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RESEARCH ARTICLE

Large scale integration of wind power: moderating thermal power plant cycling

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ABSTRACT

Power plant cycling in thermal plants typically implies high costs and emissions. It is, therefore, important to find ways to reduce the influence of variations in wind power generation on these plants without forsaking large amounts of wind power. Using a unit commitment model, this work investigates the possibility to reduce variations by means of a moderator, such as a storage unit or import/export capacity. The relation between the reduction in CO_2-emissions and the power rating of the moderator is investigated, as well as the benefit of a moderator which handles weekly variations compared with a moderator which has to be balanced on a daily basis.

It is found that a daily balanced moderator yields a decrease in emissions of about 2% at 20% wind power grid penetration. The reduction in emissions is mainly due to an avoidance of start-up and part load emissions and a moderator of modest power rating is sufficient to achieve most of this decrease. In the case of a weekly balanced moderator, emissions are reduced as the moderator power rating increases. At 40% wind power grid penetration, a weekly balanced moderator reduces emissions with up to 11%. The major part of this reduction is due to the avoidance of wind power curtailment.

The simulated benefit (CO_2-emissions and costs) from adding a general moderator is compared with emissions from Life Cycle Assessment (LCA) studies and cost data of five available moderator technologies; transmission capacity, pumped hydro power, compressed air energy storage, flow batteries and sodium sulphur batteries.

KEYWORDS
wind power; power plant cycling; integration; intermittent variation; energy storage

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1. INTRODUCTION

Whereas most scientists and decision makers would agree on wind power expansion as a way to make power generation more sustainable, a desirable development of the power system as a whole has yet to be settled. The ability to efficiently reduce CO_2-emissions through wind power integration does not only depend on regional wind speeds but also on properties of the power system already in place. 'Power system' is here meant the electricity generation units and the electricity transmission system, including possible devices such as energy storage.

The focus of this paper is on integration of wind power in an existing power system dominated by thermal base load plants, as is the most typical case when increasing the diffusion of wind power. In a wind-thermal system, production variations from the intermittent character of wind power results in an increase in system costs and a decrease in the efficiency of wind power as a means to reduce CO_2-emissions from the system. This effect gets increasingly pronounced with increased levels of wind power grid penetration and is due to the adjustment in production pattern of the thermal units to the variations in wind power production. As wind power grid penetration increases, the conventional units will run more at part load and experience more frequent starts and stops. Also, wind power may need to be curtailed in situations where the costs to stop and restart thermal units are higher than the difference in running costs of wind power and the thermal units. Thus, variations in wind power reduce the possibility of the power system to lower CO_2-emissions by adding wind power capacity to the system. In order to avoid this, a so-called moderator can be introduced in the system, such as a storage unit or transmission capacity.

Literature presents thorough evaluations on the interaction between wind power (i.e. a wind farm) and one moderating unit. Particularly well covered is the interaction between wind power and a (pumped) hydro power plant[1–2] and the interaction between wind power and a compressed air energy storage.[3–4] In such studies the wind farm is combined with a moderator so that the total output resembles a conventional power plant, i.e. closer to base load[2–3] or maximizes return according to a given price signal.[1] Korpaas *et al.*[5] investigate the sizing of a storage in connection to a single 1 MW wind turbine taking transmission capacity limitations as well as a varying demand into consideration. Paatero and Lund[6] analyze wind data to determine suitable storage capacities to handle the production variations of a single wind turbine. The economic value of storage in connection to a wind farm has been evaluated from spot market price data and the power generation of a wind farm by Bathurst and Strbac[7]. Some wind power variation moderator options have also been evaluated from a wider system perspective, i.e. considering more units in the system than one wind farm and one storage device. Blarke and Lund[8] have derived a methodology for analysing the usefulness of different moderator options and applied it to heat pumps in a system made up by a CHP unit, wind power generation at several locations and a varying demand. Salgi and Lund [9–10] have investigated the ability of a compressed air energy storage to moderate wind power variations, as well as the economic feasibility of such device. The context of their study is the power system of western Denmark on an aggregated level (all plants of a certain type modelled as an aggregated unit) with a predetermined dispatch strategy. Ummels *et al*.[11–12] investigate the impact of various integration solutions for wind power in the Netherlands, using a model which accounts for a minimum load level of thermal units as well as minimum up time and down time of the thermal units. In summary, the possibility to manage wind power variations with a moderator has been examined on a detailed level and the possibility to manage demand and wind power variations has been studied on an aggregated level. However, the ability of a moderator to handle wind power variations with respect to influence on start-ups and part load operation of conventional units has not been in focus. Since demand as well as wind power generation varies, some wind power variations will enhance the effect from variations in demand while some wind power variations will counteract the demand variations. Thus, the total variations might differ substantially from the wind power variations, which motivate evaluation of the possibility to moderate the total variations. However, the importance of moderation with respect to costs and emissions at a certain time depends on which units that would manage the variation and the power generation pattern without moderation. Only some of all variations in the system will cause power plant cycling, part load operation or wind power curtailment, implying extra costs and emissions for the system. Obviously, it is such variations that are desired to moderate. Thus, there is a need for studies considering the wind power variations in a detailed power system context. The present work is a step in this direction and investigates the ability of a moderator to reduce the number of start-ups and part load operation hours. To do this, the wind power variations are considered from a power system context, where the power system in question is described in some detail.

The power system considered in this work is an isolated thermal power system (i.e. a system consisting of thermal units such as condense power plants and combined heat and power plants) with the same power plant configuration as the power system of western Denmark. Units with rated power greater than 80 MW are described on an individual basis, while smaller units are aggregated. As mentioned above, previous studies have evaluated the possibility to manage wind power variations with a particular moderator but this work looks at the overall systems behaviour and investigates the required characteristics of the moderator to efficiently reduce CO_2-emissions from the system. The results are compared with characteristics of five available moderating technologies; pumped hydro power, compressed air energy storage, transmission capacity, flow batteries and sodium sulphur batteries. For other strategies to facilitate the integration of wind power including management of the heat and the transportation sector see, e.g., Lund and Mathiesan[13] and Göransson *et al*.[14]

2. METHOD

2.1. BALMOREL and BALWIND modelling tools

Simulations have been performed with the BALMOREL modelling tool developed by Ravn[15]. BALMOREL is a linear programming model originally designed for the countries around the Baltic Sea. It optimizes the electricity and heat production, over some geographical scope, with regard to costs and utility (maximizing consumer utility, i.e. willingness to pay for heat and power, subtracted with production costs) under the assumption that there is perfect competition on the heat and power markets. In BALMOREL, the geographical scope considered is managed at three different levels; countries, regions and areas, i.e. each country is made up by one or several regions, which in turn consist of one or several areas. The heat generation and heat demand should be balanced in each area, whereas electricity generation and electricity demand should be balanced over each region. Electricity can also be exchanged between regions to the extent that the defined transmission capacity allows. Regions within the same country share policies and regulations. Simulated countries can trade electricity with each other. Electricity can also be traded with countries outside the geographical scope of the

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simulation, in which case the amount of exchanged capacity is based on assumptions regarding price relations or total traded capacity. BALMOREL is developed and distributed as an open source code and a detailed description of the model is given by Ravn.[16] Connolly *et al.*[17] give a short description of BALMOREL for the purpose of analysing the integration of renewable energy.

In order to investigate the influence of large-scale wind power on a power system, an add-on to BALMOREL, BALWIND, has been developed in this work. The structure of BALWIND is based on a modelling tool developed in a previous work by the authors.[18] The difference from the previous work is that the present modelling includes costs and emissions related to part load operation in the large thermal plants (i.e. those with rated power greater than 80 MW). Also, the heat generation, which must be balanced with heat demand, is now part of the optimization (handled by BALMOREL). By including the heat generation, the generation in small CHP units, which is aggregated in the model, can be part of the optimization rather than predetermined according to production data as in the previous work. A final addition made to BALWIND compared with the previous work is that a reserve requirement has been included in the model, which covers for planning errors due to uncertainty in wind power forecasts when units with start-up times of more than an hour are scheduled. However, this is done in the same simplified manner as for reserves covering variations within the hour.[18] Since details regarding the model structure can be found in a previous work[18], only the most relevant parts of the BALWIND structure concerning the inclusion of start-up costs and part load costs in the optimization are given here.

