Modelling and Analysis of Distributed Energy Systems with Respect to Sustainable Energy

Focus on Electric Drive Vehicles

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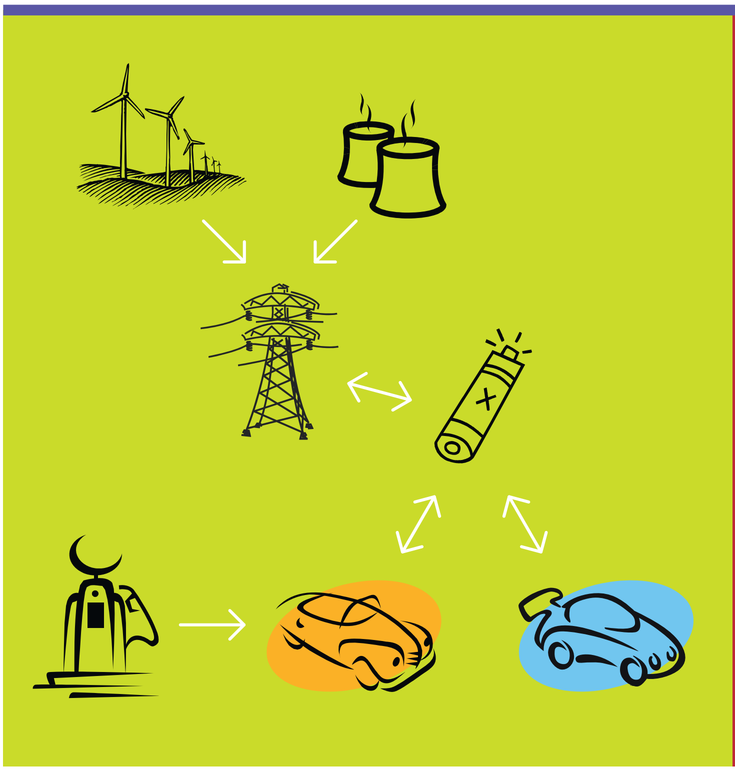
– Focus on Electric Drive Vehicles



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DTU Management Engineering

Nina Juul
June 2011

DTU Management Engineering
Department of Management Engineering

Modelling and Analysis of Distributed Energy Systems with Respect to Sustainable Energy - Focus on Electric Drive Vehicles

Nina Juul

Kongens Lyngby 2011

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Executive summary

Climate change and CO_2 emissions is an important issue on the agenda of many politicians. Trying to decrease CO_2 emissions, influences transportation, power production, etc. The power system is characterised by an increasing amount of renewables, with one of the most expanding renewable power sources being wind. Wind energy is fluctuating by nature, calling for increasing flexibility elsewhere in the energy system.

For Denmark, hydro power from Norway help stabilizing the system, as does export of excess wind to Germany, although the latter is decreasing in use because of large correlations between high wind production in northern Germany and western Denmark. To decrease CO_2 emissions through a decrease in the use of fossil fuelled plants, along with an increase the amount of renewable energy, the power system needs more flexibility such as flexible demands, storage etc.

Flexibility could also come from the road transport system. Counting for 24% of the CO_2 emissions in Denmark in 2009, the road transport system needs to move towards, e.g. electric drive vehicles. However, the electric drive vehicles are also demanding electricity from the power system. This brings both challenges and opportunities to the power system. One challenge is, that intelligence is needed unless peak-load is to increase drastically. With intelligent charging of the vehicles, though, the electric drive vehicles can be of great benefit providing flexible demand and charging at night time, instead of being regarded as yet another load and challenge for the energy system. Furthermore, discharging of vehicles can provide services to the power system.

The batteries in the electric drive vehicles are batteries invested in anyway.

Hence, why not use these actively for cheap storage by the energy system? Furthermore, the use of vehicles are opposite to the remaining demand for energy; e.g. while people are making dinner their vehicles will often be parked, being able to deliver back-up power - again, a great opportunity for the power system.

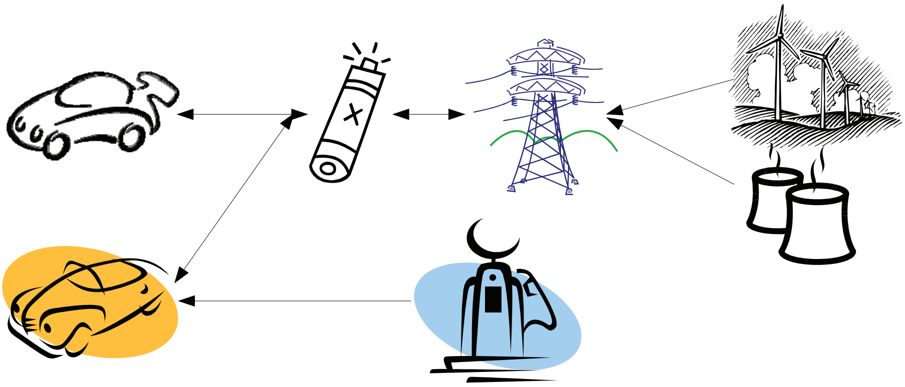

Figure 1: An integrated power and transport system with battery storage availability for both systems

In this PhD project I have focussed on modelling and analysis of a future integrated transport and power system. An integrated power and transport system enables analyses of the interactions between different parts of the energy system. The object of interest is an optimal configuration of an integrated power and transport system as well as I will be focussing on the drawbacks and benefits for the power system incorporating an electrified transport system.

I have performed analyses in terms of integrating more renewable energy, for both Denmark as an isolated system and for the northern European countries including Denmark, Sweden, Norway, Finland, and Germany. The analyses are performed using the deterministic energy systems analysis model, Balmorel. Furthermore, analyses have been made for the Irish power system on the influence of introducing electric drive vehicles in a predefined power system, using the stochastic energy systems analysis model, Wilmar.

Interesting is, that it turns out to be most profitable to invest in *enough wind to more than cover the electrified transport in Denmark.* This holds, both when modelling Denmark as an isolated country, and when including the interactions between the Nordic countries.

Furthermore, analyses show that fuel cell electric vehicles are not yet ready for competing with the other vehicle types. This is, among other things, due the technologies not being cheap enough, thus, the development is not expected to have reached a competitive stage.

Another interesting finding is the results showing that it is beneficial for Ireland to have electric drive vehicles in terms of both costs and CO_2 emissions. However, introducing the electric drive vehicles in Ireland, imply an increase in both costs and CO_2 in the Great British side, as most of the power for the vehicles is produced on British coal power plants. Thus, focusing nationally, Ireland should invest in the electric drive vehicles, although, on an international level, the investments are costly.

Dansk Resumé

Klimaændringer og CO_2-emissioner står højt på mange politikeres dagsorden. Vil man nedsætte CO_2-emissionerne, vil det have indflydelse på hele energisystemet - både varme, elektricitet og transport. Elsystemet er karakteriseret ved stigende mængder af vedvarende energi, hvoraf en af de størst voksende er vindenergi. Vindenergi er meget varierende, hvorfor stigende mængder vind kræver stigende fleksibilitet i andre dele af systemet. For Danmark kan dette blandt andet komme fra nabolandene, hvor fx import af vandkraft fra Norge og eksport af overskydende vind til Tyskland hjælper med til at stabilisere systemet.

Ønsket om at få mere vedvarende energi i systemet medfører blandt andet en nedgradering i brugen af kulkraft og gasturbiner, hvilket betyder yderligere krav for andre typer af fleksibilitet, såsom fleksibelt forbrug eller energilagring. Fleksibiliteten kunne komme fra transportsektoren, som står over for samme udfordring som elsystemet med at blive mere miljøvenlig. Transportsektoren forventes ændret indenfor en årrække, hvilket blandt andet kan betyde, at denne rykker i retning af eldrevne biler. Dette skaber en yderligere eleftersporgsel, men også muligheden for fleksibel op- og afladning og dermed mange små ellagre. Bilerne vil hermed også kunne bidrage til nogle af de services, der er brug for i det resterende energisystem. For at få alt dette til at fungere skal der indbygges en intelligens i systemet og i bilerne.

Når nu batterierne er tilgængelige og investeringerne er foretaget, hvorfor så ikke gøre brug af disse når de ikke bruges til kørsel?

I dette ph.d.-projekt fokuserer jeg på modellering og analyse af fremtidens integrerede varme-, el- og transportsystem. Jeg udvikler en optimeringsmodel for vejtransport, som integreres med en eksisterende energisystemmodel, Bal-

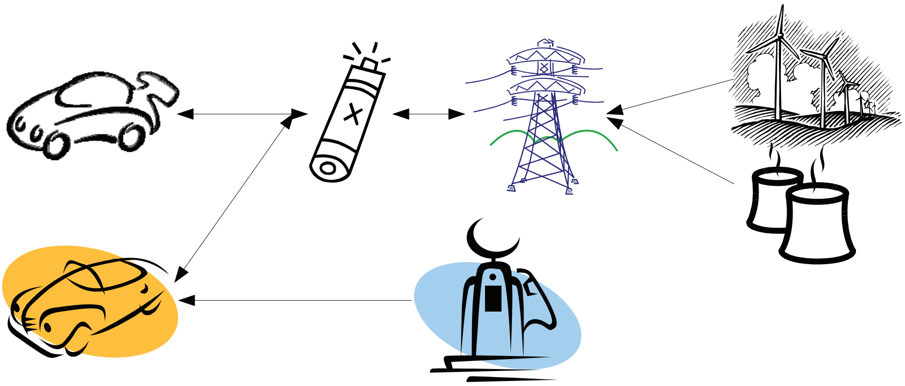

Figure 2: Et integreret varme-, el- og transportsystem med batteriet som fælles interesse for både el- og transportsystemet

morel, hvilket skaber mulighed for at analysere samspil i det integrerede system. Analyserne tager udgangspunkt i optimale investeringer og optimal drift af det integrerede energisystem, ud fra hvilke også fordele og ulemper ved indførsel af elektrisk transport kan analyseres.

Jeg har udarbejdet analyser af et isoleret dansk energisystem såvel som det Nordeuropæiske energisystem, for Danmark, Sverige, Norge, Finland og Tyskland. Analyserne er udarbejdet i den egenudviklede vejtransportmodel integreret med den deterministiske energisystemmodel, Balmorel. Derudover har jeg analyseret, hvad der sker med det irske energisystem, hvis der indføres eldrevne biler i et eksisterende system, der er sammensat til at møde en efterspørgsel, der ikke inkluderer transport. Disse analyser er foretaget i den stokastiske energisystemmodel, Wilmar.

Resultater viser blandt andet, at det er optimalt at investere i så meget mere vind ved indførsel af transport i Danmark, at det mere end dækker den efterspørgsel, der er fra vejtransporten. Dette betyder, at eldrevne biler i Danmark vil kunne køre på vedvarende energi, så længe de kører på elektricitet.

Derudover viser analyser, at brændselscellebiler ikke er klar til at kunne konkurrere med de andre typer biler endnu. Dette skyldes blandt andet at teknologierne endnu ikke er billige nok - udviklingen forventes altså ikke at have nået et konkurrencedygtigt niveau i 2030.

Analyserne i Irland viser, at det er en fordel for landet at indføre eldrevne biler både med hensyn til økonomi og hvis man ser på CO_2-emissioner. Inkluderes imidlertid tallene for Storbritanien ser resultatet markant anderledes ud.

I dette tilfælde resulterer indførsel af eldrevne biler i Irland i en stigning i både omkostninger og CO_2-emissioner. Således er det vigtigt at være opmærksom på forskellene mellem de nationale og de internationale konsekvenser.

Publications List

Papers included in the thesis

I Nina Juul Andersen and Peter Meibom, "*Optimal Configuration of Future Energy Systems Including Road Transport and Vehicle-to-Grid Capabilities*", EWEC 2009 Scientific proceedings, European Wind Energy Conference (EWEC), 2009.

II Nina Juul and Peter Meibom, "*Transport and Power System Scenarios for Northern Europe in 2030*", Risø International Energy Conference, 14 – 16 Sep., 2009.

III Nina Juul and Peter Meibom, "*Optimal Configuration of an Integrated Power and Transport System*", submitted, Energy, November 2010.

IV Nina Juul and Peter Meibom, "*Road Transport and Power System Scenarios for Northern Europe in 2030*", submitted, Applied Energy, December 2010.

V Nina Juul, Alan Mullane and Peter Meibom, "*Influences on Dispatch of Power Generation when Introducing Electric Drive Vehicles in an Irish Power System Year 2020*", submitted to Energy Policy, January 2011.

VI Nina Juul, "*Sensitivity on Battery Prices versus Battery Capacity on Plug-in Hybrid Electric Vehicles and the Effects on the Power System Configuration*", submitted to Journal of Power Sources, February 2011. Abstract accepted for RISØ International Energy Conference, May 2011

And a popular science paper based on Paper I and III (not commented upon in the thesis):

VII Nina Juul, “*Favorabelt med eldrevne biler og vedvarende energi i 2030*”, Nyhedsbladet dansk energi, nr. 15, November 2010.

Reports co-authored but not included in the thesis

- Poul Ejnar Sørensen, Mikael Togeby, Thomas Ackermann et al.,“ *Steps Toward a Danish Power System with 50% Wind Energy, EcoGrid.dk Phase 1, WP4: New Measures for Integration of Large Scale Renewable Energy*”, Funded by Energinet.dk, PSO, R& D-contract, project no. 2007-1-7816, 2009
- Alan Mullane et al., “ *Final Report, Lot 2: Irish National Task Participant, IEA R, D& D Wind Agreement, Research Task 25, Electric Vehicle Extension*”, 2008

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Abbreviations

V2G	Vehicle-to-Grid. Power going from the vehicle to be used elsewhere in the power grid.
G2V	Grid-to-Vehicle. Power from the grid used to charge the vehicles.
ICE	Internal Combustion Engines. Used for vehicles only using the internal combustion engine (not for hybrids).
EDV	Electric Drive Vehicles. All vehicles able to drive with electricity as propellant.
PHEV	Plug-in serial Hybrid Electric Vehicle. The plug-in parallel hybrid electric vehicles are not represented in this thesis.
BEV	Battery Electric Vehicle. Vehicles using only electricity as propellant.
FCEV	Plug-in hybrid Fuel Cell Electric Vehicle. Fuel cell electric vehicles are only interesting for the power system if plug ins.
OCGT	Open Cycle Gas Turbine
CCGT	Combined Cycle Gas Turbine
CHP	Combined Heat and Power
WtE	Waste to Energy
SOFC	Solid Oxide Fuel Cell
AC	Alternate Current
DC	Direct Current
TSO	Transmission System Operator

Nomenclature

Lists of indices, parameters, and variables, used in this thesis are provided below.

Indices

Description	Symbol
Areas in which investments can take place, set of areas	a, A
Countries, set of countries	c, C
Generation technology (plant), set of generation techn.	p, P
Regions, set of regions	r, R
Time steps, set of time steps	t, T
Time period where vehicles leave the grid	i
Time period where vehicles return to the grid	j
Time period when storage is depleted, use of engine starts	t_c
Vehicle technologies, set of vehicle technologies	v, V
Vehicle technologies without grid connection capability	V^{NGC}
Vehicle technologies with grid connection capability	V^{GC}

Parameters

Description	Symbol	Unit
Energy consumption of accessories in vehicle technology v at time t	$Cons_v^{EAcc}$	MWh/km
Propulsion system energy consumption in vehicle technology v at time t	$Cons_v^{EPrp}$	MWh/km
Fuel consumption of vehicle v at time t	$Cons_v^{fuel}$	MWh/km
Hydrogen consumed by vehicle v at time t	$Cons_v^{H_2}$	MWh/km
Cost of emitting CO_2	$C_c^{CO_2}$	€/tonnes
Yearly fuel costs for vehicle type v (using a particular fuel type)in area a at time t	$C_{a,v,t}^{fuelveh}$	€/Veh
Annualised vehicle investment costs for vehicles v at time t in area a	$C_{a,v,t}^{invveh}$	€/Veh
Yearly operation and management costs of vehicles v at time t in area a	$C_{a,v,t}^{OMveh}$	€/Veh
Costs from add-ons	C^{Ap}	€
Fuel costs of plant p in area a at time t	$C_{a,p,t}^{fuel}$	€/MWh
Investment costs of plant p in area a at time t	$C_{a,p,t}^{inv}$	€/MW
Operation and management costs of plant p in area a at time t	$C_{a,p,t}^{OM}$	€/MWh
Transmission costs from plant p in area a at time t	$C_{a,p,t}^{trans}$	€/MWh
Demand for electricity in region r at time t	$D_{r,t}^{elec}$	MWh
Demand for heat in area a at time t	$D_{a,t}^{heat}$	MWh
Peak-load demand for electricity in area a at time t	$D_{a,t}^{peakload}$	MWh
Yearly transport demand in region r	D_r^{tsp}	km_{pers}
Average distance driven in the hour of return from the trip	$DD_{v,0}$	km/h
Average hourly distance driven when on the road for a full hour	$DD_{v,1}$	km/h
Distance driven between time i and j	$DD_{v,j-i}$	km
Distance driven until storage is depleted for vehicle type v	$DD_v^{deplete}$	km
Annual driving of vehicle technology v	Dr_v	km
Energy left from braking when being stored in vehicle v at time t	E_v^{Brk}	MWh/km
Energy used for driving in vehicle v at time t	E_v^{Dr}	MWh/km
CO_2 emissions, vehicle v	$Em_v^{CO_2}$	ton/MWh
Electricity transmission loss, region r, time t	$L_{r,t}^{elec}$	%

Parameters continued

Description	Symbol	Unit
Heat transmission loss in area a at time t	$L^{heat}_{a,t}$	%
Storage load factor for vehicles v leaving	LF_v	
Plug in pattern. Percentage of vehicles v in area a leaving at time i, returning time j	$PP_{a,v,i,j}$	
Penalty costs for electricity demand not meeting supply at time t	Pen^{inf}_t	€
Amount of energy regenerated in vehicle v when braking	RE^{Brk}_v	MWh/km
Fuel taxes in country c on plant type p at time t	$T^{fuel}_{c,p,t}$	€/MWh
Emission taxes in country c on plant type p at time t	$T^{ems}_{c,p,t}$	€/MWh
Other taxes in area a on plant type p at time t	$T^{other}_{a,p,t}$	€/MWh
Utilisation of capacity in vehicle v	UC_v	$\mathrm{km}_{pers}/\mathrm{km}_v$
Loading capacity of electricity storage in vehicle technology v	γ^{Sld}_v	MW
Storage capacity of electricity storage of vehicle technology v	γ^{S}_v	MWh
Grid capacity of grid connection to vehicle v	γ^{Gr}_v	MWh
Average efficiency of engine in vehicle technology v	η^{Eng}_v	
Average efficiency of fuel cell in vehicle technology v	η^{FC}_v	
Average efficiency of generator converting the mechanical power output from the engine to electric power in vehicle v	η^{gen}_v	
Average efficiency of inverter from grid to electricity storage for vehicle technology v	$\eta^{inverter}_v$	
Average efficiency of the electric motor on-board vehicle technology v	η^{mot}_v	
Average efficiency of power bus converting power on-board vehicle v	η^{PB}_v	
Average electric storage efficiency proportional to unloading of vehicle v	η^{S}_v	
Average efficiency of transmission from engine or electric motor to driving wheels of vehicle v	η^{trans}_v	

Variables

Description	Symbol	Unit
Electricity generation on existing power plants p at time t in region r	$G^{ex}_{r,p,t}$	MWh
Electricity generation on new power plants p at time t in region r	$G^{new}_{r,p,t}$	MWh
Electricity generation on power plants p from electricity add-ons, time t, region r	$G^{ApElec}_{r,p,t}$	MWh
Heat generation on back pressure plants p at time t in area a	$G^{backpr}_{a,p,t}$	MWh
Heat generation on extraction plants p at time t in area a	$G^{extr}_{a,p,t}$	MWh
Heat generation on plants p producing heat only at time t in area a	$G^{HeatOnly}_{a,p,t}$	MWh
Heat generated from electricity on plant p at time t in area a	$G^{ElecToHeat}_{a,p,t}$	MWh
Heat generation on heat plants p from add-ons generating heat at time t in area a	$G^{ApHeat}_{a,p,t}$	MWh
Power loaded from the grid to the vehicle at time t for vehicle type v in area a	$Gr^{fr}_{a,v,t}$	MWh
Power loaded to the grid from the vehicle at time t for vehicle type v in area a	$Gr^{to}_{a,v,t}$	MWh
Number of vehicles of technology v in area a	$N_{a,v}$	
Engine output going into the generator at time t for vehicle type v in area a	$O^{EnGen}_{a,v,t}$	MWh
Engine output going into the generator for vehicles v plugged in at time t in area a	$O^{EnGenPI}_{a,v,t}$	MWh
Engine output going into the generator for vehicles v not plugged in at time t in area a	$O^{EnGenNPI}_{a,v,t}$	MWh
Engine output going to propulsion of the vehicle v in area a at time t	$O^{EnPrp}_{a,v,t}$	MWh
Fuel cell output going into the generator at time t for vehicle type v in area a	$O^{FC}_{a,v,t}$	MWh
Fuel cell output going into the generator for vehicles v plugged in at time t in area a	$O^{FCPI}_{a,v,t}$	MWh
Fuel cell output going into the generator for vehicles v plugged in at time t in area a	$O^{FCNPI}_{a,v,t}$	MWh
Storage level in vehicles v arriving at time t in area a	$S^{Arr}_{a,v,t}$	MWh

Variables continued

Electricity storage in region r on plant p at time t	$S^{elec}_{r,p,t}$	MWh
Storage level in vehicles v leaving at time t in area a	$S^{Leav}_{a,v,t}$	MWh
Net heat storage in area a on plant p at time t	$S^{netHeat}_{a,p,t}$	MWh
Storage level in vehicles v plugged in at time t in area a	$S^{PI}_{a,v,t}$	MWh
Unloading of on-board storage in vehicles v at time t in area a	$S^{Unld}_{a,v,t}$	MWh
Net electricity transmission into region r at time t	$Trans^{net}_{r,t}$	MWh
Change in utility of electricity consumption in region r at time t	$\Delta U^{elec}_{r,t}$	
Change in utility of heat consumption in area a at time t	$\Delta U^{heat}_{a,t}$	
Total system costs, the variable to minimise	V_{obj}	€
The dispatchable electricity capacity in area a at plant p, at time t	$\gamma^{dispatch}_{a,p,t}$	MW
The wind power capacity in area a at plant p, at time t	$\gamma^{wind}_{a,p,t}$	MW

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Part I

Introducing Chapters

CHAPTER 1

Introduction

Renewable energy is of increasing interest, and focus on climate change, CO_2 emissions etc. all point towards an energy system consisting of a large share of renewable energy sources. Many renewable energy sources are fluctuating and, thus, calling for flexibility in the remainder of the power system.

