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Plug-in hybrid electric vehicles as a mean to reduce CO2 emissions from electricity production

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Abstract

In this study we have investigated the consequences of integrating plug-in hybrid electric vehicles (PHEV:s) in a wind-thermal power system supplied by one quarter of wind power and three quarters of thermal generation. A fleet of PHEV:s with an electricity consumption corresponding to 3%, 12% and 20% of the total electricity consumption has been integrated to the system (i.e. the total electricity consumption remains unaffected while the non-PHEV consumption is 97%, 88% and 80% in the three cases). Four PHEV integration strategies, with different impacts on the total electric load profile, have been investigated by means of a mixed integer model which can model the effects of the new load profiles on the dispatch of the units in the system and, thus, on the CO_2-emissions from the system. The study shows that PHEV:s can reduce the CO_2-emissions from the power system if actively integrated, whereas a passive approach to PHEV integration (i.e. letting people charge the car at will) is likely to result in an increase in emissions compared to a power system without PHEV load.

The model simulations give that CO_2 emissions of the power sector are reduced with up to 4.7% compared to a system without PHEV:s. If the reduction in emissions is allocated to the electricity consumed by the PHEV:s, the emissions from generation of this electricity are reduced from 588 kgCO_2/MWh (wind-thermal system without PHEV:s) down to 367 kgCO_2/MWh (PHEV:s actively integrated). Under the assumption that electric mode is about 3 times as efficient as standard gasoline operation, emissions from PHEV:s would then be less than half the emissions of a standard car, when running in electric mode.

Keywords: PHEV integration, power generation system, wind power,, CO2 emissions

1 Introduction

An electrification of vehicles has been suggested as a way to both reduce emissions (primarily CO_2) and increase security of supply of the transportation sector. However, in most countries electricity generation comes to a large extent from fossil fuels and when switching from gasoline to electricity the reduction in CO_2 emissions is therefore not obvious. On the other hand, it has also been proposed that an electrification of vehicles could facilitate the accommodation of intermittent generation, such as wind power [1, 2]. In a wind-thermal power system, the intermittent nature of wind power results in variations in the load of the thermal units in the system. The thermal units have two main alternatives to manage these variations; either some units will be started/stopped or some units will decrease their production level to run at part load. If the variation is due to an increase in wind power generation there is a third option; to curtail the wind power. PHEV:s can reduce the variations in load on the thermal units by altering the profile of the electric load or by providing the system with the flexibility to freely distribute some of the load in time using the PHEV batteries as storage. The impact on the profile of the electric load in a power system due to PHEV integration depends on the power demand of the vehicle fleet (i.e. the number of gasoline vehicles replaced by PHEV:s and the extent to which their electric capacity is utilized) and the choice of PHEV integration strategy. To which extent PHEV:s provide flexibility in load distribution also depends on integration strategy. In this study the consequences from integration of PHEV:s in a wind-thermal power system (i.e. a system made up by condensing power plants, combined heat and power plants and wind power plants) have been evaluated under four different integration strategies. These strategies have different impact on the load profile and provide the system with various degrees of flexibility.

Power system integration of PHEV:s has been the topic of a handful of papers during recent years. Denholm and Short [3] have investigated the influence of large-scale PHEV integration on the power system and found that if the 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 [4] on the other hand find 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.

The benefit of discharging PHEV:s to provide the power system with electricity, so called Vehicle-to-Grid (V2G) is analysed by Denholm and Short [3], who conclude that V2G participation on the market for ancillary services, i.e. regulation and spinning reserve, is associated with a higher revenue for the PHEV owner than an active participation on the day-ahead market (i.e. replacing peak capacity). V2G participation on the day-ahead power market is concluded to be limited to periods of unusually high prices. This is in agreement with the findings of Kempton and Tomic [1] who suggest an initial niche for fleets of PHEV vehicles (such as service and delivery cars) with a predictable availability on markets for ancillary services. However, as the number of PHEV:s increases and investment costs decrease, Kempton and Tomic [1] 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 is provided by wind power some 8-38% of the light vehicle fleet would be able to provide the back-up and storage required.

