On integrating large shares of variable renewables into the electricity system

Hans Auer, Reinhard Haas*

Energy Economics Group, Vienna University of Technology, Vienna, Austria

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ABSTRACT

In recent years increasing shares of variable RES (renewable energy sources) have changed the structure of electricity markets in Western Europe, especially in Germany. The core objective of this paper is to provide insights on the conditions to integrate even larger quantities of variable RES into the electricity system by using market-based principles and how, straightforward, a sustainable electricity system could work. Our major finding is that we suggest a market-based approach to ensure that competitive forces rather than governmental interferences as capacity mechanisms shape the future of the energy system. The major conclusions of this analysis are: The transition towards a competitive and sustainable future electricity system will be based on an approach of “new thinking” which is to accept a paradigm shift in the whole electricity system. This includes switching to a more flexible and smarter system allowing a greater scope for demand participation, storage options and other flexibility measures. Developing such a system implies also that no politically motivated capacity mechanisms are needed.

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1. Introduction

The European Commission has set ambitious targets for increasing the share of electricity from RES (renewable energy sources), e.g. Ref. [1]. In recent years in the EU-28 countries electricity generation from variable sources like wind and solar has increased remarkably, with Germany, Spain, Italy leading. Between 1997 and 2014 in the EU-28 “new” renewables excluding hydro grew from less than 1% to about 13%, mainly from wind, see Fig. 1. In addition, the EU has set further ambitious targets of a share of 27% (compared to about 14% in 2013) energy from RES by 2030. This target is for all uses, heat, electricity and transport. Consequently, also electricity generation from RES will grow further continuously, as documented in the NREAPs (National Renewable Energy Action Plans) despite it is not clear to which absolute level. The major motivation for this paper is to show what is needed for integrating these higher quantities into the electricity system.

The increasing shares of variable RES have especially in Germany changed the usual pattern of electricity markets in Western Europe. Yet, variable RES-E do not provide electricity simultaneously with demand. It is important to note, that almost all other generation technologies do not either. The fact that these must run capacities are offered at Zero costs over a large time per year have led to the argumentation that fossil plants like CCGT (Combined-cycled gas turbines) or coal power stations become economically less attractive because of the lower full load hours per year. This argument has led to the call for CM (capacity mechanisms) in addition to the current “energy-only” markets. The idea is that specific owners of a flexible power plant should be paid for holding the plant ready for operation.

Due to these developments, currently, the whole electricity system is at a crucial crossing. On the one hand, the way to a sustainable electricity system based mainly on RES could be paved in the next years. In this context we emphasize especially the considerable price decreases of PV which has brought this technology close to cost-effectiveness on household level, see Refs.[2,3]. On the other hand, there are forces which try to retain the old centralized fossil and nuclear-based generation planned economies. Centralized capacity payments (e.g. in France and England) should help to freeze this anachronistic pattern. A good survey on CM is provided in Ref. [4]. Also the EU has recognized this problem, see e.g. Koch [5] for an early contribution and Ref. [6] for a recent analysis.

The core objective of this paper is to provide insights how to integrate large quantities of variable RES-E into the electricity system by using market-based principles and how, straightforward, a sustainable electricity system could work. This market-based
approach should ensure that competitive forces rather govern-
mental interferences shape the future of the energy system and
that in principle no comprehensive CM are necessary, see e.g. Ref.
[6]. Our analysis is mainly based on Western European countries
using data from Germany and Austria but in principle the findings
of this analysis can also be transformed to every other country. It
builds on basics described in Ref. [2] and extends this paper to-
wards variable renewables in general.

Regarding the state-of-the-art this work is based on the
following general contributions on the topic. Major contributions
for understanding the basic principles how to integrate large shares
of variable RES into the electricity system are [7–13]. Analyses with
special focus on the system integration of wind has been conducted
by Refs. [8,14–16]. Major country specific investigations has been
done for Denmark, Spain and China in Refs. [17,14,18].

A seminal contribution on flexible options in the electricity
system has been conducted by Ref. [19]. Lund [20] provides the so-
far most comprehensive review of energy system flexibility mea-
sures to enable high levels of variable renewable electricity.