The entire energy system includes the transport system, e.g. passenger road transport and aviation. Hence, renewables in the energy system also includes renewables in the transport system. In 2009, the road transport system counted for 24% of the total CO_2 emission in Denmark [8]. Renewable energy in the road transport system can be introduced through alternative fuels such as hydrogen in fuel cells and electricity in electric drive vehicles (EDVs). Electrifying the road transport increases electricity demand and generation, thus, in order to increase the share of renewable energy, more electricity production on renewable energy sources is needed.

A challenge in the power system is the need for supply to meet demand exactly at all times. In order to keep the power system as reliable as it is today, more flexibility is required with more fluctuating power generation. This flexibility can be provided through, e.g. flexible demands or different kinds of energy storage. This is where the power system possibly can benefit from the pluggable EDVs.

Imagine if all the batteries in the future EDVs can provide some or all of the flexibility needed. The EDVs can charge and discharge when needed, of course within certain boundaries. Hybrid electric vehicles that are pluggable can even provide power to the grid by running the engines, e.g. in times of low power production or high demand.

With the development towards an electric transport sector it is no longer sufficient to operate and configure the transport and power systems separately as has been done so far. But how does integration of the two systems influence the optimal configuration and operation of both the power and transport system? And do the two systems experience synergies affecting optimality? Or do the EDVs drive on electricity produced on coal, thus, eliminating renewable energy in the transport system? These are some of the questions arising when integrating the systems.

In order for the power system to get the best use of the transport system, the charging and discharging should be controlled. Integration of the power and transport system gives, amongst others, the following advantages, when control of charging and discharging is introduced:

- Low power prices reflect less restrictions on the power generation, thus, not much of the capacity is used. This could be due to, e.g. large amounts of wind power. Low prices are also favourable for the EDVs. Hence, charging EDVs in times of low prices is of benefit to both the power and transport system. Even if batteries contain the power required for the next trip, this is a way to store the electricity.
- In times of lack of power production, e.g. peak hours, the EDVs can provide power to the grid. These are the situations when the power is rather expensive, thus, again it is favourable for both the power and transport system.
- EDVs have a fast response time, enabling them to deliver many kinds of ancillary services.

The EDVs should not only be regarded as another load in the power system, but rather as a flexible demand and a possibility of storage. Storage decouples supply and demand enabling less strict constraints and, hence, is of benefit to the power system. Quantifying the benefits for the power system in terms of reduced costs, is of importance to the politicians choosing which technologies to support, e.g. in terms of building of infrastructure.

From above, the following research questions arise:

1 What is the economically optimal configuration of the integrated power and transport system?

2 What is the optimal use of the EDVs with regard to the power system?

3 Does the power system benefit from the EDVs in terms of integrating more renewable energy/wind in the power system?

4 What are the consequences of incorporating EDVs in a power system configured for power demand excluding transport?

During the last few years, simulation models have been developed for electricity generation and demand. Among others, the deterministic energy systems analysis model, Balmorel, and the stochastic energy systems analyses model, Wilmar, have been developed. These are used in this thesis to try to find optimality in operation and investments in the energy system. Optimality is measured in terms of overall costs of the system. Influence on the configuration and influence of the EDVs will be measured in terms of CO_2 emissions and use of fossil fuels.

The objective of this Ph.D. project is:

- Introduction of decision support tools for the energy system including the road transport system. These support tools help improve decision making on a national and international level.
- Integration of the power and road transport system by introducing an investment and operation model for vehicles to be integrated with an existing investment model for the power system.
- Improve the understanding of the effects of introducing EDVs in the power system, based on energy system analyses, primarily using the energy system model, Balmorel.
- Projection of technological development to 2030 and presentation of future vehicle configurations to be used in the interaction with the power system.
- Forecast of a driving pattern and a possible future plug-in pattern for the passenger vehicles.

The research questions are primarily considered in a Northern European context. Some analyses include only Denmark, others both Denmark, Finland, Germany, Norway, and Sweden. The last analysis includes the Irish power system as this is interesting with the limited interconnection to the remaining European power system. Forecasts are primarily based on the developments up until now, and are projections of these, thus, assuming that the developments continue as of now.

1.1 Delimitations

Projections of technological development, price forecasts etc. are subject to uncertainty. However, these are based on the best prognoses and forecasts given by leading experts within the fields. Furthermore, sensitivity analyses have been made on most parameters, ending up with valuable results, although only estimates of what the future brings.

Analyses have been made for the Danish system without transmissions, the Northern European system including transmissions between the countries in the model and the Irish system with transmission from Great Britain. It could be argued that transmissions to the surrounding countries should be included as well, ending up with a global model. However, the studies have been restricted to the above mentioned transmissions for computation reasons and the desire to keep the details in the model. Furthermore, results from the Danish case versus the Northern European case show that the differences in the Danish optima are not very large (see Chapter 6). Thus, the results give a very good indication of optimality and including transmissions will of course be subject to changes, although these are not expected to be very large.

Only road transport in passenger vehicles has been taken into account. Including other transport sectors will increase the amount of storage and most likely decrease the marginal value of the EDVs. However, results show that EDVs are still preferred even with very large batteries, yet only if the price of batteries is not extremely high (Paper V).

An average vehicle has been modelled for each vehicle type, in order to keep the investments simple. In reality, some vehicles will be smaller and some larger. Including these involves introduction of different preferences and driving patterns, thus, increasing the details of the model substantially. And still, the inclusion of average vehicles gives results that are very valuable for, e.g. decision making.

Considering investments in only 2030, a gap of more than 20 years is experienced from existing vehicles, heat and power plants until investments are made possible again. Therefore, the analyses can be used as an indication of the direction of optimality, and thus a picture of what is optimal in 2030. Decisions can still be based on these analyses, keeping in mind the optimal configuration by 2030 (or

2020 in the Irish case).

1.1.1 Politics

Political decisions and focus on, e.g. climate changes, influence the configuration and operation of the power system. No model can take into account the upcoming decisions, but the most obvious decisions can be implemented. As an example, it is expected that high percentage of renewable energy will be forced into the energy system in Denmark, due to both EU-agreements and climate changes.

On the other hand, models and analyses like the ones presented in Papers III-VI, provide the politicians with decision support tools. In the analyses no taxes are included, thus, they present a socio-economically optimal investment decisions. Including upcoming decisions, gives an idea of the economically reasonable investments on top of the decision already taken. Furthermore, taxes can be included for analyses of, e.g. effects of introducing different tax structures.

1.1.2 Environmental aspects

The environmental impact of producing batteries have not been taken into account in the thesis at hand. Neither has the impacts of producing new vehicles. Producing both vehicles and batteries will have an impact, on e.g. CO_2 emissions. Whether the impacts of producing EDVs as opposed to internal combustion engine vehicles (ICEs) are better or worse has not been considered.

1.2 Content Overview

The thesis in hand includes six papers dealing with modelling and analysis of a power system including EDVs. Papers I and III address the modelling of the electric drive vehicles. Papers II-V address different analyses on the integrated power and transport system based on the model developed and described in the previous papers. Paper VI focuses on the issue with introduction of EDVs in a predefined power system. Many scenarios are relevant for research, but due to exhaustive calculation time it has been necessary to chose between scenarios. References are made to the articles in the thesis, where relevant.

Paper I "*Optimal configuration of future energy systems including road transport and vehicle-to-grid capabilities*" has been published in the scientific proceedings of the "European Wind Energy Conference 2009". The paper presents a new model capable of calculating optimal investments in both power plants and vehicle technologies; Balmorel with a road transport model add-on. The model includes interactions between the power system and the transport system including the competition between flexibility measures such as hydrogen storage, heat storage and plug-in hybrid electric vehicles (PHEVs).

Paper II "*Transport and Power System Scenarios for Northern Europe in 2030*" has been published in the proceedings of "Risø International Energy Conference 2009". The paper presents scenario analyses based on the model developed in Paper I. Scenarios are defined for a Northern European case, whereas preliminary results presented in the paper are based on a Danish case. Optimal investments are in wind power to cover the demand for PHEVs.

Paper III "*Optimal Configuration of an integrated power and transport system*" is an article submitted to "Energy" adding an illustrative case for the Danish power and transport system in the year 2030, based on Paper I. Running Balmorel with the road transport add-on for the Danish case, shows that optimal investments are in PHEVs along with a large increase in investments in wind power. The increase in wind power when introducing the possibility to invest in EDVs more than exceeds the increase in power demand due to the EDVs.

Paper IV "*Road Transport and Power System Scenarios for Northern Europe in 2030*" is an article submitted to "Applied Energy", presenting an analysis of the optimal configuration and operation of the integrated power and road transport system in Northern Europe, including Denmark, Finland, Germany, Norway, and Sweden. The paper is based in Paper II, using the energy system analysis model, Balmorel with the transport model extension. A number of scenarios have been set up, including sensitivity on CO_2 and oil prices, inclusion/exclusion of EDVs, and change in investment possibilities in flexible power plants. The optimal investment path in the Nordic countries results in an increase in renewable energy; primarily wind energy, as well as investments in EDVs and none in ICEs. The increase in wind power depends on the country and its resources. Thus, the vehicles will drive on, wind, coal, or lignite depending on the country in which they are situated.

Paper V "*Sensitivity on Battery Prices versus Battery Capacity on Electric Drive Vehicles and the Effects on the Power System Configuration*" is an article submitted to "Journal of Power Sources". The paper presents an analysis of the integrated power and transport system focusing on the sensitivity in the power system according to battery capacity and price. The sensitivity analyses are performed in a situation where the vehicles use smart charge and are able to deliver power back to the grid (vehicle-to-grid, V2G). The analyses indicate that investments in PHEVs are very robust when it comes to battery prices. Only at very high prices along with high capacity batteries, ICEs are optimal for investment. Furthermore, when the vehicle fleet consists of 25% battery electric vehicles (BEVs) and 75% PHEVs, then batteries in the PHEVs are of greatest benefit to the integrated power and road transport system at a size of 6-7.5 kWh. As for the BEVs, the marginal benefits are almost eliminated when reaching a size of 42-58 kWh.

Paper VI "*Influences on dispatch of power generation when introducing electric drive vehicles in an Irish power system year 2020*" is an article submitted to "Energy Policy". The paper presents investigations of different charging regimes' influence on the power dispatch in the Irish power system including an inter-connector to Great Britain. Analyses show that base load plants are to generate power on a more constant level, thus, they are experiencing less start-ups. On the other hand, mid-merit power plants have more start-ups due to the introduction of EDVs. Furthermore, costs and CO_2 emissions decrease in the all-Ireland power system, but CO_2 emissions increase in the power system in Great Britain. All together, CO_2 emissions increase - an argument for making decisions regarding the energy system on an international level as opposed to a national level.

The remaining part of the thesis contains the following: in Chapter 2 the background for the model and the analyses is described. The configuration of today's heat, power, and transport system is presented as is the challenges of integrating the transport system with the heat and power system. Chapter 3 discusses the methods to be used for answering the research questions starting off with a short literature review, also placing the papers included in this thesis. This is followed by a discussion of the choice of models and some crucial assumptions for the models are commented upon. The models are described in Chapter 4. Overall descriptions of Balmorel and Wilmar are provided. Balmorel is described with enough details to understand the interaction with the transport system. The transport system model is described in details including comments on the use of the EDVs in the power system. Chapter 5 contains a description of the technologies used in the models, starting of with the vehicle technologies. Heat and power technologies are explained in brief and an overview of the services provided by the different plant types is given. Also, the possible competition between the power plants and EDVs is commented upon. Main results from the scenarios are presented in Chapter 6, commenting on the results across the papers. Finally, Chapter 7 provides conclusions and discussions along with an outline of further research possibilities.

Chapter 2

Background

The Danish energy system is very different from most other energy systems. It is characterised by a large share of renewable energy with fluctuating production (28% of the electricity production in 2009 [8]), a large share of combined combined heat and power with power production to a large extend depending on heat demand (81% of electricity production, 77% of district heating in 2009 [8]), and a large share of waste being incinerated producing a rather fixed level of heat and power (accounting for 5% of the electricity production and 18% of district heating in 2009 [8]). Based on the large amounts of inflexible power production, flexibility is needed in the remainder of the power system.

CO_2 emissions from the entire energy system amounted to 49 Mtonnes for Denmark in 2009, of which the transport system accounted for 15 Mtonnes and district heating for 4 Mtonnes [8]. The emissions split on fuel types are shown in Figure 2.1. All transport emissions come from oil. Subtracting these, the remaining CO_2 emissions from oil in the heat and power system amounts to 7 Mtonnes.

With an increasing penetration of fluctuating renewable energy, it will be increasingly harder to fulfil the security of supply in the energy system. However, new technologies can enable storage of energy and more flexible demand and supply. This chapter presents an introduction to the power, heat, and road transport systems. The introduction is followed by a section about expectations

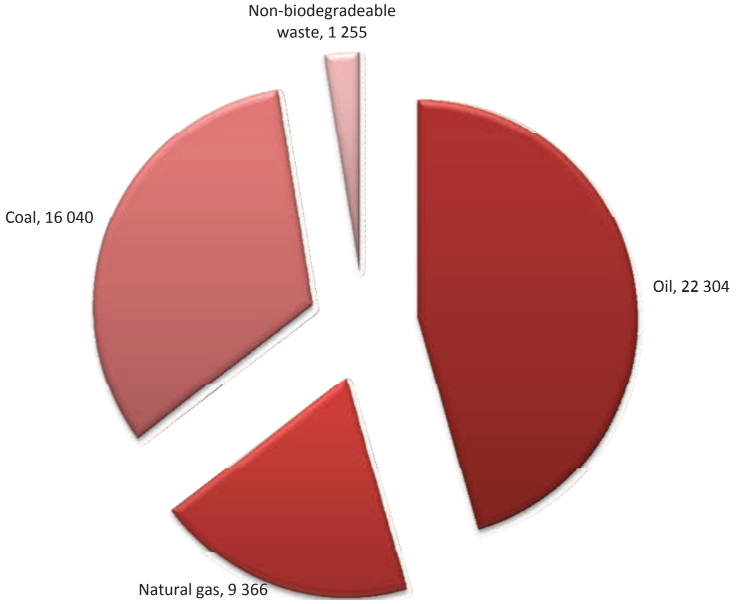


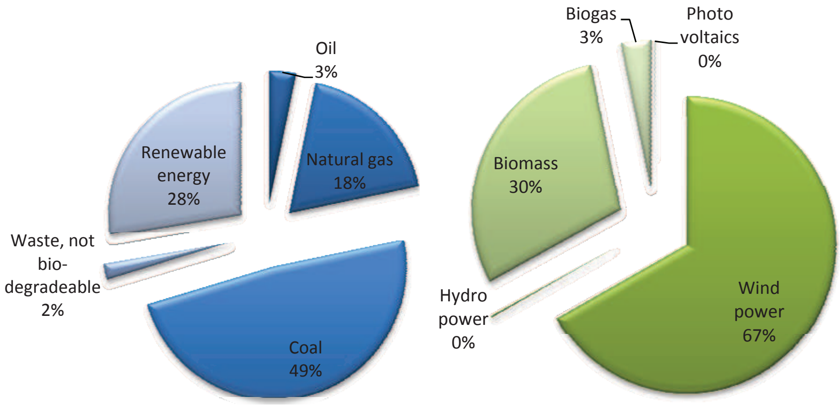
Figure 2.1: Split of CO_2 emissions in Denmark, 2009 [8] (1,000 tonnes).

of directions of development primarily for the road transport system.

2.1 The Power System

In 2009, the Danish power system was primarily characterised by 49% of the electricity generation being on coal, secondarily 28% of the electricity production being renewable, Figure 2.2 [8]. Wind power covers by far the largest share of the renewable energy. Many renewable energy sources, especially wind, provide fluctuating amounts of power. Fluctuating power supply requires flexibility from other parts of the system.

Due to differences in available resources, countries have different configurations of their power systems. The integration of renewable energy depends on these national resources, and in Denmark, a large amount of the renewable energy most likely will be coming from wind power. Norway, on the other hand, has a large amount of hydro power, including reservoirs, and Germany primarily produces electricity on coal [22]. Denmark is in between these two countries and benefits from the good and flexible power from Norway (and Sweden) and the option of sending excess wind power to Germany. The latter becomes a



(a) Total electricity production (b) Renewable electricity production

Figure 2.2: Electricity production on fuels in Denmark, 2009.

more and more limited option with the expectations of Germany increasing wind installations in the North Sea. Wind power production from these sites are highly correlated to production from wind turbines in western Denmark.

The power system is challenged by the fact that supply must meet demand exactly and at all times. Every time we turn on a switch, we expect the light to turn on, causing a change in demand and, thus, generation. In order for generation to meet demand, different types of power generating plants are required in the system:

- Base-load plants: Usually power generating plants with high fixed costs and low variable costs. The plants are often generating power at a steady rate, and have slow respond time to changes in demand when off-line. These are, e.g. nuclear power plants and steam turbines (see Section 5.2).
- Mid-merit plants: Power plants that have fast response to changes in power demand. The power plants are typically very efficient and come on-line to produce power when demand is high and can go off-line again when demand decreases.
- Peak-load plants: Characterised by power generating plants with low fixed costs and rather high variable costs. These power plants have fast response time, reacting to the increase and decrease in power demand primarily in peak-load hours.

Renewables are hard to place in these categories. However, I would place the wind turbines among the base load plants. This is due to the fact that power from, e.g. wind turbines cannot be used as regulating power as mid-merit and peak-load plants. The wind turbines are not producing power at a steady rate, though, but with the cheap production, the renewable energy resources will most likely be used before other power sources.

Ancillary services (see also [53] for more details) are needed to ensure a secure and stable operation of the power system. A number of ancillary services are required, all with different activation times: seconds, minutes and longer. Furthermore, the introduction of wind power production will require back-up power when experiencing longer time periods with no wind. It will also be beneficial to have technologies enabling reduction in the variability of the electricity load, e.g. power consumption during low load and reverse during high net load.

Examples of ancillary services, that could be of relevance to the EDVs are:

- Primary reserves. According to the Nordic Grid Code [45] each of the Nordic countries is obligated to provide primary reserves. Primary reserves are up or down regulation of power generation to be provided within seconds. Providing primary reserves requires short response time.
- Secondary reserves. Secondary reserves are like primary reserves, except secondary reserves are operating in agreed cross-boarder exchange levels [34], such as the area between western Denmark and northern Germany.
- Tertiary reserves. Tertiary reserves are reserves with response within minutes (a maximum of 15 minutes activation time).

Besides these reserves, capacities are needed for long time periods with no wind and for enabling up and down regulation in order to meet the differences in night and day time demand.

Different plant types are to provide the different ancillary services. As for the EDVs, they can provide all of these three services. However, when reserves are needed for longer times, e.g. in weeks without wind, the EDVs cannot provide the necessary reserves.

2.1.1 Electricity grid

Security of supply requires a transmission grid for both electricity and heat, the latter including natural gas pipelines as in the system today. As can be seen from Figure 2.3, Denmark has interconnections to Norway, Sweden and Germany. The blue lines are HVDC-lines, whereas the red, green, black and yellow lines are 400 kV, 220 kV, 132 kV, and 60 kV system AC-lines respectively. Dotted lines are not operating yet, except for the great belt transmission line.