In BALMOREL, power generation capacity is aggregated by type of technology. In BALWIND, each unit with a power production capacity greater than a certain limit is modelled on an individual basis in order to include the limits of flexibility of each of the units (such as part load performance and start-up ability). A start-up cost, a minimum load level and a flag indicating if the unit can be used as reserve capacity are added to the description of the units. As suggested by Schaeffer and Cherene[19], a binary variable, *spin(i,t)* is used to indicate if a unit, *i*, is available for production (warmed up) at time *t*. With this integer approach, start-up time limitations are taken into consideration and start-up costs can be determined, as illustrated by the equation

$$c(i,t)_{start} = on(i,t)\cdot C(i)_{start} \tag{1}$$

where $c(i,t)_{start}$ is the start-up cost of unit *i* at time *t* given by the cost to start the unit, $C(i)_{start}$ when the unit is started and *on(i,t)* switches from zero to one. The variable *spin(i,t)* is related to *on(i,t),* since the unit has to be turned on (*on(i,t)* switches from zero to one) a certain number of time steps before the unit is warmed up and ready to produce electricity (*spin(i,t)* switches from zero to one). The alternative to shut down units at times of high wind power production levels is to keep them running at low level. Minimum load level limitations are, therefore, taken into account by enforcing a unit, which is ready for production, to keep a production level, *g(i,t)*, at or above this minimum load level $P_{low}(i,t)$. This is handled by the equation:

$$g(i,t) \geq spin(i,t)\cdot P_{low}(i,t) \tag{2}$$

The efficiency of a power plant decreases with decrease in load. The efficiency decrease of thermal plants is normally small for power levels close to rated power, whereas it falls more rapidly at lower load levels. A load level decrease of 1% is thus more costly at low load levels than at high load levels. In BALWIND, the relationship between load level and part load cost (i.e. the additional cost from running the unit at lower efficiency level) is simplified by assuming a linear dependence. The linearization is based on knowledge of the efficiency at rated power and the efficiency at 75% load level. The relationship between the efficiency at rated power and at 75% load level (i.e. the rate of decrease in efficiency per 25% decrease in load) is referred to as the efficiency factor, N_{75} ($\eta_{75} = N_{75} * \eta_{opt}$). The efficiency factor for steam turbines is based on estimates from German coal power plants (Strömberg, L., Personal communication, Vattenfall AB, Corporate Strategies, Berlin/Stockholm, 2007) and from Carraretto[20] who evaluated the relation between load level and efficiency. The efficiency of gas turbines is assumed to decrease more rapidly as the load level decreases[21]. The efficiency factor is thus set to:

$$N_{75steam\_turbines} = 1 - 0.04/\eta_{opt} \tag{3}$$

$$N_{75gas\_turbines} = 0.5 \tag{4}$$

where η_{opt} is the optimal efficiency (i.e. normally the efficiency at rated power). Assuming a linear relationship between the part load cost and load level, each percentage the load level falls behind rated power is associated with a cost, $C_{part\_load}(i)$ in addition to the generation cost at rated power. This cost is calculated from the cost increase as the unit is run at 75% load level compared to running it at rated power, $P_{rated}(i)$, divided by the 25% deviation from this load level. The cost increase due to a 1% load decrease (at any power level) is thus:

$$C_{part\_load}(i) = P_{rated}(i)\cdot\frac{0.75}{0.25}\cdot\left(\frac{C_{fuel}}{\eta_{opt}(i)\cdot N_{75}(i)} + \frac{C_{emissions}}{(\eta_{opt}(i)\cdot N_{75}(i))} - \frac{C_{fuel}}{(\eta_{opt}(i))} - \frac{C_{emissions}}{(\eta_{opt}(i))}\right) \tag{5}$$

where C_{fuel} is the fuel cost per unit of electricity generated and $C_{emissions}$ is the cost associated with the CO_2-emissions from generation of one unit of electricity (i.e. $\frac{C_{fuel}}{(\eta_{opt}(i)\cdot N_{75}(i))}-\frac{C_{fuel}}{(\eta_{opt}(i))}$ is the additional fuel cost due to part load per MWh at 75% load level). In the simulations, each percentage step away from rated power will thus be accompanied with the cost according to Equation (5). The cost and the power level are linked by the equation:

$$c_{part\_load}(i,t)=\left(spin(i,t)-\frac{g(i,t)}{P_{up}(i,t)}\right)\cdot C_{part\_load}(i) \tag{6}$$

where $c_{part\_load}(i,t)$ is the part load cost of unit i at time t and $P_{up}(i,t)$ is the rated power level.

Since the purpose of BALWIND is to identify ways to achieve emission reductions to the lowest cost by adding wind power, wind power generation in BALWIND can be dispatched. The power system is thus allowed to cut off wind power production in order to limit start-up and part load costs. Wind power variations obviously occur continuously. In order to capture the frequency of these variations, the time resolution of the model has to be sufficiently high. However, a too high time resolution will drastically limit the scope of the simulation (i.e. the number of individual power plants which can be taken into consideration or the number of time periods which can be evaluated). There is thus a trade-off between scope and exactness. Due to local differences in environment around each wind turbine, the production variations with the highest frequency will be smoothened out over large wind farms. Taking the aggregated wind power production of an entire region, the smoothening effect will be even more pronounced. This effect, referred to as power smoothing[22], can be observed from statistics in wind data and is explained in detail by Manwell *et al.*[22]. Based on these observations, a time resolution of 1 h has been used in BALWIND. It is assumed that this resolution will capture the most important features of the interaction between power producing units (i.e. the unit commitment decision) in a power system as long as there is a reasonable amount of wind power capacity installed within each region in the simulation. However, with a 1 h time resolution the model cannot be used to estimate the need of reserves to balance generation within the hour. Reserve requirements are instead taken as fixed requirements on available capacity based on previous studies[18]. In order to limit the computational time and allow for a wider geographical scope (i.e. all power plants in the western Denmark region with rated power of at least 80 MW simulated individually), results of simulations of one representative week (i.e. based on weekly wind power production) per season (summer, autumn, winter, spring) were weighted together to represent a full year. Thus, 1 year is here represented by a total of 4 'seasonal' weeks.

2.2. Simulated cases

The study comprises two parts. First, the ability of a variation moderator to increase the CO_2-reduction efficiency of wind power is investigated. Two wind-thermal power systems have been taken into consideration; one with 20% wind power grid penetration and one with 40% wind power grid penetration (i.e. 20% and 40% share of the electric energy demand is supplied by wind power if no wind power is curtailed). The relation between the reduction in CO_2-emissions and the power rating of the moderator has been investigated, as well as the benefit of a moderator which handles weekly variations compared to a moderator which has to be balanced daily (i.e. the impact of storage capacity). Second, characteristics of five available moderators have been compared with the benefit of introducing such a moderator to a wind-thermal system (i.e. characteristics compared with the results from the simulations).

For the first part, the western Denmark system is used as a starting point. The wind power generation in the system with 20% wind power grid penetration corresponds to the year 2005 wind power generation in the western Denmark system (2374 MW supplying 20% of the demand if no wind power is curtailed). In the 40% wind system the wind power generation data from 2005 is simply taken times two. This approach to wind power scaling is reasonable due to the quantity and geographical dispersion of wind power in western Denmark (i.e. any smoothening effects are included). The electricity demand of the system equals that of the western Denmark region in 2005. The CO_2-emissions and total production costs of the power systems in the different cases have been simulated and compared. An aggregate of 500 MW oil-fired units (referred to as additional units) has been added to the system in all cases to assure that demand can be met at all times.

