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# Large Scale Integration of Wind Power in Thermal Power Systems

Lisa Göransson and Filip Johnsson  
*Chalmers University of Technology  
Sweden*

## 1. Introduction

This chapter discusses and compares different modifications of wind-thermal electricity generation systems, which have been suggested for the purpose of handling variations in wind power generation. Wind power is integrated into our electricity generation systems to decrease the amount of carbon dioxide emissions associated with the generation of electricity as well as to enhance security of supply. However, the electricity generated by wind varies over time whereas thermal units are most efficient if run continuously at rated power. Thus, depending on the characteristics of the wind-thermal system, part of the decrease in emissions realized by wind power is offset by a reduced efficiency in operation of the thermal units as a result of the variations in generation from wind. This chapter discusses the extent to which it is possible to improve the ability of a wind-thermal system to manage such variations.

The first part of the chapter deals with the nature of the variations present in a wind-thermal power system, i.e. variations in load and wind power generation, and the impact of these variations on the thermal units in the system. The second part of the chapter investigates and evaluates options to moderate variations from wind power by integrating different types of storage such as pumped hydro power, compressed air energy storage, flow batteries and sodium sulphur batteries. In addition, the option of interconnecting power systems in a so called "supergrid" is discussed as well as to moderate wind power variations by managing the load on the thermal units through charging and discharging of plug-in hybrid electric vehicles.

Data from the power system of western Denmark is used to illustrate various aspects influencing the ability of a power system to accommodate wind power. Western Denmark was chosen primarily due to its current high wind power grid penetration level (24% in 2005 (Ravn 2001; Eltra 2005)) and that data from western Denmark is easily accessible through Energinet (2006).

## 2. Impact of wind power variations on thermal plants

The power output of a single wind turbine can vary rapidly between zero and full production. However, since the power generated by one turbine is small relative to the capacity of a thermal unit, such fluctuations have negligible impact on the generation pattern of the thermal units in the overall system. With several wind farms in a power

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system, the total possible variation in power output can add up to capacities corresponding to the thermal units and influence the overall generation pattern. At times of low wind speeds, some thermal unit might for example need to be started. The power output of the aggregated wind power is, however, quite different from the power output of a single turbine. Wind speeds depend on weather patterns as well as the landscape around the wind turbines (i.e. roughness of the ground, sea breeze etc.). Thus, the greater the difference in weather patterns and environmental conditions between the locations of the wind turbines, the lower the risk of correlation in power output. In a power system with geographically dispersed wind farms, the effect of local environmental conditions on power output will be reduced. Since it takes some time for a weather front to pass a region, the effect of weather patterns will be delayed from one farm to another, and the alteration in aggregated power output thus takes place over a couple of hours rather than instantaneously. This effect is referred to as power smoothing (Manwell et al. 2005). Western Denmark is a typical example of a region with dispersed wind power generation. The aggregated wind power output for this region during one week in January can be found in Figure 1. As seen in Figure 1, variations in the range of the capacity of thermal units do occur (e.g. between 90 hours and 100 hours the wind power generation decreases with 1 000MW), but the increase or decrease in power over such range takes at least some hours (e.g. approximately 10 hours for the referred to example ).

### 2.1 Variations in load and wind power generation

Figure 2 illustrates the variations in total load (electricity consumption) in western Denmark during the same week as shown in Figure 1. As seen, the amplitude of the wind power variations at current wind power grid penetration (i.e. 24%) and the variations in load are not much different. However, there are two aspects of wind power variations which make these more complicated to manage than fluctuations in load; the unpredictability and the irregularity. Since the total load variations are predictable, it is possible to plan the scheduling of the thermal units to compensate for the load variations. The unpredictability of wind power makes it difficult to accurately schedule units with long start-up times. Variations in a system dominated by base load units create a need for what is here referred to as moderator which is a unit in the power system with the ability to reallocate power in time, such as a storage unit or import/export capacity. Since the total load variations are regular, to manage these a moderator would only need to have "storage" capacity which can displace one such variation at a time (i.e. absorb power for a maximum of 12 hours and then deliver this power to the system). Due to the irregularity of wind power variations "storage" capacities of a moderator for this application need to be more extensive than if variations were regular.

For the thermal units it is obviously the aggregated impact of the wind power and the total load which is of importance. The load on the thermal units (i.e. the total load reduced by the wind power generation) will become both less predictable and less regular as wind power is introduced to the system. In the Nordic countries, there is some correlation between wind speeds and electric load in the summer, but no correlation of significance in winter time (Holttinen 2005). However, a decrease/increase in wind power output might obviously coincide with an increase/decrease in demand at any time of the year, resulting in large variations in load on the thermal units. At times when wind power output is high and demand is low, systems with wind power in the range of 20% grid penetration or higher

might face situations where power generation exceeds demand (although this obviously depends on the extent of the variations in load). Without a moderator in the system, which can displace the excess power in time, some of the wind power generated will have to be curtailed in such situations. With base load capacity in the system which has to run continuously, situations where curtailment cannot be avoided will arise more frequently<sup>1</sup>.

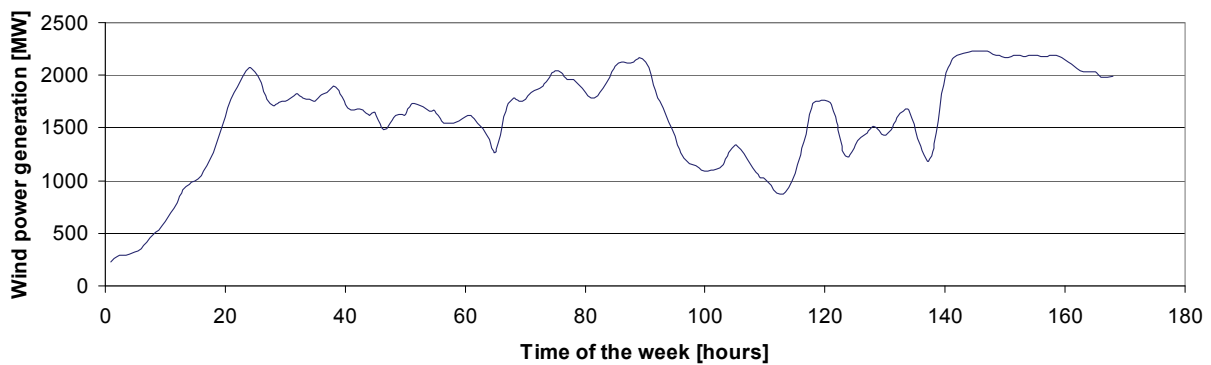


Fig. 1. Wind power generation in western Denmark during the first week in January 2005. Source (Energinet 2006)

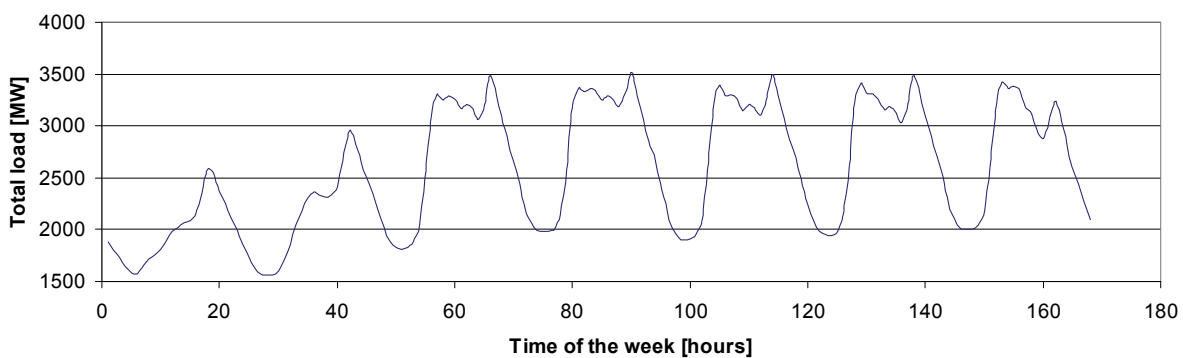


Fig. 2. Total load in western Denmark the first week in January 2005. Source (Energinet 2006)

## 2.2 Response to variations in wind power generation and electricity consumption

Variations in load in a wind-thermal power system that uses no active strategy for variation management can be managed in three different ways;

- by part load operation of thermal units,
- by starting/stopping thermal units or
- by curtailing wind power.

