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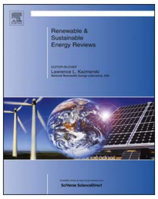

Institutional challenges caused by the integration of renewable energy sources in the European electricity sector

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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.

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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

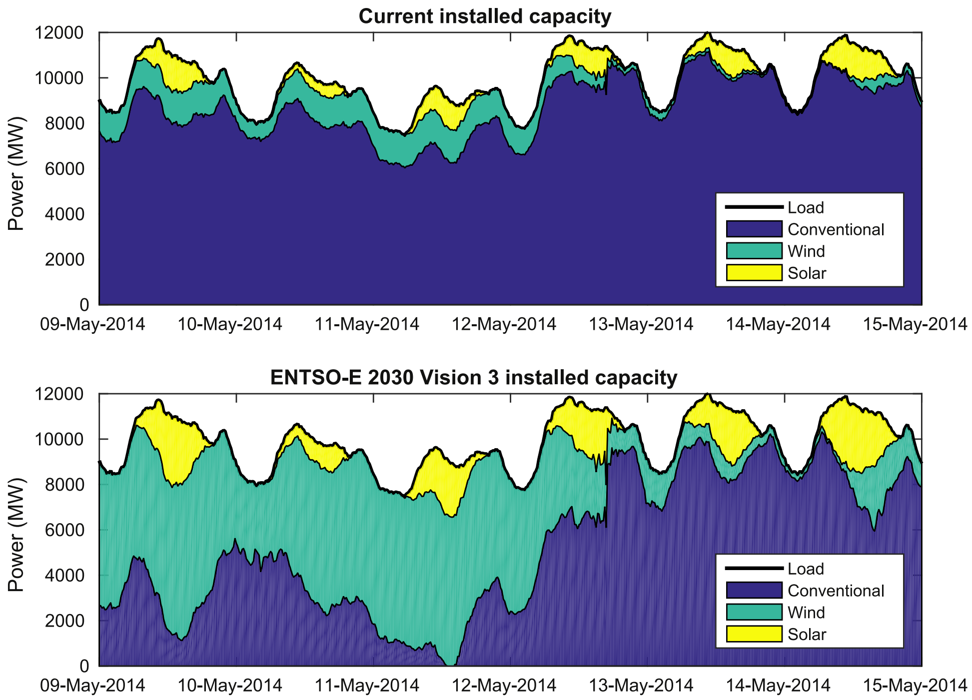


Fig. 1. Electricity demand and renewable energy production in Belgium in the current situation (top) and with the installed capacities according to the ENTSO-E Vision 3 scenario for 2030 (bottom). The part labeled conventional is the part of the demand that needs to be met by either conventional generation or imports. Data from [18]. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