In the simulations, transmission is not associated with any losses and the cost to import power is equal to the cost of exporting power and is constant over time. Thus, power exchange over the transmission line provides storage without losses and represents a general moderator. The reduction in total system costs and emissions realized by adding transmission capacity is thus a measure of how much the variation moderator can be allowed to cost and emit in order to be profitable and environmentally beneficial for the system.

In the second part, LCA literature data is used to assess the following moderators; transmission capacity, pumped hydro power, compressed air energy storage, flow batteries and sodium sulphur batteries.

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3. POWER SYSTEM CONFIGURATION

As indicated above, the configuration of the system modelled (i.e. the combination of power generation units) is based on the power system of western Denmark. Units with rated power above 80 MW are described separately, while units with lower capacity are aggregated based on fuel (i.e. small gas-fired units, small coal-fired units, small biomass-fired units and wind power). The power system of western Denmark has the highest share of power supplied by wind in the world today[23] and is thus a good example of a system with large scale wind power grid penetration. At present, transmission capacity is used as moderator in the western Denmark system and wind power variations are thereby managed through trade with Sweden and Norway which have substantial amounts of hydro power with large reservoir capacity.

Table I lists the properties of the units in the power system which are individually simulated, i.e. the 12 largest power generating units (power rating >80 MW). All of these units produce both electricity and heat and each of them is associated with one area within which the heat demand should be satisfied. Table I also includes the units smaller than 80 MW which are aggregated to three types; small gas CHP, small bio CHP and small oil CHP. These aggregated units, together with the wind power, have been assigned to a fictional area, representing western Denmark rural heat and power generation (note that the 'rural' area here includes smaller towns with district heating systems). Within this area the heat production should satisfy the rural demand. Each area also has a number of heat only boilers. The fuel composition and capacity of these boilers have been estimated from data from the Danish District Heating Association[24]. The heat only boilers define the alternative cost to satisfy the heat demand if this is not met by the units which generate both heat and power.

At the same time as the heat demand should be satisfied in each area, the electricity demand should equal the sum of the power production of the region and import/export over the transmission line (i.e. the general storage).

The capacity of the units are taken from the Chalmers power plant database[25]. Based on information from Elsam[26] each of the units were approximated to equal one of the generation technologies in BALMOREL with respect to fuel and combustion technology (see Table I where ST = Steam Turbine, B = Backpressure, E Extraction, NG = Natural Gas, CO = Coal, FO = Fuel Oil, WW = Wood Waste WI = Wind Power). In the BALWIND add-on, properties regarding the flexibility of the units are added to the original description. The BALWIND description includes start-up time, minimum load level and flags indicating whether the unit can be used as first, second or third reserve. Information with respect to start-up time and minimum load level has been collected from requirements on start-up times and load levels for thermal power plants established by Energinet[27]. The start-up time depends on the time the unit has been idle. However, this relationship cannot be included while keeping the model linear. A start-up time of 5 h (i.e. for large steam power plants) is used in the model. This start-up time corresponds to the time it takes to reach full production capacity (i.e. rated power) after a stop of up to 8 h or to reach synchronization after a stop ranging between 8 and 36 h. If the unit is started immediately after a stop, the start-up time is overestimated with 1.5 hours. If the stop is more than 36 h, it is underestimated with up to 5 h. Analysing the results of the simulations it was found that 62% of the stops were less than 8 h, 29% of the

Table I. Properties of the power generating units in the simulated system.

Unit	Area	Type	Power rating [MW]	Start-up time [hours]	Min Load [%[a]]	1st res	2nd res	3rd res
Silkeborg_CHP	Silkeborg	ST-B8-NG	98.5	5	20	Yes[b]	Yes[b]	Yes[b]
Skaerbaekvaerket_B3	Frederica	ST-E8-NG	392	5	20	Yes[b]	Yes[b]	Yes[b]
Fynsvaerket_B3	Odense	ST-E7-CO	285	5	35	Yes[b]	Yes[b]	Yes[b]
Nordjyllandsvaerket_B2	Aalborg	ST-E7-CO	285	5	35	Yes[b]	Yes[b]	Yes[b]
Enstedvaerket	Abenraa	ST-E9-COsn	633	5	35	Yes[b]	Yes[b]	Yes[b]
Studstrupvaerket_B3	Aarhus	ST-E8-COs	350	5	35	Yes[b]	Yes[b]	Yes[b]
Studstrupvaerket_B4	Aarhus	ST-E8-COs	350	5	35	Yes[b]	Yes[b]	Yes[b]
Fynsvaerket_B7	Odense	ST-E8-COs	401	5	35	Yes[b]	Yes[b]	Yes[b]
Esbjergvaerket	Esbjerg	ST-E8-COs	378	5	35	Yes[b]	Yes[b]	Yes[b]
Nordjyllandsvaerket_B3	Aalborg	ST-E9-COsn	380	5	35	Yes[b]	Yes[b]	Yes[b]
Skaerbaekvaerket_B1	Frederica	ST-C7-FO	93	5	35	Yes[b]	Yes[b]	Yes[b]
Herningvaerket	Herning	ST-B9-WW	95	5	35	Yes[b]	Yes[b]	Yes[b]
small gas CHP	Rural	ST-B8-NG	1 018.5	0	0	No	Yes	Yes
small coal CHP	Rural	ST-B8-CO	210.2	0	0	No	No	No
small bio CHP	Rural	ST-B9-WW	80.4	0	0	No	No	No
additional units	Rural	ST-C7-FOs	500	0	0	No	No	No
wind	Rural	WI-L9	2 374	0	0	No	No	No

[a] Percent of full load.
[b] If the unit is running.

stops were between 8 and 36 h and 9% of the stops were more than 36 h when a 5 h start-up time is assumed. If stops of long duration (i.e. > 36 h) would be associated with longer start-up times, and thus higher costs, it is probable that the amount of stops shorter than 36 h would be even more accentuated. The assumption of a start-up time of 5 h thus seems reasonable.

Since the units referred to as small gas, small bio and small coal are made up by several units, additional available capacity of these units cannot be used to compensate for immediate imbalances on the grid. The small gas unit is, however, assumed to be able to increase its power production level within 15 min, since many gas turbines can be started within this time span.

For simplicity, the emission of one tonne carbon dioxide has been associated with a cost of 20 EUR in the simulations.

4. RESULTS

4.1. Impact of a moderator on the wind-thermal system

Figure 1 illustrates the impact on CO_2-emissions from adding moderator capacity to the wind-thermal power system with 2374 MW and 4748 MW wind power capacity, corresponding to 20 and 40% wind power grid penetration if no wind is curtailed. As shown in Figure 1, a weekly balanced moderator is better qualified at reducing emissions from the wind-thermal power system than a daily balanced moderator. The advantage of a weekly balanced moderator, compared with a daily balanced moderator, is more significant in the power system with 4748 MW wind than in the power system with 2374 MW wind. With a weekly balanced moderator emissions are reduced as the power rating of the moderator increases, whereas the emission reduction from applying 500 MW moderator capacity is just as great as the emission reduction from applying 2000 MW moderator capacity if it is daily balanced. The greatest emission reduction is attained in the wind-thermal power system with 4748 MW wind power, in which a 2000 MW moderator which is balanced on a weekly basis can reduce emissions with 11% or 1.38 M tonnes. Applying the same moderator to the wind-thermal system with 2374 MW wind power, emissions are reduced with 5% or 0.76 M tonnes. The daily balanced moderator decreases emissions in the wind-thermal system with 2374 MW wind power with 2% or 0.30 M tonnes. The reduction is 4% or 0.42 M tonnes in the system with 4748 MW wind power when applying the same moderator.

