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Coping with Wind Power Variability: How Plug-in Electric Vehicles Could Help

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Abstract

Plug-in electric vehicles could offer flexibility for wind power and an attempt was made to quantify the effect with a power system model Wilmar. Wilmar simulates unit commitment and dispatch using mixed integer p[1]rogramming and includes wind power and load stochasticity as well as a module for plug-in electric vehicles.

Forecast errors of wind power increase the need for balancing and ancillary services. The model is able to use the plug-in electric vehicles (PHEVs) to participate in the balancing and ancillary services and decrease the costs of these services. The charging and possible discharging of the vehicles can also be optimized to most beneficial hours within the limits caused by vehicle use. We have calculated the benefits at different PHEV penetration levels.

The results indicate that benefits of peak shaving using vehicle to grid are limited due to the rather small size of storage in the batteries even with a large number of vehicles. Benefits can best be seen in the smart charging of the vehicles and in the correction of forecast errors. The marginal benefits of introducing PHEVs capable of smart charging and discharging are high for low numbers of PHEVs in the power system, but declines with higher penetration levels of PHEVs, because the demands for power system reserves and flexibility are limited.

I. INTRODUCTION

Plug-in electric vehicles have recently attracted considerable attention as means to reduce oil-dependence and CO2 emissions in the transport sector. As a result, there has also been interest to asses the possible power system benefits of smart charging and discharging [1-10].

Benefits are due to several different reasons. First, controlled charging of the vehicle batteries leads to more charging during hours with lower power prices. Second, vehicles waiting to be charged can participate in the balancing markets. These two are the main scope of this article. Third, PHEVs can act as disturbance reserves, especially if they have vehicle-to-grid (V2G) capability. We have analysed how much capacity could be available for disturbance reserves, but we have not tried to quantify the monetary benefits. Fourth, with V2G, PHEVs can shave peaks, if the daily price difference is large enough. Fifth, they can reduce the need for peak capacity. Sixth, in the long-term PHEVs can enable more cost-effective power system through changes in the power plant investments that will reflect the additional flexibility in the system.

To analyse the last two benefits requires a generation planning model and is not part of the scope of this article. We have analysed it elsewhere [11] .

The demand side flexibility due to PHEVs will help to decrease the operational costs of the power system. However, the benefits will be divided between market participants through the market mechanisms. This means, that some part of the benefits is likely to go to other market participants than the vehicle owners or their representative. We have analysed both the system benefit and the market prices from the perspective of a car owner.

The article first outlines the model and the data that has been used for the analysis. Then we proceed to show some results of PHEVs on a power system with a limited amount of wind power. We also demonstrate how PHEVs could fulfil different roles in the power system. Lastly, we discuss some problems in analysing the combination of wind power and PHEVs.

II. THE MODEL AND DATA

The model used in the analysis is called WILMAR (Wind Power Integration in Liberalised Electricity Markets) and is publicly available from the internet [4], although only as an older version with a restricted set of data. The model has been enhanced with a module to handle the plug-in electric vehicles. WILMAR analyses power markets based on a description of generation, demand and transmission between reasonably defined model regions and derives electricity market prices from marginal system operation costs. The model uses linear programming (LP) or mixed integer programming (MIP) with wind power production and electricity demand as optional stochastic input parameters. It optimises unit commitment in a day-ahead market and corrects for arising prediction errors in intraday market clearings. It also sets requirements for spinning and non-spinning reserve capacity. The latter is influenced by the

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predicted wind power production. Since the model has been developed for the Nordic countries, it has separate markets for producing heat for district or process heat networks. These are often tied to power production through combined heat and power plants (CHP). Model also handles the use of hydro power reservoirs through water values, which are either derived by luring the model towards historical levels or with a separate simplified model, which solves production for a whole year at a time and can therefore assign a value for the water value. A more detailed description of the model is given in [12, 13].

The model includes a module to handle the PHEVs from the network perspective. Work is underway to document the PHEV module in more detail, in here we just describe the general principles.

A. Data for PHEVs

Electric vehicles need to be plugged in order to be charged or discharged. Since the number of vehicles is very large, statistical behaviour is rather predictable although individual drivers might behave erratically. We assumed that there are two possible places where the vehicles might be plugged-in: at work and at home. Most people would be plugging in only at home, some would do it at both locations and only few at work. The data used for estimating the leaving and arriving vehicles was derived from the National Travel Survey conducted during 2004-2005 in Finland (HLT). It gave information on the timing and distance of travel with personal vehicles as well as data on the purpose of all travel. The information was processed to give estimates when people driving cars might arrive at work places and at homes and what kind of distances they had travelled before that.