The choice of variation management strategy depends on the properties of the thermal units which are available for management (e.g. in order to choose to stop a unit it obviously has to

<sup>1</sup> It should be pointed out that the Nordic system (Nordpool electricity market) of which western Denmark is part, is special in the context of wind power integration, since variations in wind power can, to a certain extent, be managed by hydropower (with large reservoirs).

be running) and the duration of the variation. In a power system where cost is minimized, the variation management strategy associated with the lowest cost is obviously chosen. If, for example, the output of wind power and some large base load unit exceeds demand for an hour, curtailment of wind power (or possibly some curtailment in combination with part load of the thermal unit) might be the solution associated with the lowest total system cost. If the same situation lasts for half a day, stopping the thermal unit might be preferable from a cost minimizing perspective. To be able to take variation management decisions into account in the dispatch of units, knowledge of the start-up and part load properties of the thermal units is necessary.

Two aspects of the start-up of thermal units will have an immediate impact on the scheduling of the units; the start-up time and the start-up cost. The start-up time is either measured as the time it takes to warm up a unit before it reaches such a state that electricity can be delivered to the grid (time for synchronization) or as the time before it delivers at rated power (time until full production). In both cases, the start-up time ultimately depends on the capacity of the unit, the power plant technology and the time during which the unit has been idle. Small gas turbines have relatively short start-up times, in the range of 15 minutes, and large steam turbines have long start-up times, in the range of several hours. If a large unit has been idle for a few hours, materials might still be warm and the start-up time can be reduced. Table 1 presents the required start-up times of units in the Danish power system.

The costs associated with starting a thermal unit are a result of the cost of the fuel required during the warm-up phase and the accelerated component aging due to the stresses on the plant from temperature changes. Lefton et al. (1995) have shown that the combined effect of creep, due to base load operation, and fatigue, due to cycling (start-up/shutdown and load following operation), can significantly reduce the lifetime of materials commonly used in fossil fuel power plants in comparison to creep alone. They estimate the cycling costs (the cost to stop and then restart a unit) of a conventional fossil power plant to \$1 500-\$500 000 per cycle (around EUR 1 170-400 000) with the range corresponding to differences in cycling ability of different technologies and the duration of the stop. These costs include the cost of increased maintenance, as well as an increase in total system costs due to lower availability of cycled units, and an increase in engineering costs to adapt units to the new situation (i.e. improve the cycling ability).

Time since last stop	Starting time for synchronisation	Starting time until full production
	[min.]	[min.]
Immediately after stop	120	210
Up to 8 hours	180	300
Between 8 and 36 hours	300	480
Over 36 hours (cold start)	600	840

Table 1. Maximum allowed starting time for power plants in the Danish power system with nominal maximum power above 25 MW. Source: (Energinet 2007).

One alternative to shutting down and restarting a thermal unit is to reduce the load in one or several units. The load reduction in each unit is restricted by the maximum load turn-down ratio. The minimum load level of a thermal unit depends on the power plant technology and the fuel used in combustion units. The minimum load level on the Danish

units range from 20% of rated power for gas- and oil-fired steam power plants to 70% of rated power for waste power plants (Energinet 2007). Minimum load level of coal fired power plants range from 35% to 50% of rated power depending on technology (Energinet 2007).

Running thermal units at part load is associated with an increase in costs and emissions per unit of energy generated (i.e. per MWh), since the efficiency decreases with the load level. The rate of the decrease in efficiency depends on the power plant technology and the level to which the load is reduced. Figure 3 illustrates the relation between efficiency and load level for three different thermal units. As shown in Figure 3, the rate of decrease in efficiency is lower at high load levels than at low load levels. It is also shown that the rate of decrease in efficiency is higher in the combined cycle plant (CC) than in the steam plant (since gas turbines are sensitive to part load operation).

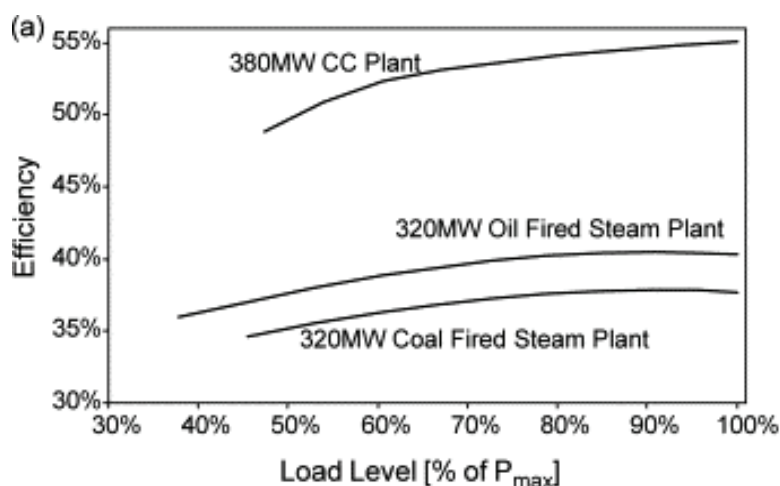


Fig. 3. Typical electric efficiency versus load level curves of different power plants. Source: (Carraretto 2006)

Work with models of the power system of western Denmark suggests that wind power variations introduce aspects that influence the competitiveness of the thermal units in the power system relative to one another (Göransson & Johnsson 2009a). In general, simulations show that an increase in the amount of wind power reduces the periods of constant production and the duration of these periods. The capacity factor of units with low start-up and turn down performance and high minimum load level (i.e. base load units) will decrease more than the capacity factor of units with high start-up and turn down performance and/or low minimum load level. This result might seem trivial. However, low start-up and turn down performance and high minimum load levels are common properties of units with low running costs designed for base load production. Thus, low running costs compete against flexibility and in a system with significant wind power capacity, the unit with the lowest running costs is not necessarily the unit which is run the most.

Figure 4 shows the capacity factors of the thermal units in the power system of western Denmark at three different levels of wind power capacity ("without wind", "current wind" corresponding to around 20% wind power grid penetration and "34% wind" with 34% wind power grid penetration) from simulations of three weeks in July 2005 (Göransson & Johnsson 2009a). As can be seen in Figure 4, the dominating trend is a decrease in import and an increase in export as the wind power capacity in the system increases.

