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Effects of electric vehicles on power system investments and operation

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RESPONSE TO REVIEWER'S COMMENTS

The Manuscript:"SDEWES11-0076 Effects of electric vehicles on power system investments and operation" has gone under review process and the decision from reviewer is: ACCEPTED as ARCHIVAL PAPER with MINOR CHANGE.

Reviewer's comments are indicated with *italic* and our responses to each of the comments are given below with normal font.

The manuscript presents a scenario analysis of the effects of the large scale implementation of electric vehicles on the power system and its required investments in the Nordic countries as well as Germany.
Some aspects of the manuscript need further explanation. Costs e.g. are assumed to be socio-economic. Electricity costs only 25% of the end-use consumer market price, while Diesel costs 50%. Are socio-economic costs realistic to model the equilibrium?

Yes, costs in the study are socio-economic, i.e. excluding taxes, tariffs and subsidies. The background for this approach is the intent to model what is optimal for the system from a socio-economic perspective. If the optimum does not correspond to what is desired for society, taxes, tariffs and subsidies can then be designed in order to reach the situation wanted. Future taxes, tariffs and subsidies towards 2030 in each of the respective countries are also difficult to predict as these will change from year to year depending on political decisions. Acknowledging your comment, it has now been made clear in the article, that socio-economic costs are used (page 5, text block 1):
"Costs in the study are socio-economic and are given in €2008".

Heat measures are introduced in the scenarios. Please explain further whether this is aimed at district heating systems or individual heat supply, and how district heating could assist in accommodating the system for larger amounts of renewable energy.

The heat measures introduced in the scenarios are aimed at district heating systems as mentioned in the article (page 2, text block 3): "Putting the impacts of EDVs into perspective, these are briefly compared to the effects of investing in heat measures in the combined heat and power (CHP) system, i.e. heat pumps, electric boilers and heat storages, forming alternative ways of increasing system flexibility." In order to make this clearer, the formulation has now been modified to:
"Putting the impacts of EDVs into perspective, these are briefly compared to the effects of investing in heat measures in the <u>district heating system</u>, i.e. heat pumps, electric boilers and heat storages, forming alternative ways of increasing system flexibility."
As requested, it is now explained how heat measures in the district heating system can assist in accommodating the system for larger amounts of renewable energy (page 9, text block 2):
"The reason for the increased investments in wind power when implementing EDVs is that their flexible charging/discharging makes it more profitable to utilise the variable production from wind power. Correspondingly, heat pumps and electric boilers in the district heating system support wind power investments as they represent a flexible electricity demand that can be activated when electricity prices are low, corresponding to periods with large amounts

of wind power. Heat storages facilitate increased wind power investments as they increase the flexibility of heat pumps and electric boilers and improve the integration of wind power into CHP systems: when wind power is high, possibilities for reducing power production from CHP plants are improved since heat demand can be satisfied from the heat storage, and when wind power is low, possibilities for increasing power production at CHP plants are improved since surplus heat production can be stored."

Possible investments in new nuclear capacities are missing in the scenarios, most likely for Finland and Sweden. New hydropower in Norway as well. It seems unrealistic to offer new coal-fired power plants in Norway to meet additional demands. Are national scenarios and policies included?

National scenarios and policies are included in the sense that nuclear power investments in Denmark, Norway, Germany are excluded based on national policies. The same applies for Sweden considering that the Swedish government has decided that investments in new nuclear power plants can only be made if replacing existing plants. If required, new nuclear power capacities in Finland and Sweden can be included (possibly in a sensitivity analysis), when submitting a revised version of the paper to a journal. Future Swedish nuclear power capacities could then be constrained to only replacing existing nuclear power plants.

Investments in new hydro power in Norway are not included since only small expansions of the Norwegian hydro power are expected towards 2030 according to Statnett (130 TWh in 2020 and around 135 TWh in 2030 compared to 128 TWh today). In a revised version of the paper, we will however consider including expected new hydro power investments in Norway. The investments in coal power in Norway are very low, and thus not important for the overall picture. If including expected new Norwegian hydro power investments, coal power investment in Norway might nevertheless be left out completely.

Finally a few general comments to the model. How does the model address long term investments? It seems that the investment suggestions change dramatically from one calculation period to the next, which seems incompatible with the long time perspectives in power system investments. It may also suggest that the model is not in a stable state or that the variability of input yields exaggerated model response.

In the model, investments are constrained by technological possibilities, geographically specified potentials and restrictions and fuel restrictions. Furthermore, allowed increases in wind power capacities per year are constrained to a level considered realistic. Within these constraints, the model finds the optimum and as such the model responses are kept within reasonable limits, i.e. the model is in a stable state. For investments, the main costs components are investment costs and variable operation costs including fuel costs and CO_2 emission costs. The investment in each year is made based on conditions for the given year integrating investment and operation costs.

The large changes in wind power investments observed from e.g. 2020 to 2025 in Denmark and Germany are as explained in the article a result of improvement in wind power technologies, decommissioning of existing wind power capacities and increasing CO_2 and fuel prices. In particular, the significant decommissioning of Danish and German wind power capacities from 2020 to 2025 is likely a key factor (from 3,154 MW to 0 MW in Denmark and from 22,967 MW to 10,886 MW in Germany). We have now pointed this out in the article (text modified on page 9, text block 4):

"Due to increasing fuel and CO_2 prices and the relatively large improvement of wind power technologies, the conditions for wind power investments generally improve over the period. This is clearly illustrated for the cases of Denmark and Germany. Moreover, existing wind power capacities in Denmark and Germany are significantly decommissioned from 2020 to 2025 (from 3,154 MW to 0 MW in Denmark and from 22,967 MW to 10,886 MW in Germany), which is likely part of the explanation for the large increase in wind power investments in Denmark and Germany in 2025."