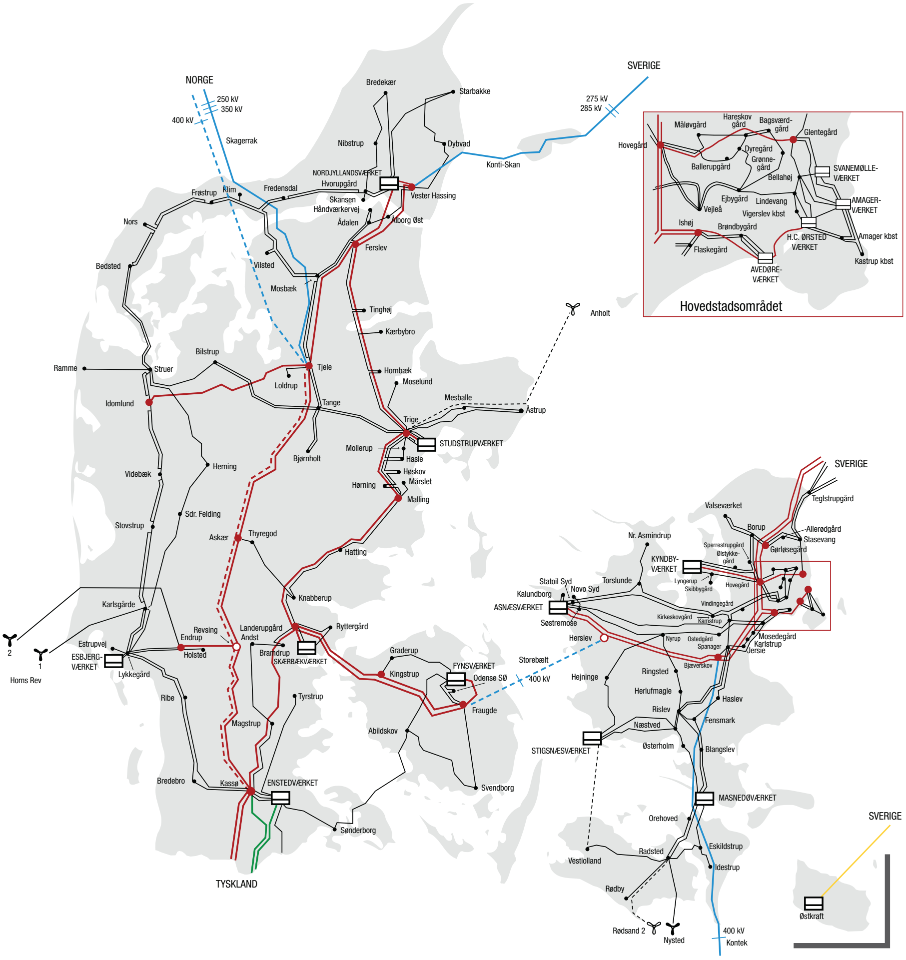


Figure 2.3: High voltage grid and placement of central electricity plants in Denmark, 2009 (*source energinet.dk*).

The electricity grid is build to handle the transmissions we see today. With increased distributed generation the electricity grid needs to be scaled up. Some up-scaling is already planned [5], but introducing EDVs increase the flow in the transmission lines further, thus, calling for even more up-scaling.

2.2 The Heating System

The Danish heating system is interesting with the large share of district heating, based on primarily combined heat and power. In 2009, the system consisted of 47% district heating and 53% individual heating [8]. In 2009, district heating was produced primarily on renewable energy sources, natural gas, and coal, as can be seen in Figure 2.4.

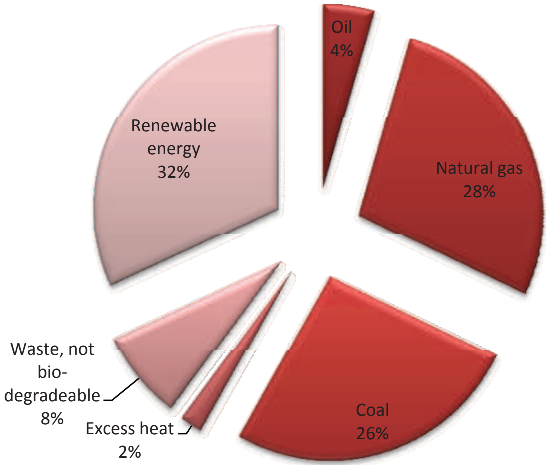


Figure 2.4: Danish district heating production on fuels, 2009 [8].

Municipal waste has to be treated. It has been politically decided that waste treatment plants, like combined heat and power (CHP) plants, are to cover the expected waste load. Thus, a large share of the municipal waste is used for district heating. District heating systems usually include heat storages, enabling a more constant load and a decoupling of supply and demand.

2.3 The Road Transport System

The Danish transport system is characterised by a high use of oil. The CO_2 emissions from road transport counts for 77% of the total CO_2 emissions from transport, as can be seen in Figure 2.5.

Denmark's road transport system is characterised by almost only internal combustion engine vehicles (ICEs) among the passenger vehicles. The amount of hybrid electric vehicles and battery electric vehicles (BEVs) with quite small

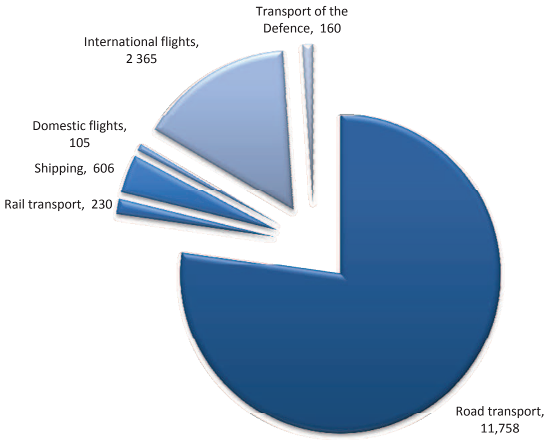


Figure 2.5: 1,000 tonnes CO_2 emissions from transportation in Denmark, 2009 [8].

batteries is increasing, but today electricity only counts for 0.01% of the passenger road transport [11].

The Danish road transport system is also characterised by a very high willingness to pay for driving your own vehicle. Denmark experiences some of the highest taxes on vehicles and fuels, yet, the vehicle fleet still increases. Furthermore, many people rather go through rush traffic, than travel with public means of transport. The freedom from having your own vehicle and deciding where and when to go for the next trip is very important and has to be taken into account when planning infrastructure etc. for a future road transport system.

With gas stations situated at many a street corner, people are accustomed to refuelling whenever needed or in times of temporary price reductions. Furthermore, people are accustomed to be able to drive far, and might not want to give up this habit. These expectations and habits may be hard to challenge and even harder to change. Again, flexibility is a key driver for many people. On the other hand, many families have more than one car and the 2^{nd}, 3^{rd}, 4^{th} etc. vehicle is usually primarily used for commuting. Hence, the flexibility needed for the primary vehicle is often not needed for the other vehicles, as long as they can make the commuting distance.

2.4 Expectations of the Future Road Transport System and the Integration with the Power System

The previous sections have described the energy system as it is today, whereas, this section describes some expectations on the future road transport system. Moving towards large shares of renewable energy calls for a shift in means of road transport. Renewable energy in the transport sector can be in terms of bio-fuels, electricity, or fuel cells. Bio-fuels are available in limited quantities and are not of interest for the power system. Thus, the focus of this thesis is EDVs, including an integration with the power system. The types of EDVs in focus in this thesis is:

- **BEV:** The battery electric vehicle is driving on electricity only. No range extender in terms of an engine or fuel cell is included. Hence, the BEV has limited driving range before charging the battery.
- **PHEV:** The plug-in hybrid electric vehicle is a vehicle with a battery for driving short distances, in the cities or the like. Besides the battery the vehicle has an engine using, e.g. diesel as propellant. The engine can be regarded as a range extender, ensuring that the PHEV can drive the long distances.
- **FCEV:** The fuel cell plug-in hybrid electric vehicle has a battery like the PHEV. Besides the battery, the FCEV has fuel cells using, e.g. hydrogen as propellant.

Expected change in fuels also changes demand for electricity. Integration of the power and road transport systems experience a number of challenges, but also a number of possibilities both mentioned in this section (based on Section 3.5 in [53]).

2.4.1 Challenges

Introducing electricity and charging in the road transport system requires a number of changes in infrastructure etc. Many challenges have to be dealt with. In the following a number of interesting challenges are touched upon.

One of the first challenges that comes to mind is the way of charging the EDVs. *Dumb charging* of the EDVs, hence, charging as soon as they are plugged-in, increases, e.g. the peak-load demand. If, on the other hand, intelligence is built into the system, the EDVs can help stabilising the demand or the power generation. With a large penetration of fluctuating renewable energy, this flexibility can be of great importance to the power system. The intelligence should, obviously, include functionalities like lower boundaries for the discharging of the vehicle, enabling smaller trips, e.g. in case of emergencies.

Infrastructure covers, e.g. grids and chargers. How much extension is needed in the grid in order to be able to meet demand? In Denmark, the first steps towards meeting the demand for electricity in the road transport system have been taken by projects like "Project Better Place" [47]. Chargers are being developed and placements are decided upon. Charging of the plug-in EDVs can be done in different ways. Discussions are still how much and what to implement. Researchers investigate the challenges and benefits for the different methods. Possible ways of loading the batteries are discussed below.

- Charging when parked at home: This is the most obvious solution. When introducing EDVs we would want these to be able to charge at home at night time. There should be no problem in charging at home when you have your own garage or driveway. In areas with apartments, on the other hand, installation of charging spots is of discussion. A lot of them are needed in very little place, they need to be guarded against malicious damage, and somehow they need to be able to tell which vehicles are plugged in and where (discussed in Section 2.4.2).
- Charging when parked at work or in public parking spots: Here we experience the same challenges as with charging spots in apartment areas, although, some locations are easier to handle than others. Yet, how many chargers are needed in public parking spots?
- Fast charge, e.g. at gas stations: Fast charge is charge of the battery within about 5-15 minutes. If on longer trips and a larger driving range is needed this is a possible solution. Fast charging does tear on the battery and should not be the primary way of charging the EDVs. Decisions on whether to use fast charge or not has to be made and concerns have been expressed regarding the power system in that respect. What will happen when a vehicle needs to charge within 5-15 minutes? There will be a massive demand in one point for a short period of time. And, how can the system be prepared for that?
- Battery swap: "Project Better Place" has introduced the mindset of battery changing stations [47]. The thought is to drive the EDV into a place like a garage, where machinery swaps the empty battery with a

> fully charged battery. Thus, the battery swapping station needs to have fully charged batteries in store.
>
> However, batteries loose power over time. Therefore, this requires for the batteries to be plugged to the electricity grid, which on the other hand can enable more reserves for the power system. Furthermore, it is rather expensive to have extra batteries and it is, thus, a large investment that has to be overcome for these stations. Also, due to the costs of the batteries, one can expect the charging stations will not invest in very many batteries. With few batteries, charging will often have to be done straight away, resulting in dumb charging.
>
> Finally, if you own your battery most people would hesitate to swap their battery with a battery of which they do not know the condition. Hence, battery swapping stations probably does require a scenery where the EDVs are privately owned, but the batteries are, e.g. leased.

Decisions have to be made on the power flow. It must be decided whether the system should support power flow in only one direction; grid-to-vehicle(G2V) or in both directions; that is including vehicle-to-grid (V2G). The last option demands for a grid that supports two-directional power flow as well as the vehicle being able to both charge and discharge to the grid. In Denmark, it has not yet been decided whether the power flow is to go in one direction or both ways.

If the power system desires to use the EDVs as flexible power supply and demand, it has to be made attractive to plug in the vehicles. An economic benefit from plugging in the vehicle and letting the battery be used by third party needs to be present, otherwise, a lot of people might as well stick to dumb charging. Furthermore, security of minimum battery capacity needs to be present. The vehicle owners need to be assured that plugging in the vehicle still means that unexpected trips can be made, such as a trip to the hospital. Finally, not only incentives, but also the infrastructure has to be in place, thus, chargers have to be placed in a way, that make the EDVs available when needed by both the power system and the vehicle owners.

2.4.2 Communication

A number of challenges must be considered when setting up communication with the vehicles. Communication from the market to the vehicles may be through price signals. Optimising market economics, high prices would make vehicles discharge, whereas, low prices would make vehicles charge. The vehicle owners need incentives to let the power system use the battery. Some incentives are given through the profit of the vehicles charging at low prices and discharging at high prices. However, the incentives have to be strong enough to overrule the high willingness to pay for the freedom of driving your own vehicle, as mentioned in Section 2.3.

A flow of information from the vehicles to the market is required for planning the use of the services to be provided by the EDVs [55]. As the power system is structured today, one cannot expect the transmission system operator (TSO) to be dealing with every single vehicle. Therefore, some sort of aggregation of vehicles has to take place. Furthermore, a monitoring of the vehicles state-of-charge is needed in order to know how much charge or discharge capacity is on board each vehicle. And, when the EDVs are providing services to the grid, some kind of metering and settling has to take place. All the above mentioned aspects are discussed in this section.

Day-ahead forecasts. As the power market works today, players can place bids on the day-ahead market [46]. In case of the EDVs, the bids on the day-ahead market would most likely contain informations about the amount of power needed for charging the vehicles during the next day, thus, the flexible demand from the EDVs. In order to place the bids one would make a day-ahead forecast, based on a number of informations and/or assumptions; e.g. availability and need for charge. Both have to do with scheduling of the trips. Furthermore, need for charge has to do with, e.g. state-of-charge, expected driving range (need for battery capacity the next day), and expectations of needed battery capacity for each trip. Since none of these parameters are known for sure, forecasts are to be made – most likely according to prior driving patterns.

Aggregators. With a minimum of 10MW to be bid on the market for minute reserves [18], the EDVs will have to be pooled or the market structure has to change. Even without the restriction on production, the transmission system operator most likely would not be dealing with every single EDV owner. Therefore, a third party may be introduced acting as an aggregator. As mentioned by Brooks and Gage [2] and Kempton and Tomic [32], the aggregator could be one of many, e.g. a retail power delivery company, an automobile manufacturer, a cell phone network provider etc. The aggregator, adding a great number of vehicles, could offer large amounts of reserves to the power market.

One way to aggregate the EDVs could be by region (western Denmark and eastern Denmark) and by type of vehicle, because of the different grid services to be provided by the different types of EDVs. Another way could be to aggregate the vehicles in a way that ensures that each aggregator could provide all of the above mentioned services to the grid. An aggregator could also cover fleets of vehicles parked in a number of parking facilities, e.g. parked rental cars or vehicles used during work hours to be charged before the next day.

The role of the aggregator will be to place the bids on the day-ahead market and on the reserve markets. All the information needed by the transmission system operator could be received either from the aggregator or from online communication. Also, the aggregator needs to make the choice of which vehicles to use when. In order to do so, the aggregator needs real time monitoring of the vehicles.

Monitoring the vehicles/On-line communication. Real time knowledge of state-of-charge, next scheduled trip, minimum capacity required by user, interconnection capacity etc. has great importance to the planning. Monitoring could be done by computers incorporated in the vehicle, measuring, e.g. battery capacity and state-of-charge. These computers could be intelligent in a way that according to prior driving patterns the computer estimates the needed battery capacity. Or the computers could contain a feature where the vehicle owner types, e.g. the hour of the next trip, reserved capacity for unexpected trips, and distance of next trip [28]. There is a risk in having people doing the programming, though. The optimal way would probably be for the computer to contain both features in order for the user to be able to override the computer if, as an example, an expected trip differs from the standard.

Furthermore, the on board computer should be able to communicate with the aggregators in order for them to make the choice between EDVs and finding the vehicles most suitable for the services asked for by the TSO. There are a number of different factors to consider when choosing, e.g.:

- Wear-and-tear. Considering only wear-and tear of the vehicle speaks in favour of using the vehicles randomly or using the vehicles in rotation – using the least used vehicles first.
- Prices. One could imagine a case where we have a “negotiation” with the EDVs signalling a price and the service asked for. The vehicle will return a respond whether or not to actually provide the service [50].
- State-of-charge. How much power can be supplied or stored from the particular vehicle.

Metering and settling. Every time a vehicle is providing services to the grid it has to somehow be metered in order to make the correct settlements afterwards. The metering could be done by the on board computer sending messages to the aggregator, either when connecting and disconnecting [3] or every time a service has been provided. The message should contain time, duration, amount of power, type of service provided etc. According to this information the accounts could be settled every day, every week, or maybe just once a month. Today, cell-phone companies are delivering a similar "billing" system, charging customers according to different types of use of their cell-phones.

For metering and settling the aggregators also need to know which vehicle is connected to the grid and where. This is to ensure, that the electricity charges or payments goes to the right vehicle owner. This information can, e.g. be given through an on board GPS device, reporting the GPS position to the aggregator [2] or through information given through the plug.

2.4.3 Grid services to be provided by the EDVs

The EDVs are potential providers of some of the ancillary services demanded by the power system. Providing these services might be of benefit to both the power system and the EDVs, when payments are in place. The power electronics in EDVs may be designed in a way, that enables deliverance of ultra-fast reserves, i.e. power to the grid as a response to a frequency drop, with an activation time of 1-2 seconds.

Primary reserves can be provided from the EDVs in terms of charging or discharging of the batteries in vehicles. Furthermore, a pause in either charging or discharging can also be regarded as delivering primary reserve. Primary reserves can equally be delivered by all types of EDVs.

The power delivered from an EDV is typically limited by the grid connection [31]. Therefore, in order to provide reserves of 100 MW about 27,180 plugged in BEVs are needed. American studies have shown that even during rush hours at least 92% of the vehicles are parked/plugged in at all times [36]. Assuming that this is also the case in Denmark, the number of BEVs/PHEVs needed in order to meet the 100 MW demand for reserves is 29,540. Using a three phase connection would reduce this number to only 2,680 BEVs/PHEVs.

Tertiary reserves, hence, providing reserves within minutes, could be provided by both BEVs, PHEVs, and FCEVs. Net revenues calculated by both Moura [43] and Kempton et al. [30] are strongly in favour of using BEVs for these types of reserves. This is due to the quite high battery-degradation costs and battery costs of the small batteries (PHEVs and FCEVs). Small batteries cannot be used very much, before state-of-charge is very low, thus, deep cycles will be experienced rather often with small batteries. The deeper the cycle of the batteries, the faster the degradation. As technology evolves, it is likely that the cost of the small batteries approach the costs of the larger ones.

Stabilising the demand curve, e.g. moving load from peak-load hours to the night time, calls for either no charge, discharge of on board batteries or power production from the engines during peak-load hours. The TSO being in control of when to charge will give the ultimate flexibility. All three types of EDVs could provide this service. Although, Kempton and Kubo [29] argue that the economics of using BEVs are far better because of the rather small batteries in both PHEVs and FCEVs.

From time to time we are experiencing a period of up to 2-3 weeks without wind. In these situations stored electricity from BEVs will not last long. The option here is to have FCEVs and/or PHEVs producing power to the grid. Since the engines will have to be running, FCEVs are preferred in these situations, due to the pollution of having diesel engines running. Although, there are differences in wear-and-tear and maximum output of the vehicles [32]. This power production is rather costly, i.e. because of the low efficiencies.

Table 2.1 summarises the choice of vehicles to provide the different kinds of services to the grid.

Vehicle type	Primary reserves	Secondary reserves	Tertiary reserves	Day/Night	2-3 weeks
BEV	+	+	+	+	-
PHEV	+	+	(+)	+	(+)
FCEV	+	+	(+)	+	+

Table 2.1: EDVs' possibilities of acting as reserves.

With no infrastructure in place, the BEVs are not very attractive. On the other hand, PHEVs can load at night time and still save both money and CO_2 emissions. Thus, it will be likely that investments and driving in PHEVs will be the main driver in electrifying the road transport system by demanding construction of the necessary infrastructure for the BEVs to seriously enter the market.

CHAPTER 3

Methods

In this chapter I discuss the research done within the relevant field and how the work in this thesis differentiate from other studies. Furthermore, answering the research questions stated in Chapter 1 calls for an analysis tool. No analysis tool integrating the power and transport systems including both investments and operation has been developed. However, energy systems analysis models have been developed, therefore, a new transport system model will be developed and integrated with an existing energy system model for these analyses. Other analyses do not include investments, nor detailed transport system modelling, hence, different power system models can be considered. Choice of model and thoughts for a road transport model is described in separate sections below.

3.1 Research Within the Field

A number of aspects are related to integration of the power and road transport systems. Research has been done within various fields such as potential benefits for the power system and for the customer, infrastructure, transition paths, and quantification of the impact and benefits. Kempton and Tomic defined and explained the concept of V2G and potential benefits of V2G in [31]. This article was followed by an article including business models as well as thoughts on dispatch of vehicles [32].