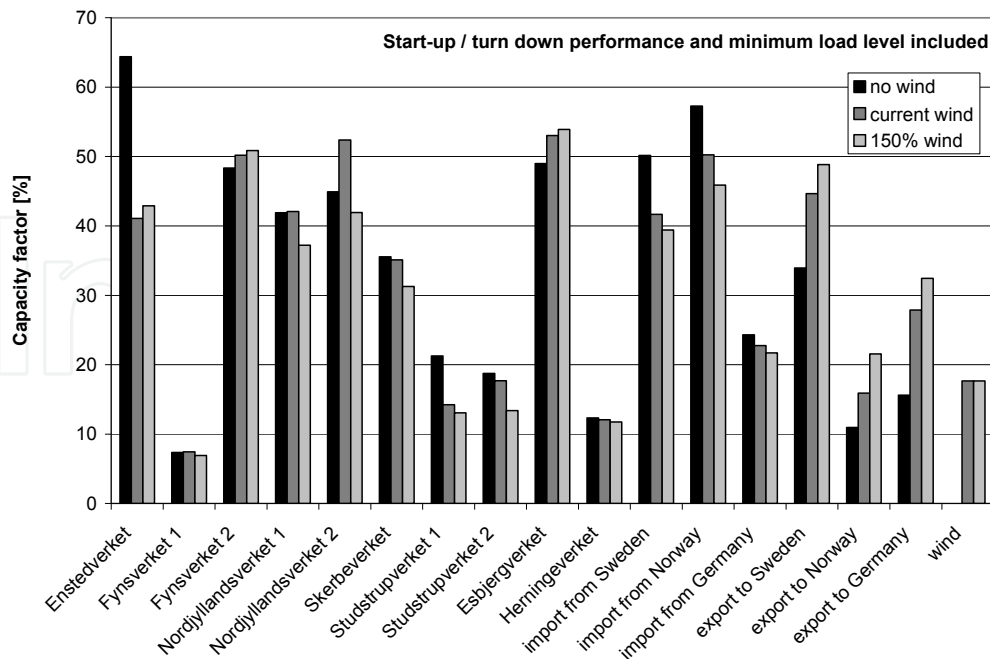


Fig. 4. Simulated impact of variations in wind power generation on the capacity factor of thermal units in western Denmark. For further details see (Göransson & Johnsson 2009a).

Enstedtsvaerket B3 also experiences a significant decrease in its capacity factor with increased wind power capacity. Enstedtsvaerket is the least flexible unit in the system (most expensive start-up and highest minimum load level), and it has a lower capacity factor than several other units in the current wind and 34% wind case despite that it has the lowest running costs of the system. The variations in wind power production have thus altered the dispatch order of the units in these two cases, favouring units with more flexible properties to the unit with the lowest running costs.

The effect of a shift from base load generation to generation in more flexible units on total system emissions depends on the specific technologies in question. A small increase in magnitude of the variations may boost the capacity factors of units with low emissions (e.g. gas-fired peak load units), whereas a large increase in magnitude of the variations may be followed by an increase in capacity factor of units with high emissions (e.g. oil-fired back-up units). The impact of the change in capacity factors on system emissions thus depends both on the power system configuration and the amount of wind power which is integrated.

### 3. Moderation strategies

The purpose of a moderation strategy is to improve the efficiency of the wind-thermal system by reducing the variations in the load on the thermal units, thus avoiding thermal plant cycling and part load operation. Moderation strategies reduce variations either by displacing power over time or by displacing load over time. Traditional storage forms displace power in time. A grid solution, where power is imported to and exported from a system, works according to the same principle from a power generation perspective. Strategies where the load is displaced over time are generally referred to as demand side management strategies. As an example, the charging of plug-in hybrid electric vehicles can be used for demand side management.

### 3.1 Storage technologies and grid strategies

Thermal units run at maximum efficiency if they generate power continuously at or near rated power whereas the demand for electricity varies in time. To avoid inefficient operation of the thermal units, the variations in load on the power system are conventionally managed by some unit which consumes some of the excess power generated (i.e. to keep the thermal units at rated power) at times of low load, to return this power to the system at times of high load levels. Storage technologies, such as pumped hydro storage and compressed air energy storage (CAES) operate in this manner. Pumped hydro has been applied for decades, while CAES is hardly a commercial alternative under present conditions. Nourai (2002) gives a thorough evaluation of storage technologies for energy management. Different types of storage technologies all have the same effect on the system, i.e. they shift some of the generated power in time. Using the grid and connections to other regions, where power is exported at times of low load and imported at times of high load levels, has the same impact on the thermal units in the system.

Shifting power in time is obviously useful also when managing wind power. The storage would then consume some of the excess wind power generated at times of high wind power generation levels and return this power to the system at times of low wind power generation levels. Literature presents thorough evaluations on the interaction between wind power (i.e. a wind farm) and one storage unit. Particularly well covered is the interaction between wind power and a (pumped) hydro power plant (Castronuovo & Lopes 2004; Jaramillo et al. 2004) and the interaction between wind power and a CAES unit (Cavallo 2007; Greenblatt et al. 2007). In such studies, the wind farm is combined with storage so that the total output resembles a conventional power plant, i.e. closer to base load (Jaramillo et al., 2004; Greenblatt et al., 2007) or maximizes return according to a given price signal (Castronuovo and Lopes, 2004). If instead the storage is a common resource which manages the total power generation level in the system, i.e. the sum of generation in thermal units and wind power plants, variations in wind power generation are allowed to compensate for variations in electric load on the power system and the benefit of the storage for the thermal units is maximized. Storage as a common resource to the system is the focus of this chapter.

#### 3.1.1 Impact on a wind-thermal system

As the storage or transmission capacity is introduced to the power system the system emissions can be influenced in four different ways; start-up emissions decrease, part load emissions decrease, wind power curtailment decrease and the capacity factors of typical base load units increase. An example of the impact of a general moderator (i.e. a lossless storage or lossless transmission capacity) on power system emissions and wind power curtailment is illustrated in Figures 5a-c. The power system used as an example here is an isolated system containing the thermal units of western Denmark and two levels of wind power (2 374 MW, generating 20% of the total electricity demand, and 4 748 MW, generating 40% of the total electricity demand if no wind is curtailed). Details are given by Göransson and Johnsson (2009b). The ability of a general moderator to displace power in time depends on the power rating and the storage capacity of the moderator. In figures 5a-c, emissions and wind power curtailment are investigated at five different moderator power ratings (0, 500, 1000, 1500, 2000 MW) and at two different storage capacities; daily and weekly, where the charging and discharging of the storage is balanced on a daily and weekly basis, respectively.