Further, is it realistic to attempt conclusions on the German power import from Denmark alone? Or is the system boundary delineation, which excludes the by far largest part of UCTE from offering import to Germany, the culprit here?

Yes, the German electricity import from Denmark observed in 2015 is likely a result of the system boundary delimitation which includes Denmark, Sweden, Norway, Finland and Germany. In the real system, German electricity import from other countries also occurs. Embracing your comment, we have now made this clear in the paper (page 4, text block 1):
"The system boundary has to be set somewhere and as the boundary applied covers only Denmark, Sweden, Norway, Finland and Germany, German electricity exchange with other countries than the Nordic, e.g. France, is not represented. The results for Germany should therefore be interpreted with this in mind."
In addition, we have now avoided specifying that German import comes from Denmark (page 9, text block 6):
"In Germany, EDVs will mainly be driving on imported power in 2015, coal and import in 2020 and then a mix of mainly coal and wind power in 2025 and 2030."

In a revised version of the paper we will if requested include the most important German electricity import not covered by the system delimitation.

At last, it is not clear how the model handles existing, but moth-balled capacities of especially coal-fired power plants as well as gas turbines. Is their re-commission included in the model?

In the model, existing power plants are decommissioned based on technical life times and moth-balled capacities are not included.

Effects of electric vehicles on power system investments and operation

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ABSTRACT

In this study, it is analysed how a large-scale implementation of plug-in hybrid electric vehicles and battery electric vehicles in the Northern European countries, Denmark, Finland, Germany, Norway and Sweden, will influence power system investments and operation towards 2030. Increasing shares of electric vehicles are assumed; comprising 2.5 %, 15 %, 34 % and 53 % of the private passenger vehicle fleet in 2015, 2020, 2025 and 2030, respectively. Results show that if charged/discharged intelligently, already at vehicle fleet shares of 2.5 %, electric vehicles can facilitate increased wind power investments and reduced need for new coal/natural gas power capacities; the latter due to vehicle-to-grid capabilities. Wind power can be expected to provide a large share of the electricity for electric vehicles in several of the countries analysed, particularly in the long term. However, coal based power will particularly in the short term also comprise a large part. The effects on investments and production vary significantly from country to country and are sensitive to variations in fuel and CO_2 prices. Total CO_2 emissions for power, heat and private passenger vehicles in the Northern European countries are more or less unchanged in 2015 and 2020 while significant reductions can be obtained in 2025 and 2030.

INTRODUCTION

Electric drive vehicles (EDVs) are considered to play an important role in transforming the transport sector towards sustainability. Various fields related to EDVs have been studied recently, i.e., building of infrastructure, how to move towards 100% renewable energy in the transport system, and potential benefits for vehicle owners as well as the power system. The concept of vehicle-to-grid (V2G) has been defined and explained by Kempton and Tomic in [1], where also potential benefits have been touched upon. In [2], Kempton et al. have looked more into the services to be provided by EDVs and economics of providing these services. Specific focus on peak load shaving in Japan is found in [3] and analyses of regulation and ancillary services are found in [4] and [5].

Modelling of the integrated power and transport system has only been the focus of few studies so far. McCarthy, Yang and Ogden [6] have developed a simplified dispatch model for California's energy market to investigate the impacts of integrating EDVs into the energy system. In [7], the impact on wind installations by introducing EDVs with grid-to-vehicle (G2V) and V2G capabilities have been studied, and in [8], it is investigated how it affects the power system when EDV charging is dispatched optimally. Kiviluoma and Meibom [9] analyse the influence of PHEVs, heat pumps, electric boilers, and heat storages on power

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system investments in Finnish high wind power scenarios. In [10], the same authors analyse the value of smart charging of EDVs compared to charging immediately when being connected to the grid. Lund and Kempton [11] have developed a rule based model of an integrated power and transport system, focusing on the value of including V2G in different wind penetration scenarios. Inclusion of investments in different vehicle types has been introduced in [12] and [13], both containing only illustrative cases. In [14], Kristoffersen et al. calculate the optimal charging patterns of EDVs when buying and selling electricity on the Nordic day-ahead power market.

The transition path towards a more sustainable transport sector has been studied with focus on how to ensure a smooth transition. In [15], the transition path towards plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) is analysed, whereas [16], [17], and [18] analyse the transition path all the way to fuel cell electric vehicles. However, in none of these studies it is investigated how transition towards sustainability in the transport system will affect the power system.

A large scale implementation of electric vehicles will not only affect power system operation but also investments. As power system investments are realised continuously, these effects are best investigated by analysing a period of several years. In this study, it is analysed how a gradual implementation of PHEVs and BEVs in the Northern European countries, Denmark, Finland, Germany, Norway and Sweden, will influence future power system portfolios and operation towards 2030. Inspired by scenarios set up the Electric Power Research Institute (EPRI) and IEA, increasing shares of electric vehicles are assumed; comprising 2.5 %, 15 %, 34 % and 53 % of the private passenger vehicle fleet in 2015, 2020, 2025 and 2030, respectively. The analyses performed are based on the model of the integrated power, district heat and transport system described in [19] and [12]. Simulations are made with five year intervals where optimal investments identified in previous years are included in the optimisations of subsequent years. Plug-in patterns based on a national investigation of transport habits are implemented as in [12] and intelligent charging/discharging is identified as part of the energy system optimisation. The results reveal the effects on power system investments, electricity generation, costs and CO_2 emissions. Putting the impacts of EDVs into perspective, these are briefly compared to the effects of investing in heat measures in the district heating system, i.e. heat pumps, electric boilers and heat storages, forming alternative ways of increasing system flexibility.

The following section presents the model, Balmorel, and the transport-addon used for the analyses. In the subsequent section, the application of the model is described including scenarios set up and input data. Finally, the last sections cover presentation of results, discussion and conclusion.

