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Optimal configuration of an integrated power and transport system

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ABSTRACT

Integrating the power and transport system, in the future energy system planning, influences the economically optimal investments and optimal operation of the power system as well as the transport system. For analysing the integrated power and transport system a new model capable of calculating optimal investments in both power plants and vehicle technologies is presented in this article. The model includes the interactions between the power system and the transport system including the competition between flexibility measures such as hydrogen storage in combination with electrolysis, heat storage in combination with heat pumps and heat boilers, and plug-in electric vehicles.

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1. Introduction

Increasing focus on reduction in emissions of greenhouse gases and an expectation of decreasing oil reserves affects the entire energy system, including both power and transport systems. Many sustainable energy sources, i.e., solar and wind energy, are stochastic by nature. The increase in variable renewable energy sources brings along a need for a larger flexibility in the remainder of the energy system. A change in the means of transportation towards plug-in EDVs (electric drive vehicles) can lead to cleaner transportation. Incorporating the abilities to control when to charge the EDVs from the grid (grid-to-vehicle, G2V), as well as feed power back into the grid (vehicle-to-grid, V2G), results in the EDVs bringing along the desired flexibility to the energy system. Thereby, the EDVs and the power system complement each other in terms of incorporating renewable energy sources.

A number of aspects are related to integration of the power and transport systems. Research has been done within various fields such as potential benefits for the power system and the customer, infrastructure, transition paths, and actually quantifying the impact and benefits. The contribution of this work is an expansion of Balmorel, a linear optimisation model covering the power and heating sectors, to include road transport. This enables analysis of the optimal investment path and operation of an integrated power and transport system, thereby, determining optimal investment in vehicle technologies and power system technologies. Bringing electrical power into the transport sector has consequences for the entire power system in terms of, e.g., optimal mix of transmission, production and storage units, fuel consumption and CO_2 emissions. These consequences, along with impacts of introducing the concept of V2G and control of when to load and unload the batteries, can be analysed with use of the optimisation model of the integrated power and transport system.

The concept of V2G is explained in Ref. [1], where they also touch on the potential benefits of V2G. More details on the economics of EDVs providing services to the power system have been analysed in Ref. [2], and focus on potential benefits of particular services has been taken in terms of peak load shaving [3], and regulation and ancillary services [4]. Brooks [5] have looked into integration of BEVs (battery electric vehicles) in particular focussing on the benefits of the vehicles providing ancillary services. Cost comparisons of providing different kinds of services has been made in Ref. [6], comparing the different kinds of EDVs with the technologies providing the services today. Lipman [7] has provided a brief overview of potentials of G2V and V2G capabilities.

Changes and additions in terms of, e.g., aggregators dealing with the system operator, monitoring and metering of the vehicles, communication with the vehicles, connection standards etc. are needed in order to integrate the power and transport systems. In this work, these changes are assumed to have taken place, in order for, e.g., control of how to use the EDVs to work in the optimisation model. Several articles have focused on possible infrastructure solutions and system needs. In Ref. [2] Kempton et al. have suggested infrastructure in terms of, e.g., connection standards and

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business models. Business models have also been touched upon in Ref. [8] as well as thoughts on dispatch of vehicles. Brooks and Gage have in their article [9] given a brief yet detailed introduction to the relevant factors in the system setup, and [10] include suggestions on the computer functionalities. As for the transition path, studies have been made on how to ensure a smooth transition path going from today's vehicle fleet to plug-in PHEVs (hybrid electric vehicles) and BEVs [8] and further all the way to FCEVs (fuel cell electric vehicles) [11–13].

Turton and Moura [14] have looked at the impacts of the availability of V2G in terms of benefits and changes in car technology market shares, focussing on different scenarios including climate policy scenarios. Analyses of retail and lifecycle costs have been made for PHEVs [15] and BEVs [16]. Furthermore, an advanced model has been developed for modelling of vehicles (ADVISOR), returning, e.g., energy usage for different kinds of vehicles, divided on the different parts of the vehicles [17]. In optimising the future configuration of the integrated power and transport system, calculations and assumptions are made in terms of, e.g., availability, costs of vehicles, and energy usage as studied above. Hereby, the analyses mentioned above contribute to the input considerations of the model described in this article.

Integrating the power and transport systems has influence on the power production as well. Few have quantified this impact so far; however, in Ref. [18] McCarthy et al. have developed a simplified dispatch model for California's energy market to investigate the impacts of EDVs as part of the energy system. Ref. [20] has analysed the contributions of flexibility to the Danish energy system, provided by EDVs and heat pumps, focussing on the amount of forced export. Short and Denholm have in their report [19] studied the impact on wind installations with more EDVs with G2V and V2G capabilities, and in Ref. [21] the impacts on the power system with optimal dispatch of EDV charging has been studied. Kiviluoma and Meibom have analysed the consequences of having flexibility provided by PHEVs on power system investments in Balmorel [22] but without co-optimisation of the investments in the vehicle fleet. In Ref. [23], Lund and Mathiesen have analysed the needs for reaching a 100% renewable energy system, including the needs for transport on non-fossil fuels such as electricity. However, except for Ref. [22] none of these studies included investment analysis, i.e., the power system configuration and configuration of the vehicle fleet was an input to the analysis. Integrating the transport system in an optimisation model calculating investments, enable analysis of the impact of introducing EDVs on future investments in the power system. A model allowing co-optimisation of investments in EDVs and in power plants potentially determines more changes and benefits in the power system than in the papers mentioned above.