Kempton and Dhanju [5] 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 by 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. Furthermore, from analyzing wind speed data they found that the duration of a typical shortfall event (i.e. where wind power generation would be less than 20% of rated power) is normally 3 hours or less and can thus be handled by rather small energy storage capacities. They conclude that the required energy storage capacities are in the range of the storage that could be provided by PHEV:s. Kempton and Lund [2] have evaluated the effects of an electrification of vehicles on a power system with large-scale wind power and they conclude that the curtailment of wind power decreases as vehicles are integrated in the power system, both if charging is fixed in time, but allocated to hours of low demand, and if the charging can be freely distributed.

The work by Kempton and Lund is similar to this study in that it also considers an integration of vehicles (in their case electric vehicles rather than PHEV:s) under strategies offering various degrees of flexibility (in their work referred to as "intelligence") in a power system with large-scale wind power. However, in the modelling approach by Kempton and Lund the generation units are aggregated according to technology and the variation management strategy is chosen exogenously.

In the present study, large power generation units are modelled individually and variation management is part of the optimization. After the evaluation of the impact of PHEV:s on the power system, results from the simulations are related to the private vehicle fleet to identify the share of the fleet which has to be converted in order put the possible emission reduction into effect, and to compare emissions of a vehicle run on electricity to the emissions of a vehicle run on gasoline. We also study the costs of implementing different integration strategies and compare these to the reduction in costs of the power system due to the PHEV integration. Finally, we make a short evaluation of the different integration strategies from a car owner perspective.

2 Method

The analysis is based on modelling the integration of PHEV:s into a wind-thermal power system with power plant configuration based on that of western Denmark. Western Denmark is chosen due to that there is already at present a high grid penetration of wind power and that wind power generation data is available. Yet, western Denmark is only used as a type system and the results cannot be used for absolute comparison with the present system, mainly due to that this study assumes that there is no exchange (import/export) with surrounding electrical systems. The reason for this approach is to be able to focus on the PHEV–power system interaction and that in fact, many regions do not have the possibility to apply hydropower as a means to moderate fluctuations in wind power, which is the case of Denmark and western Denmark (Nordic hydropower). Another important difference between the model and the real system is that the model allows wind power curtailment. The model simulations have been used to evaluate the impact of PHEV:s on total power system costs, total power system emissions and the generation pattern of the power generating units in the system.

The electric load from a PHEV fleet depends on;

- the total number of PHEV:s and their total annual driving distance,

- the specifications of the PHEV:s,

- the daily driving pattern, the road profiles and traffic situations,

- the strategies and possibilities for charging, power rating of domestic grid connection and the economic conditions.

Several of these factors, such as the specifications of the PHEV:s and the charging conditions, are yet to be determined by future development of the PHEV technology. In order to minimize the number of assumptions with high uncertainty, the PHEV electricity consumption is specified relative the total electricity consumption of the system studied. Three PHEV consumption levels have been investigated; 3%, 12% and 20% of the total electricity consumption (i.e. 0.6, 2.5 and 4 TWh/year of the total electricity consumption of 20.6 TWh/year in western Denmark). Thus, the total electricity consumption is held constant, while the PHEV share is varied. This means that the electricity consumption of households, industry etc is scaled in each integration case in order to keep the total electricity consumption constant (i.e. that from all consumers including PHEV:s). The heat consumption (which influences the combined heat and power generation) is assumed to be the same all integration strategies and at all PHEV shares of consumption. Through this scaling, the question of additional investments in generation is avoided, and emissions from the power system at different PHEV electricity consumption levels can be directly compared and related to the integration only (and assumptions on the characteristics of additional generation capacity due to expansion of consumption from PHEVs are avoided).

The profile of the PHEV electricity consumption is related to the PHEV availability to the grid and the charging time of PHEV:s. Four different PHEV integration strategies are modelled:

1. S-DIR. The charging time of the PHEV:s directly follows the driving and the PHEV:s are charged as soon as they return home (we assume that the PHEV:s will always be recharged due to the relatively low cost of driving on electricity compared to gasoline)

2. S-DELAY. The charging time of the PHEV:s is delayed (i.e. with a timer) to minimize average correlations with demand,

3. S-FLEX. The distribution of the charging in time is not fixed under this strategy, and charging of PHEV:s can take place when it is most favourable from a power system perspective. Yet, the maximum charging and discharging is restricted to the power rating at which the PHEV is available to the grid (availability depends on the time of the day) and the fleet of PHEV:s must be fully charged within specified time frames.

