Energy 42 (2012) 96–102

Contents lists available at SciVerse ScienceDirect

Energy

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

Review

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

Henrik Lund [a,*], Anders N. Andersen [b], Poul Alberg Østergaard [a], Brian Vad Mathiesen [c], David Connolly [c]

[a] Department of Development and Planning, Aalborg University, Vestre Havnepromenade 9, DK-9000 Aalborg, Denmark
[b] EMD International, NOVI Science Park, Aalborg, Denmark
[c] Department of Development and Planning, Aalborg University, A.C. Meyers Vænge 15, DK-2450 Copenhagen SV, Denmark

ARTICLE INFO

Article history:
Received 15 December 2011
Received in revised form
19 March 2012
Accepted 2 April 2012
Available online 28 April 2012

Keywords:
Smart grid
Smart energy systems
Large-scale integration of wind and solar
Electricity market
Flexible Combined Heat and Power production (CHP)

ABSTRACT

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.

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.

* Corresponding author. Tel.: +45 9940 8309; fax: +45 9815 3788.
E-mail address: lund@plan.aau.dk (H. Lund).

0360-5442/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.energy.2012.04.003

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 meet. 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]. Parallel to 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 intermittence 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