Many articles have followed and interest has increased within the fields. Focus on potential benefits of particular services has been taken in terms of peak load shaving in Japan [29], and regulation and ancillary services [54]. In [3] Brooks has looked into integration of BEVs with particular focus on the benefits of the vehicles providing ancillary services. Cost comparisons of providing different kinds of services has been made in [43], comparing the different kinds of EDVs with the technologies providing the services today. In general, the papers find that it is beneficial to introduce EDVs, although, the economics of using these for only peak load shaving (in Japan) is not very profitable without a change in the rate schedules [29].

So far, the impact on power production from integrating the power and road transport has been quantified by few. In [41] McCarthy, Yang and Ogden have developed a simplified dispatch model for California's energy market to investigate the impacts of EDVs as part of the energy system. However, this model does not take the fluctuation in power production and, thus, the need for flexibility into account. Kiviluoma and Meibom compare power system investments and CO_2 emissions in scenarios with different amounts of wind, heat pumps, and PHEVs in the Finnish power system [33]. However, the paper does not include co-optimisation of the investments in the vehicle fleet. The authors also compare the output of the stochastic optimisation model, Wilmar, and the deterministic optimisation model, Balmorel. In [38] Lund and Kempton have made a rule based model of the integrated power and transport system, focusing on the value of V2G in different levels of wind penetration.

Paper I in this thesis contributes with an investment model for the integrated power and road transport system. This model makes it possible to analyse the impact of interaction on future investments in far more detail and potentially provides more changes and benefits in the power system than in the papers mentioned above. Calculation of investments in different vehicle types has not been included in any of the above, but has been introduced in [24] in terms of illustrative cases and Papers II-V illustrates the use of the detailed transport system model. Paper II defines a Northern European case, although, presenting results on the investment and operation in the integrated power and road transport system from a Danish case.

Paper III shows how introduction of electrical power in the transport sector and co-optimising investment decisions regarding vehicle types and power system configuration has consequences for the entire power system in terms of, e.g. optimal mix of production and storage units, fuel consumption and CO_2 emissions. The case study in Paper III is limited to Denmark as an illustrative case, whereas Paper IV investigates the optimal investment paths and configuration of the power and road transport system for various scenarios for northern Europe in 2030. These analyses are based on the model developed in Paper I and III. Thereby, key drivers contributing to the path towards a 100% renewable energy system can be found. Competition between the different vehicle types as well as competition between sources of flexibility, e.g. EDVs versus heat storage in combination with electric heat boilers, is studied.

As for the transition path, studies have been made on how to ensure a smooth transition path going from today's vehicle fleet to PHEVs and BEVs [32]. In [39], 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. Changes in the power system due to the increased demand from EDVs have been studied in [23]. Paper VI presents analyses of how different charging regimes change the operation of a predefined power system for the year 2020. The focus in this paper is the transition path and how EDVs can be integrated in a power system not configured to include the transport system, introducing different penetrations of EDVs with different charging regimes.

A possibly very important, yet very uncertain factor in the introduction of the EDVs, is the batteries. The batteries are under development and expectations to the prices and capacities are many, as are the possibilities of how to charge and discharge the batteries. Fast charge versus slow charge and the impacts on the power system and, thus, the electricity price, has been studied by Shortt and O'Malley [51]. The Danish Energy Authority has focused on the challenges in interactions between the electricity grid and the transport system [10]. The technological innovation of batteries and EDVs has been touched upon by Lipman and Hwang [37], and the Danish Center for Green Energy [1] compares battery types for EDVs as well as price expectations of the batteries. For valuing a change in battery capacity, Lemoine [35] has used real options, capturing the uncertainty of the electricity prices.

The contribution of Paper V is analyses of the consequences of different battery price and capacity. The analyses are done by a sensitivity analysis of battery price vs. battery capacity in the EDVs, finding the situations where the EDVs are most beneficial for the power system. These sensitivity analyses are, as Paper IV, also based on the model developed in Paper I and III. Scenarios are analysed for the northern European power system.

For a more thorough and, for the papers, more targeted literature review, see the introduction in the respective papers.

3.2 Choosing Analysis Tool

Various models have been developed for analysing the power system. Each model has its own area of expertise. Most energy system models have been described and categorised in [4]. This section touches on the most relevant models for the area of focus in the present PhD project. The models used for the analyses will be analysed in more details in Chapter 4.

The most interesting models relevant for energy system analysis are (see Table 3.1 for outline):

- **Balmorel:** A linear optimisation model, optimising both operation and investments for the integrated electricity and district heating system. The model is a bottom-up model, and has the strengths of both optimising investments and operation in the same simulation.

- **EnergyPLAN [40]:** A rule based model, simulating electricity, district heating, and transport system operation. Investments are not included, but the model can easily be run several times, to investigate benefits in different investment strategies. The model has the advantage of being user friendly and very fast to run. On the other hand, in order to find optimal investments, manual iterations have to be made. Manual iterations and configuration of possible outcomes for the power system can be time consuming.

- **MARKAL/Times [20]:** An investment model, configuring an optimal (least-cost) energy system. MARKAL/Times includes not only power generation, but also fuel production and all demand sectors' energy consumption. The model includes emissions, efficiencies etc. The model is widely used, among others within politics as a decision support tool. However, this model does not include optimal dispatch and, thus, is not suitable for considering the potential benefits in terms of, e.g. flexibility from electrifying the road transport system.

- **Sivael [19]:** A model to optimise operation of a given energy system, considering fuel economics, emissions etc. The wind error is simulated using a stochastic process, enabling the model to estimate a need for reserves. This model is developed and used by the national TSO in Denmark.

- **Wilmar [42]:** A stochastic programming model, optimising operation of a given electricity, district heating, and transport system, introducing stochastic wind forecasts. The model has the advantage of optimising operation more precisely than, e.g. Balmorel, due to inclusion of stochastic programming, mixed integer programming, and more detailed unit restrictions.

Model	optimisation	rule based	deterministic	stochastic	inv.	dispatch
Balmorel	+	-	+	-	+	+
EnergyPLAN	+	+	-	-	(+)	+
MARKAL	+	-	+	-	+	-
Sivael	+	-	+	-	-	+
Wilmar	+	-	-	+	-	+

Table 3.1: Energy system analysis models

In order to investigate an optimal configuration of an integrated power and road transport system, an investment model is needed. Although investments are not enough when estimating the benefits from the EDVs in terms of integration of more renewables/wind in the power system. Hence, a model being able to optimise both investments and operation of the power system is needed. The only model of the above including both to a sufficiently detailed degree is Balmorel. Thus, a transportation add-on for the Balmorel model has been developed in order to enable analysis of a detailed integrated power and transport system.

Investigation of the impact of introduction of EDVs on a predefined power system does not call for an investment model. Balmorel can be used without investments, however, as shown in [33], Wilmar provides more accurate results when only estimating optimal dispatch. Thus, the Wilmar model is used to try to answer this research question.

3.2.1 Strengths and Weaknesses in the Models

Models for finding a socio-economic optimum have both strengths and weaknesses. Some of the strengths are the possibilities of optimising very large and complex systems, comparing different future scenarios, and having some very strong decision support tools. Having said that, it is important also to be aware of some of the weaknesses. Examples of these are the rationality assumption, the models cannot take preferences into account (thus, it is assumed that all actors within a category have the same optimum), and the fact that the value of different things cannot always just be given by prices. Hence, the model often acts as if the world is black and white, but as Tina Dickow says it "*Between black and white, Is a thousand shades of grey*" (Tina Dickow, Break of Day).

3.3 Thoughts About the Road Transport System Model

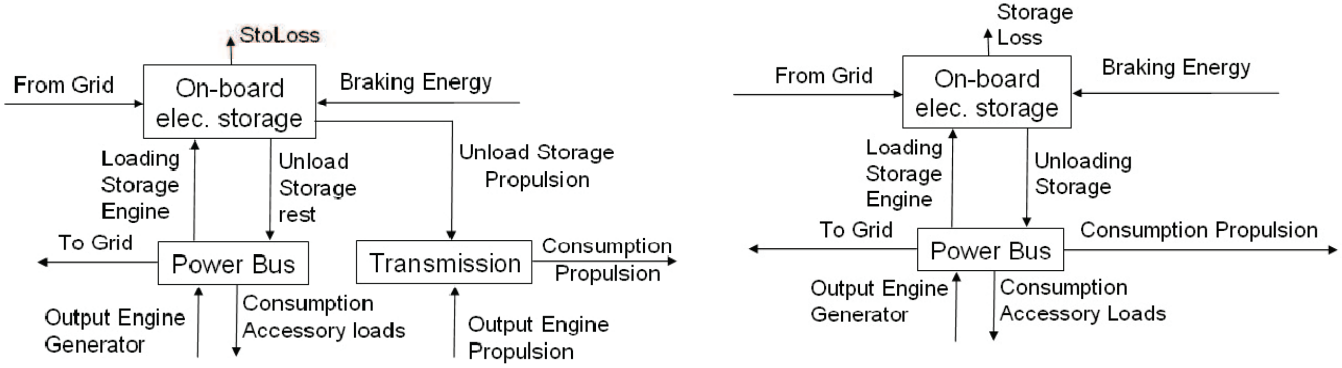
A lot of decisions and assumptions have to be made before modelling the road transport system. Important for an investment model is, of course, the investment and operation and management costs of the vehicles. For the power system, the electricity flow in the EDVs are of great importance. Therefore, modelling the road transport system has off-set in the electricity flow for charging, discharging and the use of electricity for driving, and the cost of use of other types of propellant, such as gasoline and diesel. Using yet other types of propellants, such as hydrogen or bio-diesel, has to be modelled in terms of hydrogen production to be used for both power generation and fuel, and limitations on total use of biomass.

In modelling the vehicles, one of the first things to be decided is which kinds of propulsion systems to represent in the model. In order to be able to analyse the competition between different vehicle types the following types are included so far:

- Internal Combustion Engine (ICE): defined as vehicles with an engine using either diesel or gasoline as propellant, like most of the vehicles on the roads today.
- Battery Electric Vehicle (BEV): vehicles using only electric power from an on-board battery as propellant.
- Plug-in serial Hybrid Electric Vehicle (PHEV): defined as pluggable vehicles with a serial propulsion system using either battery or diesel/gasoline as propellant. This could also be enhanced to include bio-diesel as propellant, as well.
- Fuel Cell plug-in hybrid Electric Vehicle (FCEV): defined as pluggable vehicles using either battery or hydrogen as propellant.

The latter three vehicles are all defined as electric drive vehicles (EDV), since they have the ability to use *battery only* for driving. Furthermore, the hybrid electric vehicles will, most likely, primarily use the battery for driving, since electric power is somewhat cheaper and more efficient than the other propellants. Thus, the other propellants are viewed as "range extenders".

The PHEVs are modelled with a serial drive train as opposed to a parallel drive train, as the one seen in the Toyota Prius. The parallel drive train is somewhat more complicated to model, because of a more complicated configuration of the drive train. From Figure 3.1 it is seen, that for the parallel drive train, output from engine can go to both transmission and the power bus, whereas output only goes to the power bus for the serial drive train. Thus, modelling the parallel plug-in hybrid electric vehicle would require a decision on optimality in how to use the engine/motor when driving as well as how to optimise the power flow between the EDVs and the power system when the vehicles are parked (in case the EDV uses the engine for producing power to the grid). Therefore, it has been decided not to include the parallel plug-in hybrid electric vehicles in the modelling.



(a) Parallel plug-in hybrid electric vehicles

(b) Serial plug-in hybrid electric vehicles

Figure 3.1: Power flows model, [52]

CHAPTER 4

Models

In this chapter I present the models used for the analyses. In Section 4.1 the Balmorel model is described followed by a more thorough description of the vehicle modelling, thus, the transport add-on to Balmorel. The chapter ends with a brief description of the advanced hourly dispatch model, Wilmar, used for analyses in Paper VI.

4.1 Balmorel Model Characteristics

The Balmorel model was initially developed to support energy systems analysis in the Baltic Sea region, focusing on both electricity and combined heat and power sectors [48]. In the Balmorel model, experts, researchers, or the like can analyse aspects regarding economy, energy, or environment, including future configuration of the energy sector within a region or in all the countries analysed.

Balmorel is a deterministic, partial equilibrium model assuming perfect competition [48]. The model maximises social surplus subject to 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. The energy sector experiences price inflexible demands, thus, maximising social surplus corresponds to minimising costs. Balmorel generates investments and dispatch resulting in economically optimal configuration and operation of the power system. Market prices for electricity can be derived from marginal system operation costs. Input data changes allow for sensitivity and scenario analyses.

In Balmorel, countries are divided into regions connected by transmission lines. Regions are then further subdivided into areas. Electricity and transport demand is balanced on a regional level, whereas district heating is balanced on an area level. Balmorel has a yearly optimisation horizon, with an hourly time resolution. Long term investments are typically run with either aggregated time steps or weeks, depending on, e.g. the amount of data. For some scenarios an hourly time resolution is important, therefore, an aggregation of weeks is used. Thus, the model can be run with either all hours in all weeks, all hours in selected weeks, selected hours in all weeks, or selected hours in selected weeks. Storage in Balmorel is modelled on a weekly basis. Thus, the storage level in the first and last hour of the week has to equal each other, for each week.

The investment decisions in the model are based on demand and technology costs including annualised investment costs given the particular year. Investments in Balmorel can be both endogenous and exogenous. If investments are exogenous only the operation of the power system is optimised, under the given power system configuration. Furthermore, some investments can be given beforehand, enabling the model to optimise remaining investments based on the given configuration. Data about the existing heat and power system is given on a detailed level, whereas investments are given on plant technology level in each region (for heat production in each area).

The Balmorel model is modelled in a way that allows for add-ons. That is, inclusion of more specific models for an area that needs special investigation in relation to the rest of the energy system is possible. The add-on will become part of the model, and, thus, when chosen active, the energy system model and add-on can be considered to be one model. Add-ons have previously been made for analysis of, e.g. hydrogen and detailed waste treatment [27], [44].

4.1.1 The objective function

In minimising costs the objective function of the problem is the sum of all the costs in the given year. The objective function is given by Equation(4.1), where $C^{fuel}_{a,p,t}$ are the fuel costs at time t on plant p in area a. Likewise, $C^{OM}_{a,p,t}$ are the operation and management costs, $C^{trans}_{a,p,t}$ are the transmission costs, and $C^{inv}_{a,p,t}$ are the investment costs. Then, taxes are added; $T^{fuel}_{c,p,t}$ for fuel taxes at time

t on plant p in country c, $T^{ems}_{c,p,t}$ for emission taxes, and $T^{other}_{a,p,t}$ for other taxes for district heating and heat only plants. Furthermore, the changes in utility of both electricity and heat consumption are added ($\Delta\, U^{elec}_{r,t}$ and $\Delta\, U^{heat}_{a,t}$), making it possible to model the flexible demand for heat and electricity. Finally, penalty costs of infeasibility Pen^{inf}_{t} and costs of add-on (application) contributions C^{Ap} are added. Penalty costs are to be high enough to dominate the other costs, but yet, so small as to prevent numerical problems [49].

$$
\begin{aligned}
V_{obj} = \sum_{c,r,a,p,t} \big(& C^{fuel}_{a,p,t} + C^{OM}_{a,p,t} + C^{trans}_{a,p,t} + C^{inv}_{a,p,t} + T^{fuel}_{c,p,t} + T^{ems}_{c,p,t} \\
& + T^{other}_{a,p,t} + \Delta U^{elec}_{r,t} + \Delta U^{heat}_{a,t} + Pen^{inf}_{t}\big) + C^{Ap}
\end{aligned}
\tag{4.1}
$$

4.1.2 Balance equations on electricity and heat

Numerous constraints are present in Balmorel. The two most evident are the balance equations for electricity and heat. Balancing requires for supply and demand to meet exactly. Including storage does relax the problem, making the electricity supply more reliable and the work of the TSO easier. Balance equations for electricity for each region r:

$$
\begin{aligned}
\sum_{p} \left(G^{ex}_{r,p,t} + G^{new}_{r,p,t} - \sum_{a \in r} G^{ElecToHeat}_{a,p,t} + Trans^{net}_{r,t} - S^{elec}_{r,p,t} + G^{ApElec}_{r,p,t} \right) \\
= D^{elec}_{r,t} + L^{elec}_{r,t} \qquad \forall a \in A; r \in R; t \in T
\end{aligned}
\tag{4.2}
$$

Where $G^{ex}_{r,p,t}$ is the generation on existing power plants at time t for plant p in region r. $G^{new}_{r,p,t}$ is generation on new power plants, and $G^{ElecToHeat}_{r,p,t}$ is generation of electricity for heat generation. Furthermore, the net transmission to other regions is $Trans^{net}_{r,t}$, the net loading of electricity storage $S^{elec}_{r,p,t}$ and the net electricity generation from add-ons $G^{ApElec}_{r,p,t}$. All these are required to equal electricity demand in region r, $D^{elec}_{r,t}$ and transmission loss in region r, $L^{elec}_{r,t}$.

For district heating, generation can be from back pressure plants $G^{backpr}_{a,p,t}$, extraction plants $G^{extr}_{a,p,t}$, electricity to heat, and plants only producing heat, $G^{HeatOnly}_{a,p,t}$. Furthermore, the heat generation from add-ons is $G^{ApHeat}_{a,p,t}$, and the net storage is $S_{a,p,t}^{netHeat}$. Balance equations for district heating for each area a:

$$\sum_{p}\left(G_{a,p,t}^{backpr}+G_{a,p,t}^{extr}+G_{a,p,t}^{ElecToHeat}+G_{a,p,t}^{HeatOnly}+S_{a,p,t}^{netHeat}+G_{a,p,t}^{ApHeat}\right) = D_{a,t}^{heat}+L_{a,t}^{heat} \qquad \forall a\in A; t\in T \tag{4.3}$$

To make sure the power system is configured to meet demand at all times, a capacity credit equation is introduced. This equation ensures enough power generating capacity in the system to meet peak-load demand, thus, the largest demand during every 24-hour period. Peak demand is usually experienced in the morning when people get up and in the evening when people come home from work and start cooking. It is assumed that 99% of all dispatchable power plant capacities in area a at time t, $\gamma_{a,t}^{dispatch}$ are available at peak-load, while 14% of wind power capacity, $\gamma_{a,t}^{wind}$, is assumed to contribute to meet peak-load demand. The capacity credit equation for each area a:

$$\sum_{a\in c,p}\left(0.99\cdot\gamma_{a,p,t}^{dispatch}+0.14\cdot\gamma_{a,p,t}^{wind}\right)\geq D_{c,t}^{peakload} \qquad \forall c\in C; t\in T \tag{4.4}$$

4.2 Balmorel Add-on - Modelling Road Transport

Based on input data, the Balmorel model including the transport system minimises total costs. The model needs to meet constraints on transport demand and power flow balancing. Correspondence with 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.

The transport system model, including transport demand, vehicle technologies, and V2G capabilities, is developed as an add-on to Balmorel. This section elaborates on some details of the transport add-on, described in Paper I and III. Extending the Balmorel model with the road transport sector enables analysis of:

- the economic and technical consequences for the power system of introducing the possibility of using electricity in the road transport system, 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 benefits for the power system, and investment and fuel costs of the vehicles are taken into account.

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 vehicles for passenger 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.

4.2.1 Assumptions

In modelling the EDVs, it is assumed, that all of the challenges mentioned in Section 2.4.1 are in place. Moreover, the following assumptions have been made:

- 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 (see 4.2.2).
- Regenerative braking energy is going into the on-board electricity storage and is assumed proportional to kilometres driven.
- 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 electricity from the power bus, whereas the propulsion power is delivered from an electric 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 AC/DC and DC/AC conversion.
- 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. Furthermore, this assumption seems reasonable since batteries developed today already seem to have no loss of effect before almost depleted. 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.
- Because the model is an investment model, it is a challenge to introduce all the necessary decision variables for an optimisation model that is correct, yet still solvable within a reasonable time horizon. Thus, the state-of-charge of the battery when the vehicle is leaving the grid, is assumed to be fixed. If not fixed, the model will become non-linear. Hence, the EDVs leave the grid with a vehicle dependent but fixed average storage level, given by the load factor.

4.2.2 Driving patterns/plug-in patterns

Each vehicle type is associated with a particular plug-in pattern extracted from investigations of historical driving patterns [16]. A plug-in pattern assigns percentages for each time step representing the fraction of vehicles leaving at the particular time step, returning in time step j, thus, returning in $j - i$ future time steps. A percentage is given for each combination of leavings and arrivals within a 24-hour time horizon. All EDVs are assumed to be plugged in when not driving.

