

R.A. Verzijlbergh[a,*], L.J. De Vries[a], G.P.J. Dijkema[b], P.M. Herder[a]

[a] Faculty of Technology, Policy, and Management, Delft University of Technology, Jaffalaan 5, 2628BX Delft,The Netherlands
[b] Energy and Sustainability Research Institute Groningen, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands

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ABSTRACT

The integration of large amounts of variable renewable energy poses fundamental challenges to the operation and governance of the energy system. In this article we address the main institutional challenges that are caused by the integration of variable renewable energy sources like solar and wind energy in the European power system. We first address how the variable and unpredictable nature of wind and solar energy increases the demand for flexible resources and we discuss potential sources of flexibility. Next, we elaborate on how the need for more flexibility challenges the prevailing market design of todays liberalized power systems. Furthermore, we discuss the key areas where there is a need for a more integrated approach to research and policy making. The need for a more integrated approach is motivated by exposing a number of critical interdependencies between technical and institutional sub-systems.

1. Introduction

The transition to an energy system that is largely based on renewable energy sources (RES) is one of the greatest challenges of our time. This transition, as it is currently unfolding, is leading to a number of sometimes paradoxical situations in the energy sector. To begin with, advances in RES technologies in recent years have led to sharp cost-reductions and, in concert with government support schemes, a marked growth of the installed RES capacities worldwide. At the same time, however, troublesome signatures of typical RES characteristics such as negative wholesale prices are now becoming more visible in the operation of power systems [1]. Secondly, although the German Energiewende has known significant successes, questions have been raised about its fairness and cost-effectiveness [2,3]. Thirdly, while the installed wind and solar capacities in some European countries have grown phenomenally, CO_2 emissions have hardly decreased due to lower coal prices and a consequent increase in coal generation [4,5]. Finally, the cost of wind and solar energy has fallen rapidly to levels comparable to those of traditional sources, but at the same time the price suppressing effect of RES is causing problems for many traditional electricity producers across Europe, see e.g. [6] and [7]. The above can be considered examples of friction in the energy system: the system shows itself not to be fit to accommodate the volume of RES needed to achieve our 2050 decarbonization targets. One could argue that they result from new technologies being forced on the old, fossil fuel based energy system paradigm, which resists change.

The main RES integration challenges relate to the fundamental characteristics that the most widespread RES technologies – wind and solar – posses: variability and uncertainty. These RES characteristics, often summarized in the notion of *intermittency*, cause friction – technical, operational, financial - when integrating them in the energy system.

A widely accepted approach for effectively dealing with these aspects is based on the notion of *flexibility*. In [8], flexibility is defined to '*express the extent to which a power system can modify electricity production or consumption in response to variability, expected or otherwise*'. Recent discussion papers by Eurelectric [9] and the European Distribution System Operators' Association [10] seem to indicate that there is a wide consensus on flexibility as a key prerequisite for a new RES based energy system. In several studies, see e.g. [8] and [11] for overviews, four forms of flexibility are identified: flexible generation, storage, demand response and interconnection. Others have used different but similar categorizations [12,13]. The energy system is clearly more than a collection of interlinked technologies: it also comprises market actors and network companies as well as the rules and regulations that govern them, the *institutions* of energy systems. Markets on which energy is traded, are bounded on one side by legislation and (financial) interests and on the other side by the technological system, while the markets in turn shape decisions on strategy, development and (dis)investment.

* Corresponding author.
E-mail address: r.a.verzijlbergh@tudelft.nl (R.A. Verzijlbergh).

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1.1. Goals, scope and structure of the paper

The energy system can be viewed as a system where technology and institutions are inexorably intertwined, as a socio-technical system that consists of several interconnected sub-systems. While RES integration issues have received a large amount of attention in the scientific literature lately, the focus has mostly been on the technical challenges. This paper, therefore, has two goals. The first is to review the challenges related to RES integration by extending a purely technical viewpoint to the institutional challenges that come in parallel with the technical changes. The second goal of this paper is to show how the energy transition is creating even stronger interdependencies between the technological and institutional sub-systems that require a more integrated approach to research and policy making.

The European 2050 decarbonization goals are clear about the fact that major emission reductions need to be realized in all sectors (power, industry, transport, agriculture, etc) [14,15]. For the power sector, the emission constraints will be the most stringent: by 2050, a virtually CO_2 free sector must be achieved. Simultaneously, carbon reductions in transport and heating will require a shift towards electricity as their main energy carrier - a notion generally referred to as *electrification*. These considerations justify a limitation of the scope of this paper to the integration of RES in the power system.

This paper is organized as follows. We first explore the main technological issues associated with the RES integration challenges by exploring both the demand of flexibility and its potential sources. Next, we discuss how the current institutional design falls short in supporting the integration of high volumes of RES. We treat some of the key areas in which a more integrated approach is needed, by exposing the crucial interrelations of the institutional sub-systems. We conclude by summarizing the most important elements of this paper and its implications for research and policy making.

