Energy 35 (2010) 1244–1255

Contents lists available at ScienceDirect

Energy

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

Influence of wind power, plug-in electric vehicles, and heat storages on power system investments

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ARTICLE INFO

Article history:
Received 20 January 2009
Received in revised form
2 November 2009
Accepted 4 November 2009
Available online 3 December 2009

Keywords:
Wind power
Electric vehicle
Heat storage
Electric heat boiler
Heat pump
Investment model

ABSTRACT

Due to rising fuel costs, the substantial price for CO_2 emissions and decreasing wind power costs, wind power might become the least expensive source of power for an increasing number of power systems. This poses the questions of how wind power might change optimal investments in other forms of power production and what kind of means could be used to increase power system flexibility in order to incorporate the variable power production from wind power in a cost-effective manner.

We have analysed possible effects using an investment model that combines heat and power production and simulates electric vehicles. The model runs in an hourly time scale in order to accommodate the impact of variable power production from wind power. Electric vehicles store electricity for later use and can thus serve to increase the flexibility of the power system. Flexibility can also be upgraded by using heat storages with heat from heat pumps, electric heat boilers and combined heat and power (CHP) plants. Results show that there is great potential for additional power system flexibility in the production and use of heat.

1. Introduction

Wind power is a variable and partly unpredictable power source that influences the rest of the energy system in ways that are different from conventional power plants. Wind power is also quickly becoming a major new source for power generation. As a result, new studies have been made to assess different aspects of integrating wind power into power systems.

One major aspect is the analysis of the additional costs and benefits that rise from power system operation with this variable and partly unpredictable power source. While this has been the dominant focus of research on wind power integration, increasing the share of wind power in the systems will also change the cost-optimal power production portfolio in the long-term. We analyse the investment and operational costs associated with this change. By changing assumptions about the relative costs of producing electricity and heat with different technologies, we arrive at different power system configurations and can demonstrate situations where wind power becomes the dominant source of power production. More flexible power systems enable the less costly integration of wind power. Therefore, we analyse the effect of two new forms of flexibility: plug-in electric vehicles and heat storages operated in tandem with heat pumps and electric heat boilers.

In general, wind power integration costs have been found to be relatively small, at least up to penetration levels of around 25%, as demonstrated by the several studies compared in the IEA collaboration (Holttinen [1]). The literature behind the article also establishes how to carry out wind integration studies (more detail and references in Holttinen et al. [2]). Wind power has influence on several different time scales. The main benefits of wind power result from fuel savings and lower CO_2 emissions as well as a decrease in conventional capacity requirements. Wind power also inflicts costs, mainly due to the variability of the resource and forecast errors. Costs are accrued especially from increases in the cycling of conventional power plants, partial load operation, non-spinning reserve capacity and transmission needs, as well as the relatively lower contribution to capacity than to electricity production.

Impact of wind power increases with penetration, but only a few attempts have been made to estimate the costs and benefits at higher penetrations (Meibom et al. [3], Karlsson & Meibom [4], Ea [5], Milborrow [6], Lund & Mathiesen [7] and earlier work with the same model [8,9], Ummels et al. [10]). One reason why such studies are more difficult to make is that wind power starts to affect the optimal portfolio of other power plants in the system by reducing their full load hours. With higher penetration levels, it becomes

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0360-5442/$ – see front matter
doi:10.1016/j.energy.2009.11.004

Nomenclature

Indices

i, I	Unit, set of units
I_a	Set of units in area a
$I^{HeatSto}$	Heat storage units
I_{PI}	Plug-in electric drive vehicles
$r, \bar{r}, R$	Region, neighbouring region, set of regions
a, A	Area, set of areas
t, T	Time steps, set of time steps
k, K	Country, set of countries

Variables

C	New capacity
P	Power generation
P^{Cur}	Wind curtailment
Q	Heat generation
S	Storage level
T	Electricity exchange between regions
U	Loading of electricity storage
Z	Loading of heat storage

Parameters

av	Availability of the unit
cc	Capacity credit
c^{Loss}	Transmission loss
C^{Ex}	Existing capacity
c^{Inv}	Annualized investment costs
c^{Fix}	Fixed operation and maintenance cost
$c^{Operation}(\cdot)$	Operation cost function of unit
d	Electricity demand
d^P	10-year peak demand
d_{PI}	Demand of plug-in vehicles
h	Heat demand
l	Round-trip storage loss
LC	Loading capacity of storage
SC	Storage capacity
W	Weight of time period

more and more unrealistic to assume that there would be no changes in the rest of the power system (Söder & Holttinen [11]). It is also unrealistic to implement such changes without proper investment optimization.