We start this article with a description of the existing Balmorel model. Section 3 provides a thorough description of the transport model. The analysed case is presented in Section 4, and results in Section 5. Section 6 concludes.

2. The Balmorel model

The Balmorel model is a partial equilibrium model assuming perfect competition [24,25]. Based on input data the model (Fig. 1) maximises social surplus subject to constraints including a) technical restrictions, e.g., capacity limits on generation and transmission, and relations between heat and power production in combined heat and power plants, b) renewable energy potentials in geographical areas and c) electricity and heat balance equations. With price inflexible demands, maximising social surplus corresponds to minimising operation costs. The model generates investments resulting in an economically optimal configuration

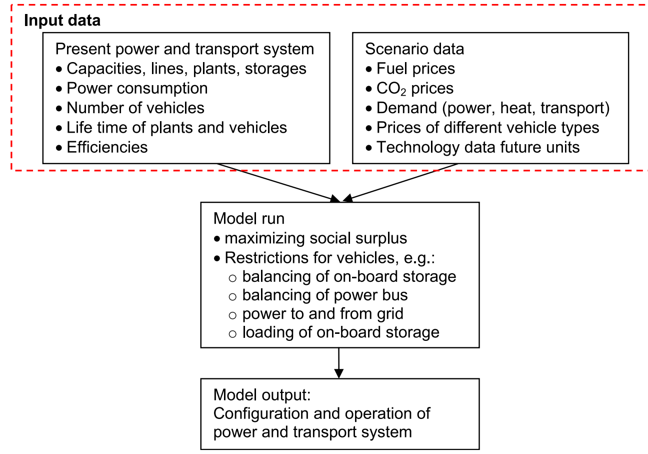

Fig. 1. Sketch of the Balmorel model including transport.

and operation of the power system. From marginal system operation costs market prices for electricity can be derived. Reruns with changes in input data allow for analysis of effects of changes.

Geographically, Balmorel works with three entities: countries, regions and areas. Countries are divided into several regions connected with transmission lines. Regions are then divided into areas. Electricity and transport supply and demand are both balanced on regional level, whereas supply and demand for district heating are balanced on area level.

Balmorel works with a yearly optimisation horizon with investment decisions based on the demand and technology costs including annualized investment costs given for the particular year. The time resolution is hourly or aggregated into fewer time steps. In long term investments the time aggregation is typically used. If an hourly time resolution is important for the modelling, a cut down in the number of weeks for the calculation is also a possibility.

3. The transport add-on

Including road transport in the power system planning is done using the optimisation model, Balmorel (Section 2). The transport system model, including transport demand, vehicle technologies, and V2G capabilities, is developed as an add-on to Balmorel (Section 3.1). Extending the Balmorel model with the transport sector enables us to analyse:

- The economic and technical consequences for the power sector of introducing the possibility of using electrical power in the transport sector, either directly in EDVs or indirectly by production of hydrogen or other transport fuels.
- The economic and technical consequences of introducing V2G technologies in the power system, i.e., BEVs and PHEVs being able to feed power back into the grid.
- The competition between different vehicle technologies when both investment and fuel costs of the vehicles and the benefits for the power system are taken into account.

3.1. The transport model

The transport model includes demand for transport services, investment and operation costs, and electricity balancing in the transport system. In this first version, only road transport using cars for persons transport is modelled. Inclusion of other types of road transport services (e.g. transport of goods) in the model is a matter of data availability and collection. Vehicles types included in the model are ICEs (internal combustion engine vehicles), and EDVs. The EDVs are BEVs, PHEVs, and FCEVs. Non-plug-in vehicles are treated in a simplified way, since they do not contribute to the flexibility of the power system.

Based on input data (Fig. 1), the Balmorel model including the transport sector minimises total costs. The model needs to meet the constraints on transport demand and the power flow balancing. Correspondence with the Balmorel includes adding net-electricity use for transportation to the electricity balance equation of the entire energy system (the electricity use subtracted the power fed back to the electricity grid). Output of the model is an optimal configuration and operation of the integrated power and transport system. Nomenclature is given in Appendix A.