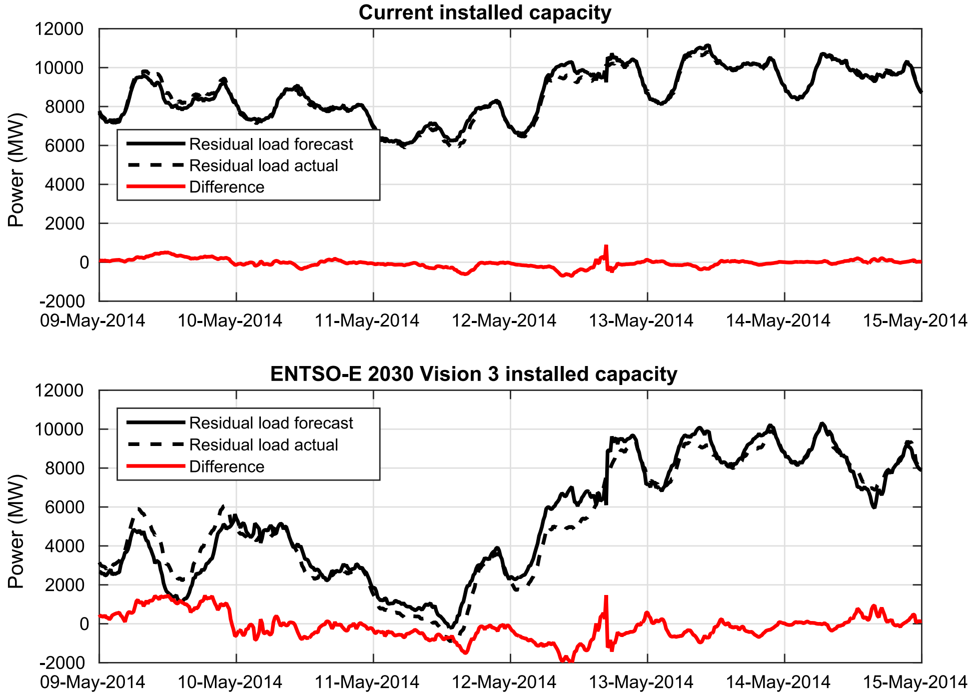
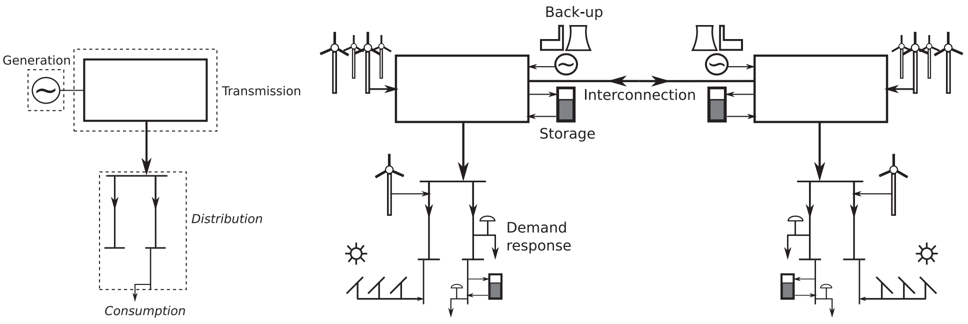


Fig. 2. Comparison of forecasted and actual residual load in the current situation (top) and with the installed capacities according to the ENTSO-E Vision 3 scenario for 2030 (bottom). Data from [18]. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

advances have been made that have rendered these plants much more flexible. However, modern gas fired power plants combine high efficiency with shorter ramping rates and start-up costs/times compared to coal and nuclear.

Nevertheless, a high-RES power system by definition reduces the consumption of fossil fuels. Several studies have shown, however, that even in high-RES scenarios, fossil fuel plant may be a cost-efficient complement to wind and solar. For example, in [21] it is shown that gas-fired back-up plants may be a cost-effective solution to pan-European RES ‘droughts’, even if they are run at very low capacity factors. When emissions become are reduced towards a 100% CO_2-free energy system, additional measures such as carbon capture and sequestration (CCS) may be needed. In anticipation of a larger scale application of CCS, there has been significant interest in flexible fossil fuel plants with post-combustion CO_2 capture, see e.g. [22,23]. As [24] argues, it is still hard to tell whether the flexible power plant fleet will evolve more towards natural gas-dominated, or flexible coal-based plants with CCS. Eventually, however, it may be an economic matter



(a) Traditional (b) High RES and flexibility

Fig. 3. The traditional technical system levels in a power system (a) and the positioning of the main RES and options for flexibility across the system levels (b).

rather than that of technical capabilities, since gas plant have higher variable and lower fixed costs than coal and nuclear, making them more attractive at lower load factors.

An alternative to fossil fuel back-up plants are bio-fuel based back-up plants. In medium-term projections, see e.g. the scenario outlook as aggregated by ENTSO-E [25], the role of biomass generation is, however, still modest. Within the available capacities, though, biomass and/or biogas may become important flexible resources for complementing a RES-based portfolio. However, a higher priority for biomass may be as a replacement of mineral feedstock for the chemical industry as well as fuel for the transport sector.

Large scale energy storage: Energy storage technologies have been created with the purpose of providing the flexibility to shift power consumption and production in time and are therefore often intuitively considered as necessary elements in a RES based power system. The range of power system applications in which storage could be important is long and diverse, with different requirements to e.g. energy capacity, power capacity and response time. In [26], for example, 28 different applications for storage in power systems are identified, with relevant time scales ranging from microseconds (e.g. power quality, frequency response) to months (seasonal storage). No single technology will thus be superior for all intended applications. Because storage can play such a key role in RES based energy system, it forms one of the central research challenges related to RES integration.