4. S-V2G. The power system is free to charge and to discharge PHEV:s as desired. There is a value of charging and

discharging based on that the option is to run the PHEV on gasoline. Maximum charging and discharging is restricted to the power rating at which the PHEV is available to the grid (as for S-FLEX) and the state of charge (SOC) of the batteries. The SOC of the batteries depends on charging and discharging history and the daily driving pattern for which electricity could have been used.

Thus, the S-FLEX and S-V2G strategies make use of the possibility to adjust the charging and discharging of the PHEV:s to match irregular variations in generation and non-PHEV load. PHEV:s which are about to be charged can be used as up-regulating reserve capacity under these strategies (S-FLEX and S-V2G), since the charging of vehicles can be interrupted at any time and thus the overall load be decreased. The benefit of providing regulation capacity is in this work accounted for as an avoided cost to keep thermal capacity available. The control power market is not part of the optimization.

The simulations have been performed using a modelling package with BALMOREL as basis. BALMOREL is a linear programming model developed by Ravn [9]. It optimizes the electricity and heat production, over some geographical scope, with respect to costs[1] under the assumption that there is perfect competition on the heat and power markets. Special features can be added to BALMOREL by the means of add-ons. In order to simulate the PHEV integration, two add-ons have been developed; one designed to take the impact of variability into account, and one which governs the charging of PHEV:s under different integration strategies. The first add-on (BALWIND) has been explained in a previous work by the authors [10]. Its main features are the inclusion of start-ups and part load operation of power plants in the optimization by the means of a binary variable. The ability of power generating units to manage variability is thus considered in the dispatch. The second add-on, designed to handle PHEV:s, includes restrictions on the displacement of PHEV load under the different integration strategies and assures that the PHEV demand for electricity is satisfied.

A time resolution of one hour has been used in the modelling. In order to limit the computational time of simulation of an entire region (i.e. western Denmark), a full year is represented as the weighted results of simulations of one week per season (summer, autumn, winter, spring).

The impact of PHEV:s on power system emissions is related to the private vehicle fleet by allocating any increase/decrease in power system emissions to the electricity consumed by the PHEV:s. Thus, the average emissions per unit of electricity used in the PHEV:s are given by the average emissions per unit of electricity generated in the wind-thermal system without PHEV:s subtracted by the decrease in system emissions per unit of electricity consumed by the PHEV:s as these are integrated. Using the results of these calculations in combination with estimates of vehicle efficiency, the emissions of the PHEV:s in electric mode can be compared to the emissions of vehicles running on gasoline.

[1] BALMOREL is designed to maximize consumer utility subtracted with production costs, thus there is dependence between demand and cost included. However, in these simulations the total electric load is constant.

Emissions from the PHEV:s (with an efficiency set to 85%) have been compared to the emissions of future vehicles running on gasoline at two different efficiencies, 30% (referred to as standard gasoline car) and 45% (referred to as efficient gasoline car), i.e. both figures considerably higher than today's standard cars. The 30% level can be seen as an assumption of future standard cars, whereas the latter level represents a future hybrid electric vehicle (HEV).

3 Data and Assumptions

Each unit in western Denmark with rated power above 80MW is modelled on an individual basis. Units with rated power less than 80MW are aggregated into four type units depending on fuel (i.e. wind, gas, coal and biomass). An aggregate of 500MW oil-fired reserve units has been added to the system to enable simulations in which peak power requirements are higher than in the present system. Wind power generation is based on wind power production data from western Denmark in 2005 [11]. Non-PHEV electricity consumption is based on data from the same time period [11]. In the four weeks simulated the wind power grid penetration was 21.5% in the cases where no wind power was curtailed.

Under the S-V2G strategy, the power system can choose to use electricity stored in the batteries of the vehicles to meet the electric load. Whether this option will be used or not depends on the cost of generating that electricity in an available power plant compared to the economic compensation which the car owner requires to provide the V2G-service. For the car owner, the value of the electricity in the battery obviously relates to the distance which can be driven on that electricity. If, instead, the electricity is sold to the power system, it is assumed that the same distance will be covered by driving on gasoline which is combusted in the internal combustion engine. The value of the electricity (i.e. the cost of the V2G service) thus equals the cost of the gasoline necessary to cover the same distance. Gasoline prices have been related to the cost of electricity by studying the historical relation between the fuel oil price and the gasoline price [2].