3.1.1. Assumptions

- Vehicles are aggregated into vehicle technologies, e.g., a limited number of BEVs are used to represent all types of BEVs.
- The transport pattern is treated with average values, i.e., statistical data. The transport patterns are assumed known making it possible to extract average values.
- Regenerative braking energy is going into the on-board electricity storage and is assumed proportional to kilometres driven in each time step.
- The energy consumption in the vehicle is divided into consumption by accessory loads and consumption used to propel the vehicle. The former is assumed to get electrical power from the power bus, whereas the propulsion power is delivered from an electrical motor and/or an engine, depending on the type of propulsion system. Both the energy consumption of accessory loads and the propulsion power are assumed to be proportional to kilometres driven in each time step.
- An average inverter loss is allocated to all power flows involving conversion from DC to AC and vice versa.
- PHEVs and FCEVs are assumed to use the electric motor until storage is depleted, due to the rather high price difference between fuel and battery use, and efficiency difference between use of engine and motor. This assumption further seems reasonable since batteries developed today already seem to have no loss of effect before almost depleted. And the depth-of-discharge in the batteries is far from the point where the batteries experience any loss of effect. Therefore, the EDVs will be able to accelerate and drive on battery only until switching to engine power.
- EDVs leave the grid with a vehicle dependent but fixed average storage level.

Each vehicle type is associated with a particular plug-in pattern extracted from investigations of historical driving patterns. A plug-in pattern assigns percentages for each time step representing the number of vehicles leaving at the particular time step, returning on *j* future time steps. A percentage is given for each combination of leavings and arrivals within a 24 h time horizon. In a first step the EDVs are assumed to be plugged in when not driving.

In principal, the electricity grid is prepared for handling V2G. However, certain connection standards are needed as for small distributed energy resources (e.g. wind turbines for households). This is in order to not reduce the voltage and power quality in the low voltage grid.

3.1.2. Costs

Costs of transport are to be added to the Balmorel criterion function. Transportation costs include investment costs, operations and management costs, fuel costs, and costs of emitting CO_2. Investments costs and operations and management costs can be calculated identically for all vehicle types, whereas fuel costs and CO_2 costs differ. Investments, Co_v^{inv} and operations and management costs Co_v^{OM}, where $N_{a,v}$ is the number of vehicles of type v:

$$\sum_{a,v}\left(\left(Co_v^{inv}+Co_v^{OM}\right)\cdot N_{a,v}\right) \tag{1}$$

Fuel and CO_2 costs, Pc_f^{Fuel} and Pc^{CO_2}, for vehicles without grid connection capability, depend on, emission, $Em_f^{CO_2}$, annual driving, Dr_v, and fuel consumption, C_v^{Fuel}:

$$\sum_{v\in V^{NGC},a}\ \sum_{f\in F(v)}\left(\left(Pc_f^{Fuel}+Pc^{CO_2}\cdot Em_f^{CO_2}\right)\cdot N_{a,v}\cdot Dr_v\cdot C_v^{\mathrm{Fuel}}\right) \tag{2}$$

Fuel and CO_2 costs for vehicles with grid connection capability depend on the use of engine, $O_{v,a,t}^{EnGen}$, as opposed to the use of motor.

$$\sum_{v\in V^{GC},a,t}\ \sum_{f\in F(v)}\left(\left(Pc_f^{\mathrm{Fuel}}+Pc^{CO_2}\cdot Em_f^{CO_2}\right)\cdot\left(O_{v,a,t}^{EnGen}/\eta_v^{Eng}\right)\right) \tag{3}$$

All costs are added for the total costs of the configuration of the transport system. For electricity and hydrogen, fuel and CO_2 costs are included through the increased fuel consumption of power plants. The costs of the FCEVs are described separately in Section 3.1.5.

3.1.3. Transport demand

Yearly demand for transport, $D_{r,x}^{trp}$, has to be equal to supply of transport during the year. Calculation of transport supply includes annual driving, and average utilisation of the vehicles, UC_v.

$$\sum_{a\in r(a)}\ \sum_{v\in x(v)}\left(N_{a,v}\cdot Dr_v\cdot UC_v\right)\geq D_{r,x}^{trp} \tag{4}$$

3.1.4. Power flows

The remaining constraints are all related to the power flows. Power flows are modelled based on propulsion system. To include all the above mentioned vehicles, three different propulsion systems are defined:

1. Non-plug-ins
2. BEVs
3. Plug-in series: including both PHEVs and FCEVs

Parallel hybrids are not included in the model yet. For each propulsion system a model of the power flow in the vehicle is constructed. For non-plug-ins, only annual driving and fuel consumption are taken into account, because they do not interact with power system. Hence, these vehicles will not be part of the power flow equations.

Configuration of the electric and plug-in series propulsion systems are similar and sketched in Fig. 2. The figure shows the interaction between different units in the vehicle, including grid connection. Power can go both ways from the driving wheels to storage and from storage to power grid. Power returning from the driving wheels is the regenerated braking energy. The power both ways from storage to the power grid resembles the V2G concept, with the ability to both load power to the vehicle from the grid and unload power from the vehicle to the grid.

Division of the vehicles into subsystems is needed for modelling the driving and interactions between the power and transport system. To the least, division into storage, engine/fuel cell, and the remainder of the system is needed. Further division enables us to study the consequences of improving specific subsystems.