As moderator capacity is introduced to the power system the system emissions are affected in three different ways: start-up and part load emissions decrease, wind power curtailment decreases and the capacity factors of typical base load units increase. Figure 2 shows the start-up and part load emissions of the power systems. The start-up and part load emissions are higher in the system with 4748 MW wind than in the system with 2374 MW wind due to the greater variations in the 4748 MW wind system compared with the 2374 MW wind system. The reduction in start-up and part load emissions is up to 0.48 M tonnes in the system with 2374 MW wind and 0.32 M tonnes in the system with 4748 MW wind. The vast majority of the reduction is realized by the first 500 MW of moderating capacity and is mainly due to load variation management. Since variations in load occur with a daily frequency, the storage capacity of a daily balanced

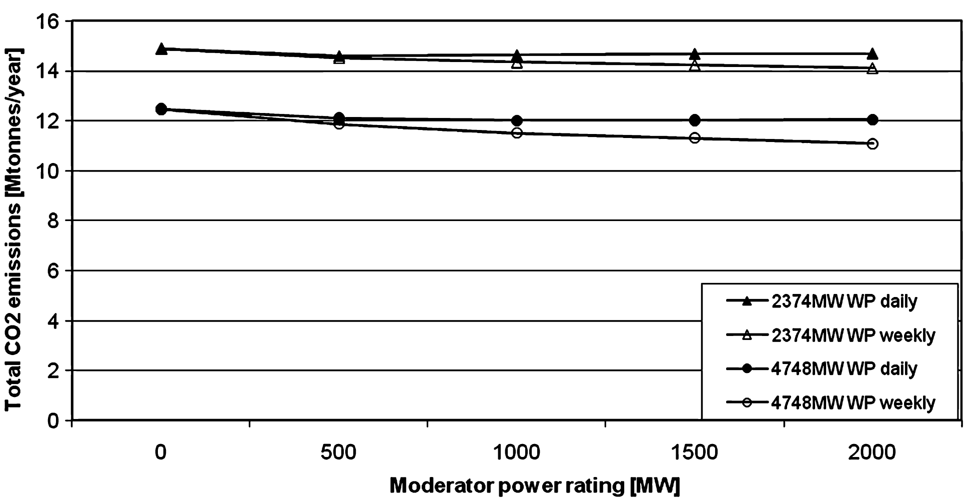

Figure 1. Impact of moderator power rating (MW) and capacity (daily/weekly) on total CO2-emissions from the wind-thermal power system.

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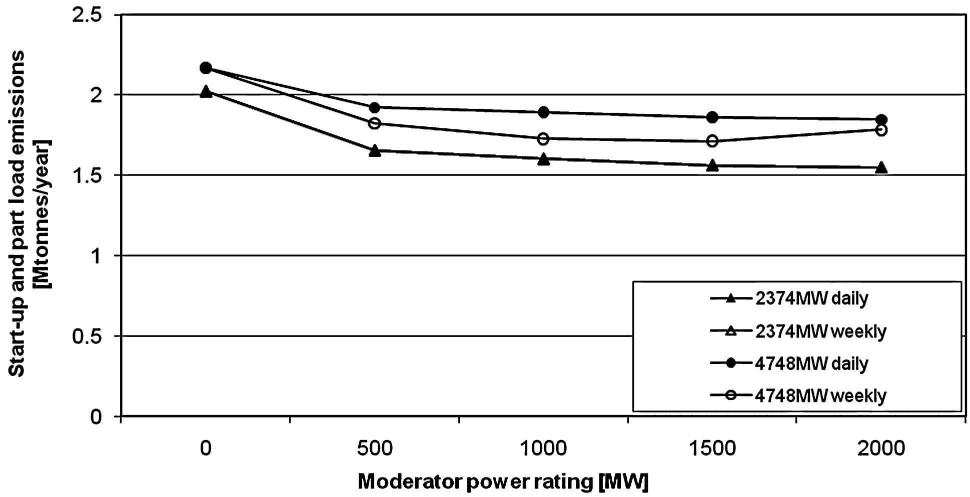

Figure 2. Impact of moderator power rating (MW) and capacity (daily/weekly) on start-up and part load emissions of the wind-thermal power system.

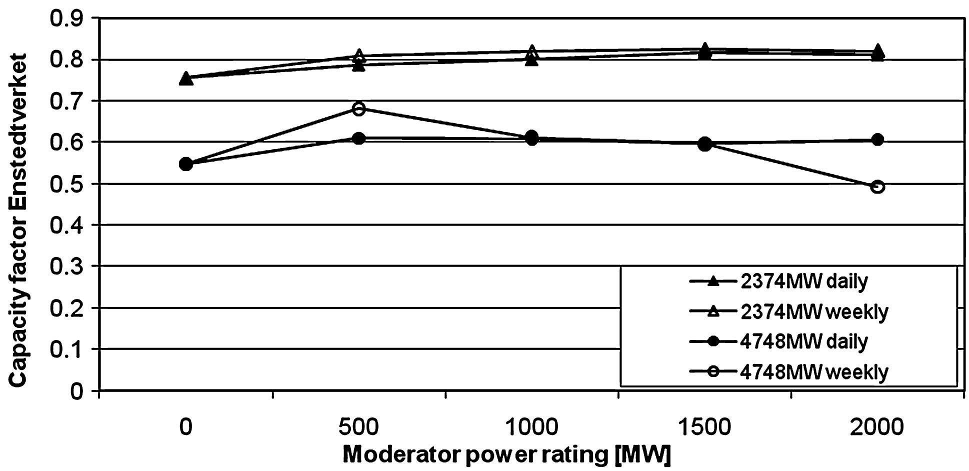

Figure 3. Impact of moderator power rating (MW) and capacity (daily/weekly) on the capacity factor of a typical base load unit.

moderator is sufficient to manage the variations. Thus, for the start-up and part load emissions of the system it is of little or no importance whether the moderating capacity is daily or weekly balanced.

Figure 3 shows the capacity factor of Enstedtvaerket in the two systems. Enstedtvaerket is a coal-fired unit with rated capacity of 633 MW. It is the single largest unit in the power system simulated (the second largest unit has a capacity of 378 MW see Table I). The capacity factor of Enstedtvaerket increases with the moderator power rating except in the case of the weekly balanced moderator in the system with 4748 MW wind power, where it competes with the option to reduce wind power curtailment as illustrated in Figure 4. With larger moderator capacities, an increase in capacity factor of Enstedtsvaerket is expected also in this case. The first 500 MW have the greatest impact on the capacity factor of the base load unit. This since the majority of the stops (and subsequent start-ups) can be avoided already at a 500 MW moderator power rating as mentioned above, and a decrease in stops allows for more base-load generation. The impact of an increase in base load generation on the power system emissions naturally depends on what unit the base load unit substitutes.

Figure 4 gives the relation between wind power curtailment and moderator power rating. By shifting the load so that the correlation between load and wind power generation is improved, the moderator enables a shift from thermal power to wind power. Avoiding 1000 GWh of wind curtailment per year (9% of the total wind power generated) corresponds to a decrease in system emissions with 0.60 M tonnes/year* for the system studied. A decrease of this magnitude is

*The average emissions of the thermal units are approximately 600 kg CO2/MWh.