Since the Danish traffic statistics only provides a measure of the traffic load, the availability of the PHEV batteries to the grid during workdays is based on a survey of daily travelling habits in the Stockholm area (Sweden) carried out prior to the introduction of tolls to limit congestion [13]. The Swedish survey gives indications of time at home and at the workplace from statistics on time of departure from home, time of departure from work and detours on the way. Statistics from measurements on a highway to Esbjerg [14] (town in western Denmark) indicate that Swedish travelling habits resemble the Danish habits. The availability of the PHEV to the grid is simply taken as the time between the arrival from work in the evening and the departure to work in the morning. It is assumed that average travelling time between home and work is 1 h in each direction [13].

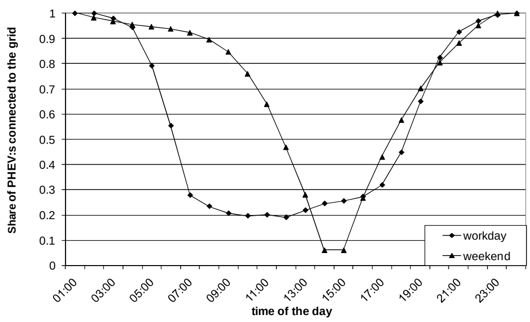
Detours are more common on the way from work (35% make detours) than on the way to work (19% make detours) [13]. A detour in the morning normally involves dropping someone off (58% of the morning detours), whereas detours in the evening normally involve shopping (46% of the evening detours). Since dropping

[2] It was found that the gasoline price was 23.7EUR/MWh higher than the fuel oil price on the average, excluding taxes. Source: [12]

someone off generally is not time consuming, this detour is not assumed to affect the time of arrival at work. However, shopping normally takes some time. Thus, 35% of the PHEV:s are assumed to be available to the grid with a delay of 2h from the work departure time given in Figure 1b (makes a detour), whereas 65% arrive home 1h after the departure time (i.e. drive directly home). It has been arbitrarily chosen to allocate 20% of the PHEV electricity consumption to daytime, representing workplace charging and, in the V2G case, possible discharging. It is assumed that vehicles which are charged also at daytime make use of the full electric range of the battery also for this charging.

The availability of the PHEV batteries to the grid during weekends is based on the previously mentioned road measurement of traffic load on the highway to Esbjerg, since the Stockholm survey did not cover weekends. During weekends, the traffic on the highway starts later in the morning than on workdays and there is a peak in the early afternoon, rather than peaks in the morning and in the evening. It has been arbitrarily chosen that the average travelling time from the point of measurement (i.e. the position along the highway where the cars were counted to determine the traffic load) to home is 1 h and that charging during daytime is not available.

Figure 1 gives the assumed relation between the vehicles and the grid over the day based on an analysis of statistics of travelling habits [13] and traffic load [14]. The share of connected PHEV:s follows the daily pattern shown in Figure 1a for workdays and weekend days (Saturdays and Sundays assumed the same). The daily profile of the share of PHEV:s charging from the grid as assumed in the simulations in the S-DIR integration case is given in Figure 1b. For the S-DELAY strategy, this curve is simply shifted in time (i.e. charging is delayed 5h). Figure 1c shows the possible discharge of PHEV batteries due to driving under the S-V2G strategy. If the most cost-efficient strategy from a power system perspective is to charge the vehicles so that the electricity in the batteries is sufficient for the



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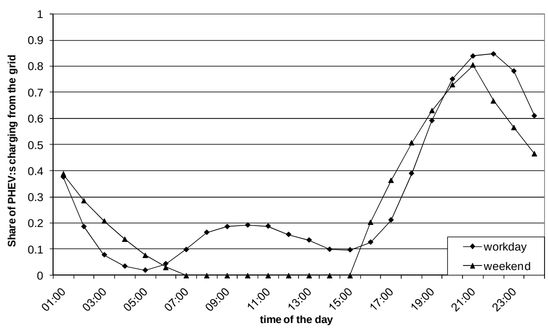

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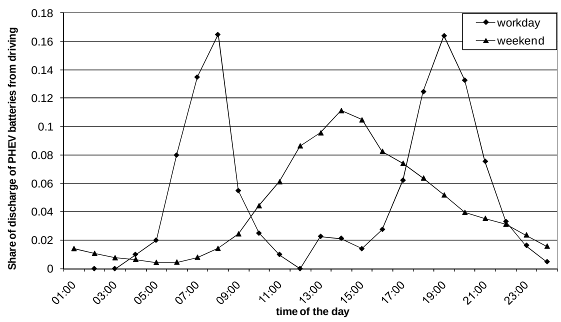


c.