For typical daily fluctuations associated with variations in demand and RES production, the currently most economic and widely used form of large-scale energy storage is pumped hydro storage. A RES-based power system, however, may require much longer storage durations than what is currently common practice. Most notorious are so called ‘wind droughts’ in winter, when solar generation is at its lowest. Such events may last several weeks, requiring very large energy quantities. Depending on assumptions on cross-border network capacities and the amount of wind and solar curtailment, the seasonal storage needs of a pan-European electricity system may be as large as 10% of the current European annual electricity use, see e.g. [27]. The combined European pumped hydro capacity is not sufficient for meeting this very large storage requirement [28].

As it is largely compatible with decentralized energy systems, battery storage is considered to have great potential. Recently, there have been numerous interesting developments in laboratories and battery production and deployment are growing [29,30,31]. Nonetheless, the costs, performance and lifespan of commercially available batteries need to be enhanced further to play a key role in high RES energy systems. Currently, the levelized costs of all large-scale energy storage options lies beyond the benefits they bring to the power system, see e.g. [32] for recent cost figures and [33,34] for estimates of the financial benefits of storage in the European power system.

So it remains unclear which large scale storage technologies will be available for overcoming long periods of low RES output. Storage technologies that appear potentially viable include pumped hydro, compressed air and flow batteries, but their technical potential may not be enough to cover all future storage needs. Chemical storage using hydrogen, ammonia, methane or methanol are again being investigated as they provide a means to store large quantities of energy. New system concepts based on long-established conversion technologies are being explored with the aim of improving their cycle efficiency and flexibility and reducing costs. Some of these can be categorized under the wider Power-to-Gas concept, which, as discussed in [35], uses hydrogen storage as an intermediate stage. Alternatively, though not necessarily relating to RES based electricity generation, seasonal thermal energy storage may be a cost-efficient complement to fulfill heat demand.

Flexibility from the demand side: smart grids and demand response: Demand response (DR) – also referred to as demand side management - can loosely be defined as electricity demand that can be shifted in time to anticipate or react to certain signals [36–38]. Despite the large body of literature that has recently been published about smart grids and demand response, the concept has been explored for decades. Traditionally studied appliances suitable for DR are non-time critical loads like refrigeration and climate control systems or washing machines, see e.g. [39] for one of the earliest treatments of the subject. With the expected electrification of transport and heating, i.e. the advent of electric vehicles and heat pumps, two potentially very large sources of flexible demand are emerging. Physically, DR is closely related to energy storage. In fact, many forms of DR *are* energy storage because energy is stored in electro-chemical form (EV batteries), in heat (heat pumps), or in ‘cold’ (refrigeration). As a fundamental difference with energy storage in the conventional use of the concept, one may note that in demand response, energy is not stored with the purpose of converting it back to electricity. DR may have an energetic advantage over energy storage because no extra conversion losses are incurred. This may, on the other hand, be at the cost of lower convenience levels for consumers, less flexibility than in the case of storage and higher thermal losses in the case of heating and cooling systems.

Demand response has been identified in a large body of literature as a promising and cost-effective option for supporting the integration of RES. For instance, in [33], it is concluded that ‘*Among the various options to achieve a cost-efficient integration of a high share of RES-E, demand response stands out as particularly promising*’. Contrary to Europe, where its current role is still modest, in the US, demand response has already claimed a significant share in many power markets [40].

The networks: *interconnection and distribution*: Originally, national transmission networks were built to interconnect different power systems for backup and reliability. Over time, cross-border interconnects were established, too. With the ongoing process of creating of an internal European electricity market and pan-European level playing field, the function of the network and the cross-border interconnects increasingly has become an economic one. Today, routinely, large volumes of electricity are transported from where it is produced at lowest cost to where it is needed most.

When transmission and interconnection capacity are sufficient, surplus RES generation can be exported instead of sold in national markets at low or even negative prices. A pan-European electric 'supergrid' has been advocated for aggregating the RES production of the continent. At a pan-European scale, the result would be a smoother and more regular RES production profile, as has been shown by e.g. [41] and more recently explored further in e.g. [42].

In parallel to the trend of strengthening the pan-European transmission backbone is the increase in importance of the regional distribution networks. Not only is a large part of RES production embedded at this distribution level, but so may two of the important sources of flexibility: storage and demand response.