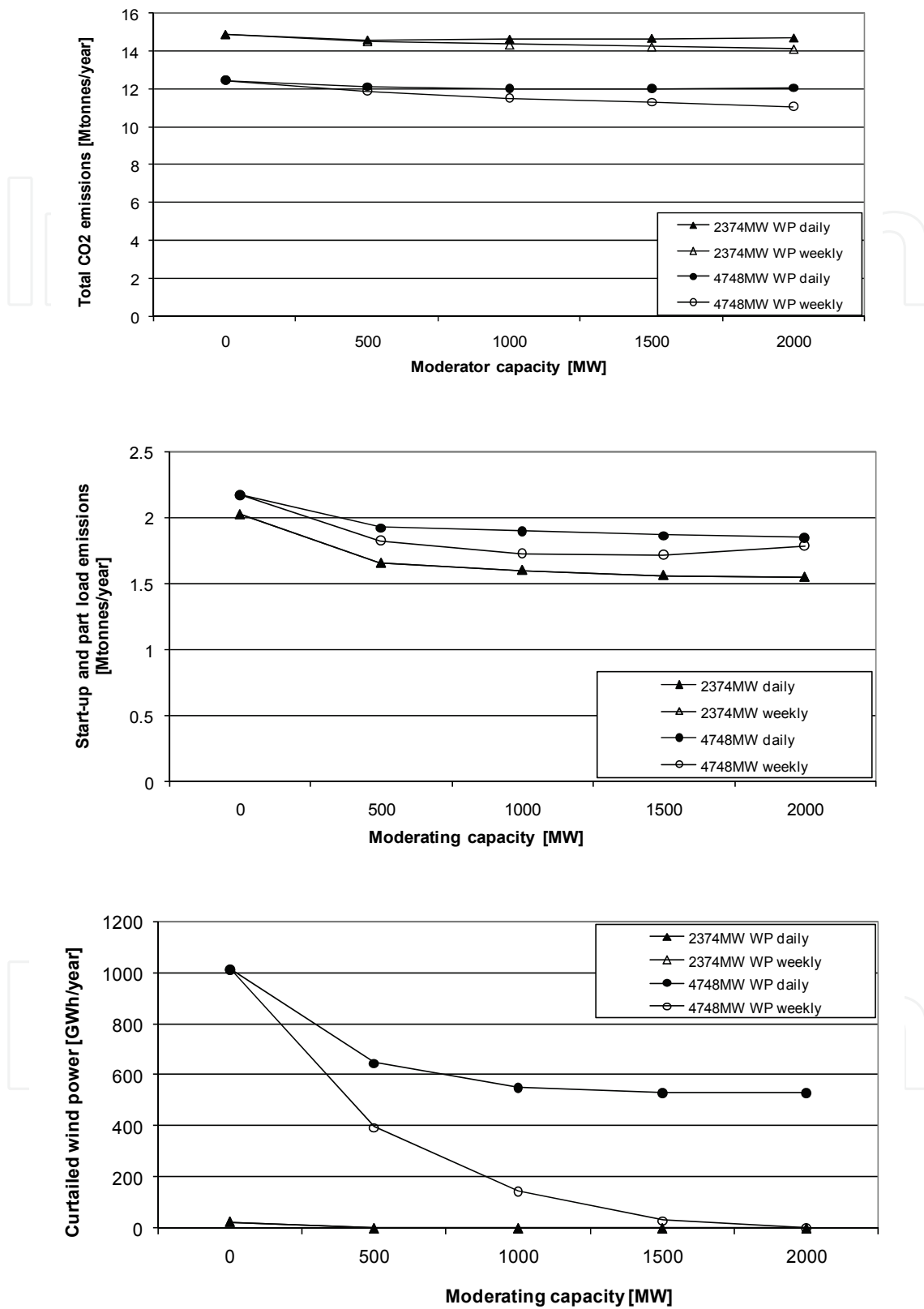


Fig. 5. Impact of moderator power rating and capacity on a: total system emissions, b: start-up and part load emissions and c: wind power curtailment. Source: (Göransson & Johnsson 2009b).

A weekly balanced moderator is obviously at least as qualified at reducing emissions as a daily balanced moderator (since the weekly balanced unit can also be balanced over each day). Figure 5a shows that the advantage of a weekly balanced moderator, compared to a daily balanced moderator, is more significant in the power system with 4 748 MW wind than in the power system with 2 374 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 large as the emission reduction from applying 2 000 MW moderator capacity if it is daily balanced. The largest emission reduction is attained in the wind-thermal power system with 4 748 MW wind, in which a 2 000 MW moderator capacity that is balanced on a weekly basis can reduce emissions with 11% (Göransson & Johnsson 2009b).

Figure 5b 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 4 748 MW wind power capacity than in the system with 2 374 MW wind power capacity due to the greater system variations in the 4 748 MW wind system compared to the 2 374 MW wind system. The major part of the reduction is realised 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 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 5c displays the relation between wind power curtailment and moderator power rating. By shifting the wind power generation in time so that the correlation between load and wind power generation is improved, the moderator enables a shift from thermal power to wind power. Avoiding 1 000 GWh of wind curtailment per year corresponds to a decrease in system emissions with 0.60 Mtonnes/year<sup>2</sup>. A decrease of this magnitude is realised in the 4 748 MW wind system by a 2 000 MW weekly balanced moderator. In this case the avoidance of wind power curtailment is the most important factor which contributes to reduction in emissions. The daily balanced moderator does not provide the same possibility to avoid wind power curtailment as a weekly balanced moderator.

### 3.1.2 The choice of variation moderator

There are many technologies for storing power. Figure 6 illustrates how different storage technologies are suitable for different applications. The focus of this chapter is to discuss the ability of a moderator to allow thermal units to run continuously, despite variations in wind power generation and load. This requires significant power ratings and charge/discharge times in the scale of hours, i.e. technologies for energy management. As shown in Figure 6 pumped hydro power, compressed air energy storage (CAES), flow batteries and sodium sulphur (NaS) batteries are moderators suitable for such a purpose.

From Figure 5 the following choice of moderator properties seem sensible for the system investigated; a daily balanced moderator (3 GWh storage) of 500 MW for wind-thermal systems with around 20% wind power grid penetration, and a weekly balanced moderator (33 GWh storage) of 2 000 MW for wind-thermal systems with around 40% wind power grid penetration. From Figure 6 it can be seen that pumped hydro stations, CAES units, flow batteries and NaS batteries have discharge times in the range of hours and are thus all

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<sup>2</sup> The average emissions of the thermal units are approximately 600kg CO<sub>2</sub>/MWh.

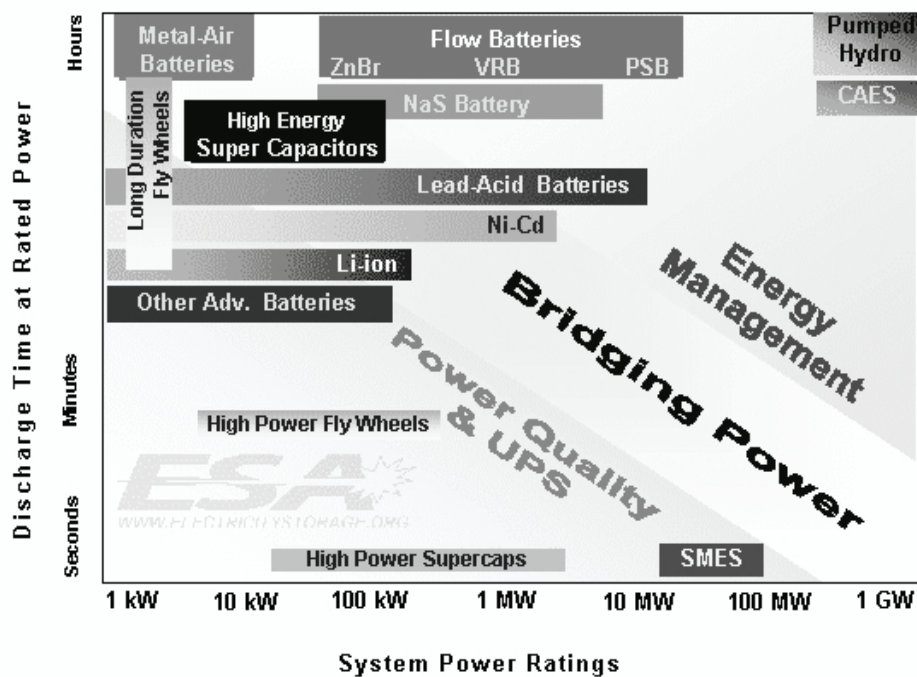


Fig. 6. Typical power ratings and discharge times of storage technologies. Source: (ElectricityStorageAssociation).

candidates to serve as daily moderation. While there are pumped hydro stations fulfilling the requirements stated (the Dinorwig pumped hydro power station in Wales has for example a power rating of 1 700 MW and is able to store 8 GWh of energy) and CAES units of this magnitude are under consideration (for example the project concerning a 2 700 MW CAES in Norton, Ohio), flow batteries and sodium sulphur batteries have only been evaluated on a 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 2 400 MW and can store 14.4 GWh energy). Reaching a power rating of 2 000 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 one 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 losing too much energy as heat. As mentioned previously, an additional alternative to moderate variations is to displace power through import and export over the system boundary. This is the main way in which western Denmark manages its variations today and the possibility to use this method on European scale is being discussed (sometimes referred to as “supergrid”). Trade over transmission lines could of course be balanced both on a daily and a weekly basis.