MODEL - BALMOREL WITH TRANSPORT

The integrated power and road transport system is modelled in Balmorel, which is a deterministic partial equilibrium model assuming perfect competition [9, 12, 19]. The model optimises investments in power/heat production, storage and transmission units and minimises total costs in the energy system, covering annualised investment costs, operation and maintenance costs of existing and new units, as well as fuel and CO_2 quota costs. The optimisation is performed subject to a number of constraints including satisfaction of demands for electricity, heat and transport in each time period, renewable energy potentials, vehicle restrictions and technical restrictions on units in the power system.

Balmorel operates with three geographical entities: countries, regions and areas. Countries are divided into regions connected with transmission lines and regions are further divided into areas. The model balances electricity and road transport supply and demand on regional level, whereas district heating is balanced on area level. The optimisation is performed with a yearly time horizon. In Balmorel, the year is divided into seasons, which may be used to represent weeks, and into time periods, which may represent hours.

Transport add-on

Road transport is modelled using the add-on presented by Juul and Meibom in [12]. The transport model includes demand for transport services, vehicle investment and operation costs and electricity balancing in the integrated road transport and power system. As such, the model makes it possible to analyse interactions between the two systems and to identify benefits and optimal investments and operation. In this study, vehicle investments are fixed to an assumed development path, while investments in the power system are generated endogenously. Among the vehicle technologies available in the model, the following are included in the analysis:

- Internal combustion engine vehicles (ICEs): vehicles driving on petrol, diesel or the like. For simplicity, only one type of ICEs, namely diesel fuelled vehicles, are modelled
- BEVs: battery electric vehicles driving on electricity only
- PHEVs: plug-in hybrid electric vehicles driving on electricity as well as a liquid fuel, i.e. electric vehicles with range extenders using an internal combustion engine. All PHEVs are for simplicity assumed to use diesel as liquid fuel.

In the model, all EDVs are assumed to leave the grid with a fully charged battery, restricting the loading to meet this load factor. The plug-in hybrids are assumed to use the electric storage (the usable part of the battery) until depletion before using the engine. This assumption is considered reasonable due to the high efficiency of the electric motor compared to that of the combustion engine as well as the low price of electricity (average prices in the neighbourhood of €50/MWh in the simulations) compared to the price of diesel (64-80 €/MWh in 2015-2030, see Table 5). Moreover, the batteries have no loss of power before almost depleted, leaving the motor able to perform as demanded until down to the minimum state of charge.

Integrating the power and transport systems as well as introducing intelligent charging and discharging requires a number of additions to the existing system, e.g. communication between vehicles and the power system, aggregators or the like dealing with the system operator and agreement upon connection standards. In the model, all such changes are assumed to be in place. The model works with a capacity credit restriction ensuring enough production capacity to meet peak power demand as presented in [9]. Due to V2G capabilities of BEVs and PHEVs, they are able to contribute in meeting peak power demand. The modelling of this contribution is taken from the PhD thesis by Nina Juul [20].

APPLICATION

The model includes the electricity sector, the district heating sector and the part of the road transport sector comprising private passenger vehicles. With the intent to obtain reasonable computation times, Norway, Sweden and Finland are each treated as one power region. Germany is aggregated into two regions, representing the transmission bottlenecks between Northern Germany with its large share of wind power and the large consumption centres in Central & Southern Germany. Denmark is divided into two regions: Western Denmark being

synchronous with the UCTE power system and Eastern Denmark being synchronous with the Nordel power system. The system boundary has to be set somewhere and as the boundary applied covers only Denmark, Sweden, Norway, Finland and Germany, German electricity exchange with other countries than the Nordic, e.g. France, is not represented. The results for Germany should therefore be interpreted with this in mind.

In order to capture wind power fluctuations and to obtain a reasonable optimisation of power flows between grid and vehicles, an hourly time resolution is chosen. To ensure reasonable computation times, 7 weeks are simulated and weighted to represent a full year. Calculation time for a model run with EDVs and heat measures covering 2015, 2020, 2025, and 2030 with this time resolution is approximately 24 hours on a 3.4 GHz quad core computer with 8 GB RAM.

The assumed implementation of EDVs is based on scenarios set up by the Electric Power Research Institute (EPRI) [21] and IEA [22]. In the Medium scenario in [21], a development in PHEVs new vehicle shares as outlined in Figure 1a is assumed. Based on the relative development in sales of PHEVs and BEVs towards 2030 in the Blue Map scenario in [22], we assume BEV market shares corresponding to half of the PHEV new vehicle shares. Applying an average vehicle lifetime of 16 years, the resulting development in the vehicle fleet shares towards 2030 is illustrated in Figure 1b. Consequently, EDVs are assumed to comprise around 2.5 %, 15 %, 34 % and 53 % of the vehicle fleet in 2015, 2020, 2025 and 2030, respectively.
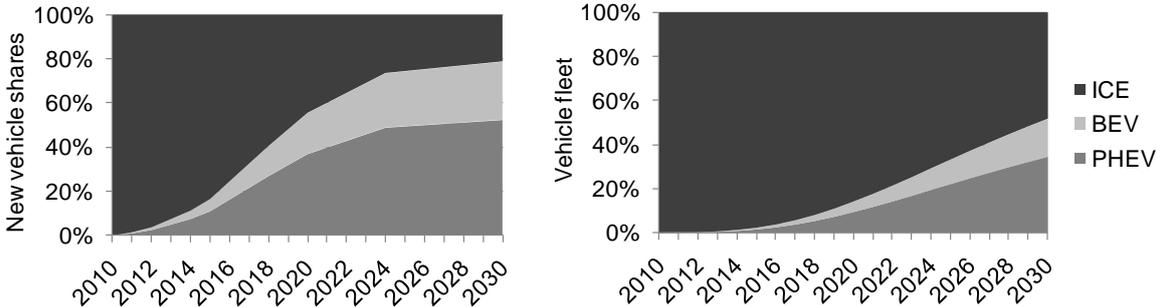

Figure 1a) Development in Plug-in Hybrid Electric Vehicles (PHEV) new vehicle shares in the Medium scenario in [21] and illustration of the assumed relation between Battery Electric Vehicle (BEV) and PHEV new vehicle shares based on the Blue Map Scenario in [22]. b) Assumed gradual penetration of PHEVs and BEVs in the vehicle fleet.