This set of data made it possible to describe the PHEVs from the power system perspective. We derived a set of equations, which govern the use of the batteries for charging and discharging. The equations also make sure that the vehicles have enough stored electricity when leaving the network.

It was assumed that people plug-in once they arrive and that 95% do this at home and 40% at work. The data was used to derive typical daily patterns on hourly time scale and these were modified to take into account differences between weekdays, Fridays, Saturdays, Sundays, holidays, and weekdays between a holiday and a weekend. A weekly index, which held the changes in driving over the year, was multiplied into the data. Then assumptions about specific consumption and plugging in were overlaid on the data.

All this lead to a couple of different full year input time series in hourly time scale for the power system model: Share of vehicles plugged in the network changes over time. This affects the size of the usable electricity storage and the charging and discharging capacities. Time series for leaving vehicles directs the amount of electricity drawn from the storage pool. Arriving vehicles bring half empty batteries that will need recharging before the vehicles leave again.

Limit to recharging is usually set by the capacity of electric wiring at home or at work. Batteries can usually take more amperes, although many battery types can prolong their lifetime with slower charging. We assumed that half of the vehicles were plug-in hybrids, which can also run on gasoline, and that half of the vehicles were full electric vehicles. For plug-in hybrids charging capacity is set to an average of 4 kW per vehicle and for full electric vehicles it is 6 kW. Average consumption of grid electricity is 0.25 kWh/km, which is a rather high estimate. On average a vehicle does three trips per day, drives 52 kilometers and has a charge opportunity every 39 kilometers. A yearly consumption of half a million of battery electric vehicles amounts to 2.16 TWh and the same for plug-in hybrids is 1.83 TWh. The total consumption of one million vehicles was just below 5 % of total electricity demand. Active personal car fleet of Finland is about two million vehicles.

B. Description of the modelled power system

The Finnish power system has a rather large amount of combined heat and power plants (CHP). Therefore heat demand is also included in the model runs and there are over hundred separate heating areas. Electricity demand and power production were divided into seven regions.

Electricity and heat demands were estimated for 2015. Heat and power plants for the system were those that were assumed to be in place by 2015. Reservoir hydro power plants were taken away, since they complicate the comparison of the scenarios. They would also offer inexpensive ancillary services and flexibility, which would overshadow the effect of the plug-ins.

Electricity demand has a large baseload fraction due to industrial use of electricity. The peak demand is 14.4 GW. Almost all CHP units follow the heat demand with a fixed ratio for producing electricity, which means that their contribution for balancing the system was small. However, they were able to act as reserves. The total electric capacity of conventional power plants was close to 16 GW and the division can be seen in Figure 1. In the base scenario wind power capacity was 2 GW, which meant 5% penetration.

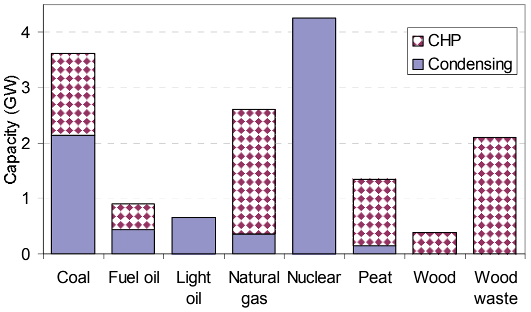

Figure 1. Capacity of conventional power plants in the analysed system.

III. RESULTS

We ran the model in two modes in order to calculate the benefits of the PHEVs. Dumb charging means that the vehicles start charging when they are plugged in and stop charging once they are full. Also a scenario without plug-in vehicles was run. We define that the difference between no plug-ins and dumb charging gives the cost of electricity to provide the required electricity for the vehicle fleet. The difference between smart and dumb charging gives the benefit of allowing the vehicle charging to be controlled according to the market conditions.

A. System benefits and market prices

We have calculated the operational costs and benefits per vehicle for different fleet sizes and different penetrations of wind power. First we consider the effects of PHEV fleet size. The costs and benefits are summed from modelling power markets for one year. The results with different electric vehicle fleet sizes are summarized in Table 1. As the number of PHEVs increased, the additional costs of operating the power system increased compared to the case where there were no PHEVs. With one thousand PHEVs and dumb charging, the additional annual cost was 156 000 euros, which means 156 €/vehicle. When the model was allowed to use smart charging and discharging, the additional cost went down to 61 €/vehicle. The benefit of smart charging was then 96 €/vehicle.