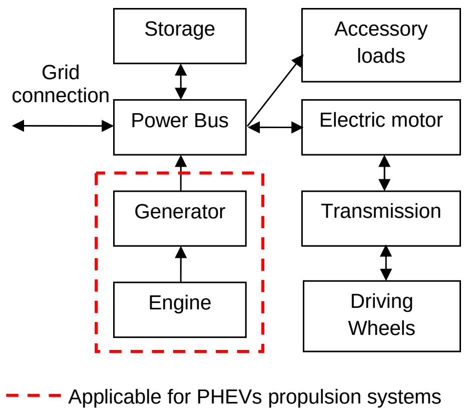

Fig. 2. Propulsion system configuration of (series) electric drive vehicles.

Based on the propulsion system configuration, power flows are sketched in Fig. 3. The power flow model reflects the assumption that regenerated braking energy goes into the on-board storage. Only subsystems with more than one in-going or out-going power flow are shown. Subsystems with only one in-going and out-going power flow (e.g. the electric motor), just calls for a scaling by the average efficiency of the subsystem.

Relevant for the power system is the available electricity storage from EDVs at each time period. This is based on, e.g., storage leaving and arriving with different vehicles, and is captured through the power flow model of the vehicles plugged in (Fig. 3a). For PHEVs and FCEVs optimising the use of electric motor versus use of fuel cell, or gasoline or diesel engine while driving, it is assumed that electric motor is used until depletion of storage. This assumption is supported by electricity being a cheaper fuel than diesel or hydrogen. Therefore, the power flow model for vehicles not plugged in as sketched in Fig. 3b, is based on storage being depleted before using the engine. For the same reason, load from power bus to storage is set to 0.

3.1.4.1. Balancing on-board electric storage. On-board electricity storage can be charged from the grid. The charging/discharging losses, η_v^{sto}, are modelled as being proportional to the unloading of electricity storage, $S_{v,a,t}^{Unld}$. On-board electricity storage capacity, $S_{v,a,t}^{PI}$, available for loading depends on last period's storage, power going into storage from grid, $Gr_{v,a,t}^{Fr}$, power going from storage to the power bus, $S_{v,a,t}^{Unld}$, charging/discharging losses, storage in vehicles leaving in period t, $S_{v,a,t}^{Leav}$, and storage in vehicles arriving in period t, $S_{v,a,t}^{Arr}$.

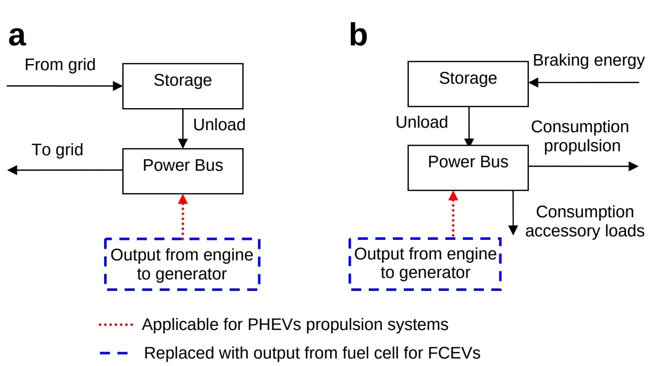

Fig. 3. Power flow model of (series) electric drive vehicles for a) vehicles plugged in and b) vehicles not plugged in.

$$S_{v,a,t+1}^{PI} = S_{v,a,t}^{PI} + Gr_{v,a,t}^{Fr}\cdot\eta_v^{inv} - S_{v,a,t}^{Unld}/\eta_v^{sto} - S_{v,a,t}^{Leav} + S_{v,a,t}^{Arr} \quad \forall v\in V^{GC};\ a\in A;\ t\in T \tag{5}$$

Calculation of storage in vehicles leaving in period t is based on the assumption that all vehicles bring along an average level of storage, which is given by a percentage of the battery capacity, LF_v. Furthermore, in accordance with statistical data on transport habits [23], it is assumed that all vehicles will be parked within a time horizon of 11 h after leaving, thus the plug-in pattern, $PP_{v,t,j}$, is derived from these data.

$$S_{v,a,t}^{Leav} = \sum_{j=t}^{t+11} PP_{v,t,j}\cdot LF_v\cdot\gamma_v^S\cdot N_{a,v} \quad \forall v\in V^{GC}; a\in A; t\in T \tag{6}$$

Storage level in vehicles arriving in period t depends on the storage in the vehicles when leaving, and thus, the capacity of the battery, γ_v^S, energy use for driving, E_v^{Dr}, and energy from braking, E_v^{brk}. The two latter are, of course, dependent on the distance driven, given as $D_{v,1}$ for all full hours of driving, and $D_{v,0}$ for the hour in which the vehicles return. A maximisation function is used, recognising that the storage will never be negative.

$$S_{v,a,t}^{Arr} = \sum_{i=t-11}^{t} \max\Big\{PP_{v,i,t}\cdot\Big(LF_v\cdot\gamma_v^S - ((i-t)\cdot D_{v,1} + D_{v,0})\cdot \big(E_v^{Dr}/\eta_v^{sto} - E_v^{brk}\big)\Big);0\Big\}\cdot N_{a,v} \quad \forall v\in V^{GC}; a\in A; t\in T \tag{7}$$