Scenarios are set up with/without gradual EDV implementation and scenario variants are created with/without the possibility to invest in heat measures. Resultantly, four main scenarios are analysed:

	Base	EV	Heat	EVHeat
Electric drive vehicle implementation		+		+
Inv. in heat storages, heat pumps and electric boilers allowed			+	+

Input data
Electricity, district heating and transport demands and annual driving per vehicle are all given exogenously as data inputs to the model (see Table 1 and 2).

Table 1. Electricity demand (TWh/yr) / District heating demand (TWh/yr) / Transport demand (10^9 person km/yr) given in rounded numbers

	2010	2015	2020	2025	2030
Denmark	33 / 28 / 57	34 / 28 / 60	34 / 28 / 63	35 / 28 / 66	38 / 28 / 69
Norway	119 / 2.7 / 53	124 / 2.8 / 55	127 / 2.8 / 57	128 / 2.8 / 59	129 / 2.8 / 61
Sweden	141 / 45 / 112	147 / 46 / 117	150 / 47 / 121	152 / 47 / 125	153 / 46 / 130
Finland	89 / 45 / 72	95 / 50 / 73	99 / 55 / 73	101 / 56 / 73	104 / 56 / 73
Germany	554 / 94 / 1025	585 / 96 / 1069	600 / 100 / 1092	614 / 101 / 1103	620 / 102 / 1116

Sweden, Finland, Germany: [23], Norway (non-EU country): scaled based on current relation between Norwegian and Swedish demands/number of cars. Denmark, electricity and district heating: [24], transport: based on [25], [23].

Table 2. Annual driving for each vehicle type

km/yr	2010	2015	2020	2025	2030
ICE/PHEV	18,009	18,072	18,401	18,676	19,126
BEV		10,230	10,230	12,671	12,671

The expected development of vehicle technologies in terms of costs, efficiencies, electric storage capacities and battery ranges is taken into account. The data applied for the different vehicle technologies and vintages are given in Table 3. Costs in the study are socio-economic and are given in €2008.

Table 3. Vehicle technology data.

Veh. type	Vin- tage	Inv. cost (€/yr)[a] [22],[26]	O&M cost (€/yr) [26]	Elec.stor. cap.[b] (kWh) [22]	Eff. (km/kWh) [12][c]	Bat. range (km)[d] [12],[27]
ICE	2015	1,058	1,168	-	1.8	-
	2020	1,058	1,168	-	1.9	-
	2025	1,058	1,168	-	1.9	-
	2030	1,058	1,168	-	2.0	-
BEV	2015	3,035	1,101	40	5.5	220
	2020	2,509	1,101	43	6.0	260
	2025	1,962	1,101	47	6.5	303
	2030	1,745	1,101	50	7.0	350
PHEV	2015	2,122	1,168	12	5.5	65
	2020	1,784	1,168	11	6.0	65
	2025	1,521	1,168	10	6.5	65
	2030	1,387	1,168	9	7.0	65

[a] A discount rate of 5 % is applied in fixed prices based on [33].
[b] The usable storage capacity of the battery.
[c] 5 km/kWh for BEV/PHEV vintage 2010 and 7 km/kWh for vintage 2030 [12].
[d] Bat. range of 150 km for BEV vintage 2010 [27] and 350 km for vintage 2030 [12].
To yield values for all vehicle vintages, source data are supplemented with linear interpolation.

As in [12], plug-in patterns for BEVs and PHEVs have been derived from driving patterns obtained from the investigation of transport habits in Denmark [28]. In this regard, it has been assumed that the EDVs are plugged-in at all times when parked. Moreover, it is assumed that driving habits are the same for all the countries in the simulation. An iterative process has been required in order to make the total transport demands fit with the number of each type of

vehicle, the annual driving distances for ICEs/PHEVs and BEVs and the driving patterns. Total transport demands thus have been adjusted and are still close to the demands in the sources used. It is assumed that BEVs of vintage 2015 and 2020 can cover trips lasting up to 2 hours (corresponding to 115 km) yielding an annual driving of 10,230 km/y and that BEVs of vintage 2025 and 2030 can cover trips of up to 3 hours (corresponding to 205 km) yielding 12,671 km/y. This is considered reasonable based on the distances supported by the BEV battery capacities in Table 3; assuming that people will be reluctant to drive close to emptying the battery and that spare battery capacity will in some cases be required for a second trip in the day.

The model includes comprehensive data on capacities, efficiencies, operation costs, and technical lifetimes etc. for existing units for power/heat production, storage and transmission. As such, gradual decommissioning of existing power/heat production capacities towards 2030 is included in the model. The power system units assumed available for investment are given in Table 4.

Table 4. Technologies available for investment over the simulation period.