Table 1. System cost of charging electric vehicles (€/vehicle/year) for different electric vehicle fleet sizes. 'Dumb' and 'smart' charging are costs while 'benefit' indicates the benefit of smart charging over dumb charging. Results are only indicative as there were some problems with the model runs.

No of cars	Dumb	Smart	Benefit
1 000	156	61	96
10 000	186	89	98
100 000	190	120	71
1 000 000	215	173	41

It can be seen that the system benefit per vehicle drops when there are more and more vehicles participating in the smart charging scheme. The reason for this is simple – the services the vehicles are providing get saturated and further increase in the capacity does not lead to as large cost reductions in the system. This implies that it does not make sense from the system perspective to equip all electric vehicles with vehicle-to-grid capability. It is enough to have the capability in vehicles that can provide higher than average benefit, e.g. those with large battery packs and most flexibility in their use. However, smart charging makes sense for higher number of vehicles as this is cheaper to implement and helps the system to fill valleys in the consumption, or more properly in the net load, which takes into account wind power or any other energy production dependant on utilizing variable energy flows.

Table 2. Market price of charging electric vehicles (€/vehicle/year) for different electric vehicle fleet sizes. This table includes the use of vehicles for peak shaving and intraday adjustments.

No of cars	Dumb	Smart	Diff.
1 000	257	0	257
10 000	258	23	234
100 000	263	113	150
1 000 000	315	278	37

Table 1 displayed system costs of plug-in electric vehicles. If vehicle owners use real time pricing for purchasing power for their plug-in vehicles as well as real time prices for using the vehicles in intraday trading, the cost of electricity will look markedly different from system costs as can be seen from the Table 2. Real time prices in the model are based on the cost of producing one more unit of electricity, which in practice is the marginal cost of the last dispatched unit. The cost of electricity is dependant on which hours the charging happens. In the dumb charging case with low number of PHEVs, charging takes mostly place in hours of lower than average demand. With a larger number of vehicles, the shape of the demand curve changes and the prices on hours with high charging start to increase. Smart charging avoids this, especially with low PHEV penetration. When the penetration increases, the valleys of low demand start to get filled with plug-in charging and the market price increases during those hours. Revenue from intraday trading also gets lower per vehicle. However, in the long term, higher prices will attract new power plant investments that will conform to the demand curve and existing power plant fleet. Therefore, PHEVs should attract new investment and market prices will once again get lower.

B. Changes in the load duration curve

In fact it is perilous to take Table 2 for granted. The scenario with one million smart charging PHEVs would mean that the average price of electricity would be 6 €/MWh higher. This should attract investments in new power plants and the results in the table would not any longer hold true. It makes more sense to have a look at the effect of PHEVs on load duration curves (see Figure 2). This will give an indication how the power system would need to change. Not surprisingly, smart charging smoothes the curve and therefore enables larger fraction of the power to be produced with baseload power plants. Dumb charging leads to steeper load duration curve and opposite effect.

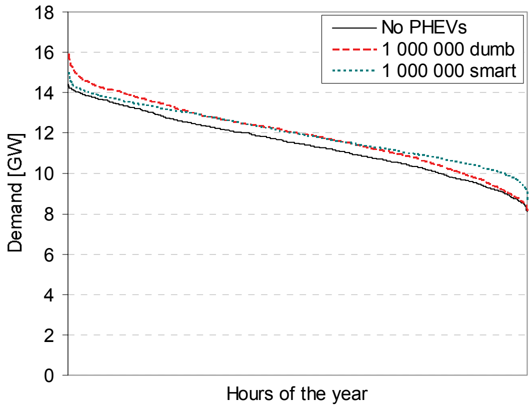

Figure 2. Load duration curves without PHEVs and with one million PHEVs. Smart charging smoothes the curve while dumb charging makes the curve steeper.

C. Start-up costs

Another result worth having a look is the changes in the start-up costs of conventional power plants. PHEVs without smart charging increase the need for starting up power plants while smart charging PHEVs can decrease the start-ups considerably (Figure 3). Especially peak power plants are prevented from starting up by discharging the batteries at peak demand. However, the magnitude of start-up costs in these model runs was quite small compared to the total operating costs or to other benefits the PHEVs bring to the system.