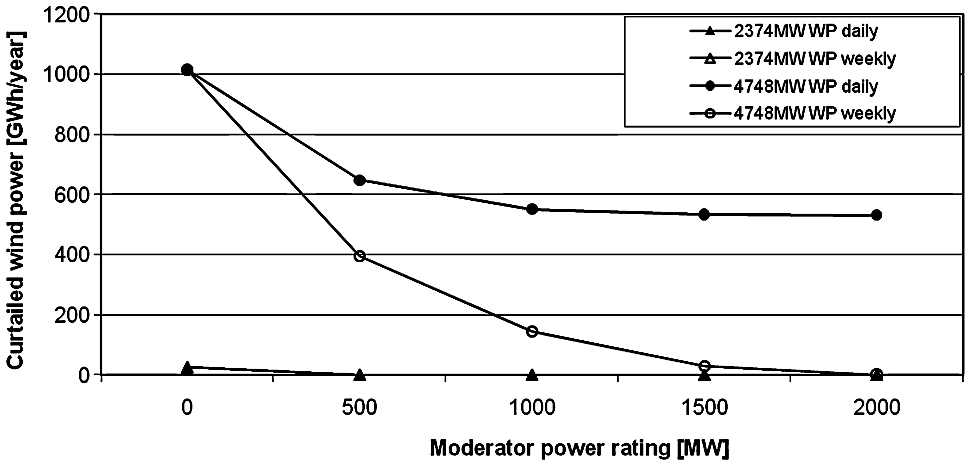

Figure 4. Impact of moderator power rating (MW) and capacity (daily/weekly) on wind power curtailment.

realized in the 4748 MW wind system by a 2000 MW weekly balanced moderator. In this case, the avoidance of wind power curtailment is the most important factor to reduce emissions. The daily balanced moderator does not provide the same possibilities to avoid wind power curtailment as a weekly balanced moderator.

4.2. Moderator technologies

The results of the simulations suggest two sensible choices of moderation which would promote wind power integration in the system in question (i.e. an isolated thermal system); a daily balanced moderator of 500 MW and 3 GWh storage for wind power capacities of around 2374 MW (about 20% wind power grid penetration if no wind power is curtailed) and a weekly balanced moderator with 2000 MW and 33 GWh storage for wind power capacities of around 4748 MW (about 40% grid penetration if no wind power is curtailed).

Daily moderation could be supplied by a pumped hydro station, a Compressed Air Energy Storage (CAES) unit, flow batteries or sodium sulphur (NaS) batteries. Whereas there are pumped hydro stations fulfilling the requirements stated (the Dinorwig pumped hydro power station in Wales has, e.g., a power rating of 1700 MW and is able to store 8 GWh of energy) and CAES units of this magnitude are under consideration (e.g., the project concerning a 2700 MW CAES in Norton, Ohio), flow batteries and sodium sulphur batteries have only been evaluated on smaller scale. Pumped hydro is the only technology which has been applied to storage schemes anywhere near the range required for the weekly balanced moderation of this work (the Guangzhou pumped hydro station, China, has a capacity of 2400 MW and can store 14.4 GWh energy). Reaching a power rating of 2000 MW with CAES or battery solutions should not pose a problem since it is merely a matter of adding a sufficient number of identical units. The problem lies in the ability to store the volumes required when reallocating power from 1 week to another. When it comes to the CAES technology, storage capacities are restricted by the volume of the cavern and the maximum pressure that can be applied to the air without loosing too much energy as heat.

Another option would be to supply daily or weekly moderation by importing and exporting power to neighbouring regions. Naturally, this option is only available if the neighbouring systems have different demand and/or wind power production patterns or excess moderating capacity. Large differences in demand and wind power production patterns generally require some geographical distance implying varying time zones and climate for differences in demand and variations in weather patterns for differences in wind power generation. Relaying on differences in demand and wind power generation, moderation by the closest neighbouring region is thus not an option, and transmission cables covering some distance are necessary. Excess moderating capacity (i.e. beyond what is needed to manage variations within the region) is mainly available in regions with large scale hydro power generation. Due to the reservoir capacity of the hydro power stations, such a region might offer its neighbours moderating capacity through import and export. Indeed, as mentioned above this is the main way Denmark presently handles the variations (together with variations in thermal plant generation). However, excess flexible capacity is rare and most countries do not have the option to balance variation in wind power production with power systems of neighbouring countries.

Tables II and III summarize costs and emissions associated with the 500 MW and 2000 MW moderators investigated in this work: transmission capacity, pumped hydro power, compressed air energy storage (CAES), flow batteries and

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Table II. Overview of costs related to the moderating process. In case of a cost difference between the 500 MW unit and the 2000 MW unit, the former is given first.

Variation moderator	Capital costs[a] [EUR/kW]	Capital costs[b] discounted [EUR/MWh]	Process costs[c] [EUR/MWh]	O&M costs [EUR/MWh]	Total costs [EUR/MWh]
Transmission	293–450	9.6–14.7 / 14.9–22.9	1.3	0.03–0.3 / 0.01–0.1[d]	10.9–16.3 / 16.2–24.3
Pumped hydro	514–1000	11.1–21.5 / 17.2–33.5	5.5	8[e]	24.6–35.0 / 30.7–47.0
CAES	367–730	8.7–17.3 / 13.6–27.0	7.3	21[f]	37.0–45.6 / 41.9–55.3
Flow battery	500–2000	16.4–65.4 / 25.4–101.8	7.5	5.5[g]	29.4–78.4 / 38.4–114.8
Sodium sulphur battery	700–1800	22.9–58.9 / 35.6–91.6	5.3	5.5[h]	33.7–69.7 / 46.4–102.4

[a] Transmission Source: EC 2003,[29] Others Source: Nourai 2002.[30]

[b] (Capital costs*r/(1-(1+r)^-lifetime)) / (number of produced hours per year). Life time assumed to be: Transmission and Batteries: 20 years, Pumped hydro: 60 years, CAES 40 years. 28%/18% utilization r = 0.05 as in one of the IEA cases.[31]

[c] Losses times an average electricity cost of 25EUR/MWh.

[d] Cost per km and year * number of km / yearly production Assumption: 1000 km, 500 MW/2000 MW, 28%/18% utilization Source O&M costs: EC 2003.[29]

[e] Source: IEA 2005.[31]

[f] (4649+518)*3,6 = 18601 EUR/GWh fuel costs + 3EUR/MWh O&M. Sources: Heat rate and gas delivery losses.[32] Gas prices and O&M costs.[31]

[g] Source: Kuntz 2005.[33]

[h] Assumed to be the same as for the flow battery.

Table III. Overview of emissions related to the moderating process based on LCA studies from literature (respective sources indicated in the footnotes). In case of a difference in emissions between the 500 MW unit and the 2 000 MW unit, the former is given first.

Variation moderator	Losses [%]	Process emissions [$kgCO_2$/MWh]	Variable emissions [$kgCO_2$/MWh]	Construction emissions [$kgCO_2$/MWh]	Total emissions [$kgCO_2$/MWh]
Transmission	5	30.5 / 22.0	2.3–33.8 / 1.2–16.8[a]	2.6–14.9 / 1.3–7.5[b]	35.4–79.2 / 26.9–46.3
Pumped hydro	22	134.2 / 96.8	1.8	35.5	171.5 / 134.1
CAES	29	(−183.0) / (−132.0)[c]	294[d]	19	130 / 181
Flow battery	30[e]	183.0 / 132.0	—	13.4[f]	196.4 / 145.4
Sodium sulphur battery	21[g]	128.1 / 92.4	—	5.3[h]	133.4 / 97.7

[a] Assuming a 1000 km line with a capacity of 500/2000 MW and utilization of 28/14%. High for overhead lines, low for underground lines. Source: Ravenmark and Normark 2006.[34]

[b] 1000 km transmission line of 500/2000 MW capacity and 28/14% utilization in 20 years. High for overhead lines, low for underground lines. Source: Ravenmark and Normark 2006.[34]

[c] As natural gas is added to the system more energy is produced than initially stored. 0.7 MWh compressed air and 4649 +518 MJ natural gas gives 1 MWh electricity. Source: Denholm and Holloway 2005.[32]

[d] Including the combustion of natural gas.

[e] Source: Rydh and Sandén 2005.[35]

[f] Electricity demand in production*OECD average emissions/total production hours, Source: Rydh 1999.[36]

[g] Source: Rydh 2005.[35]

[h] Relationship between flow battery and sodium sulphur from Rydh 1999.[36]

sodium sulphur batteries. They are expressed as costs and emissions per unit of reallocated power and below, these will be compared with the potential savings in costs and emissions due to moderation seen in the simulations. Thus, and as indicated above, the moderator in the simulations is not associated with any emissions or costs.