Technology	Fuel	Period available	Inv. cost* (M€/MW)	Variable O&M cost (€/MWh)	Fixed O&M cost (k€/MW/yr)	Lifetime (years)	Eff.**	CB	CV	Ref.
Onshore wind turbine	-	2011-2020	1.33	12.50	-	20	1.00	-	-	[29]
	-	2021-2030	1.24	11.75	-	25	1.00	-	-	[29]
Offshore wind turbine	-	2011-2020	2.50	17.00	-	20	1.00	-	-	[29]
	-	2021-2030	2.25	15.50	-	25	1.00	-	-	[29]
Steam turbine, extraction	Coal	2011-2020	1.43	7.00	-	40	0.46	0.75	0.15	[29]
		2021-2030	1.40	7.00	-	40	0.50	0.93	0.15	[29]
Open cycle gas turbine, condensing	Natural gas	2011-2030	0.32	2.40	16	20	0.37	-	-	[30]
Combined cycle gas turbine, extraction	Natural gas	2011-2020	0.52	3.20	20	25	0.59	1.55	0.13	[29, 30]
		2021-2030	0.47	3.20	20	25	0.62	1.75	0.13	[29, 30]
Steam turbine, back pressure	Wood	2011-2020	4.40	-	154	20	0.25	0.30	-	[29]
		2021-2030	3.95	-	138	20	0.25	0.30	-	[29]
Steam turbine, back pressure	Straw	2011-2020	4.35	-	174	20	0.30	0.49	-	[29]
		2021-2030	3.90	-	156	20	0.30	0.49	-	[29]
Steam turbine, extraction	Wood	2011-2020	1.68	3.20	23	30	0.46	0.53	0.15	[29]
		2021-2030	1.60	3.20	23	30	0.48	0.58	0.15	[29]
Heat boiler	Wood	2011-2030	0.50	-	24	20	1.08	-	-	[29]
Heat boiler	Natural gas	2011-2030	0.09	-	3.2	20	1.01	-	-	[29]
Heat pump ***	Electricity	2011-2020	0.65	-	6.9	20	2.8	-	-	[29, 31]
		2021-2030	0.65	-	6.9	20	3.0	-	-	[29, 31]
Electric boiler	Electricity	2011-2030	0.06	0.5	1	20	0.99	-	-	[29]
Heat storage	-	2011-2030	0.00185	-	-	20	0.99	-	-	[32]

*Based on [33], investment costs are in the model annualised with a discount rate of 5 % given in fixed prices. Investment costs for heat storage are given as M€/MWh storage. **For heat boilers and heat pumps, heat efficiency and COP, respectively; for other units, electric efficiency.

Based on [34], CO_2 prices are assumed to increase from 20 €/ton CO_2 in 2015 to 39 €/ton CO_2 in 2030, and fuel prices corresponding to an oil price of $88/barrel in 2015 and $117/barrel in 2030 (see Table 5).

Table 5. Fuel and CO_2 quota prices assumed (€/GJ) [34]

	Fuel oil	Diesel	Natural gas	Coal	Lig-nite[a]	Ura-nium	Wood	Straw	Wood waste [9], municip.waste[b]	CO_2 (€/ton)
2010	6.7	14.8	6.0	2.9	1.5	0.72	6.0	5.1	0	14
2015	8.3	17.7	8.2	2.9	1.4	0.72	6.6	5.8	0	20
2020	9.4	19.7	9.2	3.2	1.6	0.72	6.9	5.9	0	25
2025	10.2	21.0	10.0	3.4	1.7	0.72	7.2	6.1	0	32
2030	10.9	22.4	10.7	3.4	1.7	0.72	7.5	6.2	0	39

Fuel costs include distribution costs. [a]Lignite prices are assumed to correspond to half the price of coal. [b]Municipal waste is assumed to have zero cost applying a socio-economic perspective.

Wind targets and assumed onshore wind power potentials are given in Table 6.

Table 6. Wind targets for 2030 and assumed onshore wind power potentials

	Medium wind target [35]	High wind target [35]	Onshore potential
Denmark	7,291	8,020	4,500 [36]
Norway	5,980	11,970	12,000*
Sweden	10,000	17,000	17,000*
Finland	3,200	6,000	12,000**
Germany	54,244	63,587	63,600*

*Due to the large areas of these countries and uncertainties in estimating the onshore wind power potential, the maximum onshore capacity is assumed limited to the high wind power target.
** The Finnish high wind power target is considered unrealistically low and therefore, onshore wind power in Finland is assumed limited to 12,000 MW corresponding to the Norwegian high wind target.

RESULTS

Effects on power system investments

Investments in new power production capacities generated in the Base, EV, Heat and EVHeat scenario are illustrated in Figure 2. As shown, the investments cover on-shore and off-shore wind power, coal based CHP and open cycle gas turbines (OC-GT), the latter for ensuring sufficient capacity to cover peak loads.

Comparing the EVHeat scenario with the Heat scenario, the gradual implementation of EDVs can be seen to affect power system investments already when comprising only 2.5 % of the vehicle fleet in 2015. As such, in Finland, the flexibility of EDVs facilitate increased investments in wind power in 2015 and in Germany, V2G capability for covering peak loads results in a reduced need for new coal based power production capacity. In 2020, where EDVs comprise 15 % of the vehicle fleet, larger impacts can be observed mainly in Finland, where optimal investments in wind power are doubled from around 3000 MW to 6000 MW. In addition, the ability of EDVs to cover peak loads results in further reduced need for coal CHP and OC-GT capacities in Germany. At the high EDV vehicle fleet shares of 34 % in 2025 and 53 % in 2030, increased wind power investments are observed in Denmark, Germany and Norway and the ability of EDVs to cover peak loads results in a reduced need for OC-GTs in several of the countries.

Figure 2. Optimal accumulated (over each five years period) power system investments generated in the Base, EV, Heat and EVHeat scenario, e.g. investments in 2020 represent accumulated investments from 2016 through 2020.

In Finland, the assumed onshore wind power potential of 12,000 MW is reached in 2025 in the Heat and EVHeat scenario and in 2030 for the Base scenario. As such, in this case, EDVs as well as heat measures push forward the investments in wind power. Heat measures can be seen to support wind power investments in Denmark, Germany, and particularly in Sweden and Finland. The generated investments in heat measures cover heat storages for all countries, electric boilers in Denmark (54 MW-thermal(th) and 92 MW-th in the Heat and EVHeat scenario, respectively), heat pumps in Norway (44 MW-th and 22 MW-th), Sweden (374 MW-th and 2650 MW-th) and Finland (2603 MW-th and 1184 MW-th).

