From electricity smart grids to smart energy systems – A market operation based approach and understanding

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A B S T R A C T

The challenge of integrating fluctuating power from renewable energy sources in the electricity grid by the use of smart grids cannot be looked upon as an isolated issue but should be seen as one out of various means and challenges of approaching sustainable energy systems in general. Therefore, electricity smart grids must be coordinated with the utilisation of renewable energy being converted into other forms of carriers than electricity including heat and biofuels as well as energy conservation and efficiency improvements, such as CHP and improved efficiencies e.g. in the form of fuel cells. All such measures have the potential to replace fossil fuels or improve the fuel efficiency of the system. However, they also add to the electricity balancing problem and contribute to the excess electricity production and thereby to the need for electricity smart grids. The long-term relevant systems are those in which such measures are combined with energy conservation and system efficiency improvements. This article illustrates why electricity smart grids should be seen as part of overall smart energy systems and emphasises the inclusion of flexible CHP production in the electricity balancing and grid stabilisation. Furthermore, it highlights some recent developments in the Danish electricity market operation.

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1. Introduction

The challenge of integrating fluctuating renewable energy power sources such as wind, solar and ocean energy depends strongly on the share of the input. The following three phases of implementing renewable energy technologies can be defined [1]:

The introduction phase: This phase represents a situation in which there is no or only a small share of renewable energy in the existing energy system. The phase is characterised by marginal proposals for the introduction of renewable energy: e.g. wind turbines integrated into a system with only a limited share of wind power. The system will respond in the same way during all hours of the year and the technical influence of the integration on the system is easy to identify in terms of saved fuel on an annual basis. Moreover, the input of renewable power does not pose a challenge to the operation of the grid and the electricity balance.

The large-scale integration phase: This phase represents a situation in which there is already a major share of renewable energy in the system; e.g. when more wind turbines are added to a system which already has a high share of wind power. The phase is defined by the fact that further increases in renewable energy penetration will have an influence on the system and this will vary from one hour to another, e.g. depending on whether heat demand is high or low in the given hour, whether a heat storage is full or not or whether the electricity demand is high or low during the given hour. The integration of wind and solar power in the system becomes complex and requires consideration with regard to grid stabilisation.

The 100 percent renewable energy phase: This phase represents a situation in which the energy system is currently or is being transformed into a system based 100 percent on renewable energy. The system is characterised by the fact that new investments in renewable energy will have to be compared not to nuclear or fossil fuels, but to other sorts of renewable energy system technologies. These include conservation, efficiency improvements and storage and conversion technologies, e.g. wind turbines introduced to replace the need for biomass resources. The influence on the system is complex not only with regard to differences from one hour to another but also with regard to the identification of a suitable combination of changes in conversion and storage technologies. Moreover, the challenge of operating the grid in terms of ensuring frequency and voltage stability is of major importance.
Generally, the integration of wind and solar power in the European Union (EU) electricity grid and similar regions around the world is in the first phase, i.e. the introduction phase. However, in general, EU and other regions may soon go into the next phase and in many local areas this is already the case. Consequently, this article addresses the challenge of large-scale integration of renewable energy sources into existing energy systems in which the challenge of coordinating fluctuating and intermittent renewable energy production with the rest of the energy system must be met. Especially with regard to electricity production, meeting this challenge is essential since electricity systems depend on an exact balance between demand and supply at any time.

The need for change in the current electricity grid and power design and operation in order to meet such challenge has been recognised and discussed for several years under different labels. One of the authors of this article published on the subject already in 1986 [2–4] by which time the idea of a regulation hierarchy was introduced in order to manage distributed generation without causing feedback in the system. Later on, the subject has been discussed under the label “Distributed generation” [5,6] as well as been a part of the discussion of individual innovative technological concepts such as the Vehicle-to-Grid (V2G) [7–13] concept. As a part of the above-mentioned discussion regarding the large-scale electricity grid, similar discussions have for many years been part of the debate on the design of micro-grids [14–16] as well as local, regional and national energy systems [17–21].

In very recent years, the discussion has been related to the “smart grid” concept in many papers. Many of them argue for the need for smart grids in order to facilitate better integration of fluctuating renewable energy [22,23]. Even though some inconsistencies exist, the typical core of defining a smart grid consists of a bi-directional power flow, i.e. the consumers are also producing to the grid, which differs from the traditional grid in which there is a clear separation between producers on the one side and consumers on the other side resulting in a uni-directional power flow. Consequently, former concepts mentioned above such as regulation hierarchies, distributed generation, V2G concepts as well as many micro-grids all become smart grids or part of the smart grid concepts.