The major novelty of this paper is that it brings together all
important aspects for heading towards a sustainable as well as
competitive future electricity system. It considers technical options
and aspects of market design and applies it to a further increase of
RES in the electricity system. It addresses economic as well as
technical/structural issues of electricity supply and demand.
Moreover, up to the best of our knowledge it is the first one that
links the concept of residual load to price signals from the whole-
sale markets, the relevance of flexibility measures on the demand-
side as well as demand response due to those price signals and the
role of storage, power-to-heat. Finally future requirements for
competitive electricity market design including the political
dimension of CM under the condition of large shares of variable RES
in the electricity system are investigated.

2. Method of approach: how prices in electricity markets
come about

To analyze the impact of variable RES on the prices in wholesale
electricity markets it is first important to understand the current
market rules and market structures, see Ref. [2]. Of key relevance is
to understand how prices in European electricity markets currently
come about. In this context it is important to look at the historical
dynamics. The liberalization process in Europe started in the late
1980s in the UK and gradually migrated to continental Europe with
the 1999 the EU-directive [21,26]. One of the major features of the
liberalized electricity markets was that the pricing regimes
changed. In former regulated markets, prices were established by
setting a regulated tariff, which was calculated by dividing the total
costs of supplying service by the number of kWhs sold — with some
differences between different groups of customers. The major
change that took place after the liberalization was that prices were
now expected to reflect the marginal costs of electricity generation
(e.g., [6,22–24]). Since then the price formation is mainly based on

![Fig. 1. Development of electricity from “New” renewables (excluding hydro) in EU-28 between 1990 and 2014, in TWh (Source: EUROSTAT, own estimations, numbers for 2014 are preliminary).](image)

![Fig. 2. How prices come about in markets with a conventional merit order supply curve based on short-term marginal costs with conventional capacities (incl. large run-of-river hydro): intersection of supply curve and demand gives electricity price at two different points-of-time.](image)
a fundamental approach where the intersection of a merit order curve on the supply-side and the demand curves results in the corresponding market price at every point-of-time, see Ref. [2] and Fig. 2. The typical historical pattern of electricity generation in the Western Central European electricity market consisted since decades of conventional fossil, nuclear and hydro capacities. Since the late 1990s in western central Europe, most of the time nuclear contributed the largest share, followed by fossil and hydro. Non-hydro renewables were not a significant factor until recently. At the time when liberalization started huge already depreciated excess capacities existed in Europe. This led to the expectation that prices will (always) reflect the STMC (short-term marginal costs) as illustrated in Fig. 2.

As shown in Fig 2, the intersection of the supply curve with demand determines the market clearing price at the price at the short-term marginal costs of the system. The curve D1 shows the demand curve at times of low demand e.g., at night and p1 is the resulting (low) electricity price. D2 shows high demand times, e.g., at noon, and p2 is the resulting (high) electricity price. The difference between p2 and p1 is the so-called price spread further described below. It provides useful information, for example, on the economic attractiveness of storage, which will be of high relevance in markets with large share of RES. Until recently, the price spread has been of interest mainly with respect to pumped storage. That is to say, during periods when prices are low, water can be pumped into reservoirs; while generating electricity when the opposite is true.

This fundamental approach of price formation has led to quite different price developments in different European electricity sub-markets from 2000 to 2015, see Fig. 3. In this period a high volatility and considerable differences of electricity spot market prices between different sub-markets are observed. Within this period Italy always faced the highest prices due to its over-reliance on imported electricity, congested cross-border transmission lines and heavy reliance on expensive natural gas. In the case of the NORDPOOL, which includes Sweden, Norway, Finland, and portions of Denmark, the pattern is different due to heavy reliance on hydro and lack of strong interconnection with Continental Europe. Yet, the other countries illustrated in Fig. 4 show a remarkable convergence of prices. Currently, there is a wide-integrated Western-Central European electricity market which consists (at least) of Germany, France, The Netherlands, Austria, Switzerland, Poland, Czech Republic. That is to say that any measure in one of these countries will affect the market structure in others. Regarding the magnitude of prices the reason for high prices in 2008 in Continental Europe was the low hydro availability while the falling prices after 2008 may at least to some extent be attributed to the economic crisis. Most interesting in this context is that since 2011 the day-ahead prices in virtually all observed countries has decreased almost continuously. The core issue of interest is, what caused this decline?

3. How variable RES impact prices in electricity markets

The major reason for this decline in day-ahead prices between 2011 and 2015 can be seen in Fig. 1. It is the remarkable rise of variable RES with zero short-term marginal costs. This increase of renewables has started to impact spot prices, trading patterns and the dispatch of conventional generation by about 2011. The explanation is simple. Assume e.g. a sunny day with ample solar generation. Then the supply curve is shifted to the right as schematically shown in Fig 4, which essentially pushes nuclear and fossil fueled generation “out of the market”, [26].