2. Technical changes

2.1. The increasing demand for flexibility

Flexible generation capacity has traditionally been used to cope with changes in demand, foreseen and unforeseen, and outages of generating units. With the continuing growth of renewable energy sources, the system needs to cope with even larger variations to ensure the load-generation balance. (See e.g. [16] for an analysis of European flexibility demand). Two aspects of renewable energy play a key role: variability and uncertainty.

The former is related to the variability of atmospheric processes, which take place on a large number of time scales. Small-scale atmospheric processes like turbulence and the formation of small clouds cause fast fluctuations in output of wind and solar, but since they are short-lived and local phenomena, the aggregate power output over a larger regions (e.g. national power systems) shows modest variability on this time scale. Larger spatial and temporal scales are associated with weather phenomena such as high and low pressure areas, front passages and large cloud systems. These phenomena typically occur on spatial scales of 10 – 1000 km and time scales ranging from hours to days or weeks, and they are the dominant factor that shape the variability of RES production profiles.

As an example, Fig. 1 shows a recent time series of electricity demand and renewable energy production in Belgium. The blue area denotes the residual load: the part of the load that needs to be met by either conventional generation or imports. The top graph shows the current situation, whereas the bottom graph shows the situation in which the wind and solar production time series have been scaled by a factor that corresponds to their installed capacity as given in the Vision 3 scenario of the European Network of Transmission System Operators for Electricity [17]. One observes how the residual load curve becomes increasingly volatile, with both fast ramp events (note e.g. the fast reduction in wind and solar energy on May 13th) and longer periods of high and low RES output. In addition, seasonal and even year to year variations are present in both wind speed and solar irradiance, the latter obviously showing a strong seasonal and diurnal trend.

The aspect of uncertainty or unpredictability of RES is related to the inevitable forecast errors of numerical weather forecast models that form the primary input of RES forecasting models. Fig. 2 shows the residual load time series that was forecast 24 h in advance (i.e. the actual load time series minus the forecasts of wind and solar power) and the actually realized residual load. The difference between the forecasts and realizations, indicated by the red line, can be interpreted as the volume of back-up power that needs to be available to absorb the unforeseen changes in RES output. Naturally, as RES capacity increases, the required volume of flexible power also increases, as one observes in the bottom graph of Fig. 2. One notes that the system may rapidly alternate between large surpluses and deficits of RES output. In addition, comparing Figs. 1 and 2, one observes how flexible power may also be needed when the residual load is close to zero, i.e. when RES are covering all production and no conventional generators are required to be on-line.

2.2. The supply of flexibility

In order to deal with foreseen and unforeseen fluctuations in consumption and, more importantly, RES production, a certain level of flexibility is needed. As stated earlier, in the scientific literature one observes a classification of flexibility in four forms: flexible generation, demand side resources, interconnection and energy storage (see e.g. [8,19] and [11], chapter 5). Other authors distinguish even more forms of flexibility, for example by separately listing technologies such as power-to-gas in a category called *advanced technologies* [13].

The transition from a traditional power system (with relatively few large generators that feed into the transmission network and the energy transported down to consumers through the distribution system) into a renewable energy-based power system therefore constitutes a major paradigm change. Fig. 3 schematically shows the differences between the two systems. The typical plant size of RES is much smaller that those of conventional thermal energy plants. Hence, the number of points where energy is fed-in will increase. In addition, a large part of this energy will be fed in at the distribution level. This is especially the case for solar energy. Secondly, because energy is injected at the distribution level, two-way flows of energy may occur here. This, together with consumption peaks due to storage and/or demand response, may increase congestion of distribution networks. On the other hand, increased interconnection between power systems leads to a less fluctuating aggregate RES production profile and increases the volume of flexible resources. Finally, the flexible resources are much smaller in size and thus more numerous than the conventional generators that were the main source of flexibility in the old paradigm. They are found at different voltage levels, both in the transmission and distribution system. Because the different forms of flexibility will play a crucial role in the future RES based power system, we will discuss them separately.

Flexibility from the supply side: solar and wind vs. conventional and biomass: The main RES integration issues are largely due to the variable and uncertain nature of wind and solar energy. However, despite the intermittent nature of wind and solar irradiance, there exists some flexibility of wind and solar energy output in the form of curtailment: in some instances it may be the least-cost option to limit or ramp down RES production.

Brouwer et al. [20], Appendix B provide a detailed discussion on flexibility aspects of different power plants. Flexibility of power plants may be expressed in terms of the parameters minimum load level, ramp rate, start-up time and start-up costs. Contrary to the conventional coal-fired and nuclear thermal power plants that have been built to run steadily at their most efficient operating point, significant