Figure 1. Relation between vehicles and the grid over the day based on an analysis of statistics of travelling habits [13] and traffic load [14]. a: Share of PHEV: s available to the grid (S-FLEX and S-V2G). b: Fixed charging pattern under the S-DIR strategy given as share of the PHEV:s. c: Possible discharge of PHEV batteries due to driving (S-V2G).

driving as given by Figure 1c, the PHEV electricity consumption under the S-V2G strategy equals the PHEV consumption under the other strategies, i.e. corresponding to maximum PHEV electricity demand.

The distribution of the PHEV load is based on the assumption that the PHEV:s are charged at domestic voltage level. The maximum charging power of the PHEV:s is thus limited by the power rating of the domestic grid connection, and the charging time of an intermediate sized battery (~10-20kWh) is in the range of a few hours. Under the S-DIR and S-DELAY strategies, it is assumed that it takes six hours to fully charge the vehicle (i.e. only 1/6 of the connected capacity can be charged each hour). This has a smoothening effect on the PHEV load. Under the S-FLEX and S-V2G strategies, the loading is optimised, but the maximum energy which can be absorbed, and for V2G also delivered, by the PHEV:s each hour is also limited to 1/6 of the connected capacity. The charging time is highly dependent on future development of the PHEV and battery technology and associated equipment. With a development towards more rapid charging, due to higher power rating of PHEV grid connection (i.e. in the case of a wide establishment of charging stations) or due to smaller battery capacities, other effects might evolve than the ones presented here.

4 Results and Discussion

Figure 2 shows the impact of PHEV:s on CO_2-emissions associated with electricity generation for the four different PHEV integration strategies. 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 directly follows the driving and the PHEV:s are charged as soon as they return home (S-DIR) there is a clear increase in CO_2-emissions from the power system as the share of PHEV electricity consumption increase above the lowest level modelled. The other integration strategies give emissions in between the S-V2G and the S-DIR cases. The differentiation in impact on system emissions is due to the various degrees in which the PHEV load is adjusted to the load imposed on the system by households and industry and to the wind power generation. In the case of low emissions the PHEV load is well adjusted and the thermal units can operate continuously at a level of efficient performance.

Figure 3 illustrates how the PHEV load is well adjusted to the load of households and industry under the S-DELAY strategy, in difference to the PHEV load under the S-DIR strategy. Under the S-FLEX and S-V2G strategies the PHEV load is adjusted to irregular variations in the power generation system, such as variations in wind power generation, as well as the regular variations imposed on the system by households and industry. Thus, these strategies therefore give

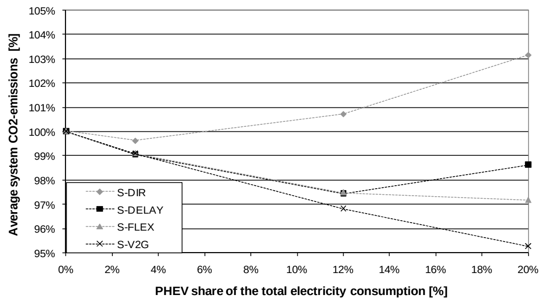
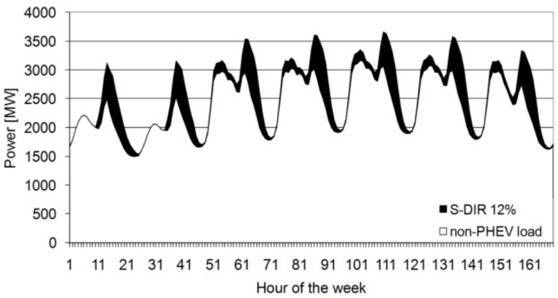


Figure 2. Impact on power system CO2 emissions due to PHEV integration for different integration strategies and PHEV load (vehicle emissions not included).

additional reduction in system emissions as shown in Figure 2.