Figure 7 compares the reduction in emissions and costs due to the introduction of a weekly balanced moderator in the system with 40% wind power and the total LCA costs and emissions of possible moderators. Applying existing moderator technology, a net reduction in emissions of 7.5 to 10.3% is possible (Göransson & Johnsson 2009b). However, if assuming a cost of 20 EUR for emitting one tonne of carbon dioxide (corresponding to the solid line in Figure 7), overhead transmission lines is the only moderator which can lower the system

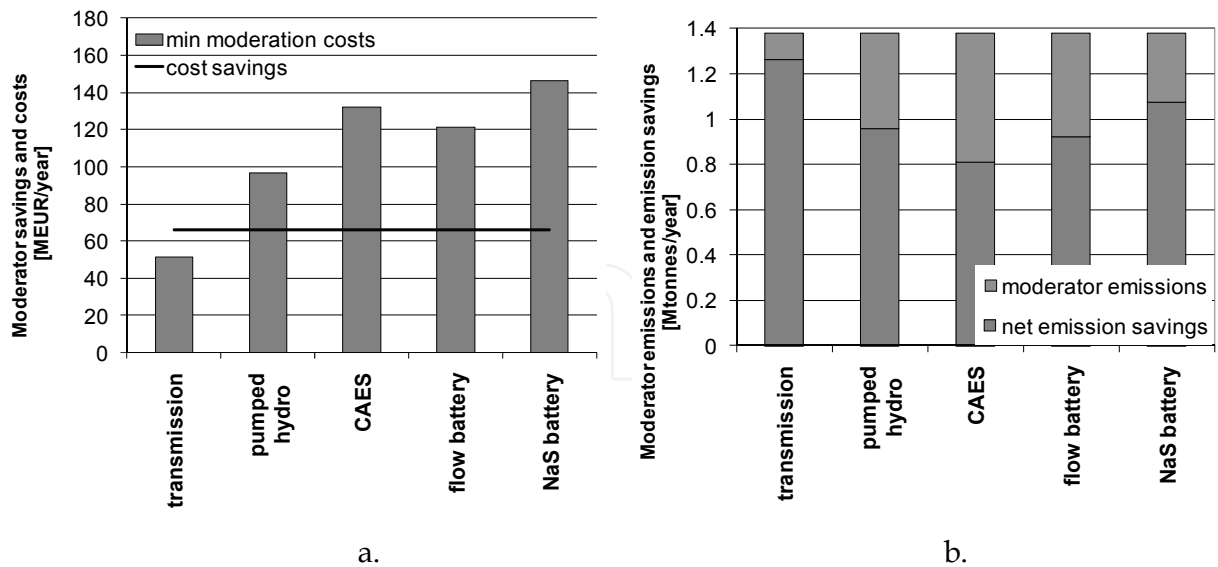


Fig. 7. Costs for different moderators and their emissions (weekly balanced moderator as example). a) Cost savings (solid line) compared with costs for moderation (bars). b) Emission savings reduced by emissions associated with moderation. Sources: (Rydh 1999; Nourai 2002; EC 2003; Denholm & Holloway 2005; IEA 2005; Kuntz 2005; Rydh & Sandén 2005; Ravenmark & Normark 2006; Göransson & Johnsson 2009b).

costs. With overhead lines, system costs can be decreased if the imported power can be bought at prices which do not exceed the yield from exported power by more than about 4 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 smaller (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 (Airtricity 2007) to handle wind power variations in Europe. The results from the work by Göransson and Johnsson (2009b) indicate that investments in transmission lines is generally attractive since costs and emissions associated with transmission lines are lower than those of other moderator options (*cf.* Figure 7). This, provided that it is sufficient for each country to invest in 1 000 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 compensates for the cost to install overhead lines (Figures 7a), 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 are associated with a cost lower than the other moderator technologies in Figure 7 (Göransson & Johnsson 2009b). Thus, transmission in general seems to be a good option with regard to both costs and emissions compared to alternative moderation. However, at the moment construction of

local storage seems to be closer to implementation than transmission lines for variation management. There are at least two factors which steer 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 European Commission (2008) 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 be favoured since they retain the green electricity within the national boundaries. Another factor counteracting the supergrid is the desire to protect the local power market.

Finally, it should be noted that when comparing different moderator technologies, the order of preference of moderator technologies depends on the average emissions of the power system in which the moderator will be integrated. This is also exemplified in the work with the western Denmark model. In the system with up to 20% wind power, average emissions are still higher than emissions from generating electricity from the combustion of natural gas. In this situation the CAES technology is the storage solution which reduces emissions the most amongst the energy management technologies in Figure 7 (Göransson & Johnsson 2009b). For a system with up to 40% wind power, and lower average emissions associated with the power generation, the CAES technology is less efficient at reducing emissions than the other alternatives (see Figure 7). Since major rearrangements of present power systems are under consideration, it is important to take future development of the system into account when choosing moderator technology.

### **3.2 Demand side management**

Another way to keep the generation in thermal units constant at desired level is to displace some of the load, rather than some of the generated power. This strategy is referred to as demand side management. Demand side management can be exercised by any load which can be allocated to any point in time. Demand for electricity for heating purposes is suitable for demand side management since heat is relatively easy to store. One example of this is given by Stadler (2008), who shows how storage heaters have decreased the variations in electric load in Germany. Stadler further suggests a joint strategy combining CHP systems and heat pumps to improve the system ability to integrate renewable generation. This strategy, where heat pumps generate heat while consuming electricity at times of excess electricity generation and the CHP unit generates heat and power at times when the system experiences electricity shortage, is also suggested by Blarke and Lund (2007). However, there are many ways in which heat can be produced resulting in lower losses with regard to exergy (waste heat, CHP, solar collectors). Demand side management strategies where electricity is difficult to replace or where electricity replaces more emissive alternatives should obviously be prioritised to minimize overall system emissions. Stadler (2008) give several examples of loads where electricity is difficult to replace; ventilation systems, refrigeration and pumps in hot water heating systems to mention a few. An example where electricity could potentially replace more emissive fuels is the electrification of the transportation sector. Below follows an example of how demand side management could be exercised by means of choosing appropriate charging strategies for Plug-in Hybrid Electric Vehicles (PHEV).

PHEV:s have the potential to reduce the effects of variations in demand and wind power generation (i.e. to reduce the variations in load on the thermal units in the case of a wind-thermal system) through two different mechanisms, here referred to as the correlation mechanism and the flexibility mechanism. The correlation mechanism is a result of the change in load profile, which arises as soon as the non-PHEV load (dominated by the electricity consumption of households and industry) is not perfectly correlated with the demand for electricity to charge the vehicles. The flexibility mechanism is due to some active control (built-in intelligence) of charging and discharging of the PHEV:s which offers the possibility to adjust the charging and discharging of the PHEV:s to fit the generation and load pattern. Obviously, vehicles will typically be charged when the non-PHEV load is low or when wind power generation is high in order to minimize changes in load on the thermal units in the system. With a flexible load in the system, reserve requirements can be relaxed since variations in generation or non-PHEV load partly can be managed by starting/stopping charging of the vehicles.

