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ANALYSIS

System and market integration of wind power in Denmark

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ABSTRACT

Denmark has more than 10 years' of experience with a wind share of approximately 20 per cent. During these 10 years, electricity markets have been subject to developments with a key focus on integrating wind power as well as trading electricity with neighbouring countries. This article introduces a methodology to analyse and understand the current market integration of wind power and concludes that the majority of Danish wind power in the period 2004–2008 was used to meet the domestic demand. Based on a physical analysis, at least 63 per cent of Danish wind power was used domestically in 2008. To analyse the remaining 37 per cent, we must apply a market model to identify cause–effect relationships. The Danish case does not illustrate any upper limit for wind power integration, as also illustrated by Danish political targets to integrate 50 per cent by 2020. In recent years, Danish wind power has been financed solely by the electricity consumers, while maintaining production prices below the EU average. The net influence from wind power has been as low as 1–3 per cent of the consumer price.

1. Introduction

In many countries and regions, the political wish to combat climate change as well as to secure energy supply and create industrial development and jobs has led to the formulation of long-term objectives of sustainable energy as well as short and mid-term strategies of implementing the first steps. The Danish Parliament has decided on the long-term target of a fossil-free energy system by 2050 and has, in the spring of 2012, agreed on an ambitious plan to implement the first step by 2020, including an increase in the wind power production from around 25 per cent to 50 per cent of the electricity demand.

In neighbouring Germany, a phase-out of nuclear power and a parallel expansion of renewable energy is envisioned to reach a renewable energy share corresponding to 80 per cent of the electricity demand in 2050 [1]. Likewise, in the United Kingdom, ambitions include an 80 per cent reduction in carbon dioxide emissions by 2050 compared to 1990 and, as a stepping stone to this, *"power sector emissions need to be largely decarbonised by the 2030s"* [2]. Sweden has adopted similar targets and plans to be carbon neutral by 2050 with a short-term objective of 50 per cent renewable energy by 2020 [3].

Such and similar targets have generated significant activity in the research community in the development of theories, tools and methodologies to design, analyse and implement such strategies.

In terms of discussing future systems and the market integration of wind power, such as the smart grid concept, Denmark is an interesting case. Today, the Danish wind power production is equivalent to approx. 25 per cent of the electricity demand, and Denmark has more than 10 years' of experience in producing and utilising a wind power input of approximately 20 per cent of the national electricity demand. In some municipalities in the western part of Denmark, the share is even in the order of magnitude of 100%.

During the same 10 years, electricity markets have been subject to developments with a key interest in integrating wind power as well as trading electricity with neighbouring countries.

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Frequently, strategies aiming at curbing carbon dioxide emissions combine energy efficiency and conservation with the replacement of fossil fuels by a combination of wind power or similar fluctuating renewable energy sources and biomass. Consequently, the integration of fluctuating power sources into the electricity grid becomes essential and the discussion and development of so-called smart grids have attracted a lot of attention.

Smart grids may be perceived as electricity systems adapted to the requirements of distributed generation based on fluctuating energy sources in the sense that they offer the required flexibility for an adequate system integration of these. Typically, the separation of production and demand is not strong in these systems, thus allowing the bidirectional use of the grid. This issue has been researched for a long period of time in different terms [4–10]. Elements of this research include flexibility in the production system, flexibility in demand [11–13], flexibility by using storage systems [14], impacts on the grid [15–18] and improved integration between energy sectors, as deliberated in a series of articles [19–32]. Holistic energy systems analyses encompassing both technologies with a fluctuating nature and technologies adding flexibility [33–41] also present work which may effectively be labelled smart grids, but as argued more explicitly in [42], there is a need for a transition to smart energy systems, not just smart grids, and framework conditions including market constructs need to adapt to the needs of more flexible systems [43]. In terms of wind power integration, the referenced work addresses many of the technical challenges associated with large-scale wind power integration.

The fact that Denmark has exchanged significant amounts of electricity on the Nordic electricity market as well as with Germany during some years has led some observers to conclude that Denmark does not utilise the wind but exports it instead. On this basis, it is claimed that other countries cannot copy the Danish example.

Moreover, the fact that private household consumers pay a high electricity tax has led observers to claim that Danish wind power is extremely expensive and that wind power is a large burden on Danish taxpayers.