The reason for the increased investments in wind power when implementing EDVs is that their flexible charging/discharging makes it more profitable to utilise the variable production from wind power. Correspondingly, heat pumps and electric boilers in the district heating system support wind power investments as they represent a flexible electricity demand that can be activated when electricity prices are low, corresponding to periods with large amounts of wind power. Heat storages facilitate increased wind power investments as they increase the flexibility of heat pumps and electric boilers and improve the integration of wind power into CHP systems: when wind power is high, possibilities for reducing power production from CHP plants are improved since heat demand can be satisfied from the heat storage, and when wind power is low, possibilities for increasing power production at CHP plants are improved since surplus heat production can be stored.

The Norwegian power system already today possesses high system flexibility due to the large amount of hydro power and moreover has large wind resources in terms of obtainable full load hours. Therefore, as illustrated in Figure 2, wind power investments are already highly attractive in 2015 and 2020 even without EDVs and the assumed onshore potential of 12,000 MW is by then nearly reached. As a result, when larger EDV vehicle shares are implemented in 2025 and 2030, only small increases in wind power investments are observed.

Due to increasing fuel and CO_2 prices and the relatively large improvement of wind power technologies, the conditions for wind power investments generally improve over the period. This is clearly illustrated for the cases of Denmark and Germany. Moreover, existing wind power capacities in Denmark and Germany are significantly decommissioned from 2020 to 2025 (from 3,154 MW to 0 MW in Denmark and from 22,967 MW to 10,886 MW in Germany), which is likely part of the explanation for the large increase in wind power investments in Denmark and Germany in 2025.

Affected electricity generation
By observing the changes in electricity generation in the EVHeat scenario relative to the Heat scenario the model can reveal how electricity for the EDVs will be produced (see Figure 3). As shown, EDVs in Denmark will generate an increased coal based electricity production in 2015 and 2020 while in 2025 and 2030, the generated increased will mainly be based on renewables; mainly wind power. The increases in power production are more than enough to cover the electricity demand for the EDVs and as such, the EDVs result in increased net export; mainly due to increased export to Germany and reduced import from Norway and Sweden.

In Germany, EDVs will mainly be driving on imported power in 2015, coal and import in 2020 and then a mix of mainly coal and wind power in 2025 and 2030. The Finnish case stands in contradiction to the Danish and German cases. As such, Finnish EDVs will be driving on wind power in 2015 and 2020 until the assumed onshore wind power potential is

reached. After that point, the EDVs will be based on coal fired power production. The power production increase generated in Finland is significantly larger than the electricity demand for EDVs; mainly due to a decrease/increase in import/export from/to Sweden.

In Sweden, wind power investments are reduced in 2020, being out competed by the Finnish wind power (see Figure 2). This leads to reduced wind power production in 2020, 2025 and 2030. With its large hydro power resources, Sweden is a net exporter before the implementation of EDVs and for the larger part it is therefore cheapest to provide electricity for the EDVs by cutting down export. Further, import is increased in 2025 and 2030 and overall, Sweden changes from being a net exporter to a net importer in 2020-2030. This explains why the electricity demand for Swedish EDVs is not met by an increased domestic power production and also explains the reduction in coal based power production.
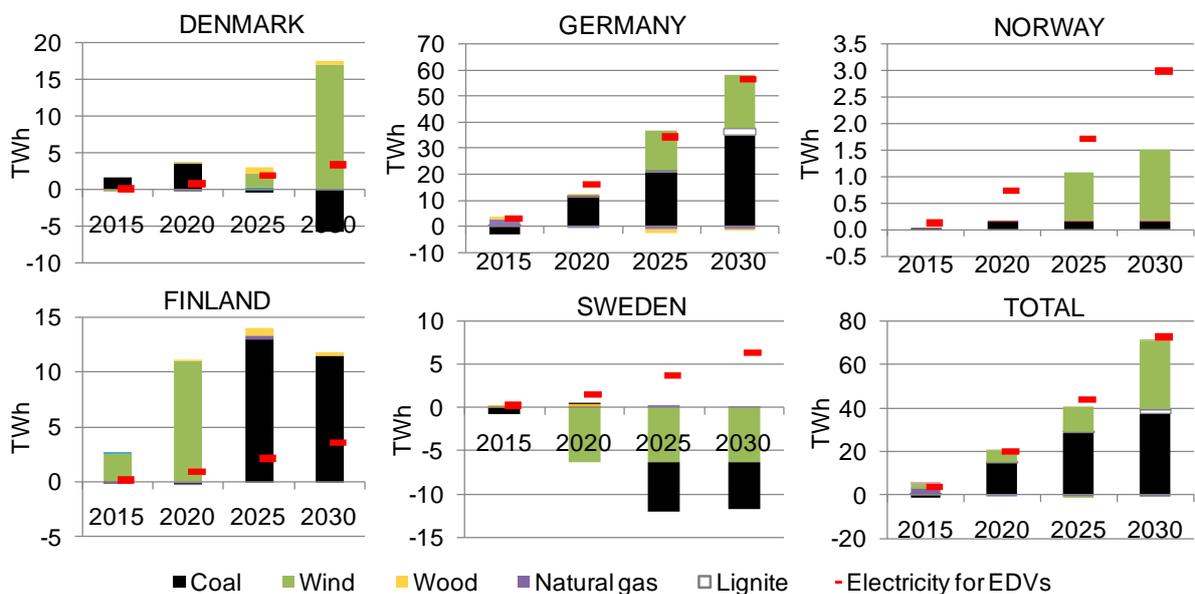

Figure 3. Changes in power production due to implementation of electric drive vehicles (EVHeat scenario relative to Heat scenario). Due to import/export and changes in electricity consumption for heat pumps and electric boilers, generated power increases will not necessarily correspond to the electricity demand for electric drive vehicles.