Energy use for driving is based on consumption for propulsion, C_v^{Eprp}, and accessory loads, C_v^{Eacc}, and motor and transmission efficiencies, η_v^{mot} and η_v^{trs};

$$E_v^{Dr} = C_v^{Eacc} + C_v^{Eprp}/(\eta_v^{mot}\cdot\eta_v^{trs}) \quad \forall v\in V^{GC}$$

Energy from braking depends on regenerated energy going to storage from braking, RE_v^{brk}, as well as motor, power bus, η_v^{PB}, and transmission efficiencies;

$$E_v^{brk} = RE_v^{brk}\cdot\eta_v^{mot}\cdot\eta_v^{PB}\cdot\eta_v^{trs} \quad \forall v\in V^{GC}$$

3.1.4.2. Balancing of the power bus. Power going out of the power bus needs to equal power going into the power bus at all times. For vehicles plugged in, power from the power bus only goes to the grid, $Gr_{v,a,t}^{To}$. Power into the power bus comes from either the engine, $O_{v,a,t}^{EnGenPI}$, or the on-board storage, $S_{v,a,t}^{Unld}$.

$$Gr_{v,a,t}^{To} = \left(O_{v,a,t}^{EnGenPI}\cdot\eta_v^{gen} + S_{v,a,t}^{Unld}\right)\cdot\eta_v^{PB} \quad \forall v\in V^{GC}; a\in A; t\in T \tag{8}$$

Where $O_{v,a,t}^{EnGenPI} = 0$ for BEVs, and $O_{v,a,t}^{EnGenPI} = O_{v,a,t}^{FCPI}$ for FCEVs. The formula includes the possibility of parked vehicles to produce power through use of engine while parked.

3.1.4.3. Output from engine to generator. Calculation of fuel and CO_2 consumption due to the use of engine power at each time period needs to be kept track of. Output from engine to generator for vehicles plugged in is calculated through Equation (8). Assuming that the vehicles use battery power before turning on the engine, calculation of the output from engine to generator for vehicles not plugged in is a question of finding the time step when the vehicles start using the engine (Fig. 4). In the figure, the area above the x-axis resembles use of on-board storage and the area below the x-axis resembles use of engine. To find the crossing of the x-axis, we need to distinguish between three operating situations: the vehicle returns to the grid before the storage is depleted, the vehicle

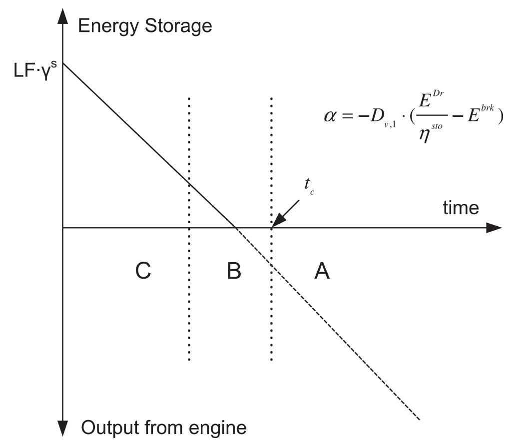

Fig. 4. Use of energy storage versus engine depending on time. α is the slope of the line and $LF_v \cdot \gamma^s$ the storage level when the vehicle is leaving the grid. t_c is the time period where the on-board storage is depleted.

returns in the same time period as the storage is depleted, and the vehicle returns in time periods after the storage is depleted. The first case does not involve usage of engine, and is therefore not treated in the following. The distance driven until storage is depleted will be:

$$D_{v,t_c-i} = \begin{cases} (t_c - i - 1)D_{v,1} + D_{v,0} & \text{if } t_c = j \\ (t_c - i)D_{v,1} & \text{if } t_c < j \end{cases}$$

To find t_c in the case where $t_c = j$, we calculate the following

$$LF_v \cdot \gamma_v^S - \left((t_c - i - 1) \cdot D_{v,1} + D_{v,0}\right) \cdot \left(E_v^{Dr}/\eta_v^{sto} - E_v^{brk}\right) = 0 \quad \forall v \in V^{GC} \tag{9}$$

If $t_c < j$

$$LF_v \cdot \gamma_v^S - (t_c - i - 1) \cdot D_{v,1} \cdot \left(E_v^{Dr}/\eta_v^{sto} - E_v^{brk}\right) = 0 \quad \forall v \in V^{GC} \tag{10}$$

The term $t_c - i$, which indicates the number of hours before the storage is depleted and the vehicles start using the engine can now be found using Equations (9) and (10).