While we agree that there are significant challenges associated with transforming the Danish and any other energy system based on centralised power plants to accommodate high shares of wind power, our analysis contradicts the claims that this transformation leads to higher taxes, more discarded electricity, and low-priced export. The circulation of such wrong claims makes the public debate and policy making about these complex issues even more difficult. For methodological clarity, this article presents a particular Danish case of such a circulation of wrong claims and misunderstandings. The chosen case study contains all the elements mentioned above. The study which we present and against which we argue is "*Wind energy – The case of Denmark*" from September 2009 [44], produced and published by the Danish think tank CEPOS. The study claims 1) that most of the Danish wind power has been exported in recent years, and 2) that wind turbines in Denmark are very costly to Danish taxpayers and electricity consumers.

The study states that wind power "*has recently (2006) met as little as 5% of Denmark's annual electricity consumption with an average over the last five years of 9.7%*". Later, the same study states that "*a significant fraction of the charges and taxes paid for by Danish domestic consumers is recycled to support [..] the feed-in tariffs that make it attractive [..] to invest in wind power*".

Based on a graphical pattern, Sharman makes a similar interpretation of Danish wind power: "*west Denmark makes full use of its interconnections for balancing wind power as there is a strong correlation between wind output and net power outflows*" [45]. Ferguson points to efficiency loss in operating thermal power plants: "*No one knows exactly just how much less efficiently a plant actually operates when it has to run in harness with wind turbines, however the effect is not small*", and, based on other papers by himself [46,47], Ferguson continues to state that "*In the extreme case of an all-natural-gas system, it can be shown that the loss of efficiency of the plant operating 'in harness' outweighs the benefit from the wind input*". A purportedly questionable effect of wind power and the associated cost represent a recurring theme in the Optimum Population Trust Journal, in which the listed papers are published. Through an analogy with the lower fuel efficiency of automobiles running intermittently in urban traffic compared to highway traffic, Inhaber [48] points to the same issue of efficiency loss in the case of the thermal power generation plants.

Evidently, both issues are essential to the understanding of the challenges related to the future integration of wind power. Therefore, this article presents and applies a methodology to analyse to which extent the historical Danish energy system has been able to make use of the Danish wind power production domestically and applies the methodology to the year of 2008. Based on the results, it is discussed how to design the future system to adapt to the plans of a further increase in wind power input. Moreover, this article analyses the influence of the same wind power input on electricity consumer prices in the period 2004–2008.

2. Danish wind power and export

From 2000 to 2010, Danish wind turbines generated in a normal year the equivalent of approx. 20 per cent of the Danish electricity demand. In 2008, the figure was 19.3 per cent.

The question is if one can determine to which extent the wind power has been exported or used to meet domestic demands.

This is not a simple calculation, since the load balancing of an electricity system requires access to balancing and regulating reserves in order to make the system function, and, in such regard, Denmark is well-connected to neighbouring countries through transmission lines.

Denmark is part of the European Network of Transmission System Operators for Electricity (ENTSO-E) [49]; an international collaboration in which a large number of European countries assist one another in securing the balancing task, e.g. within the supply of primary automatic reserves. Thus, Denmark draws upon the assistance of other countries and helps them in return. That includes the balancing of wind power in Denmark as well as in Denmark's neighbouring countries. One of these countries is Germany, and the northernmost state of Germany, Schleswig-Holstein, has an installed wind power capacity similar to that of Denmark.

When wind capacity in Denmark increases, the system may need more regulating power due to the fluctuating nature of wind power. Historically, and starting before the wind power era, Denmark has shared a well-functioning regulating power market with Finland, Norway and Sweden, which has the necessary capacity to provide all the up- and downward regulating power needed in order to operate the system. It is most cost-effective to handle the regulation in the Nordic power system via a common regulating power market, analogous to the distribution of primary (frequency) reserves among countries. Danish regulating power resources are used whenever it is most cost-effective, given the particular mix of energy production technologies in the system and the corresponding market prices at any point in time. Moreover, all the costs of operating this regulating power market are included in the electricity price. As regulation based on Norwegian or Swedish hydro power with storage capacity is often more cost-effective than local Danish regulating resources, the hydro power will be prioritised in the merit order. Given the present institutional set-up, this solution is working well for all countries involved, but it does not reflect the ability of the Danish system to regulate solely by the use of local resources; i.e., the ability to regulate power resources and load balancing by using local-regional resources. This issue is addressed later in this article.