The load factor of the 500 MW moderator is 28% in the simulations and the load factor of the 2000 MW moderator is 18%, resulting in a differentiation of the average costs and emissions expressed per MWh. The capital costs of the different moderators vary widely, both within and between studies. Reasons for this span in costs are given by Nourai.[30] For transmission lines, the span in investment costs is due to the difference in costs of overhead lines and underground lines. In the CAES and pumped hydro cases, the lower costs apply to situations where suitable natural formations, such as dams and caverns, are in place, whereas the high costs apply if these formations have to be constructed. In the case of batteries, technology is still under development and the wide span in costs reflects the uncertainty in future prices. Process costs represent the costs that would be added to the system because of the additional generation to compensate for the losses in producing and operating the moderator. Emissions associated with the moderators are based on LCA studies from literature and are divided into three parts: process emissions representing the losses in the storage systems, variable emissions (i.e. emissions related to operation of the moderator, excluding losses) including combustion of fuel if applicable (natural gas in the CAES case) and emissions related to operation and maintenance, and construction emissions (mainly due to energy use in the construction process). The process-related emissions depend strongly on the composition of the power system and the total emissions related to the moderator have, therefore, been evaluated separately for the two wind power penetration levels. Average emissions are 610 kg CO_2/MWh in the system with 2374 MW wind power and a 500 MW daily balanced moderator and 440 kg CO_2/MWh in the system with 4748 MW wind power and a 2000 MW weekly balanced moderator.

Figures 5 to 8 summarize the cost savings and net emission savings for the different moderator data applied to the simulation results for the system with 20% wind power and a 500 MW moderator (Figures 5 and 6) and for the system with 40% wind power and a 2000 MW moderator (Figures 7 and 8). For the cost savings compared in Figures 5 and 7, the lowest costs of the moderator technologies have been used, i.e. the cost in the lower end of the span given in Table II. The net system emission savings given in Figures 6 and 8 correspond to the emission savings due to moderation as

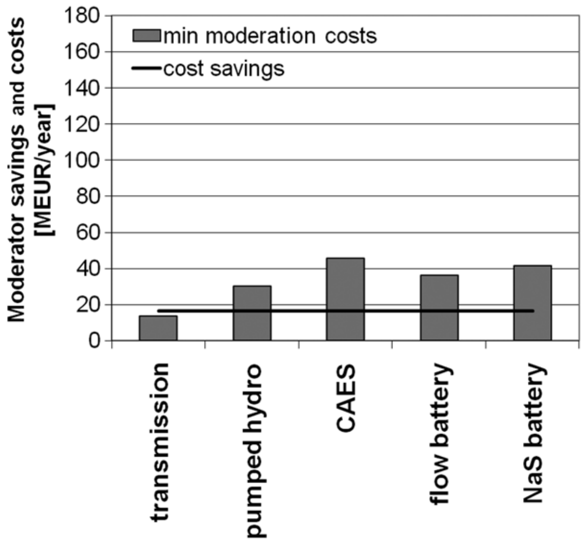

Figure 5. Cost savings by daily balanced 500 MW moderators in a system with 20% wind power from simulations (solid line) compared with costs for moderation (bars) as obtained from literature (see Table 2).

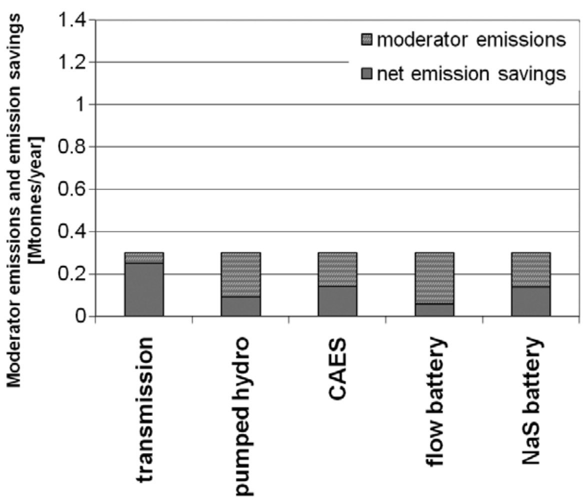

Figure 6. Emission savings by daily balanced 500 MW moderators in a system with 20% wind power from simulations reduced by emissions associated with moderation as obtained from literature (see Table 3).

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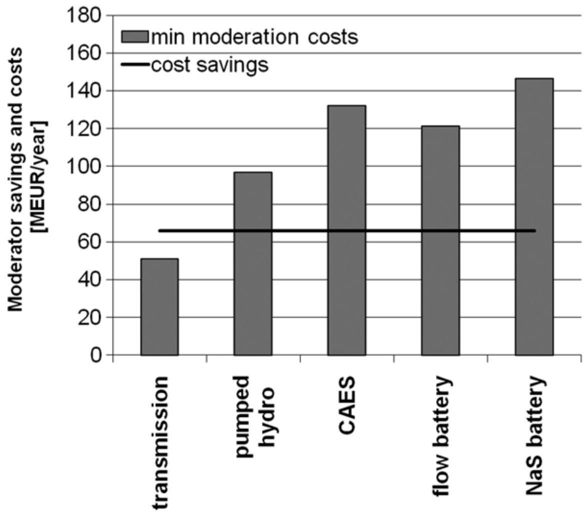

Figure 7. Cost savings by weekly balanced 2000 MW moderators in a system with 40% wind power from simulations (solid line) compared with costs for moderation (bars) as obtained from literature (see Table 2).

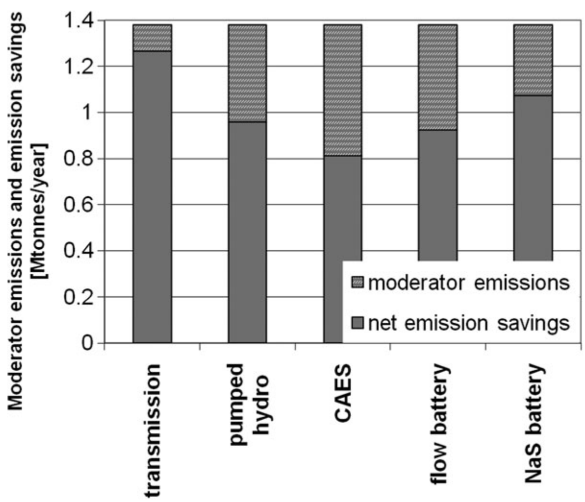

Figure 8. Emission savings by weekly balanced 2000 MW moderators in a system with 40% wind power from simulations reduced by emissions associated with moderation as obtained from literature (see Table 3).

obtained from the simulations, reduced by the emissions associated with the five different moderator technologies given in Table III.

For the system with 2374 MW wind power and a 500 MW daily balanced moderator, simulations indicate that a general moderator (i.e. without losses) would save the system 16 MEUR/year by reducing variations in wind power generation and load, as shown in Figure 5 (solid line). With a load factor of 28% (according to simulations), the cost of the moderator would, therefore, have to be less than 13 EUR/MWh (yearly savings divided by the product of the load factor, the capacity and the number of hours in a year) to be profitable to the system. As indicated in Table II, only transmission lines can fulfil this requirement. Figure 5 compares the cost savings due to moderation to the minimum costs of the five moderator technologies. Figure 6 compares the corresponding emission savings with the emissions associated with the moderator technologies. The emission savings of the simulated system are 0.30 M tonnes CO_2/year (top of bars in Figure 6). The operation of the moderator is associated with up to 197 kgCO_2/MWh (flow battery) but can be kept as low as 35 kgCO_2/MWh (transmission lines), corresponding to 0.24 and 0.05 M tonnes CO_2/year, respectively (dashed areas in Figure 6). The net emission savings achieved by the moderator therefore range from 0.06 to 0.25 M tonnes CO_2/year (filled part of bars in Figure 6). Due to the high average emissions of the system (610 kgCO_2/MWh), the most important property of the moderator in order to achieve high net emission savings is low losses associated with the moderation process. This gives an advantage to the transmission and sodium sulphur battery solutions. For the system investigated (i.e. 2374 MW wind power), the compressed air energy storage is also a good alternative since the emissions from the combustion of natural gas are low compared to the average system emissions.