This impact of variable RES on electricity prices is already...
known since volatile hydro power was used for electricity generation. The best example is the Nordic market, mainly Norway and Sweden, where since decades almost only technologies with Zero short-term marginal costs meet the whole supply. In about 2007–2010 — in Denmark already earlier — there was experience with temporarily high wind in the systems and sometimes even negative prices, see also [8,25,27–29]. In recent years increasing production from Photovoltaic system was added to the production portfolios, mainly in Germany, Italy and Spain.

What makes the impact of the aggregate of various variable RES now specifically different? Aside from the above-described effects, variable RES will also influence the costs at which fossil generation — especially natural gas — are offered. The reason is that they would lead to much lower full load hours, e.g. only 1000 instead of 6000 h/yr before. Yet, the revenues earned from these hours must cover both the fixed and variable costs, see also Haas [2]. And in a market with large shares of renewable energy sources the role of conventional capacities will change see e.g. Refs. [30–34].

This leads to the following categories of presumed “problems”: (i) Prices decrease to Zero or become even negative at a number of days; (ii) Lacking contribution margin to fixed costs for conventional flexible power plants. However, it is not yet clear, on how many days very high and on how many days very low (or negative) prices will prevail and how high or how low these prices will be.

Fig. 5. Development of variable RES from wind, PV and run-of-river hydro plants over a week in summer on an hourly base in comparison to demand and resulting electricity market prices with total costs charged for conventional capacities (Source: own analysis).

Fig. 6. New thinking: The concept of residual load referring to Fig. 4.
Of further relevance in this context is how the price spread in European markets will evolve in the future as larger amounts of PV, solar thermal and wind generation are added to the network. The consequence for electricity prices are shown in Fig. 5 where a hypothetical scenario with high levels of generation from wind, PV and run-of-river hydro plants over a week in summer are depicted using synthetic hourly data for an average year in Austria. The figure shows significant volatilities in electricity market prices with total costs charged for conventional capacities – black solid line – within very short-term time intervals, see also Perez [13].

Our method of approach is based on the following principles:
(i) Crucial is coverage of residual load (= difference between final electricity demand and generation provided by non-flexible electricity generation from variable RES as well as coal and nuclear power plants, see Fig. 6); this is modeled on an hourly base over a calendar year based on assumed RES electricity generation
(ii) Deduction of available conventional and backup capacities including must-run (iii) flexibility on the demand side based on consumer behavior incl. flexibility instrument such as batteries etc.
(iv) Hourly electricity prices equal to short-term marginal costs and scarcity rents.

The longer-term impact of variable RES on the price spread is that it will increase. The intuitive explanation is that when renewables are plentiful, say during windy or sunny periods, the prices will be extremely low, approaching zero or possibly going negative, while at other times – when demand is high and renewables are scarce – prices can be much higher due to strategic bidding by fossil generators exercising market power. This is graphically shown in Fig 9. Another major finding from Fig. 9 is that in the long run large amounts of variable RES will lead to increasing new price spreads. It is important to note that future high prices will not necessarily appear at peak-demand times but at times of low renewables availability. This will also change the operation of pumped hydro facilities and lead to new investment in energy.

Fig. 7. Magnitude of price spikes and possible new price spreads (adapted from Haas [3]).

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Fig. 8. Development of residual load in Austria 2013 and in a scenario up to 2030 with high share of variable RES.

![Fig. 8. Development of residual load in Austria 2013 and in a scenario up to 2030 with high share of variable RES.](image)
storage technologies to take advantage of significant price differentials. Over time, the familiar patterns of the night-to-day-shift of generation will change in response to the unpredictable and variable rhythm of renewable generation. The most likely consequence of increased price volatility will be to make storage and flexible peaking units much more valuable than they currently are.

Given the price pattern in Fig. 7 we are convinced that it would be attractive for some but sufficient power plant operators to stay in the market or even to construct a very efficient new plant! Moreover, these price spreads would provide incentives for new flexible solutions, see later. This would lead to the market model of a revised energy-only market.