Several smart grid papers focus on the consumer and how to involve the consumer in the active operation of the power balance by introducing technical operation systems and/or economic incentives to facilitate flexible demands [24], including the development and design of proper information and communication systems [25,26], heat pumps and electric vehicles [8,27–29]. Other papers focus on the new challenges of dealing with uncertainties, risks and precautions [30,31].

The above-mentioned papers and approaches regarding smart grids all seem to have a sole or predominant focus on the electricity sector. However, a few papers emphasise the need for intelligent management of a complete set of energy forms including electricity, heat, hydrogen, biofuels etc. [22]. Additionally, several papers focus on the market integration [32–37]. This article emphasises why smart grids should not be seen as separate from the other energy sectors and what the integration of the other sectors means for the identification of proper solutions to the integration problem. There are two main points: Firstly, it does not make much sense to convert the electricity supply to sustainable energy if this is not coordinated with a similar conversion for the other parts of the energy system. Secondly, if one seeks to follow such coordination, additional and better solutions to the implementation of electricity smart grids arise compared to seeking solutions with a sole focus on the electricity sector.

2. Large-scale integration of wind and solar power

Large hydropower producers are an exception among renewable power producers, since such units are typically well suited for electricity balancing. In contrast, given the nature of solar, wind, wave and tidal power, very little can be gained by regulating these renewable resources. The possibilities of achieving a suitable integration are thus to be found within the surrounding system, i.e. the power and CHP stations which constitute the rest of the supply system. The regulation in supply may be assisted by flexible demands, such as e.g. heat pumps, consumers’ demand, and electric boilers. Moreover, the integration can be helped by the use of different energy storage technologies.

The issue has been analysed carefully in the book Renewable Energy Systems – the choice and modeling of 100% Renewable Solutions [1]. The book refers to and deduces the essence from a series of studies applied to the analysis of large-scale integration of renewable energy sources (RES) into the Danish energy system. At present, the Danish energy system already includes a relatively high share of fluctuating renewable energy and is therefore suitable for the analysis of further large-scale integration.

The question in focus is how to design energy systems with a high capability of utilising intermittent RES. The method addresses the comparison of different systems in terms of this capability, including the problem that the fluctuations and intermittency of e.g. wind power differ from one year to another. Such a challenge is met by analysing and illustrating different energy systems in so-called excess electricity diagrams. In these diagrams, a curve represents the inability of the system to integrate fluctuating RES-based power against the yearly production of the specific technology in question.

A number of studies of large-scale integration of RES are presented in [1] and, finally, some reflections and conclusions sum up with regard to the methodologies and principles as well as the technical measures involved. This leads to a series of recommendations concerning the most feasible technical measures; how to combine the measures, and when to use them considering the share of RES in the system. With regard to large-scale integration of RES, the following general recommendations can be made:

The large-scale integration of renewable energy should be seen as a way of approaching renewable energy systems. The integration of RES must be coordinated with energy conservation and efficiency improvements, such as CHP and improved efficiencies e.g. in the form of fuel cells. All such measures improve the fuel efficiency of the system. However, they also add to the electricity balancing problem and contribute to the excess electricity production.

The point is that RES should not be regarded as the only measure when conducting analyses of large-scale integration. The long-term relevant systems are those in which such measures are combined with energy conservation and system efficiency improvements. In that respect, the Danish energy system with a high share of CHP-based district heating can be regarded as a front-runner and a system well suited for the analysis of large-scale integration of renewable energy. In such systems with a high share of district heating and CHP, excess electricity production can best be dealt with by giving priority to the following technologies:

The CHP stations should be operated in such a way that they produce less when the RES input is high and more when the RES input is low. When including heat storage capacity, such measures are likely to integrate fluctuating RES up to around 20 percent of the demand without losing fuel efficiency in the overall system. After this point, the system will begin to lose efficiency as heat production from CHP units is replaced by thermal or electric boilers [1,36].

Heat pumps and any additional heat storage capacity should be added to the CHP stations and operated in such a way that further
RES can be efficiently integrated. Such measures will allow for the integration of up to 40 percent of fluctuating RES into the electricity supply without losing overall system efficiency. The economic feasibility of the investments in heat pumps proves very high for Danish society. Moreover, the investment in wind power is substantially improved [1,36].

Electricity should be utilised in the transport sector, preferably in electric vehicles. Such measures will serve as an efficient improvement of the integration of fluctuating RES [1,36].