From Figure 7 it can be seen that the simulations indicate that a weekly balanced 2000 MW moderator would save the system 66 MEUR/year (solid line in Figure 7), allowing a moderation cost of 21 EUR/MWh. As in the 500 MW case, only transmission lines are favourable to invest in under these conditions (Figure 7). From the simulations, it is also found that a 2000 MW moderator decreases system emissions with 1.38 M tonnes CO_2/year corresponding to 438 kg CO_2/MWh displaced by the moderator. The inclusion of available moderator technologies in this system is associated with emissions from 37 kg CO_2/MWh (transmission lines) to 181 kg CO_2/MWh (CAES), corresponding to 0.12 and 0.57 M tonnes CO_2/year as indicated by dashed areas in Figure 8. Since average emissions per unit of power are lower for the system with the larger share of wind power (in average 440 kgCO_2/MWh in the system with up to 40% wind power), the combustion of natural gas associated with the CAES storage becomes a drawback for this technology. The emissions due to losses are, on the other hand, lower than in the more coal dominated 20% (i.e. 2,374 MW) wind system. The net emission savings in Figure 8 (filled part of bars) range from 0.81 M tonnes CO_2/year (CAES) to 1.26 M tonnes CO_2/year (transmission lines).

5. DISCUSSION

In the model developed in this work, the way in which variations are managed is part of the optimization. Thus, the magnitude, duration and context (the model has perfect foresight) of the variation and the cost of the variation management strategies influence the dispatch of the units in the system. Part load costs and start-up costs have been assessed to reflect the physical limitations of the thermal units. The cost to run at part load is, therefore, determined by the decrease in efficiency of the unit associated with such operation and start-up costs are assessed based on the time it takes for the unit to reach synchronization and full production. For further details, see Göransson and Johnsson[18]. In the future, new operational requirements and incentives for flexibility may arise, stimulating thermal plant operators to decrease part load and start-up costs. Such a change would decrease the benefit of the moderator both with regards to system costs and emissions. On the other hand, a future power system may combine large amounts of wind power with less flexible capacity, such as nuclear power and power plants with carbon capture (which need to be operated in base load) and in such a system the benefit of moderation would be large.

The simulations show that if assuming a cost of 20 EUR for emitting 1 tonne of carbon dioxide, transmission lines is the only moderator which can decrease the system costs. The findings of Lund and Salgi[10] support these results as far as CAES is concerned, while these authors also note that CAES can be economically feasible on the regulation power market. With transmission lines, system costs could decrease if using overhead lines and if the imported power can be bought at prices which do not exceed the yield from exported power with more than about 2 EUR/MWh. However, as noted earlier, using transmission as moderator requires either transmission lines to a region with excess flexible capacity or to a region sufficiently far away to make wind speeds and/or demand uncorrelated. Transmission lines to such a region would in many cases have to cover some distance and pass several other regions. The profitability and acceptance of building such transmission lines would improve if all regions within some large geographical scope share a system of lines for cooperative variation management. Also, the risk of correlated variations is generally lower (i.e. the moderation of variations is more efficient) over a wider geographical scope. A system of transmission lines of such a kind, often referred to as a 'supergrid', has been proposed to handle wind power variations in Europe. The results from this work point to that investments in transmission lines is generally attractive since costs and emissions associated with transmission lines are lower than those of other moderator options (see Tables II and III). This, provided that it is sufficient for each country to invest in 1000 km of line (i.e. the distance assumed necessary to provide moderation in the calculations presented here). However, since the reduction in system costs from moderation only just compensate for the cost to install overhead lines (Figures 5 and 7), the cost for underground lines and cables at sea (which are likely to make up a significant part of a 'supergrid') will probably not be compensated for at a cost of 20 EUR per tonne of carbon dioxide emitted.

Although more expensive than overhead lines, underground cables and transmission in general seem to be a good option with regard to both costs and emissions compared to the other moderation technologies investigated (Tables II and III). However, at the moment the construction of local storages seems to be closer to a stage of implementation than transmission lines for variation management. The reason for the preference of local storage solutions is beyond the scope of this paper and we will content ourselves with bringing attention to two factors which govern the development in this direction. To start with, the EU renewable energy targets are translated into national goals, stimulating national rather than international solutions. Using transmission as wind power moderator, part of the green electricity is exported and there may be uncertainties regarding how this should be accounted for until the system of guarantees of origin is properly in place. See the proposal from the European Commission[28] for details regarding such a system. Thus, even though the reduction in emissions would be maximized on an EU level with transmission as moderator, storage technologies might

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be favoured since they retain the green electricity within the national boundaries. Another factor counteracting the 'super-grid' is the desire to protect the local power market.

The moderators investigated would decrease system emissions with 0.5 to 1.7% in the 500 MW moderator/2374 MW wind case and 7.5 to 10.3% in the 2000 MW moderator/4748 MW wind case (see Figure 6 and Figure 8). In the system with 2374 MW wind power, corresponding to 20% wind power grid penetration, average emissions are still rather high (610 kgCO_2/MWh). In this situation the CAES technology is the storage solution which reduces emissions the most (see Figure 6). For the system with 4748 MW wind power (40% wind power grid penetration), and lower average emissions associated with the power generation, the CAES technology is less efficient at reducing emissions than the other alternatives (see Figure 8). Thus, the order of preference of moderator technologies depends on the average emissions of the power system in which the moderator will be integrated. Since major rearrangements of present power systems are under consideration, it is important to take future development of the system into account when choosing moderation technology. It should also be noted that since the option to use transmission lines as moderator is not available to all systems and the cost to invest in pumped hydro are high if the geographical conditions are not favourable, batteries could become an alternative worth consideration for moderation of variations in demand and wind power generation, if the costs end up in the lower end of the range (see Figures 5 and 7).

To realize the decrease in system emissions offered by the moderators the decrease in system costs due to moderation have to exceed the costs associated with the moderator and the net benefit has to be allocated to the investor of moderating capacity. Since the moderators reduce system CO_2-emissions, the cost of moderation could be compensated for if the cost of emitting CO_2 would equal the cost of abatement through moderation. From the simulations it was found that the cost of abatement through transmission in overhead lines is less than 20 EUR/tonne CO_2 for the system considered. Assuming the dispatch of the units remain unaffected by an increase in cost of CO_2, the abatement cost of pumped hydro can be estimated to 22 EUR/tonne[†] (under favourable conditions) and of flow batteries to 40 EUR/tonne (under favourable conditions) at 40% wind power grid penetration. In a system with 20% wind power, the abatement costs are higher (since the reduction in emissions is lower); about 50 EUR/tonne and 80 EUR/tonne under favourable conditions, respectively.