The parameter $t_c - i$ can be calculated for each vehicle type, since all the other parameters are fixed on vehicle type level. Output from engine to generator can now be calculated for all combinations of vehicles leaving in time period $i = 1,2,\ldots,t$ and returning to the power grid in time period $j = t,t+1,\ldots,t+11$. $\sum_{i=1}^{t}\sum_{j=t}^{t+11} PP_{v,i,j}$ is the sum of all vehicles not plugged in at time t. The calculation of the output from engine to generator in time period t now depends on t being before, equal or after t_c. In Fig. 4 the three situations are sketched; A, B, and C. In situation A where electric storage is depleted, the engine output in each hour of driving will be

$$O_{v,a,t>t_c}^{EnGenNPI} = \sum_{i=1}^{t}\sum_{j=t}^{t+11} N_{a,v} \cdot PP_{v,i,j} \cdot D_{v,1} \cdot \left(E_v^{Dr}/\eta_v^{sto} - E_v^{brk}\right) \quad \forall v \in V^{GC}; a \in A; t \in T \wedge t > t_C \tag{11}$$

If in situation B, the electric storage depletes in the time period under consideration and the output from engine to generator is:

$$O_{v,a,t=t_c}^{EnGenNPI} = -\sum_{i=1}^{t}\sum_{j=t}^{t+11} N_{a,v} \cdot PP_{v,i,j} \cdot \left(LF_v \cdot \gamma_v^S - D_{v,1} \cdot \left(E_v^{Dr}/\eta_v^{sto} - E_v^{brk}\right)\right) \quad \forall v \in V^{GC}; a \in A; t \in T \wedge t = t_C \tag{12}$$

In Equations (11) and (12) $D_{v,1}$ is replaced with $D_{v,0}$ if the vehicle returns in the time period under consideration, that is $j = t$. Finally in situation C the vehicle only uses electric storage, such that the sum of the results of Equations (11) and (12) gives the total output from engine to generator in period t for vehicles not plugged in. Then the total output from engine to generator is:

$$O_{v,a,t}^{EnGen} = O_{v,a,t>t_C}^{EnGenNPI} + O_{v,a,t=t_C}^{EnGenNPI} + O_{v,a,t}^{EnGenPI} \quad \forall v \in V^{GC}; t \in T; a \in A \tag{13}$$

As with vehicles plugged in, $O_{v,a,t}^{EnGenNPI} = 0$ for BEVs, and $O_{v,a,t}^{EnGenNPI} = O_{v,a,t}^{FCNPI}$ and $O_{v,a,t}^{EnGen} = O_{v,a,t}^{FC}$ for FCEVs.

3.1.4.4. Storage level. The storage level is to stay between 0 and maximum capacity of the battery.

$$0 \le S_{v,a,t}^{PI} \le N_{a,v} \cdot \left(1 - \sum_{i=1}^{t}\sum_{j=t}^{t+11} PP_{v,i,j}\right) \cdot \gamma_v^S \quad \forall v \in V^{GC}; a \in A; t \in T \tag{14}$$

3.1.4.5. Capacity restrictions on loading and unloading of on-board storage, power flow to and from grid, and engine output. These restrictions depend on the single vehicle capacities of respectively loading, unloading, grid connection and engine output multiplied with the number of vehicles plugged in at each time step. As an example the power flow into storage when plugged in at each time step is given by

$$Gr_{v,a,t}^{Fr} \cdot \eta_v^{inv} \le N_{a,v} \cdot \left(1 - \sum_{i=1}^{t}\sum_{j=t}^{t+11} PP_{v,i,j}\right) \cdot \gamma_v^{SLd} \quad \forall v \in V^{GC}; a \in A; t \in T \tag{15}$$

Similar restrictions apply for unloading of on-board storage, power to and from grid $(Gr_{v,a,t}^{Fr})$ and engine output although not shown here.

3.1.4.6. Addition to the electricity flow balance equation in Balmorel. For balancing the power flows in the power system, the net power flow from the transport system to the power system is added.

$$+ \sum_{a \in R(a)} \left(\left(Gr_{v,a,t}^{To} - Gr_{v,a,t}^{Fr}\right)\right) \tag{16}$$

3.1.5. Interactions with hydrogen

The hydrogen add-on for Balmorel has been described in Ref. [24]. To capture the cost of hydrogen, the hydrogen demand from FCEVs has to be added to existing hydrogen demand as an addition to the hydrogen balance equation.

Hydrogen demand for non-plug-ins is dependent on number of vehicles, fuel consumption, $C_v^{H_2}$, and annual driving:

$$\sum_{a,v} \left(\left(C_v^{H_2} \cdot N_{a,v} \cdot Dr_v\right)\right) \tag{17}$$

For plug-ins hydrogen demand is dependent on output from fuel cell, $O_{v,a,t}^{FC}$, and efficiency of the fuel cell, η_v^{FC}:

$$\sum_{v,a,t} \left(O_{v,a,t}^{FC}/\eta_v^{FC}\right) \tag{18}$$

Equations (17) and (18) are similar to Equations (2) and (3) without the fuel and CO_2 costs.

4. Application

To illustrate the model we run a simple case, focussing on the power and transport system in Denmark in the year 2030. The model presented makes it possible to analyse many aspects of

Table 1
Demand input data year 2030.