3. Institutional challenges

Now we extend our discussion from technological issues to the energy markets, rules and regulations – the institutional sub-system – that govern the operation and development of the energy system. First we discuss the shortcomings of the current system when it comes to a massive RES integration. Next we highlight some important interdependencies between different technical and institutional sub-systems.

3.1. The need for institutional change

While the technical energy system as we know it today has been shaped in the last 50 years, the social subsystem we see today is the result of the process of unbundling and liberalization that (only) started in the 1990s. A central role in liberalized power systems is played by the spot-market, also referred to as wholesale market or day-ahead market: a market place where electricity can freely be traded between producers and consumers, that are usually represented by retailers. A number of additional markets and mechanisms are needed to deal with the characteristics that make electrical energy a peculiar commodity: intra-day markets and balancing markets make sure that uncertain demand and supply are matched in real-time. Capacity based reserve markets, ancillary services (frequency and voltage control) and transmission congestion management further enhance the reliability of the power system. The central tenet of this system, though, is that the conventional, controllable, fossil fuel based generation capacity is providing the majority of this energy. Marginal generators set the electricity price; all generators that are dispatched under this price collect revenues they need for capital cost recovery. Together, the generators provide the additional system functions required for system stability and security. It is this picture that is rapidly changing however, with the continuing growth of renewable energy sources.

RES, in principle, have a marginal cost of zero. According to the merit-order logic underlying our electricity markets, in times of high RES production, the resulting electricity price will fall [43], and may increasingly reach zero if RES generation exceeds demand. In fact, due to a lack of flexibility in the current system, negative wholesale prices are being observed more frequently. They can be seen as the price that large, inflexible generators are willing to pay to avoid temporary shutdowns [1]. With near-zero or negative prices, not only will RES generators receive insufficient revenues, but the spot-market will provide too little incentive to conventional generators to be on-line to provide the essential system services, too. Clearly, the system must be organized differently when the RES shares grow to the levels required to meet 2050 emission targets. This pertains both to the short-term operation of the system, i.e. how the market signals allocate the given assets, and to the long-term, i.e. how the markets incentivize investments in renewable energy and the required flexibility options.

3.2. Key areas where a more integrated approach is needed

We will now specifically address a number of key areas where a more integrated approach is needed in particular, i.e. where different elements of the technical and institutional landscape are interdependent and need to be considered jointly in order to achieve the main policy goal of a transition to a renewable, affordable and reliable energy system.

Changes to the design of short-term markets: An in-depth discussion of how the prevailing European electricity market design may be improved towards the integration of large shares of RES is given in [44]. The proposals for market design made herein are based on two important principles: to reduce the need to increase resource flexibility in the first place and to make the value of resource flexibility more visible in market prices. In addition, the importance of demand side resources is emphasized once more.

Regarding the first principle, i.e. mitigating the need for greater resource flexibility, an important advantage may be realized by increasing the size of the balancing control areas. This advantage is mostly based on the previously discussed fact that weather patterns are decorrelated over large distances, rendering a less volatile RES production profile when aggregated over a large geographic area. In addition, forecast errors of RES production are decorrelated over larger distances, too. To reap the benefits of these phenomena, the area over which the energy is traded should be as large as possible, i.e. a further integration of national markets is needed. Other measures to mitigate the need for flexibility are to reduce the time-step of day-ahead and intra-day markets (e.g. to 5 min instead of 1 h, as is common in many markets), to have the intra-day market close as late as possible and to have a liquid intra-day market in the first place.

The second principle is that markets better reflect the value of flexible resources to the system. This is especially important to ensure that the markets properly signal the investment needs for flexibility. Currently, a part of the resources that are needed for reliable system operation fall outside the markets; they are procured in long-term bilateral contracts between system operator and suppliers of flexible resources, mostly conventional generators. In [44], a variety of measures is proposed addressing amongst others the pricing of system security actions taken by the system operator, scarcity pricing in the balancing markets and the lack of locational pricing. Similar measures have been proposed in [45]. Institutional barriers for demand-side flexibility resources have also been addressed as a concern [44,46].

In addition to improvements to the functioning of electricity markets, there is a large debate about the need for capacity mechanisms to attract RES generation and the flexible resources required to complement it. In [44], it is also emphasized that no capacity mechanism can compensate for all flaws in electricity market design, which gives the list discussed above a character of non-regret measures. In [47], the authors even explicitly distinguish between a series of non-regret adaptations to market design and the "*fundamental policy decision*" of an optimized electricity market or a capacity market alongside the electricity market.