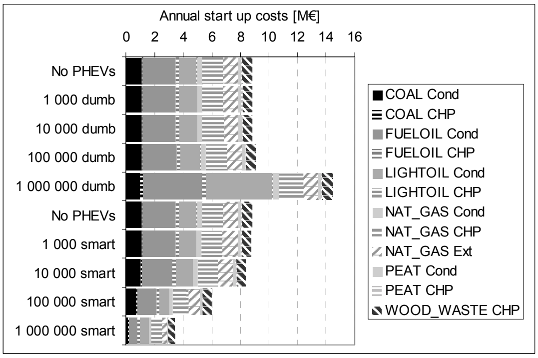

Figure 3. Changes in start-up costs between different plug-in scenarios.

While WILMAR model reserves capacity for primary and secondary reserves, for the most part this did not appear as a cost for the system in our model runs. During most situations there were reserves available without any extra effort, for instance CHP plants were considered capable of increasing their output if the need arises. Our model runs did not include events where the reserves would have actually been used, so the associated costs did not show up either. This part of the analysis should be improved. However, the changes in the wind power and load forecasts did take place in the stochastic model runs and PHEVs were able to decrease the costs of forecast errors.

D. Available capacities

Based on our assumptions, the share of PHEVs plugged in at the network varies between 50-90 % during a typical weekday. If the average network connection has a capacity of 6 kW and there are one million vehicles, then the plugged-in capacity varies between 3 and 5.4 GW. This is a rather large number in a power system with peak load of about 15 GW. However, unless every vehicle is equipped with V2G and has spare electricity in the battery pack, this capacity is not fully available. Figure 4 demonstrates capacities available for the power system. Highest line shows the output capacity if all vehicles have V2G. The lines depicting the two different charging patterns show how much capacity could be stopped from charging if the power system would require that. The charging capacity could act as disturbance reserves unless the charging has to happen in order to get the battery pack full in time. The demand for positive primary reserve in this 15 GW peak system has been 464 MW and secondary reserve demand has been 1300 MW.

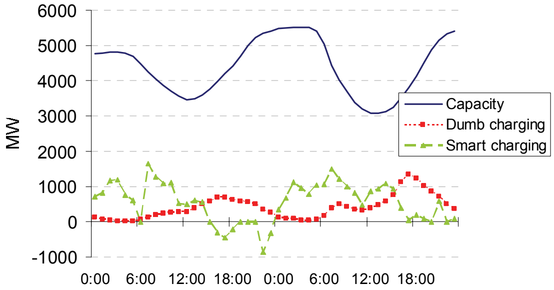

Figure 4. Behavior of PHEVs during typical Sunday and Monday.

E. Balancing

As said before, the forecast errors of both load and wind have been considered separately from the primary and secondary reserve requirement. In the case of 100 000 smart charging PHEVs, these vehicles covered over 30% of the balancing of the forecast errors. In case of one million PHEVs, they covered almost all of the errors. This means that most of the time the conventional power plants do not need to be rescheduled in order to correct the prediction errors from wind and load. Wind power penetration in these scenarios was about 5% of electricity consumption.

F. Wind power and PHEVs

We also ran scenarios with different wind power penetration levels. The penetration increased from 0% to 15% in 5% steps. The benefits of smart charging changed rather unpredictably from scenario to scenario. One would have assumed that the benefit would increase with increasing wind power penetration. However, wind power changes the net load duration curve and change the utilization times of different power plants. In effect the scenarios were not comparable between each other as we were not able to keep all other things constant. In order to understand how the results came by, a more simple power system should be inspected. Our data set had over 500 heat and power plants divided between seven regions and over 100 separate district heating areas. It could also be that the analysis cannot be made without including a generation planning model to properly take into account the changes caused by increasing wind power penetration.

IV. CONCLUSIONS

Plug-in electric vehicles increase the power system flexibility, if they are capable of smart charging. They can give a sizable contribution to system reserves just by being able to stop charging. With V2G the contribution can be much larger than what the system actually requires, which means that at least disturbance reserves can be saturated with PHEVs. PHEVs also change the shape of the load duration curve, so that either more baseload or more variable production can be accommodated in the system. However, it proved to be difficult to setup scenarios to prove the latter. Despite this, the results did show that the smart charging PHEVs can be very useful in correcting prediction errors of wind power.

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