Both the correlation mechanism and the flexibility mechanism reduce variations in the total load. A difference between the mechanisms is that the flexibility mechanism can manage irregular variations whereas the correlation mechanism only manages regular trends. The flexibility mechanism can thus manage variations in intermittent generation (such as wind power generation) and reduces the need of reserve capacity of the system whereas the correlation mechanism will not directly benefit the system with respect to influence from intermittent generation.

Kempton and Tomic (2005) propose the use of large parts of the light vehicle fleet as operational back-up and storage of wind power. They have calculated that if 50% of the US electricity would be provided by wind power, some 34% of the light vehicle fleet can provide the back-up and storage required if operated as PHEV:s under a V2G contract. Kempton and Dhanju (2006) have looked further into the ability to handle wind power variations with PHEV:s and conclude that if the light vehicle fleet was entirely made up of PHEV:s, the power rating of the batteries in the vehicles if connected at 15kW, would significantly exceed the average national load on the power system in most OECD countries. Göransson et al. (2009) found that if the electricity consumption of PHEV:s correspond to some 12 % of the electricity consumption, wind power curtailment in a system with 20% wind power can be completely avoided.

### 3.2.1 Impact on a wind-thermal system

The load managing ability of the PHEV:s depends on the PHEV share of total electricity consumption as well as limitations under which the power system is free to allocate the PHEV load. Denholm and Short (2006) found that if charging of the PHEV:s is optimally dispatched from a power system perspective, the PHEV:s will decrease the cycling of the power plants and increase the load factor of the base load plants. Hadley and Tsvetkova (2008) on the other hand found that, with a fixed PHEV load starting at 5 p.m., the evening peak in load will be augmented and the use of peak load units increase. A comparison of the PHEV impact on power system emissions at four different integration strategies is presented in Figure 8, taken from Göransson et al. (2009). The example in Figure 8 is a wind-thermal system (thermal units and total wind power generation from western Denmark in 2005) to which PHEV:s have been integrated at three implementation levels (3%, 12% and 20% of the total electricity consumption). The four integration strategies have the following characteristics;

- S-DIR where the charging time of the PHEV:s occurs immediately after driving and the PHEV:s are charged as soon as they return home (it is assumed that the PHEV:s will always be recharged due to the relatively low cost of driving on electricity compared to gasoline).
- S-DELAY where the charging time of the PHEV:s is delayed (i.e. with a timer) to minimize average correlations with demand,
- S-FLEX where the charging of PHEV:s can take place when it is most favourable from a power system perspective, but the entire PHEV fleet has to be charged during the night and a part of it during the workday,
- S-V2G where the power system is free to dispatch the PHEV load and to discharge PHEV:s as desired. However, charging and discharging is restricted to the PHEV capacity available to the grid and the power level of the batteries. The power level of the batteries depends on charging and discharging history and the daily driving pattern for which electricity could have been used.

As shown in Figure 8, the lowest emissions are obtained for the S-V2G strategy at 20% PHEV share of the total electricity consumption and a 4.7% reduction in power system emissions is obtained. On the other hand, when the charging time of the PHEV:s occurs immediately after driving and the PHEV:s are charged as soon as they return home (S-DIR) there is a clear increase in CO<sub>2</sub>-emissions from the power system as the share of PHEV electricity consumption increase. The other integration strategies produce emissions between the S-V2G and the S-DIR cases. As seen in Figure 8, strategies where the flexibility mechanism is present (S-FLEX, S-V2G) have lower emissions than the strategies which are limited to the correlation mechanism at high PHEV shares of consumption (i.e. 20%).

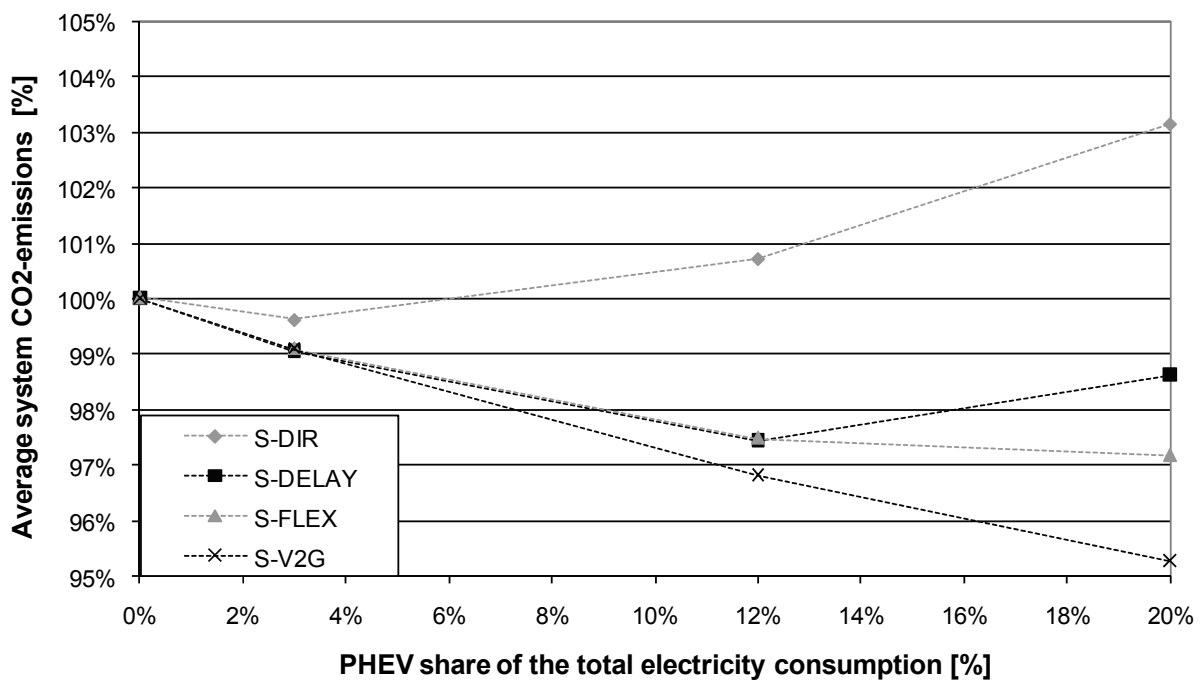


Fig. 8. Impact on CO<sub>2</sub>-emissions due to PHEV integration as obtained from the simulations of an isolated wind-thermal power system (vehicle emissions not included). Average system emissions in the system without PHEV:s are 649kgCO<sub>2</sub>/MWh, thus, in the plot 1% is equivalent to 6.49kg/MWh Source: (Göransson et al. 2009)

Which are the mechanisms behind the increase/decrease in emissions under the four different integration strategies? Figure 9 shows a weekly time series of the total consumption of electricity divided into consumption of household and industry (white) and