Coordination between flexible resources and network management: The prevailing model in Europe's electricity systems are national price zones where cross-border energy trade is facilitated via market coupling. In the market clearing process, internal transmission constraints are essentially ignored and the possible congestion issues are solved via re-dispatch. Because the network constraints are not taken into account in the commitment decisions of the generating units, the outcome of the re-dispatch process will differ from the optimal one. With further RES integration, this is expected to become ever more costly [48]. [49] have assessed available options for congestion management and have concluded that nodal pricing, or locational marginal pricing, is the most viable option to efficiently align generation and demand resources with network management. In addition, there may be complexities that are the result of the fact that balancing mechanisms are not well aligned with congestion management [50]. Such issues could be efficiently handled by nodal pricing, too [45,49]. However, the creation of a European nodal pricing system is a complex operation with considerable political barriers, rendering alternative solutions more feasible in the short-term.

Management of the distribution networks may change even more profoundly. As discussed in Section 2 of this paper, large parts of generation and flexible resources will be embedded at the distribution level. This may lead to large network peaks due to feed-in of RES, but also due to flexible demand and storage units that react to market prices – an effect sometimes referred to as load clustering [51]. This can be a desired effect when the RES are embedded at the distribution network itself, like the case of rooftop PV, because generation peaks are locally absorbed by demand response. When RES are, however, mainly embedded at higher network levels (e.g. large wind parks), the energy has to flow all the way down to the responsive demand at distribution network. This may lead to high network load peaks that, in turn, cause costly network reinforcements [52]. A coordination mechanism is thus needed to align the network capacity, RES production and demand volumes and location by market signals. Such a mechanism, essentially a form of congestion management, is more common on the transmission level, but its extension to the distribution level is a new feature that results from the increased RES penetration and the role of flexible demand [53]. Current research focuses on the exact design of such a mechanism, either price based or capacity based, and its practical implementation, see e.g. [54,55] and [56]. The enabling IT infrastructure will be a crucial component of such a systems, which translates to a range of business opportunities on the cross-section of the IT and energy sector. Furthermore, unbundling (the legal separation between network management by DSOs and commercial activities) currently prohibits some of the actions that may be taken by DSO to apply some form of congestion management. New regulatory frameworks for grids with a more active role for DSOs are therefor being considered [57].

Flexible resources and CO_2*policy*: In the current market structure, the power system is operated from a profit maximization or cost minimizing point of view. This implies that additional flexibility will be employed to steer the system further towards the minimum cost operating point. In a situation where the generation capacity with the lowest marginal cost is simultaneously the most polluting, like in portfolios that include coal and lignite, this boils down to using the flexibility to keep coal plants running, thereby saving expensive start-up costs and fuel costs of the more expensive gas plants. This results in the paradoxical situation that in a mixed portfolio with RES, gas and coal, the availability of extra flexibility, be it interconnection, storage or demand response, leads to a shift from gas to coal and thus causes higher emissions. In various model studies, this effect has been observed, see e.g [58–60] and [34]. One could argue that in practice, we already observe signatures of this phenomenon, too. At times of high wind and solar generation, the German coal and lignite plants keep running while energy is exported abroad [4]. Without these exports, these plants would be forced to experience more shut-downs, favoring the more flexible and cleaner gas plants. A higher CO_2 price where coal and gas would switch places in the merit order would remedy such effects. Alternatively, a regulated decommissioning of some inflexible and polluting base load plants has been proposed, because they are not only incompatible with emission targets, but they are also suppressing market prices and thereby hampering investment into more flexible and cleaner units [61,44].

Carbon policy and RES support schemes: The European Union Emission Trading System (EU-ETS) system has been labeled the EU's main instrument for energy transition. The carbon price has been very low because there has not been real scarcity in emission rights. This is due to shortcomings and inherent flaws in its design, and too many rights issued and banked, a situation which has been exacerbated by the financial crisis which stalled electricity production growth [62].