Converting data from the Danish transport habits into data used on Balmorel The survey of Danish transport habits was made in 2006 [16]. The transport habits consist of a number of data related to trips and transport, including walking, bicycling and driving a vehicle. Data needed for making driving patterns relevant for usage of the batteries, has been enquired, and the following vehicle data is found relevant:

- Start time for the trip: time of day on an hourly basis
- Time used on the trip: minutes split into intervals. The 1^{st} hour is split into 6 intervals, 2^{nd} hour into two intervals, 3^{rd} hour is an interval, 4^{th} and

5^{th} hour are one interval, 6^{th} through 10^{th} hour one interval, and finally 11^{th} hour and above are one interval.

- Whether you are driving the vehicle or just a passenger: only trips by driver are contributing, since it is the vehicle trip (and not the persons trip) that is of interest
- Amount of transport per weekday: an average of kilometres driven per person on the particular weekday. No two days are the same.

Balmorel hour	Algorithm estimates	Survey min.
1	sum of all	1-5 6-10 11-20 21-30 31-45 46-60
2	sum of all	61-90 91-120
3	equal	121-180
4	2/3	181-300
5	1/3	
6	1/3	301-600
7	4/15	
8	1/5	
9	2/15	
10	1/15	
11	equal	601+

Table 4.1: Conversion of length of trip from the Danish transport survey (based on minutes) to Balmorel (based on hours).

Based on these data the driving patterns are extracted (see Table 4.1). Because Balmorel is using hourly time steps, the data is changed accordingly. It is easy with the first three hours. For the 4^{th} and 5^{th} hour, an approximation is made recognising that the number of trip are decreasing with increasing trip length. 2/3 of the trips in the interval are assigned to the 4^{th} hour, whereas, 1/3 of the trips are assigned to the 5^{th} hour. The same challenge is seen for the next interval. The last interval contains very few observations, thus, all of these vehicles are considered to be driving for a maximum of 11 hours.

Having changed the intervals, the number of vehicles leaving in each hour are split into these intervals, thus, they are split into how many hours the trip takes (see Table 4.2). These numbers are then changed to percentages of vehicles leaving a particular hour, e.g. at 7 o'clock, returning after 1-11 hours respectively, thus summing to 100% for each hour. Based on the same data, the share of vehicles leaving in each hour has been found. Thus, multiplying the two gives percentages analogue to the driving pattern for a 24 hour time interval, but without information of the difference between weekdays.

Return time Time leaving	1	2	3	4	5	6	7	8	9	10	11
1	85%	9%	2%	2%	1%	0%	0%	0%	0%	0%	0%
2	82%	5%	9%	2%	1%	0%	0%	0%	0%	0%	0%
3	66%	11%	0%	0%	0%	8%	6%	5%	3%	2%	0%
4	71%	12%	3%	9%	5%	0%	0%	0%	0%	0%	0%
5	71%	21%	2%	3%	1%	1%	1%	0%	0%	0%	0%
6	79%	12%	5%	2%	1%	1%	0%	0%	0%	0%	0%
7	83%	12%	3%	1%	1%	0%	0%	0%	0%	0%	0%
8	84%	10%	3%	1%	1%	0%	0%	0%	0%	0%	0%
9	78%	13%	4%	2%	1%	1%	1%	0%	0%	0%	0%
10	76%	13%	5%	4%	2%	0%	0%	0%	0%	0%	0%
11	78%	11%	4%	3%	1%	1%	1%	0%	0%	0%	0%
12	80%	10%	4%	3%	1%	1%	1%	1%	0%	0%	0%
13	79%	11%	5%	2%	1%	0%	0%	0%	0%	0%	0%
14	82%	10%	4%	2%	1%	0%	0%	0%	0%	0%	0%
15	83%	11%	3%	2%	1%	0%	0%	0%	0%	0%	0%
16	85%	10%	3%	1%	1%	0%	0%	0%	0%	0%	0%
17	84%	10%	3%	1%	1%	0%	0%	0%	0%	0%	0%
18	86%	9%	2%	1%	1%	0%	0%	0%	0%	0%	0%
19	86%	9%	2%	2%	1%	0%	0%	0%	0%	0%	0%
20	85%	12%	2%	1%	1%	0%	0%	0%	0%	0%	0%
21	85%	11%	2%	1%	1%	0%	0%	0%	0%	0%	0%
22	86%	9%	2%	1%	1%	0%	0%	0%	0%	0%	0%
23	88%	9%	1%	0%	0%	1%	1%	0%	0%	0%	0%
24	88%	7%	4%	0%	0%	0%	0%	0%	0%	0%	0%

Table 4.2: Driving patterns transformed into trips by the hour. Percentage of vehicles coming home after 1-11 hours, for each hour in a 24-hour time interval.

Based on the investigation of transport habits, weights for each weekday is found. Multiplying the 24-hour driving pattern with the weights gives a rather detailed weekly driving pattern. It could be argued, that the driving pattern should be seasonal based on feasts, vacations etc. Data is not that detailed and average weekly data should be enough to give a good picture of the interaction between the power system and the road transport system.

For BEVs the driving patterns are somewhat more uncertain. First of all, the BEVs cannot drive very far, thus, either other vehicles are needed for the longer trips or our driving habits will have to change. Both things will probably happen. However, in order to analyse BEVs compared to PHEVs, the number of vehicles being 2^{nd}, 3^{rd} etc. vehicle in a family has been found using [12]. For some analyses it has been assumed that these vehicles are BEV – amounting to 25% of all the vehicles in DK. Driving patterns are then adjusted accordingly, in order to only include the first three hours of driving (no matter what time the vehicle is leaving) for the BEVs, using the 350 km driving range restriction on the battery. Hence, the driving pattern for the remaining vehicles have to be adjusted likewise. In order to compensate for the long trips not being driven by the BEVs, a larger share of the remaining vehicles are driving the long trips,

Assuming that all vehicles are plugged in when parked, the plug-in pattern is the complement of the driving pattern. However, it is possible to use other plug-in patterns.

4.2.3 Costs

Costs of transport are added to the objective function in Balmorel. Transportation costs include investment costs, operation and management costs, fuel costs, and costs of emitting CO_2. Investment costs, $C_{a,v,t}^{invveh}$, and operation and management costs, $C_{a,v,t}^{OMveh}$, can be calculated identically for all vehicle types (Equation 4.5), whereas fuel costs and CO_2 costs differ. $N_{a,v}$ is the number of vehicles of type v in area a:

$$+\sum_{a,v,t}\left((C_{a,v,t}^{invveh}+C_{a,v,t}^{OMveh})\cdot N_{a,v}\right) \tag{4.5}$$

Total fuel and CO_2 costs (Equation 4.6) for vehicles without grid connection, depend on fuel costs at each time step t for each vehicle type v in area a, $C_{a,v,t}^{fuelveh}$, cost of CO_2 emissions, $C_c^{CO_2}$, CO_2 emissions per MWh, $Em_v^{CO_2}$, number of vehicles, annual driving, Dr_v, and fuel consumption, $Cons_v^{fuel}$:

$$\sum_{c,a,v,t}\left((C_{a,v,t}^{fuelveh}+C_c^{CO_2}\cdot Em_v^{CO_2})\cdot N_{a,v}\cdot Dr_v\cdot Cons_v^{fuel}\right) \tag{4.6}$$

Total fuel and CO$_2$ costs for vehicles with grid connection (4.7) depend on the use of engine, $O_{a,v,t}^{EnGen}$, as opposed to the use of the electric motor. η_v^{Eng} is the average engine efficiency.

$$\sum_{c,a,v,t}\left((C_{a,v,t}^{fuelveh} + C_c^{CO_2} \cdot Em_v^{CO_2}) \cdot \frac{O_{a,v,t}^{EnGen}}{\eta_v^{Eng}}\right) \tag{4.7}$$

Costs of the FCEVs

The hydrogen add-on for Balmorel has been described in [27]. Activating the hydrogen add-on, makes hydrogen production part of the model. 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 (Equation 4.8) is dependent on number of vehicles, hydrogen consumption, $Cons_v^{H_2}$, and annual driving:

$$\sum_{a,v,t}\left(Cons_v^{H_2} \cdot N_{a,v} \cdot Dr_v\right) \tag{4.8}$$

For plug-ins, hydrogen demand (Equation 4.9) is dependent on output from fuel cell, $O_{a,v,t}^{FC}$, and efficiency of the fuel cell, η_v^{FC}:

$$\sum_{a,v,t}\left(\frac{O_{a,v,t}^{FC}}{\eta_v^{FC}}\right) \tag{4.9}$$

Equations (4.8) and (4.9) are similar to Equations (4.6) and (4.7) without the fuel and CO$_2$ costs.

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 increased power or hydrogen demand.

4.2.4 Transport demand

As for electricity and heat, transport demand for each region has to be met by supply. Supply is found by multiplying number of vehicles, the annual driving per vehicle, and the utilisation of capacity in vehicle technology v, UC_v, thus, the fraction of people transported by each vehicle. Supply is calculated on areas, whereas, demand is on regions. Thus, supply areas have to be summed to match the regions.

$$\sum_{a\in r,v} (N_{a,v} \cdot Dr_v \cdot UC_v) = D_r^{tsp} \tag{4.10}$$

4.2.5 Power flows

All constraints except for the demand constraint (Equation 4.10) are related to the power flows. Power flows are modelled based on propulsion systems. 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

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.

Configuration of the electric and plug-in serials propulsion systems are similar and sketched in Figure 4.1. The ICEs, not using power as propellant, are only to be incorporated in the system as a cost. The figure shows the interaction between different units in the vehicle, including grid connection. Power can go both ways from driving wheels to storage and back, and from storage to power grid and back. Power returning from the driving wheels is the regenerated braking energy. The power both ways from storage to the power grid resembles the ability to both load power to the vehicle from the grid (G2V) and unload power from the vehicle to the grid (V2G).

Division of the vehicles into subsystems is needed for modelling the driving and interactions between the power and road transport systems. 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.

Based on the propulsion system configuration, power flows are sketched in Figure 4.2. The EDVs will be connected to the grid when charging, and the flow of

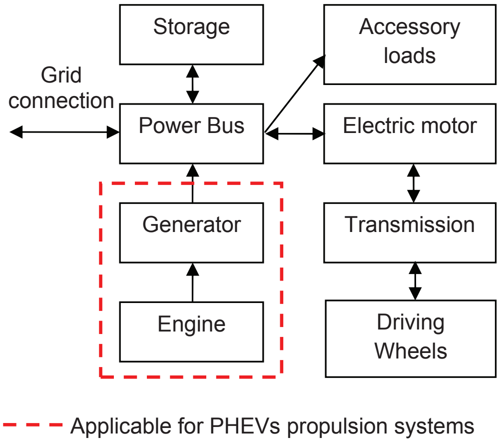


Figure 4.1: Propulsion system configuration of (series) electric drive vehicles.

power both when plugged in and when not plugged in has to be modelled. 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 outgoing 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 efficiency of the subsystem.

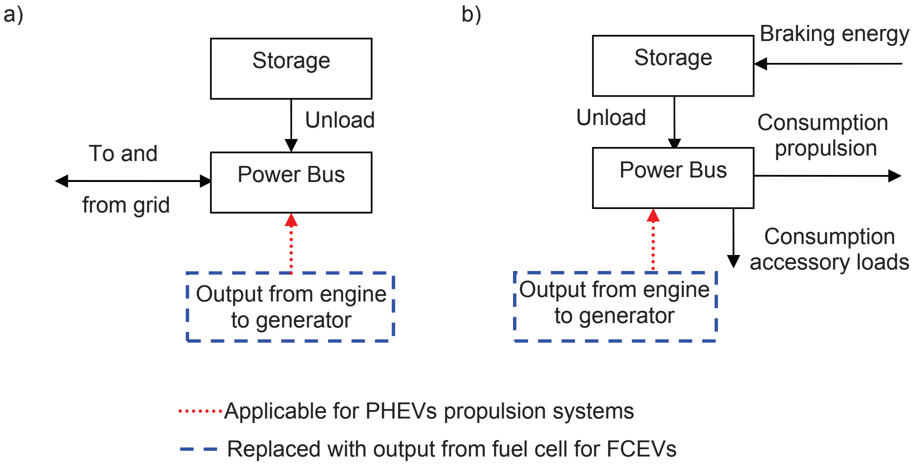


Figure 4.2: Power flow model of (series) electric drive vehicles for a) vehicles plugged in and b) vehicles not plugged in.

Relevant for the power system is the available electricity storage from EDVs at each time step. 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 (Figure 4.2a). For optimising the use of an electric motor versus the use of fuel cell, gasoline or diesel engine in the FCEVs and PHEVs while driving, it is assumed that the electric motor is used until depletion of storage. This assumption is supported by electricity being a cheaper fuel than diesel, gasoline, and hydrogen. Therefore, the power flow model for vehicles not plugged in (Figure 4.2b), is based on storage being depleted before using the engine.

Balancing on-board electric storage:
On-board electricity storage can be charged from the grid. The charging/ discharging losses are modelled as being proportional to the unloading of electricity storage, $S^{Unld}_{a,v,t}$, thus modelled as a charging and discharging efficiency, η^S_v. On-board electricity storage, $S^{PI}_{a,v,t}$, depends on last period's storage, energy from the grid, $Gr^{fr}_{a,v,t}$ (needs to be scaled by the inverter efficiency, $\eta^{inverter}_v$, in order to equal the amount of energy going into storage), energy going from storage to the power bus, charging/discharging losses, storage in vehicles leaving in period t,$S^{Leav}_{a,v,t}$, and storage in vehicles arriving in period t, $S^{Arr}_{a,v,t}$.

$$S^{PI}_{a,v,t} = S^{PI}_{a,v,t-1} + Gr^{fr}_{a,v,t} \cdot \eta^{inverter}_v - \frac{S^{Unld}_{a,v,t}}{\eta^S_v} - S^{Leav}_{a,v,t} + S^{Arr}_{a,v,t} \tag{4.11}$$

$$\forall a \in A; v \in V; t \in T$$

Calculation of storage in vehicles leaving in period t is based on the assumption that all vehicles bring along an average level of storage, given by a percentage of the battery capacity, LF_v, the load factor. Furthermore, in accordance with statistical data on transport habits [16], it is assumed that all vehicles will be parked within a time horizon of 11 hours after leaving. γ^S_v is the storage capacity and $PP_{a,v,i,j}$ is the plug-in pattern.

$$S^{Leav}_{a,v,t} = \sum_{j=t}^{t+11} PP_{a,v,t,j} \cdot LF_v \cdot \gamma^S_v \cdot N_{a,v} \qquad \forall a \in A; v \in V; t \in T \tag{4.12}$$

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

$$\begin{aligned}S^{Arr}_{a,v,t} = \sum_{i=t-11}^{t} \max\{PP_{a,v,i,t} \cdot \Bigg(LF_v \cdot \gamma^S_v - ((t-i) \cdot DD_{v,1} + DD_{v,0}) \\ \cdot \left(\frac{E^{Dr}_v}{\eta^S_v} - E^{Brk}_v \right) \Bigg) ; 0\} \cdot N_{a,v} \qquad \forall a \in A; v \in V; t \in T\end{aligned} \tag{4.13}$$

E^{Dr}_v is determined by consumption for propulsion, $Cons^{EPrp}_v$, accessory loads, $Cons^{EAcc}_v$, and motor- and transmission efficiencies, η^{mot}_v and η^{trans}_v respectively;

$$E^{Dr}_v = Cons^{EAcc}_v + \frac{Cons^{EPrp}_v}{\eta^{mot}_v \cdot \eta^{trans}_v} \qquad \forall v \in V \tag{4.14}$$

E^{Brk}_v depends on regenerated energy going from braking to storage, RE^{Brk}_v, as well as motor-, power bus-, and transmission efficiencies; η^{mot}_v, η^{PB}_v, and η^{trans}_v respectively;

$$E^{Brk}_v = RE^{Brk}_v \cdot \eta^{mot}_v \cdot \eta^{PB}_v \cdot \eta^{trans}_v \qquad \forall v \in \tag{4.15}$$

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, $Gr^{to}_{a,v,t}$. Power into the power bus comes from either the engine, $O^{EnGenPI}_{a,v,t}$, or the on-board storage, $S^{Unld}_{a,v,t}$.

$$Gr^{to}_{a,v,t} = \left(O^{EnGenPI}_{a,v,t} \cdot \eta^{gen}_v + S^{Unld}_{a,v,t}\right) \cdot \eta^{PB}_v \qquad \forall a \in A; v \in V; t \in T \tag{4.16}$$

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

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 (4.16). Assuming that the vehicles deplete the battery 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. In Figure 4.3, 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 (C), the vehicle returns in the same time period as the storage is depleted (B), and the vehicle returns in time periods after the storage is depleted (A). The first case does not involve usage of engine and, therefore, is not treated in the following.

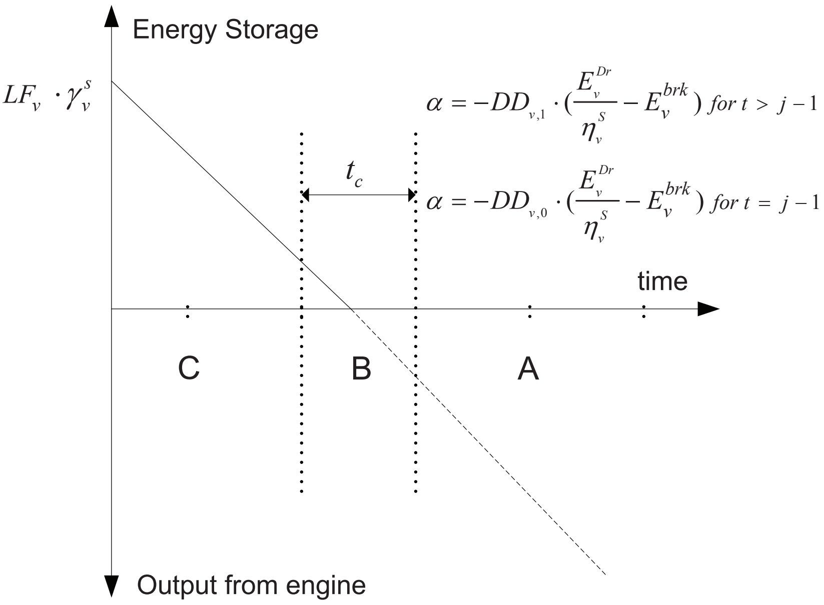


Figure 4.3: Use of energy storage versus engine depending on time. α is the slope of the line and $LF_v \cdot \gamma_v^S$ the storage level when the vehicle is leaving the grid. t_c is the time period where the on-board storage is depleted.

The distance driven until storage is depleted will be:

$$DD_v^{deplete} = \begin{cases} (t_c - i) \cdot DD_{v,1} + DD_{v,0} & \text{if } t_c = j \\ (t_c - i + 1) \cdot DD_{v,1} & \text{if } t_c < j \end{cases}$$

The vehicle leaves the power grid in time period $i = 1, 2, ..., t$ and returns to the power grid in time period $j = i, i+1, ..., i+11$. To find t_c the following is calculated;

If $t_c = j$, t_c is found by setting the capacity left on the battery equal to zero. Calculating the capacity used includes both full hours of driving and the driving in the hour of return;

$$LF_v \cdot \gamma_v^S - ((t_c - i) \cdot DD_{v,1} + DD_{v,0}) \cdot \left(\frac{E_v^{Dr}}{\eta_v^S} - E_v^{Brk}\right) = 0 \tag{4.17}$$

$$\forall v \in V; t \in T$$

If $t_c < j$, t_c is found the same way as above, except that the capacity used is calculated using only full hours of driving;

$$LF_v \cdot \gamma_v^S - (t_c - i + 1) \cdot DD_{v,1} \cdot \left(\frac{E_v^{Dr}}{\eta_v^S} - E_v^{Brk}\right) = 0 \qquad \forall v \in V; t \in T \tag{4.18}$$

The term $t_c - i$ indicates the number of hours before the storage is depleted, and thus, the vehicles start using the engine. $t_c - i$ can be found using Equations (4.17) and (4.18).

$t_c - i$ can be calculated for each vehicle type, since all the other parameters are fixed on vehicle type level. Output from engine to generator can then be calculated for all combinations of vehicles leaving in time period i and returning in time period j. $\sum_{i=1}^{t}\sum_{j=t}^{t+11} PP_{a,v,i,j}$ is the total share of all vehicles not plugged in at time t in area a. The calculation of the output from engine to generator in time period t now depends on t being smaller than, equal to or greater than t_c. In situation A, where electric storage is depleted (Figure 4.3), the engine output in each hour of driving will be;

$$O_{a,v,t>t_c}^{EnGenNPI} = \sum_{i=1}^{t}\sum_{j=t}^{t+11} (N_{a,v} \cdot PP_{a,v,i,j} \cdot DD_{v,1} \cdot \left(\frac{E_v^{Dr}}{\eta_v^S} - E_v^{Brk}\right) \tag{4.19}$$

$$\forall v \in V; t \in \{t^{'} \in T : t^{'} > t_c\}$$

If in situation B, the electric storage depletes in time period t_c (Figure 4.3). The output from engine to generator is:

$$\begin{aligned} O^{EnGenNPI}_{a,v,t=t_c} &= -N_{a,v} \cdot \sum_{i=1}^{t} \sum_{j=t}^{t+11} \left(PP_{a,v,i,j} \cdot \left(LF_v \cdot \gamma^S_v - (t_c - i + 1) \right.\right. \\ &\left.\left. \cdot DD_{v,1} \cdot \left(\frac{E^{Dr}_v}{\eta^S_v} - E^{Brk}_v \right) \right) \right) \qquad \forall a \in A; v \in V; t \in \{t^{'} \in T : t^{'} = t_c\} \end{aligned} \tag{4.20}$$

In Equations (4.19) and (4.20) $DD_{v,0}$ is included if the vehicle returns in the time period under consideration, that is $j = t$. Thus, $(t_c - i + 1) \cdot DD_{v,1}$ is replaced with $(t_c - i) \cdot DD_{v,1} + DD_{v,0}$.