6. CONCLUSIONS

A unit commitment model to investigate the benefits of introducing a moderator in a regional power system with large scale wind power has been developed and applied to an isolated 5550 MW thermal power system with 20 and 40% wind power grid penetration. Simulations indicate that a daily balanced moderator with modest power rating (i.e. 500 MW) is sufficient to reduce the majority of the emissions due to start-ups and part load operation, whereas higher moderator power ratings and storage capacities are necessary to avoid wind power curtailment. In the wind-thermal system with up to 20% wind power (i.e. 2374 MW), wind power curtailment is modest and the advantage of a weekly balanced moderator with high power rating (i.e. 2000 MW) compared to a daily balanced moderator with low power rating (i.e. 500 MW) is small. In the system with up to 40% wind power (i.e. 4748 MW), however, wind power curtailment is substantial and the avoidance of curtailment is the most important factor in the reduction of emissions through moderation. Based on these findings, a daily balanced moderator of 500 MW (requiring 3 GWh storage capacity) for wind power capacities of around 2374 MW (about 20% wind power grid penetration if no wind power is curtailed) and a weekly balanced moderator with 2000 MW capacity (requiring 33 GWh storage capacity) for wind power capacities of around 4748 MW (about 40% grid penetration if no wind power is curtailed) were selected for further analyses. It was found that the 500 MW daily based general moderator (without losses) saves the system 16 MEUR/year (1.4% of the total costs) and reduces emissions with 0.3 M tonnes CO_2/year (2.0% of the total CO_2-emissions). The 2000 MW weekly balanced general moderator saves the system 66 MEUR/year (6.0% of the total costs) and reduces the emissions with 1.38 M tonnes CO_2/year (11.1% of the total emissions). Comparing these costs and emission savings to the costs and emissions associated with five available moderation technologies (transmission, pumped hydro, compressed air energy storage, sodium sulphur batteries and flow batteries), it is found that all moderators investigated are able to decrease system emissions (between 0.5 and 1.7% in the 500 MW moderator/2374 MW wind case and 7.5 to 10.3% in the 2000 MW moderator/4748 MW wind case) but only transmission lines can decrease the total system costs at the cost assumed for emitting CO_2 (20 EUR/ton of CO_2).

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[†]Where the abatement cost (x) is calculated by : (Yearly emission savings* x + Yearly cost savings)/(electricity generated in the storage per year) = Moderation cost per unit of electricity produced.

REFERENCES

1. Castronuovo E, Lopes JP. Optimal operation and hydro storage sizing of a wind–hydro power plant. *Electrical Power and Energy Systems* 2004; **26**: 771–778.
2. Jaramillo OA, Borja MA, Huacuz JM. Using hydropower to complement wind energy: A hybrid system to provide firm power. *Renewable Energy* 2004; **29**: 1887–1909.
3. Greenblat J, Succar S, Denkenberger D, Williams R, Socolow R. Base load wind energy: modeling the competition between gas turbines and compressed air energy storage for supplemental generation. *Energy Policy* 2007; **35**: 1474–1492.
4. Cavallo A. Controllable and affordable utility-scale electricity from intermittent wind resources and compressed air energy storage (CAES). *Energy* 2007; **32**: 120–127.
5. Korpaas M, Holen AT, Hildrum R. Operation and sizing of energy storage for wind power plants in a market system. *International Journal of Electrical Power and Energy System* 2003; **25**: 599–606.
6. Paatero VJ, Lund PD. Effect of energy storage on variations in wind power. *Wind Energy* 2005; **8**: 421–441.
7. Bathurst GN, Strbac G. Value of combining energy storage and wind in short-term energy and balancing markets. *Electric Power Systems Research* 2003; **67**: 1–8.
8. Blarke MB, Lund H. The effectiveness of storage and relocation options in renewable energy systems. *Renewable Energy* 2008; **33**: 1499–1507.
9. Salgi G, Lund H. System behaviour of compressed-air energy-storage in Denmark with a high penetration of renewable energy sources. *Applied Energy* 2008; **85**: 182–189.
10. Lund H, Salgi G. The role of compressed air energy storage (CAES) in future sustainable energy systems. *Energy Conversion and Management* 2009; **50**: 1172–1179.
11. Ummels BC, Pelgrum E, Gibescu M, Kling WL. Comparison of integration solutions for wind power in the Netherlands. *IET Renewable Power Generation* 2009; **3**: 279–292.
12. Ummels BC, Pelgrum E, Kling WL. Integration of large-scale wind power and the use of energy storage in the Netherlands. *IET Renewable Power Generation* 2008; **2**: 34–46.
13. Lund H, Mathiesen BV. Comparative analysis of seven technologies to facilitate the integration of fluctuationg renewable energy sources. *IET Renewable Power Generation* 2009; **3**: 288–293.
14. Göransson L, Johnsson F, Karlsson S. Integration of plug-in hybrid electric vehicles in a regional wind-thermal power system. *Energy Policy,* In Press, 2009.
15. Ravn H. *BALMOREL: A Model for Analyses of the Eletcricity and CHP Markets in the Baltic Sea Region*, ISBN 87-986969-3-9, Balmorel Project, Main report, March 2001.
16. Ravn, H. *BALMOREL*. [Online]. Available: www.balmorel.com. (Accessed 15 October 2007).
17. Connolly D, Lund H, Mathiesen BV, Leahy M. A review of computer tools for analyzing the integration of renewable energy into various energy systems. *Applied Energy* 2010; **87**: 1059–1082.
18. Göransson L, Johnsson F. Dispatch modeling of a regional power generation system—Integrating wind power. *Renewable Energy* 2009; **34**: 1040–1049.
19. Schaeffer P, Cherene L. The inclusion of 'spinning reserves' in investment and simulation models for electricity generation. *European Journal of Operational Research* 1989; **42**: 178–189.
20. Carraretto C. Power plant operation and management in a deregulated market. *Energy* 2006; **31**: 1000–1016.
21. Lazzaretto A, Carraretto C. Optimum production plans for thermal power plants in the deregulated electricity market. *Energy* 2006; **31**: 1567–1585.
22. Manwell JF, McGowan JG, Rogers AL. *Wind Energy Explained* Wiley: New York, 2005.
23. Eriksen PB, *et al*., System operation with high wind penetration. *IEEE Power and Energy Magazine* 2005; **3**: 65–74.
24. DanishDistrictHeatingAssociation, *StatistikogDriftsdata*, Statistik2005/2006.xls, Editor. [Online]. Available: www.dff.dk. Table (Accessed October 15, 2007).
25. Kjärstad J, Johnsson F. The European power plant infrastructure—Presentation of the Chalmers energy infrastructure database with applications. *Energy Policy* 2007; **35**: 3643–3664.
26. DongEnergy. [Online]. Available: www.dongenergy.com. (Accessed 15 October 2006).
27. Energinet. *Technical Regulations for Thermal Power Station Units of 1.5 MW and higher*. Energinet.dk: Fredericia, Denmark, 2007.
28. European Comission. *Proposal for a Directive of the European Parliament and of the Council on the Promotion of the use of Energy from Renewable Sources*. European Commission: Brussels, Belgium, 2008.

Wind Energ. 2011; **14**:91–105 © 2010 John Wiley & Sons, Ltd.
DOI: 10.1002/we

29. EC. *Undergrounding of Electricity Lines in Europe*., Commission of the European Communities: Brussels, Belgium, 2003.
30. Nourai A. Large-scale electricity storage technologies for energy management. in *Proceedings of the IEEE Power Engineering Society Transmission and Distribution Conference*. Chicago, IL, 2002.
31. IEA. *Projected Costs of Generating Electricity*. OECD/IEA: Paris, 2005.
32. Denholm, P. and T. Holloway, Improved accounting of emissions from utility energy storage system operation. *Environmental Science and Technology* 2005; **39**: 9016–9022.
33. Kuntz MT. 2-MWh Flow Battery Application by PacifiCorp in Utah, *Presentation given at California Energy Commission Staff Workshop: Meeting California's Electricity System Challenges through Electricity Energy Storage* VRB 24 February 2005.
34. Ravenmark D, Normark B. Light and invisible. *ABB Review* 2006; **4**: 25–29.
35. Rydh CJ, Sandén BA. Energy analysis of batteries in photovoltaic systems. Part I: Performance and energy requirements. *Energy Conversion and Management* 2005; **46**: 1957–1979.
36. Rydh CJ. Environmental assessment of vanadium redox and lead-acid batteries for stationary energy storage. *Journal of Power Sources* 1999; **80**: 21–29.