RES support schemes (public funding for new RES generation capacity) ceteris paribus reduce the demand for CO_2 rights. This will lead to lower carbon prices, which benefits the most polluting generators. Effectively, a part of the public funding in clean generation capacity goes directly to the pockets of polluting generators, and emission reduction achieved may be much lower than anticipated. Hence, if public money is invested in clean generation capacity, the equivalent amount of CO_2 credits should be taken out of the market. This example illustrates how CO_2 policy cannot be decoupled from RES policy, and the two need to be considered in coherence, see also [63] and [64]. In addition, it justifies further research to alternative CO_2 pricing mechanisms, such as carbon taxation [65] and the currently proposed changes to the design of the ETS [66].

International harmonization of energy policies: Market coupling brings economic advantages by efficiently matching production and demand across national borders. This means, however, that certain effects of national energy policies are also ‘transported’ across the border. For example, in Germany, the large installed capacity of RES has mainly been realized with the help of the feed-in tariff. In the Netherlands, however, RES production is to be traded on the electricity market like any other form of electricity generation. So when a German wind surplus is lowering wholesale prices in the Netherlands [67], the Dutch wind producers will collect lower revenues. The spatial correlation of wind energy production, i.e. when it is windy in the Netherlands, it is, on average, also windy in Germany, enhances this effect. A same reasoning applies to the cross-border effects of capacity mechanisms [68,69] and CO_2 policies [70]. All of these are examples where a national policy influences the generation fleet in a certain country, but this influence crosses the national borders by the market coupling mechanisms that are in place. In addition, national policies often explicitly protect energy intensive industry from high energy prices by mechanisms such as subsidies, tax exemptions, etc [71]. Such measures clearly have a marked influence that extends beyond national borders, too.

Social acceptance and a renewed perception of the energy system: In addition to the technical changes and the restructuring of the markets and regulations, a whole renewed public perception of the energy system may be needed. One could classify this at as a required change on the social level. Currently, the continuous availability of cheap energy is a matter of course. When production of energy will be largely driven by fluctuating weather conditions, it seems inevitable that stronger energy price fluctuations will be the result. While such price volatility may currently be perceived as undesirable, it is not unthinkable that some day it will be socially accepted, like is the case for many other commodities with volatile prices. People may adapt to it, and become used to plan their EV charging or washing clothes on those days when energy prices are expected to be lowest. Comfort, utility (in the economic sense of the word) and energy costs may be weighed more carefully. Promising field experiments have been conducted and reported in e.g. [72] and [73].

For energy intensive industries, too, the transition to a RES based electricity system may offer opportunities. Perhaps surprisingly, flexibility of the electricity demand of industrial consumers has received far less attention in the scientific literature than that of household electricity demand. One could argue that this is partly the result of the low electricity tariffs that energy intensive consumers are generally paying [71]. However, instead of designing industrial production processes to run 24 h per day against a reduced electricity tariff (of which small consumers or tax-payers usually bare the costs [2,3]), one could think of designing a flexible plant that runs only when energy is available at very low prices [74]. Recently, more research has been exploring such opportunities, see e.g. [75–77].

Changes on the social and institutional level described above might create more price-elasticity of energy demand, which will have a dampening and stabilizing effect on the system. Policies promoting such change may need to be considered and contrasted to the current policies that essentially subsidize energy-intensive industry.

4. Conclusions

We have discussed the major changes and challenges that the European power sector faces in the light of the transition to a system largely based on renewable energy sources. At the technical level, we showed how variability and uncertainty of RES output is requiring a higher degree of power system flexibility and we discussed various flexibility options.

The first goal of this paper was to go beyond the technical viewpoint and to explore how required technical changes are posing new institutional challenges to the sector. We have identified a number of key challenges, such as the necessary reforms of short-term electricity markets, the coordination of energy trade and network management, the coordination of CO_2 policies with renewable energy policy and the international harmonization of energy policies.

The second goal was to identify how the integration of renewable energy sources magnifies certain inter-dependencies between the different technical and institutional elements that comprise the energy system. Recognizing these interdependencies, we advocate a more integrated approach to research and policy making, in which the technical and institutional sub-systems are considered in coherence. This integrated approach is not only a necessary condition for shaping the energy system of the future, it is a challenge in itself to develop this approach. Hence, to effectively guide the transition process, new modeling and decision making tools need to be developed that can capture the complex interdependencies of a RES based energy system.

Competing interests

The authors declare that they have no competing interests.

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