Finally, in situation C, the vehicle only uses electric storage, such that the sum of the results of Equations (4.19) and (4.20) gives the total output from engine to generator in period t for vehicles not plugged in. The total output from engine to generator is:

$$\begin{gathered} O^{EnGen}_{a,v,t} = O^{EnGenNPI}_{a,v,t>t_c} + O^{EnGenNPI}_{a,v,t=t_c} + O^{EnGenPI}_{a,v,t} \\ \forall a \in A; v \in V; t \in T \end{gathered} \tag{4.21}$$

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

Storage level:
The storage level is to stay between 0 and aggregated storage available.

$$0 \leq S^{PI}_{a,v,t} \leq N_{a,v} \cdot \left(1 - \sum_{i=1}^{t} \sum_{j=t}^{t+11} \mathrm{PP}_{a,v,i,j} \right) \cdot \gamma^S_v \qquad \forall a \in A; v \in V; t \in T \tag{4.22}$$

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,

γ_v^{Sld}, 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

$$Gr_{a,v,t}^{fr} \cdot \eta_v^{inverter} \leq N_{a,v} \cdot \left(1 - \sum_{i=1}^{t} \sum_{j=t}^{t+11} PP_{a,v,i,j}\right) \cdot \gamma_v^{Sld} \qquad (4.23)$$

$$\forall a \in A; v \in V; t \in T$$

Similar restrictions apply for unloading of on-board storage, power to and from grid, and engine output although not shown here.

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 to Equation (4.2).

$$+ \sum_{a \in r,v} \left(Gr_{a,v,t}^{to} - Gr_{a,v,t}^{fr}\right) \qquad \forall t \in T \qquad (4.24)$$

Thus the entire electricity flow balance equation looks like this:

$$\begin{aligned} &\sum_{p} \left(G_{r,p,t}^{ex} + G_{r,p,t}^{new} - G_{r,p,t}^{ElecToHeat} + Trans_{r,t}^{net} - S_{r,p,t}^{elec} + G_{r,p,t}^{ApElec}\right) \\ &\quad + \sum_{a \in r,v} \left(Gr_{a,v,t}^{to} - Gr_{a,v,t}^{Fr}\right) = D_{r,t}^{elec} + L_{r,t}^{elec} \qquad \forall r \in R; t \in T \end{aligned} \qquad (4.25)$$

4.2.6 BEVs

With BEVs not having the same driving range as the remainder of the vehicles, different driving patterns, plug-in patterns etc. are needed. In order to ensure, that all trips are covered, the other vehicle types are to cover the trips not covered by the BEVs, especially the longer trips. Thus, the share of long trips will be higher for these vehicle types, and will depend on the amount of BEVs. So the final driving patterns are not known until the share of BEVs are known, making the inclusion of BEVs an iterative process.

Based on these observations, modelling the BEVs require an extra feature that is very costly in calculation time. Therefore, it is chosen to let the model invest in BEVs with the same driving patterns as the remaining vehicles, except, they will not be driving the longer trips. In case it is optimal to invest in BEVs, the driving patterns and plug-in patterns for these will be introduced accordingly. This does result in an approximation, but in favour of the BEVs, due to the BEVs figuring as if they are driving the long trips, although, they are not. In the situation of investments in BEVs, the model acts as if more trips are on electricity and fewer on diesel, resulting in cheaper overall costs. Thus, if investments in BEVs are not optimal in this situation, they are certainly not optimal in the more precise situation. In scenarios where BEVs are forced to be part of the investments, driving patterns and plug-in patterns are changed accordingly, before running the model.

4.3 EDVs Contributing to the Capacity Credit Equation

One could argue, that the EDVs could help out providing capacity in peak load hours, thus, contributing to the capacity credit equation (Equation 4.4). Comparing driving patterns to the peak load hours, clearly, most vehicles are parked in peak load hours. Thus, assuming that the EDVs are plugged in when parked, the vehicles are available to the power system - also during peak hours.

In order to incorporate the vehicles in the capacity credit equation, an estimate of the available battery capacity is needed. Some vehicles are leaving the grid soon, therefore, they experience restrictions on the on-board storage. Furthermore, some batteries have just been used, and only some or none of the battery capacity is left. Hence, a limited amount of energy is available for peak load hours. As shown in [36], at least 92% of the vehicles are parked at all times. Being conservative, an estimation can be that only 70% of the PHEVs and 76% of BEVs are available for the electricity system during peak load.

To find out how much the EDVs can unload and, thus, with how much they can contribute to the capacity credit equation, the storage level when the peak-load starts needs to be estimated. Assuming that the storage is at an average level of 50% by the time peak-load hours start, an assumption of an average of 30% of the battery available for peak load seems to be conservative. Based on these estimates, the addition from the road transport to the capacity credit equation is:

$$+0.3 \cdot \sum_{a \in c} \left(N_{a,BEV} \cdot 0.76 \cdot \gamma^{S}_{BEV} + N_{a,PHEV} \cdot 0.7 \cdot \gamma^{S}_{PHEV} \right) \tag{4.26}$$

This is only for a short period of time, though, since the battery's state-of-charge will be decreasing and will reach the minimum state-of-charge.

The grid capacity also puts a limit on the discharge. Each vehicle have an assumed grid connection capacity, γ_v^{Gr}, of 6.9 kW, corresponding to a standard 230V connection with 3 phases 10 Amps each. Hence, the storage in the BEVs should last, but the storage for the PHEVs will not. Scaling the storage in the PHEV with 2/3 (an estimate, trying to ensure that storage will last), changes the contribution to Equation 4.4 from the EDVs to;

$$+\sum_{a \in c} \left(N_{a,BEV} \cdot 0.76 + N_{a,PHEV} \cdot 0.7 \cdot \frac{2}{3} \right) \cdot \gamma_v^{Gr} \qquad \forall a \in A \tag{4.27}$$

A calculation to verify the availability of capacity. Take a vehicle fleet with 1 mill. pluggable EDVs and assume the on-board storage of these plug-ins is half full. It then takes more than 3 hours to empty the on-board storage, leaving respectively 5% and 20% of on-board storage in the PHEVs and BEVs. Peak-load usually lasts for a period of 1-2 hours, thus, even with vehicles leaving the grid with more storage than those arriving, the storage should last.

The capacity credit equation including EDVs:

$$\begin{aligned} D_{c,t}^{peakload} &\leq \gamma_v^{Gr} \cdot \sum_{a \in c} \left(N_{a,BEV} \cdot 0.76 + N_{a,PHEV} \cdot 0.7 \cdot \frac{2}{3} \right) \\ &+ \sum_{a \in c,p} \left(0.99 \cdot \gamma_{a,p,t}^{dispatch} + 0.14 \cdot \gamma_{a,p,t}^{wind} \right) \qquad \forall c \in C; t \in T \end{aligned} \tag{4.28}$$

In the analyses made for the papers included in this thesis, the vehicles have not been included in the capacity credit equation. However, an analysis has been made superior to writing the articles, and the results will be given in Section 6.3.

4.4 Wilmar Model Characteristics

Wilmar is used for analysing the effects of including different penetrations of EDVs in a predefined power system. Thus, no investments are included, only the dispatch of the power plants.

Wilmar is a stochastic unit commitment and dispatch model optimising the operation of a given power system. The model is stochastic in three elements; the forecasts of electricity demand, wind power production, and demand for replacement reserves. Thus, a scenario tree representing these three elements is implemented. Replacement reserves represent reserves with activation times longer than five minutes. They can be provided by on-line power plants and off-line power plants that are able to start up in time to provide the reserves in the hour in question.

The model is a stochastic multi-stage linear model with recourse. The model uses an hourly time resolution. It has a planning horizon of 15-36 hours depending on the planning loop in question. Furthermore, rolling planning is used in 3-hour steps, thus, 8 loops a day. Figure 4.4 illustrates three stages, stage 1 modelling the first three hours, stage 2 hours 4-6, and stage 3 the remaining period in the planning horizon. Perfect foresight of demand and wind generation is assumed for the first three hours, but to get a more realistic picture, forecast errors are introduced in terms of replacement reserves.

The root decision is the decision for the day-ahead market (stage three), where the forecast of electricity demand, wind power production, and replacement reserve demand are all uncertain. The recourse decision is taken after knowing the uncertain outcome, thus, when rolling forward, planning the next “stage 1”, the recourse decision is taken on the last two stages. Hence, the recourse decision consists of up and down regulations of power production relative to the production plan determined day-ahead.

As with Balmorel, Wilmar employs countries, regions and areas as the geographic entities. Wilmar is not used with a transport system model in this thesis. In order to include the vehicles, electricity demand of the EDVs has been given exogenously, either as fixed or flexible demand.

A more thorough description of Wilmar is provided in [42]. Furthermore, numerous articles have been written using the model for different analyses, e.g. [33], [15], and Paper VI.

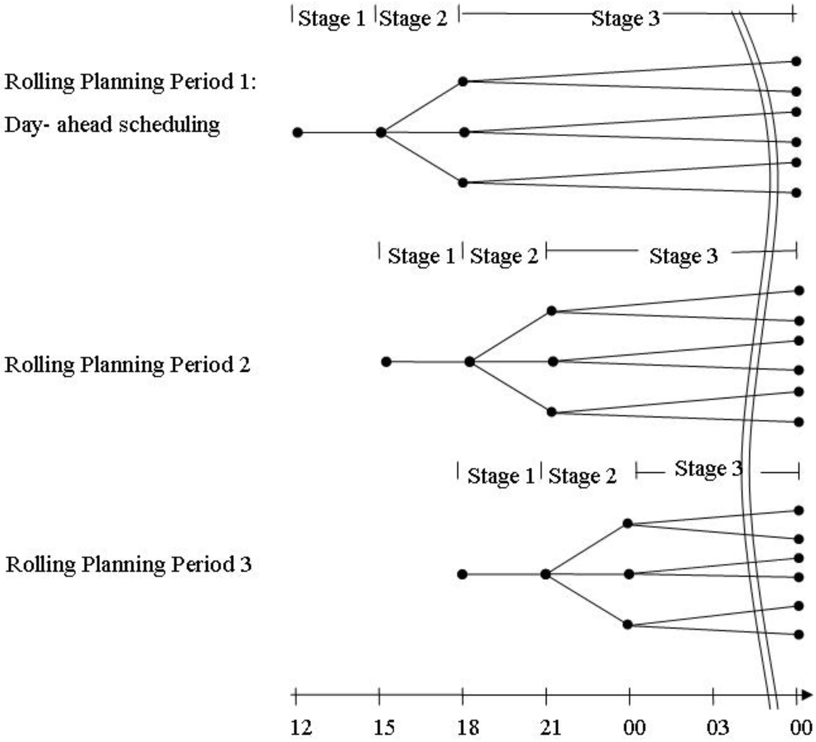


Figure 4.4: Illustration of the rolling planning and decision structure in each planning period [42]

Chapter 5

Technologies

For future investments, technologies need to be defined. In the integrated power and transport system, technologies are needed for heat, electricity, and transport. In the following, these are divided into vehicle technologies, and heat and power system technologies.

The thesis in hand being a PhD-project in the field between operations research and energy systems analysis, technologies in this chapter are defined for the sake of operations research people reading the thesis. People already acquainted with both the vehicle and heat and power system technologies may jump to the next chapter or just skim the tables shown in this chapter.

5.1 Vehicle Technologies

The vehicles can be divided into two categories: ICEs and EDVs, the latter covering all vehicles using batteries for driving, both hybrids and all electrics. From a modelling perspective the interesting vehicles are those that can be plugged in (plug-in hybrids or BEVs). In the future it is expected that all hybrids will be developed in a way that enables them to plug in. Only plug-ins are treated since the efficiencies of the other fuels are rather low and, therefore, will be much more interesting with fuel as a range extender instead of the primary propellant. Furthermore, plug-ins are more interesting from a power system perspective.

The model developed for Balmorel supports four different vehicle technologies:

- Internal Combustion Engines (ICE): vehicles as on today's market using diesel or gasoline as propellant. ICEs will have no influence on the power system, only on fuel and CO_2 costs. Diesel as propellant has been chosen because of the fuel economy being better than that of the gasoline vehicles.
- Plug-in (serial) Hybrid Electric Vehicles (PHEV): vehicles using batteries and for extended trips also diesel or gasoline. PHEVs influence the power system as they can be charged from the power grid and might also be able to discharge as well (V2G). PHEVs can in principle deliver power to the grid with the motor running as well, although the efficiency is low and it is not very good for the environment, thus, the sustainability is debatable.
- Battery Electric Vehicles (BEV): vehicles using only batteries for driving. The batteries will most likely be quite large, enabling use for everyday driving. BEVs influence the power system with charging and possibly discharging.
- Plug-in Fuel Cell hybrid Electric Vehicles (FCEV): vehicles using hydrogen in fuel cells as propellant. Only hydrogen is chosen, since hydrogen can be produced within the existing model. FCEVs influence the power system in the same way as the PHEVs. FCEVs can produce (clean) power while parked as well.

Parallel hybrids are not included in the model yet. For all of the above mentioned technologies, a number of different vehicles can be defined by entering different input data. Example of input for the vehicles used in Paper III is seen in Table 5.1, showing one of each vehicle type, characterised by the investment costs, operations and management costs, storage capabilities, and driving range on a fully loaded battery in 2030. Furthermore, possibilities of using the different vehicles as reserves in the energy system are included. All four vehicle types are assumed to be average standard vehicles.

ICEs are affordable, but what is not shown in Table 5.1 is the fuel and CO_2 costs, making PHEVs and maybe even BEVs competitive. BEVs have the obstacle that they cannot drive the longest trips. Therefore, they are not competing with all the PHEVs, ICEs, etc., but rather with the share of vehicles that are either never driving very far (e.g. the second vehicle in a household), only driving far

Vehicle type	Annual inv. cost (€)	O&M cost (€/yr)	Storage (kWh)	Driving range	Second reserve	Minute reserve	Day/ Night	2-3 week
ICE	1,065	1,168	0.8	-	-	-	-	-
PHEV	1,484	1,168	10	65 km	+	+	+	(+)
BEV	1,513	1,101	50	350 km	+	+	+	-
FCEV	1,893	1,101	10	65 km	+	+	+	+

Table 5.1: Vehicle data prescribed for the year 2030, based on [7]

a few times a year enabling rental cars for those trips or the like. In case of a large penetration of BEVs, the driving patterns of today may change a lot as may the behaviour in terms of renting cars or travelling by other means.

As seen in Table 5.1 the FCEVs are quite expensive. Research is split when it comes to the development of FCEVs. The investment price shown in the table above, indicates the belief that by 2030, the FCEVs will be on their way, but have not reached a development or production level where the FCEVs are affordable. Thus, investments by the model in FCEVs in 2030 are most unlikely. All these facts speaks in favour of the PHEVs by 2030 using a battery for most trips, but having the range extender in terms of an engine.

In order to enable investments in FCEVs, hydrogen is needed. Hydrogen can either be included in the model by exogenously defining a hydrogen price or by enabling endogenous investments in electrolysis plants. In the integrated power and transport model it has been chosen to have hydrogen produced by electrolysis (described in Section 5.2.7). Hydrogen can be used for both propellant in the FCEVs and for energy storage to be used in the remaining energy system.

5.1.1 Storage sizes

The size of the electric storage capacity, shown in Table 5.1, reflects the usable size of the battery. Today, the electric vehicle efficiency used is approx. 5 km/kWh [50, 14, 13], therefore, an assumed efficiency of approx. 7 km/kWh by 2030 is believed to be reasonable. Further, it is believed that the battery size for BEVs by 2030 will provide a driving range of approx. 350 km, leading to the 50 kWh. For both FCEVs and PHEVs the batteries could be almost as large as for BEVs, but additional weight as well as trade-off between additional driving range and additional cost leads me to believe that a battery covering a driving range of approx. 65 km is reasonable for everyday purpose. Furthermore, it is shown that approx 80% of all trips in Europe are of a range below 25 km [26], thus, the 65 kWh range is enough to cover a round trip.

5.2 Heat and Power System Technologies

The choice of power system technologies for future investments in Balmorel is based on an expectation of a move towards more renewable energy and other expectations of developments in the energy sector. EDVs can provide storage in the energy system, but not in the quantity and over the time period that is sometimes needed. Thus, other future energy storage technologies are also included. In this way, analyses of amount of competition versus ”cooperation” can be made. The list of technologies in this section contains for some, a short description of the technology itself. Focus is, of course, security of supply calling for flexible production.

The energy system consists of both power and heat generation (as well as the transport system described above). Both power and heat generation has to meet demand calling for flexible supply. The system consists of base load plants, running stable all the time, regulating plants and plants primarily used for peak load or reserves. The EDVs might be able to out-compete some or all of the peak load plants - especially in cooperation with the heat pumps. However, the EDVs cannot compete with the base load plants, although, a different structure of the power system might be optimal once all the different renewable power generations are in place.

Forcing the use of waste-to-energy as in the Danish energy system is done by setting the waste treatment prices to zero in Balmorel. This forces the heat and power generation on waste to be used before other heat and power sources. Limitations on the waste are, of course, included.

5.2.1 Thermal generation

Thermal generation power plants are different types of steam power plants and gas turbines. A number of fuel types are to be used in the plants, including coal, uranium, biomass, hydrogen, and natural gas. The steam turbines in general works with the steam spinning a turbine, producing power. Thermal generation can be either electricity only plants or combined heat and power plants.

5.2.1.1 Electricity only

Electricity only plants can be, e.g. gas turbines or nuclear.

- **Gas Turbine, Open Cycle (OCGT):** Due to rather high operating costs but short start up and close down times, the OCGTs are preferred as peak-load plants. Using natural gas or light oil as propellant the OCGTs do emit CO_2. OCGTs come from micro plants (min 3 kW) up to large scale plants (max 125 MW) [6].
- **Nuclear:** Nuclear power plants are no emission plants and are favourable in a climate perspective. They are not renewable energy plants, but because of their zero emission, they are considered *sustainable*, along with renewable power plants. However, uranium has the disadvantage that the residues are unhealthy (deathly) to humans. Therefore, it has been politically decided not to build nuclear power plants in some countries (including Denmark). Nuclear power is used as base load and have long ramp up times.

5.2.1.2 Combined heat and power

Combined heat and power (CHP) plants are using different kinds of fuel, i.e., biomass, waste, gas, or coal. For CHP plants, the electricity generation is tied up to the heat generation. Examples of CHP plants:

- **Gas Turbine, Combined Cycle (CCGT):** CCGTs have the same benefits and drawbacks as OCGTs. Often CCGTs are producing both heat and power. The CCGTs generally are larger plants than the OCGTs - from medium sized plants (min 10 MW) to large scale plants (max 400 MW) [6].
- **Solid Oxide Fuel Cells (SOFC):** oxidizing, i.e. hydrogen, through an electrochemical conversion produces electricity. One advantages of SOFC is the high efficiency and low emissions. However, due to a need for high temperatures, SOFC have long start up times.

5.2.2 Hydro power

Hydro power uses the power of rivers going down hill to produce power. Power production comes from the water going through a turbine, generating the electricity.

- **Hydro (w/pumped hydro storage):** For producing hydro power two water reservoirs are needed. An upper reservoir and a lower reservoir. The pressure of the water going from the upper reservoir to the lower reservoir is generating power. Hydro power is both very flexible and has a fast response time. Pumped hydro storage provides storage possibilities comparable with batteries, though with a smaller efficiency (around 70-80% [9]). In pumped hydro storage water is pumped up into the top reservoir in times of excess electricity for use to produce electricity at a later point in time.

5.2.3 Electricity to heat

When a surplus of electricity is experienced, it can be beneficial to use this for heat production. Different technologies are developed to do that, including:

- **Heat pump:** Heat pumps convert power to heat that can be stored. The heat pumps are flexible and can produce heat when a surplus of electricity is experienced. Operating costs are low and the heat pumps could potentially be competing technology lowering the benefit of the flexibility provided by the EDVs.
- **Electric heat boiler:** Electric heat boilers convert power to heat. The efficiency of the electric heat boilers is lower than the efficiency of the heat pumps, thus, focusing on efficiency, heat pumps are preferred.