A comparison of the emissions from a vehicle supplied by electricity from the wind-thermal system to a vehicle fuelled with gasoline can be found in Table 1. It can be concluded that even though the CO2-emissions related to gasoline (about 255kg/MWh) are significantly lower than those of coal (about 349kg/MWh), the emissions of the PHEV:s are lower than the emissions of the standard gasoline cars (30% efficiency) at all implementation levels and under all integration strategies. The PHEV:s have lower emissions than the efficient gasoline cars (45% efficiency) under all active integration strategies at low and medium PHEV shares.

At a 20% PHEV share of consumption, however, the fleet of PHEV:s will only have lower



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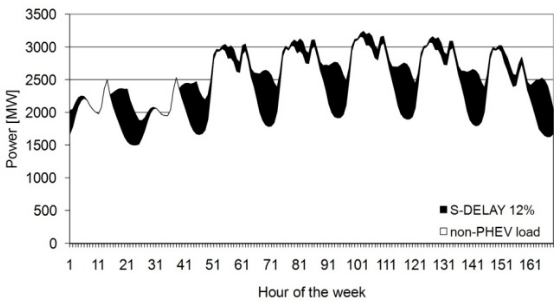

b.

Figure 3. Total electricity consumption in the modelled system divided into consumption of household and industry (white) and consumption of vehicles (black). for a 12% PHEV share of electricity consumption. **a:** S-DIR integration strategy. **b:** S-DELAY strategy.

Table 1. Emissions of PHEV:s relative to efficient gasoline cars (eff.) and standard gasoline cars (stand.) under different PHEV integration strategies and shares of electricity consumption. Savings in system emission due to PHEV:s are allocated to the vehicles. Assumed efficiencies: PHEV (85% efficiency), efficient car (45% efficiency) standard car (30% efficiency).

	20% PHEV:s		12% PHEV:s		3% PHEV:s	
Integration Strategy	PHEV /eff.	PHEV /stand.	PHEV /eff.	PHEV /stand.	PHEV /eff.	PHEV /stand.
S-DIR	1.42	0.95	1.30	0.86	1.04	0.69
S-DELAY	1.13	0.75	0.95	0.63	0.76	0.51
S-FLEX	1.04	0.69	0.95	0.64	0.78	0.52
S-V2G	0.92	0.61	0.89	0.59	0.79	0.53

emissions than a fleet of efficient gasoline vehicles if the S-V2G strategy is applied. In the wind-thermal system without PHEV load, the average CO_2-emissions of the electricity generated is 588kg/MWh. Emissions from running a PHEV on this electricity (i.e. if the PHEV load would have no impact on the load profile) would be 15% higher than emissions from running on gasoline in an efficient car. However, if allocating the reduction in power system emissions due to active PHEV integration to the PHEV:s, the CO_2-emissions of the electricity used by PHEV:s is down to 367kg/MWh (i.e. at a 3% PHEV share under the S-V2G strategy). Emissions from PHEV:s are then 24% lower than the emissions from an efficient gasoline car. Whether the integration of PHEV:s is considered as a means of reducing emissions or not therefore depends on if the benefit of PHEV:s providing flexibility to the power system are accounted for.

From a CO_2 reduction perspective, the S-V2G strategy is the preferable integration alternative. However, 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 agreements for which the transmission system operator has full control of the charging and discharging of the vehicle whereas the car owner is without influence on in which state 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.

5 Conclusions

A modelling package for simulating the effect of PHEV integration in a wind-thermal power system is developed. From the simulations it can be concluded that in a power system where variations in load and generation results in start-ups and part load operation with high emissions, PHEV:s can substantially reduce the emissions from the power generation system. With a 20% PHEV share of the electricity consumption, the simulations of this work results in that total emissions of the power system can be reduced with 4.7% compared with a system without PHEV:s. Allocating the decrease in emissions to the private vehicle fleet, the emissions of the PHEV:s when running in electric mode can be up to 47% lower than the emissions from standard cars (efficiency arbitrarily estimated to 30%) and 24% lower than emissions from efficient cars (efficiency arbitrarily estimated to 45%). Yet, to realise a reduction in emissions at higher PHEV integration levels, an active integration strategy is required. Some reduction in emissions can be achieved simply by shifting the PHEV charging time to hours of low electricity consumption in households and industry. However, the greatest reduction potential is realised by giving some freedom to transmission system operators to distribute the PHEV load. It is important to point out that with a passive integration (i.e. S-DIR), PHEV:s in electric mode will give higher emissions than standard cars running on gasoline, since vehicles arrive home while households experience a peak in electricity consumption.

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