With its vast amounts of hydro power, Norway is a large net exporter and the most optimal response to the implementation of EDVs is therefore foremost to reduce the export. In addition, wind generation is increased in the longer term. Seen over all the Northern European countries in total, the average EDV is driven on a mix of mainly coal and wind power with increasing shares of the latter over the period.

CO$_2$ emissions
Total CO$_2$ emissions from the power, heat and transport sector are more or less unchanged in 2015 and 2020 with the implementation of EDVs (see Figure 4a). The minor CO$_2$ emission increases in these years are mainly due to the reduced investment in new coal CHP capacity in Germany in the EDV scenarios, due to V2G capability. This results in a larger production on less efficient coal based plants resulting in larger coal consumption.

In 2025 and 2030, significant CO$_2$ reductions are obtained; 15 and 34 Mtonnes, respectively, compared to the Heat scenario, corresponding to a 3 % and 6 % reduction for the transport, heat and power sector as a whole. The most important factors behind the significant

improvement in the CO_2 balance over the period are 1) the increasing share of wind power in the electricity used for the EDVs, 2) the gradual improvement in the efficiency of the EDVs and 3) the increasing shares of EDVs in the fleet. As illustrated for year 2025 in Figure 4b, while EVDs generate increased CO_2 emissions from power&heat production and fuel combustion in PHEVs, a larger CO_2 reduction is obtained by displacing fuel combustion in ICEs. It can be seen that the CO_2 reductions in 2020 and 2030 resulting from EDVs alone (EV scenario) are larger than the reductions obtained by heat measures alone (Heat scenario). For each of the countries, the EDVs provide national CO_2 reductions in all years, except for the case of Denmark and Germany in 2015 and 2020, where CO_2 emissions are increased.
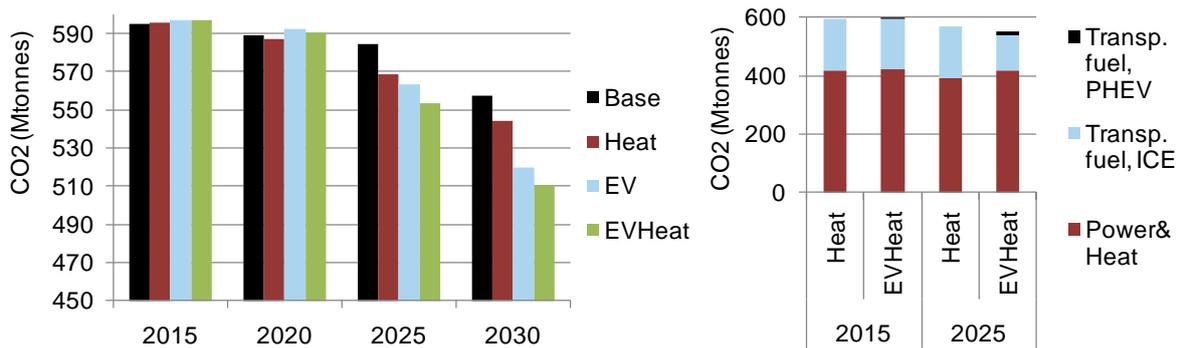

Figure 4a) Total CO_2 emissions for the simulated power, heat and transport system in the Base, Heat, EV and EVHeat scenario (Note that y-axis is set to 450 Mtonnes as min.) b) Distribution of total CO_2 emissions in 2015 and 2030 (ret til:2025), divided on sources for the Heat and EVHeat scenario (*ret til bare Total CO2 in 2015..ellers dobkonf.*).

Costs

The implementation of EDVs results in an increase in total costs for the power, heat and transport sector; around 1.4-5.5 €Billion/yr depending on the year, corresponding to around 0.8-3 % increase (see Figure 5).
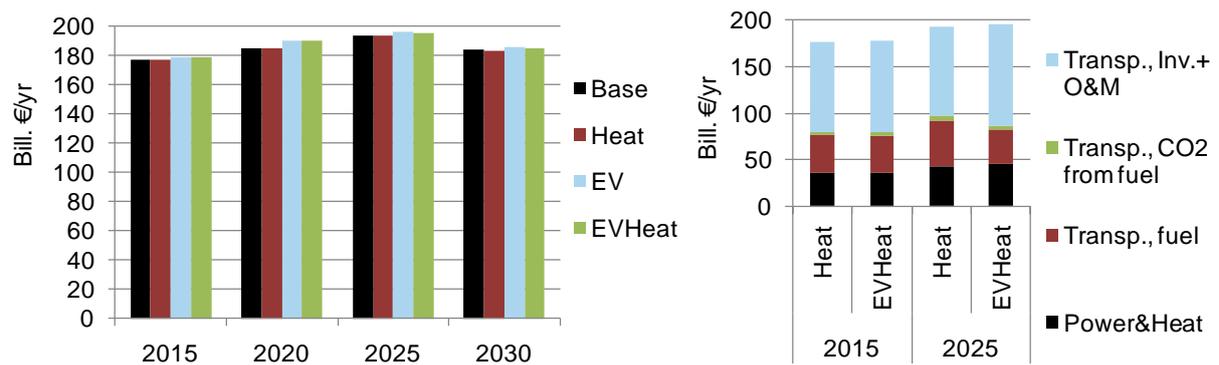

Figure 5a). Total costs for the simulated power, heat and transport system for the Northern European countries in the Base, Heat, EV and EVHeat scenario. b) Distribution of total costs in 2015 and 2025, divided on sources for the Heat and EVHeat scenario.(*ret til bare Total costs in 2015..ellers dobkonf.*).