5.2.4 Storage

Heat and power can be stored in various ways. With increasing focus on a sustainable heat and power system, focus has also increased on storage possibilities, providing flexibility to the system.

- **Pumped hydro:** Pumped hydro storage is in connection to hydro power plants (see Section 5.2.2).
- **Hydrogen storage:** Electricity can be stored as hydrogen. Stored hydrogen can be used in SOFC, making electricity and heat. By storing

hydrogen, substantial amounts of energy is lost, nevertheless, the technology provides flexibility as do the EDVs.

- **Batteries:** Electricity can be stored in the batteries, like in the EDVs as described above. With rather high efficiencies and availability this way of storing energy is preferred (without regarding the cost differences).
- **Heat storage:** Storing heat is done in tanks containing either warm or hot water. The water is then used when needed in the energy system. Heat storage is often used in connection to heat pumps or heat boilers.

5.2.5 Fluctuating power

Fluctuating power covers all power production from, e.g. renewables like wind. This type of power generation is fluctuating due to changes in wind, solar or the like, and thus, is not controllable unless down regulated or turned off. Fluctuating power generation is characterised by high investment costs and low variable costs, thus, it is inefficient to use the down regulation, due to the basically free power as soon as the initial investments have been made. The more fluctuating power generation, the more flexible power production or flexible demand (e.g. provided by EDVs) is needed.

- **Wind:** wind power is stochastic by nature. Wind power can be down regulated, if too much wind in the system. Wind turbines are produced in many sizes. Some are for households, with import and export of electricity to the surrounding energy system, to balance the production and demand. Some wind turbines are very large and placed in wind parks at sea.
- **Photo voltaic:** Photo voltaic solar cells convert sun shine into electricity with a very low voltage. To produce electricity, cells are linked like a series of batteries to reach the right voltage needed for the power system. Photo Voltaic has not yet been included in Balmorel, but are mentioned here as they are believed to be of future interest, both in terms of modelling and as part of the power system in the Nordic countries.

5.2.6 Heat only

In Denmark most heating is either individual or district heating. Individual heating is often provided by either wood pellets, oil, or natural gas, not treated by the model. As more and more consumers transfer to district heating or heating in terms of heat pumps and electric boilers, the demand will be treated by the model. District heating can be provided by, e.g. CHP (section 5.2.1.2) or heat boilers.

- **Heat boiler, district heating:** Produces heat on either electricity, natural gas, or wood-chips.

5.2.7 Electrolysis

Electrolysis is the process of sending power through fluids to extract different kinds of gas [9].

- **Solid oxide electrolysis:** Solid oxide electrolysis is making hydrogen from water/steam and electricity. The electricity makes the water split into oxygen and hydrogen. The hydrogen can either be used as propellant for the FCEVs or it can be stored and used in a CHP plant using hydrogen as fuel.

5.2.8 Reserves or services

The different technologies have different potentials in the power system. Table 5.2 illustrates the capabilities of the different heat and power generating plants.

Techn.	Elec.	Heat	Storage	Second reserve	Minute reserve	Day/ Night	2-3 week	Base load	Peak load
Wind	+	-	-	(+)*	(+)*	(+)*	(+)*	-	-
Hydro	+	-	+	+	+	+	+	-	-
OCGT	+	(+)	-	+	+	+	+	-	+
CCGT	+	+	-	+	+	+	+	-	+
Nuclear	+	-	-	+	-	(+)	+	+	-
CHP	+	+	-	+	+	+	+	(+)	-
Heat pump	-	+	+**	+	+	+	+	-	-
Heat boiler	-	+	+**	+	+	+	+	-	-
Elec boiler	-	+	+**	+	+	+	+	-	-

*for down regulation only

**with a warm/hot water tank

Table 5.2: Generation technology abilities

Some of the flexible power generating plants are possibly competing with the EDVs, thus, making the benefits of the EDVs decrease. These are most likely the gas turbines, heat pumps, and electric boilers, although the latter two are also used by the heating system, not only as a flexible power demand. However, the EDVs cannot provide the 2-3 weeks reserves, requiring other maybe flexible power plants. Of course, these power plants do not have to be flexible, but since they are used for maybe a month a year, the fixed costs are preferably low, as with, e.g. the gas turbines. Thus, the EDVs cannot completely out-compete the other flexible power plants, but the question that remains is whether these power plants can out-compete the EDVs or devalue these.

For investments in Balmorel, prices and efficiencies for each of the power technologies are included as shown in Table 5.3. In the table, both the variable operations and management costs (V O&M cost) and fixed operations and management costs (F O&M cost) are given. The fixed costs are costs independent of the amount of power produced, whereas the variable cost is per MWh.

Technology	Source	Fuel	Inv costs* (M€/MW)	V O&M cost (€/MWh)	F O&M cost (k€/MW/yr)	Efficiency**
Wind, onshore	[9]	-	1.22	11.5	-	1
Wind, offshore	[9]	-	2.2	15	-	1
OCGT	[9]	Natural gas	0.57	3	8.6	0.42
Nuclear	[25]	Uranium	2.81	7.7	55.5	0.37
CHP, medium	[9]	Wood	1.6	3.2	23	0.485
CHP, small	[9]	Wood-waste	4	-	140	0.25
Steam extraction	[9]	Coal	1.1	-	34	0.51
CCGT, condensing	[25]	Natural gas	0.56	3.4	21.4	0.58
CCGT, extraction	[9]	Natural gas	0.47	4.2	-	0.61
SOFC	[9]	Hydrogen	0.5	-	25	0.6
Solid Oxide electro.	[9]	Electric	0.57	-	14	0.98
Hydrogen storage	[25]	Hydrogen	0.00058	-	-	0.83
Heat storage	[17]	-	0.00178	-	-	0.99
Heat pump	[9]	Electric	0.55	-	3	3
Heat boiler, biom.	[9]	Wood	0.5	-	23.5	1.08
Heat boiler, NG	[9]	Natural gas	0.09	-	0.32	1
Electric boiler	[9]	Electric	0.06	0.5	1	0.99

*Investment costs will be annualised with a discount rate of 3% (low rate is due to fixed prices)

**For heat pumps coefficient of performance (COP)

Table 5.3: Technology investment options in Balmorel for Paper II. Investment costs for heat storage and hydrogen storage are given as M€/MWh storage capacity.

Chapter 6

Results

The results of the analyses are presented in the respective papers. In this chapter I compare the results from the different papers and comment on similarities and differences. The chapter starts with a short overview of the cases studied in the papers, including comments on expectations. The case descriptions are followed by comparisons of the cases in the different papers, e.g. differences in results when including only the Danish power and transport system and when including the entire northern European power and transport system.

6.1 The Cases Studied

Paper III is an extension of Paper I, describing the road transport model we have developed for Balmorel. Paper III includes a case study of the Danish energy system in the year 2030. Sensitivity analyses on CO_2 and fuel prices are included as are quantifying the benefits of including V2G or only G2V. The model developed is illustrated through the analyses, and the value of integrating the power and transport systems is estimated. The results are interesting since these are the first results from an integrated power and transport system model, enabling calculation of the benefits of using the EDVs actively in the power system.

Paper II contains a description of scenarios to be invested in a Northern European case, including Denmark, Finland, Norway, Sweden, and Germany, again for the year 2030. The expansion from the Danish system is in order to include transmissions with the surrounding countries as well as including the flexibilities from the hydro power in Norway and Sweden. My expectations were that the value of the EDVs would decrease with the inclusion of extra flexibility and transmission capacities.

Paper IV is an extension of Paper II including analyses of the northern European countries. The scenarios were developed in order to try and answer the following three questions:

- What is the influence on the configuration of the power system when introducing V2G and what are the consequences/benefits of introducing a percentage of BEVs?
- What is the economic value of the EDVs?
- How do the EDVs compete with other flexible technologies?

Wind targets (minimum required investments in wind power plants) are introduced in some scenarios, recognising that it probably will be a political decision how much wind to include in the national power systems. And finally, a scenario has been run with a battery load factor of 50% (as opposed to 100% in the remaining scenarios).

Doing the analyses gave me a better understanding of how robust the results were. Furthermore, from the results it became evident how different the resources are in these northern European countries, resulting in five quite different power system configurations.

In Paper V sensitivity analyses on battery prices and capacities are performed. The model is applied to the same northern European case as in Paper IV. Focusing on the road transport system, diesel ICEs, diesel series PHEVs and BEVs are included, the latter two with varying battery sizes.

Two analyses were made in Paper V:

1 Analysis of the influence of the battery capacity and the change in this. In this analysis it is assumed that 25% of the vehicle fleet is BEVs and 75% PHEVs.

2 Analysis of the influence of battery pricing. This is done by having the price change for different battery capacities. The model then invests in an optimal vehicle fleet as well as an optimal heat and power system.

These analyses were performed to analyse the different possible outcomes of the possible future configuration of batteries. Many uncertainties are apparent when focusing on both battery prices and capacities. Doing the analyses, I got an impression of whether the EDVs are beneficial even with different battery prices and capacities.

Paper VI is analysing national versus international impact of introducing EDVs to a power system in the year 2020 for a power system not configured to include the transport system. Four different charging regimes were introduced for different levels of EDV penetrations. Consequences of introducing the different charging regimes were analysed, focusing on how well these levels of EDVs could be incorporated in a power system not configured to include the EDVs. Questions asked were, whether the low use of electricity capacity during night time would be enough to cover the charges. And, whether flexibility is preferred to cover the charging if all of the charging could be placed at night time.

For more details about the cases, see the description in the respective papers.

6.1.1 The hydrogen module

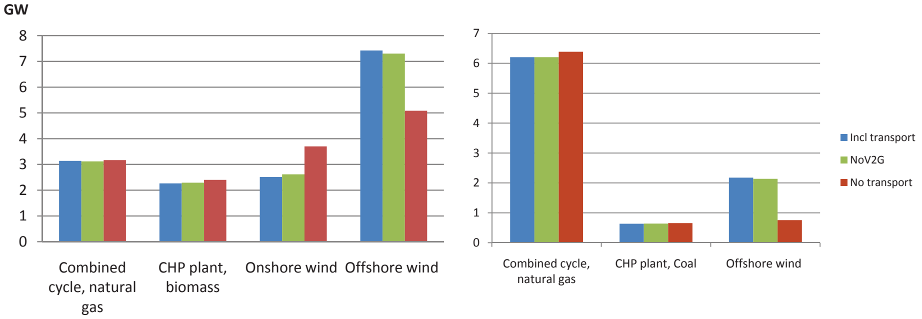
After running the model several times with great variety on oil and CO_2 prices, it becomes obvious that investments will never be in hydrogen related plants or vehicles. The technology is simply assumed to be too expensive, even by 2030. Therefore, the remaining analyses have been made excluding the hydrogen module, improving the calculation time drastically.

6.2 Comparison of Results

In this section results from Papers III, IV, V and to some extend VI are put together and discussed in the context of having the results of all the analyses. Detailed results on the different scenarios are found in the respective papers.

6.2.1 Configuration of the energy system

Doing the analyses I was expecting to see the inclusion of EDVs resulting in integration of a larger share of wind power. However, I was surprised to see that the introduction of EDVs made it attractive to invest in so much wind power. In Denmark the increased investments in wind power more than cover the demand from the EDVs, leaving the system with a wind power share of 69% of the electricity production in the year 2030 (Paper III).



(a) Denmark without transmissions

(b) Denmark with transmissions

Figure 6.1: Investments in power generating capacity, 2030

Focusing on Denmark, the configuration of the power system changes with the introduction of transmission to the neighbouring countries (see Figure 6.1). Although, the EDVs in Denmark will still be driving on wind (Papers III and IV). The difference in the configuration between a system with and without an integrated power and transport system is an increase in wind power investments more than covering the demand for power in the road transport system. However, introducing transmission results in a large import of electricity to Denmark. Thus, the amount of new power generating plants invested in decreases with 7.3 GW for the system with an integrated transport and power system, and decreases with 6.3 GW for the separated systems.

Results from the analyses cannot be compared completely, since the analyses differ in terms of investment costs of the different technologies (updated data were available when writing Paper IV). This can primarily be seen in the investments in wind and in combined cycle gas turbines. However, the import is mainly from Norway and Sweden, resulting in more power generated on wind and water.

Furthermore, oil prices in Paper III were \$100/barrel, whereas they were \$120/barrel in Paper IV. Focusing only on the change in oil prices should result in less investments in fossil fuelled power plants. Hence, the opposite of what is happening, due to transmissions and different power technology prices.

Results from Paper IV show that in Denmark, Norway, and Sweden, the EDVs will be considered sustainable (not emitting any CO_2) because they help incorporate more renewable energy than used for driving. In Germany and Finland, on the other hand, the EDVs are primarily driving on coal. For Finland, driving on coal is due to investments in wind power having reached the limit. For Germany, driving on coal is due to bad wind resources. And increasing battery capacities, increase the investments in power plants using coal, as shown in Paper V. Thus, the degree of renewable energy does not only depend on the introduction of more flexibility, but also on the available resources.

An interesting result for Norway and Sweden in Paper IV is, that introduction of EDVs does not really change investments nor generation. For Sweden and Norway, being net exporters due to large hydro resources, makes it cheaper to cut down on export before investing in more power generating capacity. Furthermore, the facilities of hydro power plants with reservoirs help integrate high amounts of wind power – both in Norway and Sweden and in the neighbouring countries. However, increasing battery capacities do change investments in wind power in Norway, whereas the level stay the same for Sweden (PaperV).

6.2.2 CO_2 emissions

Introducing EDVs I would expect CO_2 emissions to decrease, if new investments are allowed in the power system. This is due to an expectation of the flexibility of the EDVs enabling increased investments in wind power. As has been seen, wind power is not beneficial in all countries, and in the German case the EDVs can be considered as driving on coal. However, the overall CO_2 emissions are decreasing with the introduction of EDVs.

The largest CO_2 emissions, by far, comes from the German and the Finnish power system. In both Germany and Finland CO_2 emissions from electricity generation increase with increasing battery sizes. This is because the increase in electricity production comes from primarily coal and lignite power plants when supply has to meet the increasing demand from changes in the driving on electricity. However, CO_2 emissions from the transport system decrease with increasing battery sizes. It is evident, that the decrease in transport system CO_2 emissions is proportional to the size of the EDV fleet. The approximate CO_2 emissions decrease in the transport system going from ICEs to PHEVs are shown in Table 6.1.

Country	CO_2 emissions (mio. tonnes)
DK	7
FI	8
GE	123
NO	7
SE	14

Table 6.1: Approximate CO_2 decrease in the transport system from introducing PHEVs instead of ICEs in northern Europe (based on a scaling of the Danish decrease from Paper III)

In Denmark, the CO_2 emissions from electricity production are higher the lower the battery sizes, due to increased driving on diesel. Thus, this is the opposite of the German and Finnish cases. With a decrease in CO_2 emissions in the transport system, the overall CO_2 emissions decrease, as for the rest of the countries.

In the Danish case (Paper III), only a quarter of the CO_2 emissions experienced in northern European case (Paper IV) are seen. This is likely due to change in technology data, thus, the investments in CCGT instead of wind turbines. In Denmark, Norway, and Sweden, the transport system accounts for the largest CO_2 emissions in the respective energy systems. This is due to the high percentage of renewable energy in the remainder of the energy system in these countries.

6.2.3 Value of V2G

The value of introducing V2G and not only G2V in a Danish energy system without transmission is M€2 (Paper III). Focusing on the northern European energy system, the value rises to M€18 (Paper IV). Although, the size of the power and transport system is very different, the decrease in system costs due to the introduction of V2G does not change that much. In the Danish case, the decrease in costs amounts to 0.023% of the total system costs, whereas in the northern European case, the decrease amounts to only 0.009%.

Furthermore, V2G is used very differently from country to country as shown in Paper V. In Norway the V2G is not used at all. In Germany, however, V2G is heavily used at all times of day, due to the batteries enabling a more stable production on the remaining fossil fuelled power plants. Thus, Germany creates a large proportion of the cost decrease due to introduction of V2G.

I was surprised to see how few benefits the contribution of V2G gave to the power system. I was expecting the value of including V2G to be greater. However, digging into the reasons, I found that the main value in V2G lies within the hour. Thus running Balmorel with hourly time steps cannot capture the *real* benefit of the EDVs contributing with V2G.

6.2.4 Battery expectations

A battery size expectation of 10 kWh for the PHEVs and 50 kWh for the BEVs has been used in Papers II-IV. However, focusing on Paper V, most of the benefits with the introduction of the EDVs are found when reaching a level of 7.5 kWh for the PHEVs and 43-58 kWh for the BEVs. Thus, for the BEVs the primary benefits should be included, whereas, for the PHEVs it seems like the batteries could provide almost the same benefits for less cost at a size of 7.5 kWh instead of 10 kWh as used. The cost reduction of the integrated power and transport system, of course, depends on the battery prices and varies from approximately M€200 to approximately M€4,000.

Results being this robust to the changes in both battery prices and capacities was rather surprising for me. However, it also shows that the benefits provided to the power system by the EDVs are very valuable. These benefits could be of great importance when trying to get people to both buy the EDVs and securing that they will let the power system get good use of the batteries.

These results are in favour of not having the vehicle owners bye the batteries, since the high vehicle prices might have people choose different vehicle types. However, having the power system own the batteries and the vehicle owners rent these, seems like a good solution. With an agreement of the power system being able to make use of the batteries while the vehicles are parked, the solution seems beneficial for both the consumers and the power system.

6.2.5 Oil and CO_2 prices

Sensitivity analyses in Paper III show that changing oil prices from $100/barrel down to $90/barrel does not change investments in the vehicles, neither does reductions in CO_2 prices to €30/ton. However, low oil prices in the case with the northern European countries (Paper IV) changes investments to include only diesel ICEs.

As for the power system in Paper IV, high oil and CO_2 prices result in increased investments in wind power. Even for Germany, high prices on both oil and CO_2 results in some investments in wind power being attractive. Low CO_2 prices, on the other hand, results in a shift in investments in most power systems from wind to coal, in Denmark generation on coal increases from 4 TWh to over 30 TWh. Low oil prices also results in a shift from wind to coal although the shift is not as pronounced.

In the Danish case (Paper III) the changes in the power system configuration are very small, with oil prices varying from $90/barrel to $130/barrel and with decreased CO_2 prices.

Hence, neither inclusion of transmissions nor the technology data change resulting in more expensive wind changes the configuration of the Danish power and transport system.

6.2.6 Competition between EDVs and flexible technologies

Focusing on Table 5.1 (page 57) and Table 5.2 (page 62), it seems like the EDVs can compete with the flexibility provided by heat pumps, electric boilers, gas turbines and heat storage (the latter not mentioned in the tables). Heat storage, electric boilers and heat pumps all provide flexibility for the heating system as well, thus, excluding these will also have influence on the heating system. However, EDVs cannot provide the flexibility of providing power or not demanding any power for 2-3 weeks that can be provided by the others. Based on these observations, I believe the EDVs are able to compete with the electric boilers (being rather expensive) and heat storage. To some extend I also believe the EDVs to be able to take over some of the role of the gas turbines as peak-load plants.

Eliminating heat storage and electric boilers (Paper IV) does not influence much on the configuration and operation of the rest of the power system. EDVs are used more actively, especially in the case with BEVs included in the system. Thus, the EDVs can replace and, hence, be in competition with the heat storage and the electric boilers. This effect is also reflected in Paper V, where investments in heat storage decreases with increasing battery sizes, especially in Germany and Finland.

Eliminating heat pumps and gas turbines (Paper IV), on the other hand, have massive influence on the investments in wind power and coal steam turbines. For Denmark, Norway, and especially Finland, investments in wind power decrease in these scenarios. On the other hand, investments increase in coal steam turbines for both Denmark and Finland. The use of the EDVs by the power system also reflects this observation, since no significant changes are to be found. Thus, EDVs cannot replace all of the flexibility provided by gas turbines neither can they replace heat pumps, however, this might be due to the heat pumps also producing heat.

Surprisingly the EDVs do not make a difference to the peak-load plants. This might be due to the EDVs not contributing to the capacity credit equation in any of these analyses. This will be commented upon in Section 6.3.

6.2.7 Electricity prices

With an introduction of an extra demand, I would expect electricity prices to increase. However, because of an expectation of an increasing penetration of wind power, the prices would probably not increase very much. Furthermore, I believe that the electricity prices will experience smaller oscillations due to the flexibility of the EDVs being able to charge or discharge at times when the power system is experiencing high fluctuations in either generation or demand.

In Paper IV, including EDVs remove some of the fluctuation in the electricity prices (Figure 6.2). Thus, the EDVs supply some of the flexibility needed in order to meet demand. The prices of electricity do not increase with the introduction of EDVs (except for Sweden). This is due to better utilization of the base load power plants as well as integration of more wind with cheaper power production. Hence, besides the power system being cheaper, the EDVs do provide benefits to the electricity system, no matter if the power system contains more renewable energy or not.