Karlsson & Meibom [4] use the same investment optimization model as in this article and consider high wind power penetration levels. However, their analysis concentrates on the cost competitiveness of hydrogen in road transport. In the All Island Grid Study, Meibom et al. [3] analyse wind power integration costs for six different power plant portfolios. Doherty [12] created these portfolios using a separate model, arriving at least-cost options according to varying input parameters. Furthermore, the influence of high wind power penetration on transmission systems was analysed by Nedic et al. [13] in the same study. While the study was comprehensive in many respects, it did not include the flexibility mechanisms studied in this article, namely plug-in electric vehicles and heat storages.

Ea [5] employed a similar approach and the same model as here, but again did not include the additional flexibility provided by heat storages and plug-in electric vehicles. Milborrow [6] quotes a tentative study by EnergiNet.DK, which indicates that there are no technical constraints for very large wind power penetrations and that the costs of variability should remain reasonable.

In work by Lund & Mathiesen [7], very large wind penetrations are achieved with power system flexibility from hydrogen generation and biomass CHP plants. Their model does not include endogenous investments and the investment decisions are based on expert opinions about energy system development. The results serve a somewhat different purpose than this article, as we have sought to focus on the merits of different ways of increasing power system flexibility. In another article [14], the same authors compare different ways of facilitating the integration of fluctuating power sources. Again their model does not include endogenous investments. As can be seen from this article, variable sources of power and different flexibility mechanisms change the optimal reference power plant portfolio, leading to deviation in the comparative results. Their analysis demonstrated that heat storages can have an important impact on power system flexibility, which also comes out strongly in our results. They also show that the use of electrolysers to produce hydrogen for fuel cell vehicles or combined heat and power plants does not appear to be cost competitive with the flexibility mechanisms provided by heat measures and battery electric vehicles.

Ummels et al. [10] analysed compressed air energy storage, pumped hydro storage and conventional heat boilers as means to increase flexibility. The model only analysed operational costs and did not make investment decisions. Of the three options, heat boilers were the most promising from the economical perspective, although their usefulness is limited to low load, high wind situations.

For a lower wind power penetration level of 20%, a large study was conducted by the US DoE [15]. The study used a generation expansion model and also incorporated a simple transmission system expansion. The assumptions about the relative costs of different technologies were such that wind power would not be cost competitive even in 2030 and would remain at the pre-ordained 20% minimum. In this study, wind power was more competitive and as a result higher penetration levels were cost-optimal. As there is no a priori knowledge about the relative competitiveness of different power production technologies in 20–30 years – and wind power cost is location dependant – it is prudent to also analyse situations where wind is the least-cost source of electricity. However, there will be a limit on the cost-optimal penetration level as integration costs keep increasing in step with penetration. This article analyses those situations and additionally takes into account the possibility of making use of new forms of flexibility to decrease integration costs.

The different time scales involved in investment optimization and operational optimization make the wind integration problem more complicated. A model that can analyse the operational costs of a power system is too detailed for analysing long-term investments. Therefore we use a model that optimizes the investments and somewhat simplifies the operational characteristics of power plants. This model, Balmorel, does not include start-up costs, part-load efficiencies or wind power forecast errors, all of which would increase the costs of integrating wind power into the system. The next step would be to feed the long-term investment results from Balmorel into a more complete power system model and analyse the missed costs. However, this step is not included in our analysis.

Our analysis seeks to fill a gap in the knowledge of wind power integration. We include long-term investment analysis with wind integration, enabling us to estimate the long-term total system costs of switching from conventional power production toward wind power. Portfolio planning has a long history and work has been done to include wind power (Doherty et al. [16]). Our extension also accounts for the effect of storages in heating and transport in the