	Denmark East	Denmark West	Total demand
Electricity demand (TWh/yr)	15	23	38
District heat demand (TWh/yr)	16	19	35
Transport demand (b. persons km/yr)	32	42	74

Table 3
Vehicle technology investment options [29].

Type of vehicle	Inv. costs (€) (yearly cost)	O & M costs (€/year)	Electric storage cap. (kWh)
ICE	11,766 (1086)	1168	0.8
BEV	19,078 (1760)	1101	50
PHEV	15,496 (1430)	1168	10
FCEV	21,154 (1952)	1101	10

the integrated power and transport system. We have decided to investigate when it becomes beneficial to invest in the different kinds of EDVs as opposed to the diesel ICE. Another aspect to investigate is the change in the configuration of the power system due to the availability of energy storage in the transport system. We believe that with storage capacity available from the vehicles, the optimal configuration of the power system will be more focused on variable renewables and in the case of Denmark especially wind.

Finally, we will focus on whether it makes a difference if only the G2V capability is available and, thus, not the V2G, meaning that we get to control when to load the batteries, but cannot unload these for use in the power system.

4.1. Case description

Running Balmorel for the year 2030 requires a number of inputs. In Balmorel, fuel prices, CO_2 prices, demand data, and technology data are exogenously given, as are vehicle technology data. Oil-prices are assumed to be \$100/barrel and we have assumed rather high CO_2-prices of €40/ton. For all the other fuel prices, we have assumed constant price elasticities as in Ref. [24]. We have run the model for 18 weeks, each with 168 time steps. In the model Denmark is divided into two regions, eastern and western Denmark, requiring data, such as the demand data (Table 1), to be given for each region. Currently, there is no transmission between the two regions, but by 2030 we have set the transmission capacity to 1.2 GW with a transmission loss of 1%.

To meet the demand in 2030 the model invests in new power production technology. Table 2 shows the possible technologies to invest in on the power system side. Investments are only allowed in these technologies to keep the case simple. For a more in depth analysis, further technologies should be included. Enabling investments in FCEVs require investments in electrolysis and hydrogen storage. The conversion of electricity to hydrogen and subsequent storage of compressed hydrogen does result in significant energy losses.

Table 2
Technology investment options in the simulation (all data except for Electric boiler are from the Danish Energy Authority [27]).

	Investment costs (M€/MW)	Variable costs (€/MW)	Annual costs (k€/MW)	Efficiency
Onshore wind	0.5	7	0	1
Offshore wind	1	4	4	1
CHP plant, biomass	1.3	2.7	25	0.45
Open cycle gas turbine	0.5	2	72	0.4
Heat storage	0.6	0	1	1
Solid oxide electrolysis	0.18	0	5.4	0.93
Heat pump	0.6	0	3	3.9
Electric boiler	0.04	0	1.2	0.98
Combined cycle, natural gas	0.55	1.5	12.5	0.56
Hydrogen storage, cavern	0.00058	0	0	0.83

With focus on the competitiveness of the different vehicle technologies as well as the incorporation of more renewable energy sources, we have decided only to consider four types of vehicles; Diesel ICE, BEV, series PHEV (diesel), and series plug-in FCEV (to be referred to as FCEV for the remainder of the article). Table 3 shows the vehicle investments allowed for the model in this simulation. The size of the electric storage, shown in the table, reflects only the usable size of the battery – the actual size of the battery depends on assumptions about depth-of-discharge. By 2030 we believe that the size of the battery for BEVs will support a driving range of approx. 350 km, needing a battery of about 50 kWh. For plug-in hybrids (both FCEVs and PHEVs) the batteries could be quite large, but the trade-off between additional cost and additional driving range leads us to believe that a battery covering a driving range of approx. 65 km is plenty for the everyday purpose. Therefore, we have set the size of these batteries to 10 KWh. These battery sizes are based on a belief that, with a vehicle efficiency of approx. 5 km/kWh today as used by Refs. [19,21,28], the vehicle efficiency will reach 7 km/kWh by 2030.

Due to limited driving range, the assumed average annual driving of the BEVs is less than for the other EDVs. Driving patterns on a weekly basis and other information concerning driving are all taken from the investigation on transport habits in Denmark [26]. Average plug-in patterns are derived from the driving patterns. Furthermore, average hourly travelling distance can also be derived from the investigation on transport habits in Denmark.

5. Results

The model has been run on a computer with 3.5 GB RAM and a 2.59 GHz processor. The calculation time is approximately 15 h.

Introducing the integration of the power and transport system results in PHEV's being the most profitable solution to the optimisation problem – both with and without the introduction of the V2G technology. As for the power system, we experience a large increase in investments in offshore wind, a slight increase in investments in electric boilers and decrease in investments in combined cycle, biomass, and onshore wind (Fig. 5). The increase in wind power production caused by wind power investments exceeds the energy used by the transport system, meaning that the EDVs clearly bring a desired flexibility to the power system and

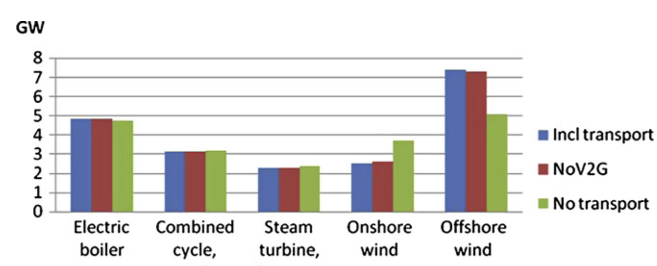

Fig. 5. Investments in plants.