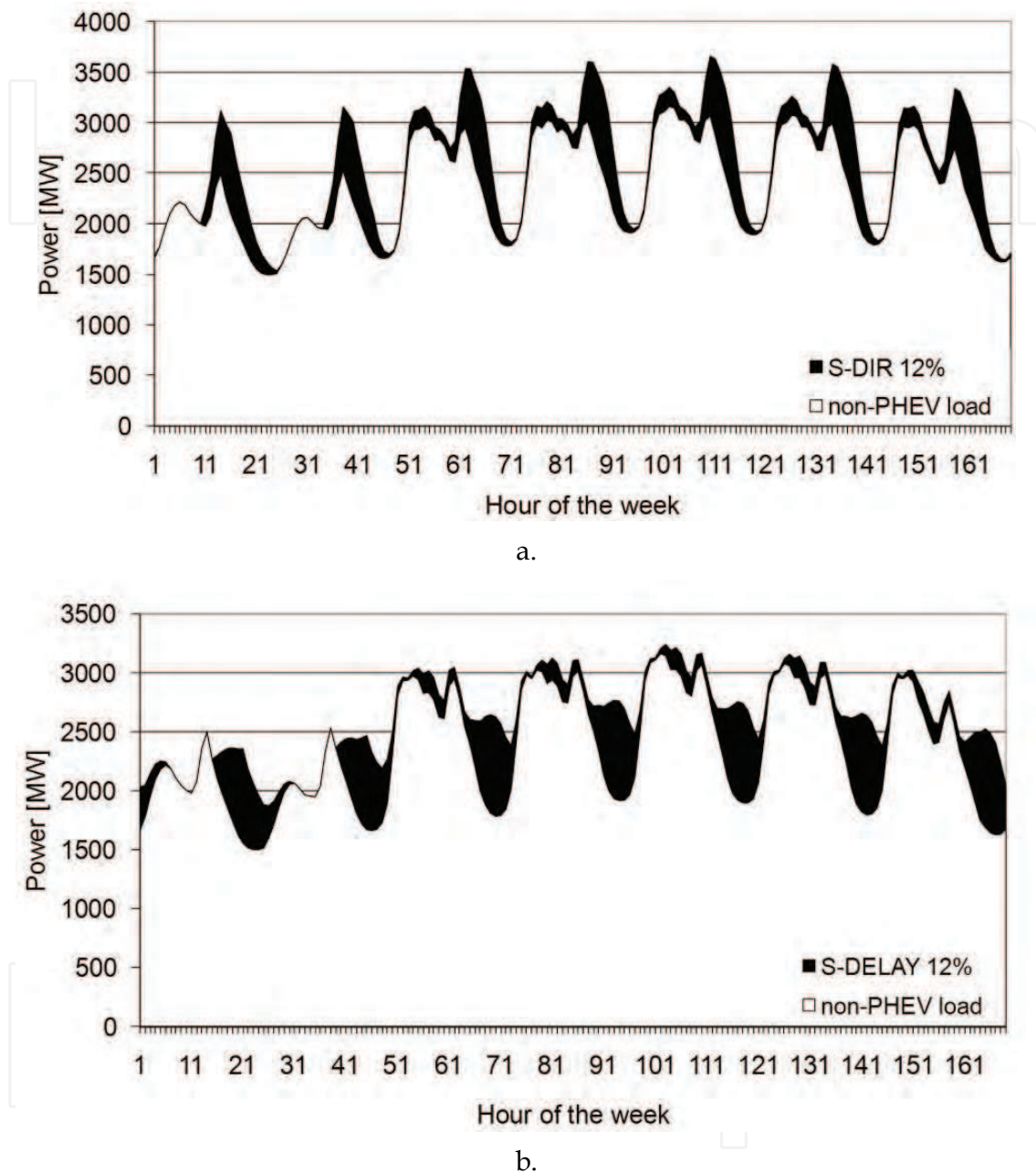


Fig. 9. Total electricity consumption in the system modelled by Göransson et al. (2009) divided into consumption of household and industry (white) and consumption of vehicles (black). The example shown is for 12% PHEV share of electricity consumption. a: S-DIR integration strategy where consumption of households and industry is strongly correlated with the consumption of vehicles. b: S-DELAY strategy where a shift in charging start time decreases the correlation and evens out overall electricity consumption. This smoothing of electricity consumption through a decrease in correlation is, in this work, referred to as the correlation mechanism. Source: (Göransson et al. 2009)



consumption of PHEV vehicles (black). Data of the household and industry consumption was obtained from Energinet (Energinet 2006) and PHEV consumption was taken from (Göransson et al. 2009). In Figure 9, the PHEV consumption is 12% of the total electricity consumption, and the household and industry consumption is scaled down to 88%. As can be seen from Figure 9a, in the S-DIR strategy (i.e. vehicles are charged as soon as they return home), the PHEV integration in the system does not imply a smoothening of the total load, but rather an accentuation of the peaks. As PHEV:s are integrated under the S-DIR strategy, there is a decrease in the amount of thermal units which can run continuously and most units also have to cover peak load. The result is an increase in emissions from the power generation system compared to the reference case without PHEV:s (cf. Figure 8).

Applying the S-DELAY strategy (i.e. where vehicle charging is delayed with a timer), the PHEV consumption is shifted so that it occurs at times of low non-PHEV load, and the overall load is evened out as shown in Figure 9b. This simple adjustment proves to be an efficient way to smoothen the overall load, and the integration of PHEV:s will reduce average system emissions under this strategy (cf. Figure 8). However, a large PHEV share of consumption would create new peaks in the total load at times when the PHEV load is at maximum. These new peaks would increase part load emissions of the system and the total reduction in system emissions is counteracted (cf. Figure 8 at a 20% PHEV share).

Under the S-FLEX strategy a moderate PHEV share (i.e. 12%) is sufficient to avoid situations where wind power generation competes with the generation in base load units with low running costs and high start-up costs. Start-up emissions and wind power curtailment are thus minimized already at a moderate level of integration. If the PHEV share increases, the capacity which has to be charged is of such magnitude that it creates new variations. However, due to the flexible distribution of the charging, these new variations can be allocated so that they can be met by units which are already running. Changes in capacity factors of these units cause a decrease in emissions (cf. Figure 9).

Under the S-V2G strategy the system ability to accommodate variations of both short and long duration increases with the PHEV load share, since charging is optional at all times and any increase in PHEV capacity in the system thus improves the system flexibility. However, wind power curtailment is lowest at a 12% PHEV share. This is due to the car-owners' great willingness to pay for the electricity in this example. In a system where the willingness to pay for PHEV charging is small, vehicles would always be charged so that the load would suit the generation under the V2G strategy. However, when the willingness to pay for charging is great, as in the system considered in Figure 8, vehicles are charged as much as the battery capacity and availability allows and the load variations due to PHEV charging will increase. In such situations, a higher PHEV share of consumption does not imply a greater ability of the system to accommodate wind power.

### 3.2.2 The choice of integration strategy

The choice of PHEV integration strategy obviously depends on the cost to implement the strategies. If the majority of the charging of the vehicles takes place at home, there is an implementation cost associated with each vehicle. The implementation cost then simply corresponds to the cost of the device for connecting and controlling PHEV:s at the charging point (e.g. the garage). There is a significant difference in implementation cost between the strategies, where the cost for sophisticated controlling (i.e. S-V2G) is particularly high. However, under a sophisticated controlling mechanism, the fleet of PHEV:s is able to improve the power system efficiency (and thus reduce costs) more than under a less

sophisticated controlling mechanism. Table 2 compares the costs of implementing PHEV:s with the change in cost to supply the electricity generation system with power as PHEV:s are integrated for the western Denmark example. As shown in Table 2, the reduction in costs is always smaller than the implementation cost for the S-V2G strategy, whereas the implementation costs of the S-FLEX and S-DELAY strategies are compensated for at a 3% and 12% PHEV share.