In general, it is not beneficial to include electricity storage capacity in the above-mentioned steps. Such storage capacity is both inefficient and expensive compared to the benefits which may be achieved. Moreover, the nature of fluctuating RES dictates the need for high capacities of both conversion units and storage capacities in combination with a low number of full load hours. Thus, the electricity storage technologies call for high investments in combination with low utilisation. If such technologies are to be competitive, they should provide further benefits such as saving installed power station capacity and/or involving ensuring grid stability [35,38–40].

It is not important to include flexible consumer demands in the regulation. The use of such measure raises the same problems as for electricity storage technologies. Due to the amount of flexible energy required and the timeline it is required for, it is unrealistic based on current estimates that there will be enough flexible consumer demand to increase fluctuating RES.

It is very important to involve the new flexible technologies such as CHP, heat pumps and the electrification of transport (batteries and electrolysers) in the grid stabilisation tasks, i.e. to secure and maintain voltage and frequency in the electricity supply. Such involvement becomes increasingly important with an acceleration of the share of RES.

Additional to the above, a new component can be added as a result of a four-year research collaboration between seven Danish university departments and research institutions in the project Coherent Energy and Environmental System Analysis (CEESA). The project has, among others, taken a focus on the identification of the long-term potential of biomass for energy in different scenarios of agricultural development in combination with a life cycle perspective. Moreover, the CEESA project has developed a comprehensive study of the different aspects of the transportation sector including all means of transportation (cars, lorries, bicycles, trains, ships, aircraft, etc.) as well as different scenarios of technological development. The results are documented [41] and lead to the following conclusion with regard to smart energy systems:

In order to balance the concern between, on the one hand, biomass resources for energy being scarce in the long-term perspective and, on the other, the complexity of transforming the transportation sector into 100 percent renewable energy calling for different forms of renewable energy gases and liquid fuels such as biogas, syngas and methanol, it leads to the need for transforming electricity via electrolysis and hydrogen into various forms of renewable energy gases and liquids. Consequently, in the long-term perspective, a new option arises of helping the electricity balancing by converting electricity into various gases and liquids before

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**Fig. 1.** Skagen CHP plant located in Frederikshavn Municipality at the northern tip of Denmark.
storing these. In the Danish system, this opens for utilising the substantial storage capacity already existing as part of the Danish natural gas distribution system.

3. The case of flexible operation of Skagen CHP plant

As described before, the integration of renewable power sources into electricity grids has to be seen in connection with parallel transformations of the energy system including energy conservation and efficiency improvements such as expansion of CHP. Seen in this light, some of the most efficient ways of facilitating the large-scale integration of renewable power are to be found in the operation and regulation of CHP plants, which can be enhanced by adding large-scale heat pumps and involving flexible CHP plants in the task of ensuring the stability of the electric grid.

The case of flexible operation of Skagen CHP plant illustrates the significance of including distributed CHP and renewable power production units in the task of grid stabilisation, i.e. securing voltage and frequency stability of the electricity supply. Today, in most countries, electricity is produced either by hydro power or by large steam turbines on the basis of fossil fuels or nuclear power. Electricity from distributed generation constitutes only a small part of the production. Until now, the tasks of balancing supply and demand and securing frequency and voltage on the grid have been managed only by such large production units.

However, the large-scale integration of renewable power into the electricity supply as well as the expansion of CHP are necessary for future renewable energy systems. Consequently, sooner or later such distributed production units need to contribute to the task of securing the balance between electricity production and consumer demands. The case of Skagen presents technical designs of potential future flexible energy systems which will be able to both balance production and demand and fulfil voltage and frequency stability requirements of the grid and it illustrates how such operation has already been implemented in a few places in Denmark. The Skagen CHP plant is located in Northern Jutland in Denmark as illustrated in Fig. 1.

Skagen CHP plant has three gas engines, heat storage, a gas peak load boiler and an electric boiler as listed in Fig. 2. Moreover, Skagen CHP plant receives heat from a waste incineration plant and waste heat from industry, and is considering investing in a large-scale heat pump.

The organisation of the Danish electricity markets - being part of the Nordic system — is shown in Fig. 3. As shown, the market is divided into a day-ahead spot market and a number of regulating power markets. The specific organisation varies from one European system to another, but the principle shown in Fig. 3 is typical for most countries.

Access to the different markets was granted for small CHP plants, like the one in Skagen, along this timeline:
Skagen CHP has been operating at the day-ahead spot market for several years and was one of the first small CHP plants to enter the regulating power market. Since November 2009, Skagen CHP has also been operating in the automatic primary reserve market.