Fig. 6 shows the concept of residual load over a week, Fig. 8 shows the corresponding graph over a year classified by magnitude in decreasing order. As an example in Fig. 8 the profile of residual load in Austria 2013 and the development in a scenario up to 2030 with a much higher share of variable renewables is described. The major finding of Fig. 8 is that the duration curve of the residual load profile will become steeper and that the number of hours with excess generation will become higher. This effect will lead straightforward to higher price spreads and will also increase the attractiveness of storages and other flexibility options.

In Fig. 9 the classified residual load curve over a year in the case of high shares of variable renewables corresponding to the profile in the scenario of Fig. 8 is described including the relevant areas for the discussion. The crucial areas in this load duration curve are on the top left and on the bottom right. In the circle on the top left the question is how to cover under shortage on these hours, in the circle on the bottom right the question is how to use this excess generation of electricity.

For both areas there are in principle two options:

- By regulated capacity payments?

or

- By competition between supply-side and demand-side technologies and behavior (incl. Storages, grid and other flexibility options)?

Important remarks: Flexibility measure will contribute in a competitive way to reduce these price spikes and consequently the price spreads and lead to new equilibria between supply and demand!

4. Regulated capacity payments

If the above described price pattern is not accepted by politicians another option are capacity payments. The fact that the renewable must run capacities are offered at Zero costs over a large time per year have led to the argumentation that fossil plants like CCGT or coal power stations become economically less attractive because of the lower full load hours per year. This argument has led to the call for “capacity” payments in addition to the current “energy-only” markets. The idea is that specific owners of a flexible power plant should be paid for holding the plant ready for operation.

The major reason, why at least currently there is no need for centralized CM in Europe that there are still many other options in the market, which we think are by far not yet exhausted. However, to exhaust these options some dogmas has to be changed. Especially the historically prevailing and still existing definition of supply security that every demand has to be met at every point-of-time regardless of what are the costs has to be revised in a way that compares the costs of (all) supply-side and demand-side options as well as customers WTP for capacity depending on time.

The major open questions regarding centralized CM are, see Refs. [35–37]:

- Which quantity of capacity should get payments and where?
- How to split in existing and new capacity?
- How to tune with grid extention? Every grid extension has undoubtedly an impact of necessary capacities in a specific area
- Who would plan? On national or international level?

5. A market design approach for supply security

One major argument for the call for centralized CM is to retain supply security in the electricity system. The historical (anachronistic) definition of supply security is: At every point-of-time every demand has to be met regardless of the costs. In this context it is
important to note that supply security is an energy economic term. It is different from technical system reliability.

The core problem is that so far world-wide the demand-side has been neglected widely with respect to contributing to an equilibrium of demand and supply in electricity markets. Major exceptions are: (i) in the 1980s and 1990s in the U.S., Sweden, Denmark and other advanced countries DSM-measures have attracted attention. After the liberalization of the electricity markets most of these programmes disappeared. (ii) In Denmark – the leading country for integrating variable renewables especially wind – has integrated a lot of power-to-heat technologies, that not only play an important role on energy markets, they also cover primary reserve needs. According to [10] power-to-heat technologies can allow for an increase of penetration of variable renewables in Denmark up to 40% (with 5–10% curtailment).

The major reason for this ignorance of the demand-side is that in times of regulated monopolies every demand could be met due to significant excess capacities. And still in the liberalized markets huge excess capacities remained. This aspect — to develop the impact of demand-side and customers WTP – is essentially for a real electricity market and it is actually regardless of the aspect of an integration of larger shares of RES. In the context of the discussion of market design this historical view of supply security plus centralized CM would lead to a new market design in the sense of a centrally planned economy.

On contrary to the central planning approach a market-based one would take into account customers WTP (willingness-to-pay). The equilibrium between demand and supply would come about at lower capacities. It is also important to note that where WTP is lowest the MC (marginal costs) of providing capacity are highest, see Fig. 10. The still applied concept of supply security is anachronistic and contradictory to market principles. It has to be revised in a way that considers customers' WTP;

6. Flexibility: the key term of the future

Our major findings for integrating large quantities of variable RES-E into the electricity system by using market-based principles and how, straightforward, a sustainable electricity system could work are, that the following conditions have to be fulfilled, see also [38]:

1) Of core relevance for integrating larger shares of RES-E in a competitive way is a pricing system in an energy-only market where the prices signal provide information on scarcity or excess capacities at every point-of-time (quarters of an hour);
2) Another important issue is that a demand-side capacity market is developed. So far consumers have never been asked what the value of capacity is for them and what they are willing to pay for specific quantities of capacity. An important analysis in this context has been conducted by Praktiknjo [39]. He clearly identifies two findings: (i) there is a quite different WTP between different groups of customers; (ii) it is very unlikely that generating electricity is always cheaper than saving capacity.
3) More flexibility in the organization of the market is required: To better integrate electricity from RES in the market the time intervals in markets should be reduced (more emphasis on intraday markets, shorter trading intervals (from hours to ¼ hours); shorter ahead leading times for market clearing and forecasting of electricity generation from variable RES);
4) Most important to balance variations in residual load is an optimal portfolio of flexibility options which already exists today. A very comprehensive review of energy system flexibility measures to enable high levels of variable renewable electricity is provided in Ref. [20]. Currently these potentials are not fully harvested due to low economic incentives, see next chapter. The most important flexibility options to balance variations in residual load are, see also [31,40–43] and Fig. 11:
short-term and long-term storages such as batteries, hydro storages, or chemical storages like hydrogen or methane;

- Technical demand-side management measures conducted by utilities like cycling, load management, e.g. of cooling systems, see also [44];
- Demand response due to price signals mainly from large customers to price changes, time-of-use pricing
- Transmission grid extention leads in principle to flatter load and flatter generation profiles;
- Smart grids: They allow variations in frequency (upwards and downwards regulation) and switch of voltage levels and contribute in this context to load balancing

How an interaction between these options could take place is shown in Fig. 12.

5) A key role in this new concept will play balancing groups. These are the entities which finally have to balance generation, flexibilities and demand options.

7. Economic incentives for flexibility

A crucial question is now why these flexibility measures are not yet in the market. The simple answer is that currently there are no economic incentives at all to harvest these flexibility options because of very low price spreads, in the markets, see Figs. 13 and 14. In these Figures it is depicted that the price spread for 1200
full load hours decreased from about 50 EUR/MWh in 2008 to about 30 EUR/MWh in 2012. There is no economic argument to launch flexibility measures today except in the control power market. 

An important aspect in this context is how the price spreads will develop. These price spreads will depend on the development of the duration curve of residual load. As seen from Fig. 7 these price spreads will in future increase again and then flexibility measures will become more attractive.

8. Conclusions

The major conclusions of our analysis are:

- Most important are correct price signals in a revised energy-only market with scarcity and excess pricing signals; the only “negative” aspect of a market without a capacity component is that prices will be higher or lower than the short-term marginal costs. After some time the market will learn to benefit from these higher costs and also from the very low costs at times when RES are abundant. A reasonable price spread will emerge providing incentives for different market participants to benefit;
- The key for a sustainable competitive electricity system is the full exhaustion of flexibility options based on correct price signals in the wholesale as well as in the retail market. Currently on both levels the market does not yet provide proper price signals to trigger flexibility options, such as technical demand-side management, economic demand-response due to price signals as well as short-term and long-term storage options and other flexibility measures will even out a large part of the residual load profile. These days we actually have a very flat and low price curve over the last years. Flexibility options will only be harvested when sufficiently high price signals from the electricity markets trigger these options, when “the exploration principle in the markets work” (Erdmann [45]).
- Yet this will only be done if the market is not distorted by centralized capacity payments. Calls for such payments are a last try of the old fossil and nuclear system to survive and are a step back to a planned economy with — all in all — much higher costs for society. Hence, a very big danger in this context is the introduction of centralized capacity payments. In our view they would be death of competition, and head back to a strictly planned economy;
- Regarding market design also more flexibility in the organization of the market is required: To better integrate RES-E in the market the time intervals in markets should be reduced (more emphasis on intraday markets, shorter trading intervals (from hours to quarters of hours, shorter ahead leading times for market clearing and for forecasting of RES-E generation);

The concluding remark is that the transition towards a competitive and sustainable future electricity system will be based on the following principle of “new thinking”, which is to accept a paradigm shift of the whole electricity system — including switching from an inflexible and one-way system where variable load is met with changes in generation to a more flexible and smarter system allowing two-way electricity flows — to our understanding — a greater scope for demand participation by consumers needs to be included. In addition, suppliers (or balancing groups) are the most important part of the whole energy service providing chain, see also Fig. 15. The evolution of such a creative system of integration of RES in Western Europe may also serve as a role model for electricity supply systems largely based on RES in other countries world-wide.

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