Thus, from a maximum CO<sub>2</sub> reduction perspective, the S-V2G strategy is the preferable integration alternative. However, as indicated above (the rightmost column in Table 2) the implementation cost of the S-V2G strategy is higher than the implementation cost of the other strategies. Also, it might be difficult to reach agreement for a strategy for which the transmission system operator has full control of the charging and discharging of the vehicle and the car owner has no say in the state in which he/she will find the car (charged/discharged). Under the S-FLEX and S-DELAY strategies, the car owner will always find the car charged at a specified/contracted time, so these strategies would probably be more convenient to implement in reality.

[EUR/vehicle and year]	Reduction in cost 20% PHEV	Reduction in cost 12% PHEV	Reduction in cost 3% PHEV	Implemen- tation cost <sup>3</sup>
S-DIR (fixed load -no control)	-17.16	-11.58	-4.00	0
S-DELAY (fixed load -timer)	1.54	11.23	20.85	4
S-FLEX (free load distribution)	6.29	15.25	28.76	14
S-V2G (free load, V2G allowed)	12.57	19.39	32.07	52

Table 2. Reduction in total system costs (as compared to the case without PHEV integration) per vehicle compared with implementation cost (rightmost column) under different PHEV integration strategies and implementation levels. Negative numbers imply an increase in system costs due to PHEV integration. From Göransson et al. (2009).

#### 4. Summary

Emission savings due to wind power integration in a thermal power system are partly offset by an increase in emissions due to inefficiencies in operation of the thermal units caused by the variations in wind power generation. To reduce the variations a moderator or some demand side management strategy, i.e. a fleet of PHEV:s, can be integrated in the wind-thermal system. A reduction in variations (in load and/or wind power generation) will be

<sup>3</sup> (Capital costs\*r/(1-(1+r)<sup>-lifetime</sup>))

10 years' life time assumed. r =0.05 as in one of the IEA cases IEA (2005). Projected Costs of Generating Electricity, OECD/IEA.. Costs for S-FLEX US\$150 and S-V2G US\$550 from Tomic and Kempton (2007) Cost for S-DELAY 298SEK at standard hardware store. 2007 average exchange rate from the Swedish central bank.

reflected in the generation pattern of the electricity generating units in the system in one or several of the following ways:

- Reduction in number of start-ups
- Reduction in part load operation hours
- Reduction in wind power curtailment
- Shift from peak load to base load generation

All of the above alterations in production pattern will decrease the system generation costs. The first three effects also imply a decrease in system emissions and an improvement of system efficiency, whereas the consequences of the fourth effect depend on the specific peak load and base load technologies. By using the moderator or the fleet of PHEV:s as a common resource of the system (i.e. managing the aggregated variations of load and wind power generation), the operation of the thermal units will be more efficient after the implementation of variation management than prior the wind power integration.

Examples from results from a simulation model of the power system of western Denmark in isolation shows that a daily balanced moderator with modest power rating (i.e. 500 MW) is sufficient to reduce a significant share of the emissions due to start-ups and part load operation, whereas higher power ratings and storage capacities are required to avoid wind power curtailment. In a wind-thermal system with up to 20% wind power (i.e. 2 374 MW), wind power curtailment is modest and the advantage of a weekly balanced moderator with high power rating (i.e. 2 000 MW) compared to a daily balanced moderator with low power rating (i.e. 500 MW) are small. In a system with up to 40% wind power (i.e. 4 748 MW), however, wind power curtailment is substantial and the avoidance of curtailment is the heaviest post in the reduction of emissions through moderation. A comparison between the costs and emission savings due to moderation to the costs and emissions associated with five available moderation technologies (transmission, pumped hydro, compressed air energy storage, sodium sulphur batteries and flow batteries) indicate that all these moderators are able to decrease system emissions but only transmission lines can decrease the total system costs at a cost of 20EUR/tonne for emitting CO<sub>2</sub> (i.e. higher CO<sub>2</sub> prices are required to make the other moderators profitable for the system exemplified).

The chapter looks closer at Plug-in Hybrid Electric Vehicles as moderating wind power and it is shown that the ability of a fleet of PHEV:s to reduce emissions depend on integration strategy and the PHEV share of the total electricity consumption. An active integration strategy (rather than charging vehicles as they return home in the evening) is desirable already at moderate shares of consumption (i.e. 12%). An integration strategy which gives the power system full flexibility in the distribution of the charging (i.e. S-V2G) is particularly desirable at high PHEV shares (i.e. 20%). However, such a strategy is perceived as difficult to implement for two reasons; the high implementation cost relative to the system savings from moderation and the uncertainty of the car owner with respect to the state in which he/she will find the battery.

Finally, there is obviously no difference from a wind power integration perspective if variations are managed by shifting power in time compared to if they are met by shifting load in time. This, since the objective is to match load with power generation. Yet, what seems to be of importance is the time span over which the shift can be implemented. Demand side management in general implies a shift in load within a 24 hour time span since most loads are recurrent on a daily basis. This corresponds to a daily balanced storage. By shifting power or load over the day it is possible to avoid competition between wind power

and base load units and thus the efficiency in generation will be improved (by a decrease in start-ups, part load operation and/or wind power curtailment). Also, the daytime peak will be reduced and some associated start-ups avoided (although start-up avoidance is of secondary importance, since the peak load units generally have good cycling ability). Results from simulation of the western Denmark system indicate that it is sufficient to manage the variations in load over the day (by shifting power or load) to efficiently accommodate wind power generation corresponding to 20% of the total demand.

It should be noted that, just as in the case of any daily balanced demand side management strategy, it is possible to avoid competition between wind power and base load units through night time charging of PHEV:s. However, unless V2G is applied, there still has to be sufficient thermal capacity in the system to supply the peaks in demand of household and industry at times of low wind speeds. Implementing PHEV:s under a V2G strategy the batteries of the PHEV:s serve as storage. It seems reasonable to assume that the PHEV battery is (at the most) sized to cover the average daily distance driven (typically to and back from work). Thus, the electricity which is stored in the battery as the vehicle leaves home in the morning corresponds to the demand of the vehicle throughout the day and any electricity which the vehicle is to deliver to the grid during the day has to be delivered to the vehicle during that same day. The V2G ability of the PHEV:s thus corresponds to storage balanced over the day (i.e. from the time people leave home in the morning until they return in the evening).

With wind power generation in the range of 40% of the total demand, the variations in wind power exceed the variations in load and, since the variations in wind power often are of longer duration (i.e. there can be strong winds affecting a region for more than 12 hours), power or load has to be shifted over longer time spans. As mentioned above, a weekly balanced moderator (typically pumped hydro or transmission) would be suitable for a wind-thermal system in this case. Some flexible generation such as hydro power or co-generation might also be applicable. However, since it is difficult to find a demand for electricity which can be delayed with a week, demand side management is difficult to apply for wind power variation management at these grid penetration levels.

For the future it seems crucial to evaluate the potential of matching wind power generation and electricity consumption on a European level. Thus, also on a European level, it is of interest to investigate the interaction between wind power variations and load variations. It is also perceived as important to evaluate the correlation between variations in wind power and other renewable power sources. The aggregated effects of large-scale wind power and solar power is of particular interest.

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This book is the result of inspirations and contributions from many researchers of different fields. A wide variety of research results are merged together to make this book useful for students and researchers who will take contribution for further development of the existing technology. I hope you will enjoy the book, so that my effort to bringing it together for you will be successful. In my capacity, as the Editor of this book, I would like to thank and appreciate the chapter authors, who ensured the quality of the material as well as submitting their best works. Most of the results presented in the book have already been published on international journals and appreciated in many international conferences.

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Phone: +86-21-62489820  
Fax: +86-21-62489821

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