Table 4
Total costs of running the integrated power and transport system.

Billion	Incl. transport	No V2G	No transport
Costs	8.535	8.537	9.143

Table 5
Annual CO_2 emissions on power, heat and transport (mio. tons).

	Incl. transport	No V2G	No transport
Electricity generation	0.855	0.864	0.923
Heat generation	0.332	0.332	0.321
Transport	1.300	1.300	8.418

thereby allows for the large increase in wind energy. Furthermore, the electric heat boilers provide flexibility on the heat production side of the power system. The costs of running the integrated power and transport systems, and thereby, being able to invest in plug-ins amounts to 8.535 billion Euros or 606 million Euros less than running the power and transport systems separately (Table 4). Further, adding the V2G facilities saves another 2 million Euros in the system.

Looking at the CO_2 emissions on power and heat generation these are given in Table 5. There is a significant decrease of 85% in transport related CO_2 emissions associated with the introduction of EDVs.

Table 6 shows the loading and unloading of power to the vehicles in the case of an integrated power and transport system with V2G. The unloading of the vehicles is used in peak hours, although not to a great extend. Average prices when loading and unloading are given in Table 7. As expected, the average prices are low when loading and higher when unloading the on-board batteries. Due to the simplified case run with only few investment opportunities in power plants, the power price differences between time steps are relatively small, causing a small utilisation and effect of V2G.

The average electricity price, returned from running the model is €27/MWh. Calculating the costs with this average electricity price gives the costs shown in Table 8. This shows that the PHEVs are somewhat cheaper than ICEs.

Sensitivity analysis shows that changing prices on oil from $100/barrel down to $90/barrel does not change the optimal investments in the vehicles. Neither does reductions in CO_2 prices to 30 €/ton.

The restriction on grid capacity is another figure that could influence the possible usage of the storage in the vehicles. However, neither a large increase nor a large decrease of the grid capacity restriction changes the investment in vehicles, in the overall costs of the system, or the usage of the vehicles. From that we can conclude that the grid capacity restriction is not binding with the actual setup.

Table 6
Power going to and from the vehicles for the year 2030.

Region	From grid (MWh)	To grid (MWh)
Eastern Denmark	2,934,954	39,124
Western Denmark	3,917,933	87,829
Total	6,852,887	126,952

Table 7
Average prices when loading and unloading power to the vehicles.

€/MWh	Average loading price	Average unloading price
Eastern Denmark	22.93	29.10
Western Denmark	21.25	25.03

Table 8
Approximated costs using the electricity prices returned from running the model.

Type of vehicle	yearly costs (€/year)	Fuel and CO_2 costs (€/year)	Difference in costs relative to the ICE (€/year)
ICE	2254	796	–
BEV	2861	76	112
PHEV	2598	229	223

6. Concluding remarks

In this article we have presented a new and advanced investment model for the integrated power and transport system. The model diverge from existing literature with the rather detailed way of expressing both the power and transport system in one optimisation model for configuring and operating the integrated power and transport system.

The case study shows that when analysing the integrated power and transport system it is beneficial to invest only in PHEVs. The preference of PHEVs instead of ICEs is due to the benefits experienced from the interaction between the power and the transport system as well as the price differences in using diesel versus electricity as propellant. Although BEVs have lower fuel and CO_2 costs than PHEVs (see Table 8) it is not enough to cover the difference in investment cost. The power needed for the transport system is more than covered by the increase in investments in wind energy, due to the system being more flexible with EDVs. Thus, the inclusion of the EDVs indeed introduces more renewable energy in the integrated power and transport system. The value of adding V2G to the system for this case of a simplified Danish power system is very small. It brings along a cost decrease of 2 million Euros as well as an increase in investments in wind energy on 17.2 MW – with the same amount of PHEVs. Thus, due to the investments in V2G facilities in the electrical grid not being included in the analyses, the actual value of adding V2G is expected to be close to zero.

Detailing the model in terms of adding more vehicles, splitting into different driving patterns depending on groups of drivers such as commuters and dividing storage into smaller groups, again depending on driving patterns are all subject for future work. Also, adding more countries and transmissions are of great interest, since, e.g., hydro power from Norway might make investments in flexibility, hence, EDVs less attractive. The model described in this article has a very simplified approach to the storage load factor when vehicles are leaving for a trip. Future works could make the load factor part of the decision model, having the load factor change depending on the expected distance of the next trip.

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Appendix. Supplementary material

The supplementary data associated with this article can be found in the on-line version at doi:10.1016/j.energy.2011.03.058.

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