The simultaneous operation of the plant at all these markets is done in the following sequence: Bids are given a day ahead on the spot market. Bids for electricity production from the CHP units are given on the basis of alternative costs of supplying heat from the gas boiler or the electric boiler. In the calculation of the bids, the heat storage option is carefully taken into account. How the bids are calculated, is described in [33] and considerations on optimising the heat storage investment are described in [34].

The CHP units can be operated at the regulating power market in the following two ways: If operation at the spot market is won, a downward regulation can be offered; if not, an upward regulation can be offered. The reverse situation applies for the electric boiler.

Additionally, the CHP units can be operated at the automatic primary reserve market. This is done by offering the CHP plants to the spot market at full capacity minus 10 percent. If the bid is won, the same unit can be offered for a plus/minus 10 percent operation at the primary automatic reserve market. The same principle can be applied to the electric boiler.

Fig. 4 illustrates the operation of the plant on Thursday, May 13th 2010. On that day, the three CHP units traded their full load into the spot market during the well-paid hours in the middle of the day and in the evening. On Friday May 14th, the three CHP units were traded into the spot market during the well-paid hours in the middle of the day - however not full load - the remaining capacity was traded into the primary reserve market. On Sunday May 16th, the electric boiler was run half load - allowing it to be offered both as positive primary reserve (reducing consumption) and as negative primary reserve (increasing consumption). On Tuesday May 18th, all three CHP units were activated at the regulating power market.
market for an upward regulation. The following day, the 10 MW electric boiler was activated at the regulating power market for a downward regulation.

Another interesting example of Skagen CHP’s regulating potential occurred on the 25th of March 2011, as displayed in Fig. 5. In the first 4 h of the day, Skagen won negative primary reserve with the 10 MW electrical boiler. Hence, it operated below full capacity. A little before 3 o’clock, Skagen won a downward regulation in the regulating power market, so the electric boiler increased its output to approximately 4 MW. At the same time, Skagen still performed the frequency regulation which it had won in the primary reserve market. After 4 o’clock, Skagen had not won anymore primary reserve and so the electric boiler was offered at full capacity (i.e. 10 MW) for downward regulation in the regulating power market, winning it for a full hour. From 16 to 20 o’clock, only part of the CHP units were sold in the spot market which made it possible to offer both positive primary reserve and negative primary reserve during these 4 h.

The online operation of Skagen CHP and the prices at the spot market and the balancing market can be seen at www.emd.dk/desire/Skagen. The investment cost of making it possible for Skagen CHP plant to be involved in the primary reserve market has been surprisingly low. The cost of control equipment to the existing CHP units, i.e. making it possible to offer plus/minus 1.4 MW, has been only 27,000 Euro and the cost of the 10 MW electric boiler has been 0.7 million Euro.

4. Conclusion

The challenge of integrating renewable energy power into electricity grids cannot be looked upon as an isolated issue but should be seen as one out of various means and challenges of approaching sustainable energy systems in Europe. Therefore, the integration of renewable energy power into the electricity sector must be coordinated with other sectors such as heat supply and transportation as well as energy conservation and efficiency improvements, such as CHP and improved efficiencies e.g. in the form of fuel cells.

Seen in this light, this article comes to the result that some of the most efficient ways of facilitating the large-scale integration of renewable energy power are to be found in the operation and regulation of CHP plants, including those which involve them in the stabilisation of the electric grid.

The case of flexible operation of Skagen CHP plant illustrates the significance of including distributed CHP and renewable power production units in the task of grid stabilisation, i.e. ensuring voltage and frequency stability of the electricity supply. Today, in most countries, electricity is produced either by hydro power or by large steam turbines on the basis of fossil fuels or nuclear power. Fluctuating and intermittent renewable power production constitutes only a small part of the production. Until now, the tasks of balancing supply and demand and securing frequency and voltage on the grid have been managed only by such large production units.

However, the opening of the spot market and later on both the regulating power market and the primary reserve market has made it possible for small distributed CHP plants to enter such markets. The case of Skagen CHP plant equipped with CHP units, heat storage and electric boilers illustrates how such small plants can provide valuable grid stabilisation at very low additional investment and operating costs. Moreover, the case illustrates how seeing the electricity sector as part of a complete sustainable energy system paves the way for better and more cost-effective solutions to smart grid applications compared to looking at the electricity sector as a separate part of the energy system. Consequently, one will benefit from taking a smart energy system approach rather than a solely electricity smart grid approach.

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