The increase in costs is partly caused by larger investment costs per vehicle for BEVs and PHEVs compared to ICEs. Moreover, due to the lower annual driving of BEVs compared to ICEs, a larger amount of BEVs are required to provide the same transport demand. Overall, this increases total investment and O&M costs for the transport sector and the cost reduction from displacing fuel use in ICEs is not enough to compensate for this (see Figure 5b).

Considering the CO_2 reductions obtained by implementing EDVs, average CO_2 reduction costs can be estimated to 159 €/ton in 2025 and 43 €/ton in 2030. Comparing with heat measures, these can be seen to reduce total costs with 0.1-1 Billion €/yr depending on the year, corresponding to around 0.06-0.5 % reduction.

Sensitivity analysis

In a sensitivity analysis, variants of the Heat and EVHeat scenarios are set up assuming low/high fuel prices and low/high CO_2 prices, respectively:

- Fuel prices: set to low at $80/barrel in 2015 increasing linearly to $90/barrel in 2030 and at high increasing linearly from $88/barrel in 2015 (as in the standard case) to $150/barrel in 2030. Ratios between prices on different fuels in 2015 and 2030 are based on [34].
- CO_2 prices: set to low at 15 €/ton CO_2 in 2015 increasing linearly to 20 €/ton CO_2 in 2030 and at high increasing linearly from 20 €/ton CO_2 in 2015 (as in the standard case) to 60 €/ton in 2030

The sensitivity analysis shows that also at low/high fuel and low/high CO_2 prices, EDVs begin to facilitate increased wind power investments (in Finland/Norway/Sweden depending on the fuel and CO_2 price scenario) and reduced need for new coal/natural gas production capacities already at the low vehicle shares of 2.5 % in 2015. However, the changes in investments and electricity production caused by the EDVs in the different countries over the period are found to be sensitive to the development in fuel and CO_2 prices.

As such, e.g. in the low fuel price scenario, wind power is in Denmark and Germany not included in the fuel mix for EDVs before year 2030 and in the low CO_2 price scenario not at all. EDVs will in the low CO_2 price scenario to a large extent be based on coal fired power production in Denmark, Germany and Sweden. A different pattern is observed for Norway and Finland, where low fuel and CO_2 prices have the effect of increasing the relative impact of EDVs on wind power investments leading to significantly increased shares of wind power in the fuel mix for EDVs in certain years.

In the high fuel price scenario, wind power provides all electricity for EDVs in Sweden in 2010 and Norway in 2030 and around half in Finland in 2030 (for Norway and Finland due to offshore wind power investments). In the high CO_2 price scenario, investments in wood based CHP (steam turbine extraction plants) become highly competitive with coal based CHP plants. Consequently, electricity for the average EDVs in the Northern European countries is in this case almost exclusively based on renewable energy, wood or wind power, in 2025-2030 and for the large part in 2015-2020. Moreover, it can be mentioned that in the high CO_2 price scenario, electricity production for EDVs is in Finland exclusively based on wind and wood in the whole period and in Denmark, wind power comprises a large part of the electricity mix for EDVs from year 2020, i.e. five years earlier than in the standard case.

The assessment of CO_2 emissions being more or less unchanged in 2015 and 2020 and then significantly reduced in 2025 and 2030 is found to be robust towards low/high fuel prices and high CO_2 prices. However, in the low CO_2 price scenario, emissions are more or less unaffected also in 2025 and only a small reduction is obtained in 2030.

DISCUSSION

The power system portfolios generated in the study reflect socio-economically optimal solutions based on the assumption that investments in new production capacities are a result of economic rationales alone. Obviously, investments in particularly wind power are in reality also influenced by national energy and climate policies. However, if enforcing wind power investments by implementing national wind targets as minimum wind power capacity levels over the period, the effect of EDVs on wind power investments would in many cases not be reflected, resulting in unaffected wind power generation levels. This is the background for modelling wind power investments based on economic optimisation alone. The accumulated wind power capacities generated for each of the Northern European countries at the end of the simulation period are considered to be realistic as they (in the EVHeat scenario) all reach at least the medium wind target for 2030 and none exceed the high wind target drastically.

CONCLUSION

The results reveal that if charged/discharged intelligently a gradual large-scale implementation of electric drive vehicles (EDVs) will begin to facilitate increased wind power investments already at the low vehicle fleet shares of 2.5 % assumed for 2015. As such, EDVs will in a transition period with increased electrification of the transport sector support the integration of wind power into power systems. Moreover, it is found that even at low vehicle fleet shares, the vehicle-to-grid capability of EDVs for covering peak loads can reduce the need for new coal/natural gas production capacities.

Wind power can be expected to provide a large share of the electricity for EVDs towards 2030 in several of the countries analysed, particularly in the last part of the period. However, a significant share of the power for EDVs will in many cases be coal based, particularly in the short term. The effects on power system investments and production vary significantly from country to country and are found to be sensitive to variations in fuel and CO_2 prices. As such, it is difficult to draw more general conclusions regarding how electricity for EDVs will be produced over the period.

CO_2 emissions for power, heat and private passenger vehicles in the Northern European countries in total are more or less unchanged in 2015 and 2020 while significant reductions can be obtained in 2025 and 2030; 3 % and 6 %, respectively, with the fuel and CO_2 prices assumed in the standard case. The CO_2 reductions are larger than those obtained by allowing investments in heat measures, i.e. heat storages, heat pumps and electric boilers.

The EDVs result in increased total costs for power, heat and transport corresponding to average CO_2 reduction costs of 159 €/ton in 2025 and 43 €/ton in 2030. Considering that CO_2 quota prices in the neighbourhood of 40 €/ton are expected for 2030, the results indicate that EDVs can provide cost effective CO_2 reductions in the long term.

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