Introducing 25% BEVs results in electricity prices smoothing out further and staying at the same level as without BEVs for all countries but Sweden. This is also evident from the observation of electricity prices having smaller and fewer oscillations the larger the batteries, in both Denmark, Norway, and Germany (Paper V). Thus, lower peaks and higher downs in the prices are experienced. In Finland, the electricity prices are increasing slightly with larger battery capacities, although, still with less distinct peaks and downs. Finally, Sweden experiences increasing prices with increasing battery capacities. The stable production and, thus, less export results in the increase of the power prices.

I find it both interesting and surprising, that Germany do not experience an increase in the electricity prices. The EDVs only results in incorporation of

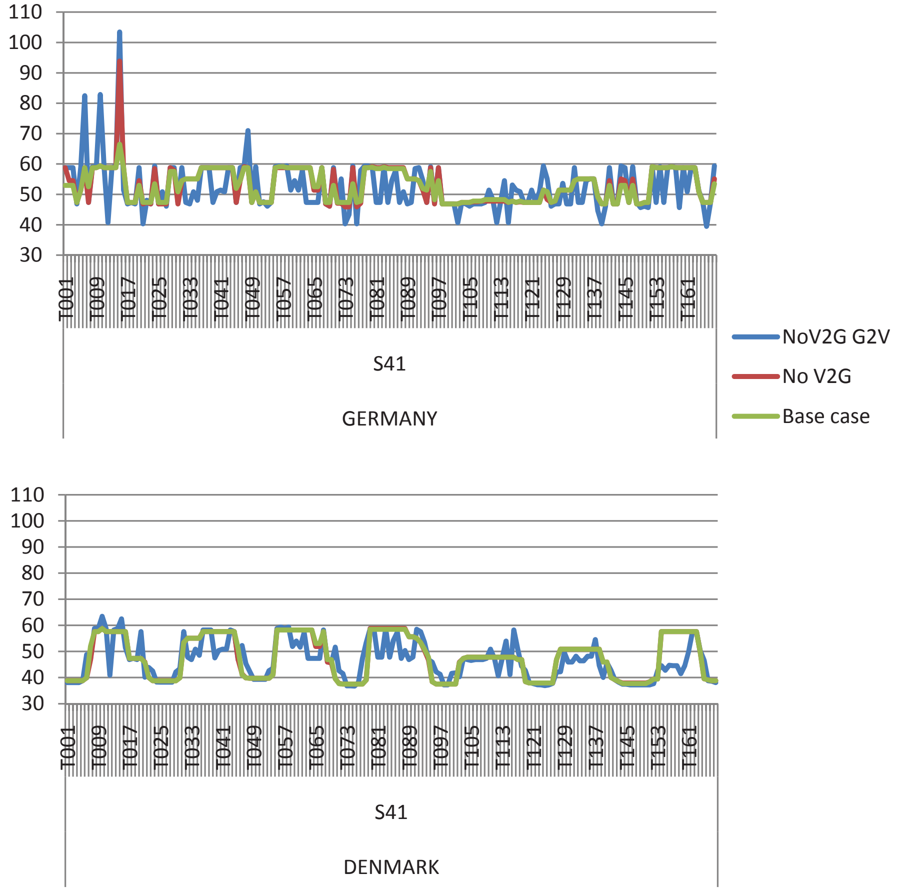


Figure 6.2: Electricity prices in Germany and Denmark in a selected week (week 41), 2030 (Paper IV)

more coal fuelled power plants into the power system. However, the electricity prices staying at the same level could be an indication of the coal fuelled power plants benefiting from not having to up and down regulate the production all the time. This is also evident from the intensive use of V2G in Germany.

Furthermore, I was surprised to see the prices in Sweden increase. However, since investments stay do not increase and export decreases to cover the demand from the EDVs, the price increase is rather plausible.

6.2.8 Other parameters

Investments in EDVs, and thus the power system, are not very sensitive to changes in the battery prices, except when batteries become very expensive and large (Paper V). Furthermore, results are not sensitive to the grid capacity restriction (Paper III), but to the sizes of the batteries (Paper V). Thus, the power system does not need to draw more power at once, but rather be able to use the power more flexibly.

As in Paper IV, introducing wind targets changes investments in some countries. The wind targets are already met in Finland, Norway, and Sweden in the base case. In Denmark, however, the introduction of wind targets reduces investments in gas turbines and increases investments in heat pumps. For Germany, wind targets result in a decrease in use of coal power plants and a slight increase in investments in heat pumps and electric boilers. Thus, even though introduction of wind target costs €1.5 bill for medium wind targets and €2.2 bill for high wind targets, they do generate the desired effect towards more renewable energy, and EDVs help integrate the large amounts of wind.

The load factor is included in the transport model as a parameter. In most analyses the load factor is fixed to 100%, meaning that the EDVs leave the grid with a fully loaded battery. Reducing the battery load factor (Paper IV) to 50% reduces the charging throughout the 24 hour period. Furthermore, the reduced load factor increases the total costs of the system because of the increased use of diesel for some vehicles.

6.2.9 National versus international aspects

From the results above the simulations indicate that the reasonable investment and operation change when focusing on northern Europe rather than only Denmark. The same counts for focusing on investments and operation in Ireland versus Ireland and Great Britain when introducing changes in the Irish power system (Paper VI). Nationally, Ireland experiences a cost and CO_2 emission decrease, whereas, the international effect is a cost decrease and a large CO_2 emission increase. Thus, decisions on energy system configurations should include analyses with an international aspect.

6.3 Results from Including the EDVs in the Capacity Credit Equation

In this analysis, EDVs have been allowed to be part of peak-load capacity, thus, they are made an active part of the capacity credit balance equation (Equation 4.28, page 52). With the contribution of the EDVs to the capacity credit during peak-load, power system investments change in most countries.

Germany has not been included in the figures for this analysis because they do not experience any change. Furthermore, the German power system is much larger than the other countries, thus, an inclusion of the results from Germany would make it hard to focus on the changes in the results in the other countries.

Figure 6.3 shows the investments in both the base case (the same base case as in Paper IV) and a case with the inclusion of EDVs in the capacity credit equation. It is interesting to see how the inclusion of the EDVs in the capacity credit equation removes all investments in combined cycle gas turbines (CCGT, called CC_NG in the figure). In Section 6.2.6, I showed that inclusion of EDVs could not out-compete the investments in CCGT. However, the EDVs can in fact take over the CCGTs if they are part of the capacity credit during peak-load hours.

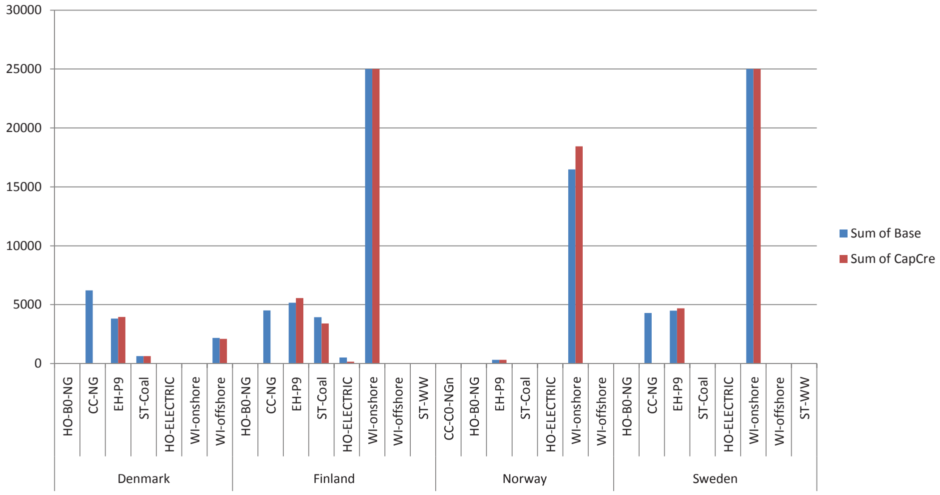


Figure 6.3: Investments in 2030 (MW)

Furthermore, there is a slight change in other investments. More wind power investments in Norway and less coal steam turbine investments in Finland are the largest changes.

Even more interesting is the electricity generation shown in Figure 6.4. Here it becomes evident that the CCGTs, which are no longer invested in, actually hardly provided the power system with any load! Hence the plants have been sitting there, just to satisfy the restrictions on the capacity for peak-load hours.

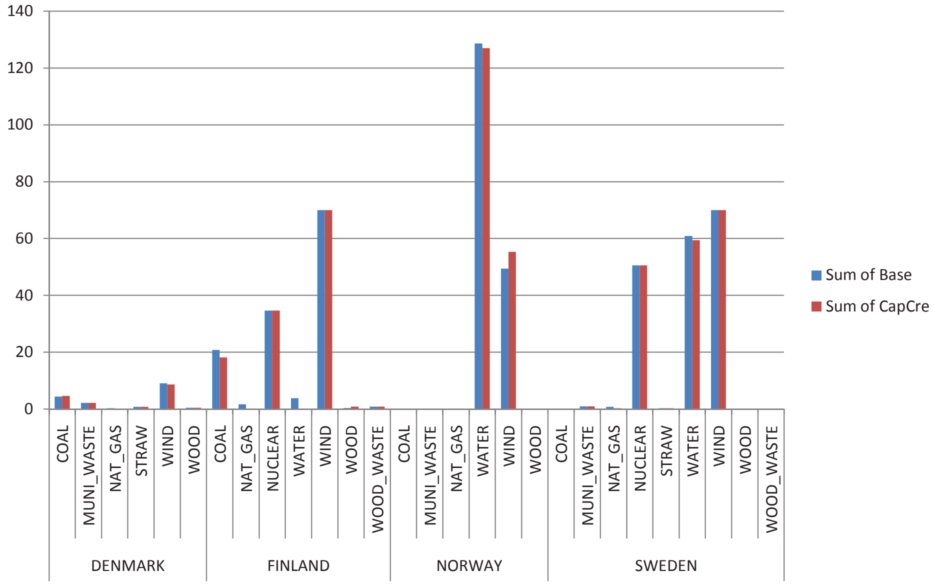


Figure 6.4: Electricity generation on fuel types, 2030 (TWh)

As a consequence of the investment changes in Norway and Finland, the electricity generation do increase on wind in Norway and decrease on coal in Finland. This also results in the CO_2 emission decrease seen in Figure 6.5. A slight CO_2 emission increase is experienced in Denmark, due to a slightly higher level of use of coal and slightly lower level of investments and, thus, use of wind power. This is likely due to the wind power penetration being as large as beneficial with the remaining flexibility in the system. Hence, coal power takes over a small part of the production.

Focusing on the electricity prices, the power system has become more vulnerable to changes in production for Denmark, Finland, and Sweden. This is seen by a general increase in the size of the oscillations. Thus, the electricity prices experience an increase in peaks in particular (see Figure 6.6, page 80). For some weeks the increases in the size of the oscillations are more evident than in others.

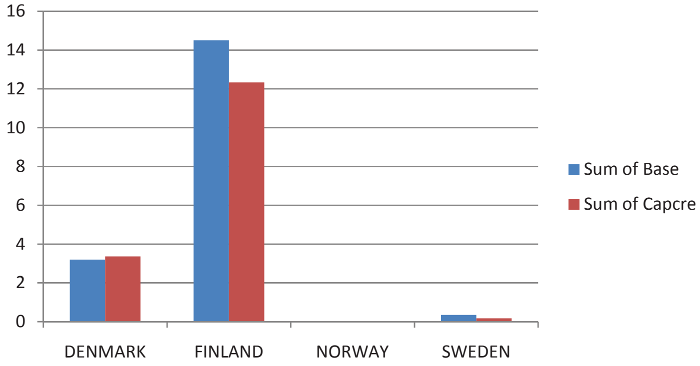


Figure 6.5: CO_2 emissions from electricity generation, 2030 (TWh)

6.4 Summary of Results

Based on the observations in Papers II, IV, and V, it is evident that the simulation indicates that an optimal solution in Denmark, Norway, and Sweden includes renewable energy as the energy source for EDVs. Drastic changes have to be experienced in the parameters included for sensitivity analyses to change this, e.g. large decrease in expected oil prices. With Germany and Finland experiencing investment in coal powered plants for meeting the demand for the EDVs, rational investments obviously also depend on resources in countries analysed.

Electricity prices experience fewer oscillations with increasing flexibility, and thus battery capacity, in the power production. However, the changes in oscillations are more significant with a marginal increase from small amounts of flexibility than from large. Thus, the marginal value of the EDVs are decreasing with increasing amounts of flexibility.

These results are very plausible, interesting and in favour of en electrified transport system. However, models also do have flaws to be aware of. Modelling the integrated power and transport system gives a very black and white solution to the challenge of integrating more renewable energy in both systems and changing the means of transport from diesel or gasoline. The model finds optima often including either buying one type of vehicle or the other. Thus, the model does not recognise different preferences of different people but only indicates what is economically reasonable.

However, even though decisions should not be made only focusing on the results of the model, the model can be regarded as a very good decision *support* tool. The simulations show what is economically rational in the system defined, thus, giving, e.g. politicians, an idea of the direction the different decisions can lead the economy. Furthermore, as it is shown in the analyses, the EDVs are very beneficial for the power system, thus, indicating that it would be a good idea for the power system operators to fight for support schemes or other types of economic support for the EDVs. The support could be in terms of consumers leasing the batteries instead of owning them.

Hence, models can be of great value as a decision support tool and they can give good insight into consequences of different decisions.

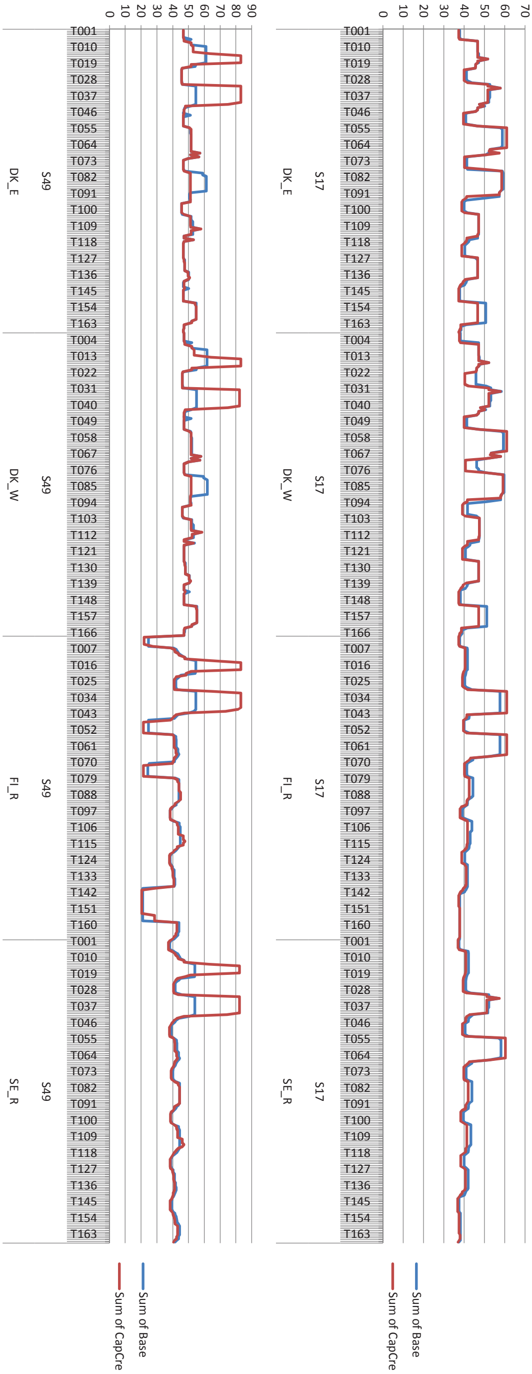


Figure 6.6: Electricity price fluctuations for selected weeks, 2030

Chapter 7

Conclusion and Discussion

In this chapter the research questions presented in the introduction are answered, followed by a discussion of the conclusions. Afterwards, a general discussion of the energy system and EDVs is presented, followed by a section commenting upon the objectives of the PhD and how these are reached. The chapter ends with a discussion of areas of further research.

7.1 Economically Optimal Configuration of the Integrated Power and Transport System

To answer this question, analyses from Paper II, IV, and V are used. In most situations it is optimal to invest in PHEVs, no matter if optimising a closed Danish energy system or the Northern European energy system. Only in situations with very low oil prices or very large and expensive batteries it is optimal to invest in diesel ICEs.

Configuration of the power system, however, is country dependent. For Denmark, the model indicates that it is optimal to invest in wind to cover the increase in power demand coming from the EDVs. However, in situations with low CO_2 prices the optimal investments include large proportions of coal instead of wind. Increasing the storage level increases the possibility of wind power investments accordingly.

The Norwegian power system is characterised by a large share of hydro power. The model indicates that investments in Norway are in wind power no matter the scenarios, battery capacities etc. Only in situations with both low oil and CO_2 prices, it becomes optimal to invest in a very small amount of power plants on natural gas. Thus, by 2030 it is optimal for Norway to produce power on renewable energy only, including the power needed for transportation.

The Swedish power system is somewhat like the Norwegian, although, the power system consist of a large amount of nuclear power plants along with wind and hydro power. The model indicates no changes in the power system investments, except when CO_2 prices are low. In this case investments are in coal instead of wind. Investments are almost stationary no matter the power demand from the vehicles. Thus, increasing battery capacities do not results in increasing investments, rather decreased export.

The Finnish and German power systems are different from the other Nordic countries. In the Finnish system, simulations show that investments in wind power reach the limit of maximum wind capacity to be installed in almost all scenarios. Besides wind, the model invests in CCGTs (due to the CCGTs being cheaper than the OCGTs in latest data from the Danish Energy Authority [9]), heat pumps, coal steam turbines, and nuclear. When including EDVs, the only changes seen are increases in investments in the coal power plants, since wind investments cannot increase any further. Thus, the conclusion is that the EDVs are driving on coal although very large amounts of the power generation comes from wind power. Configuration of the power system is sensitive to low oil and CO_2 prices, as to the inclusion of heat pumps and CCGT. Excluding the latter two or having low oil or CO_2 prices results in a large amount of the wind power investments being replaced with investments in coal steam turbines. Increasing battery capacities also increase investments in coal steam turbines.

The German power system is characterised by investments being in coal only, except when experiencing high oil and CO_2 prices. The simulated power system configuration indicates that it is reasonable with more than half of the production being on coal steam turbines. The rest of the power production is divided between lignite and nuclear power plants, with a small share of municipal waste, though. Increasing battery capacity increase investments in coal steam turbines as well. However, introducing wind targets replace investments in coal with investments in wind power without needing more flexibility. Thus, the EDVs do provide the flexibility needed for introducing large amounts of wind power in the German system as well.

Basically renewable energy is dominant in Denmark, Sweden, and Norway, characterised by large hydro power resources in Norway and Sweden and big wind resources in all three countries. For Finland, the renewable energy is dominant as well - the amount of integrated wind power even reaches the limit in most scenarios. Thus, the remaining electricity demand is covered by other sources of fossil fuelled power plants. For Germany, however, the power system is characterised by coal powered power plants, due to bad wind resources. The differences in power system configuration gives an idea of the different resources available in the different countries.

Discussion

The above results are all based on mathematical modelling of the energy system. All the assumptions and limitations included are influencing the results, introducing uncertainties to the conclusions. First of all, the optimisation model assumes rational behaviour. Thus, investments in the heat, power and transport systems are assumed to be rational. For the heat and power systems, most players are maximising profit, in many cases including minimising costs. For these players the assumption is not far off. However, some of the players are politicians. Politicians have in many cases shown that they are not rational, e.g. by not reacting to economically optimal solutions like with the Danish tax stop agreement or the Danish “efterløn” (pension benefits for early retirement). Rather the politicians seem to optimise their chances for winning the next election. Thus, the players in the heat and power system are not always being rational.

For the individuals investing in future vehicles, preferences seem to play a big role in the investment decisions. Why do people buy, e.g. a Porsche instead of a Mazda or Toyota? Hence, the rationality assumption does not hold completely. On the other hand, the results do give a very good indication of what could be a reasonable solution in the combined system. These results can then be used as support for decision making on how to structure the future market, taxes, subsidies etc.

Average driving patterns have been assumed, and the load factor has been fixed. Making the load factor a variable, and thus, excluding the investment option in the vehicles, and making more diversified driving patterns, would probably result in an increase in the value of the EDVs. However, a change in load factor to 50% has been tested without big changes in the results.

In the analyses large investments are placed in wind power. The value of the wind power is determined by many factors, including the observed wind profiles. Wind profiles included in the model are on country level and are based on historic data on wind profiles on different country specific sites. However, with increasing shares of wind power, the best sites will be taken. Thus, one could argue that the wind profiles should have decreasing value with decreasing value of the sites. I would not expect large changes in investments because of changes in the wind profiles, although investments in the last MWs might be replaced with other sources.

All put together, investments might change slightly with the refinements. However, analyses show that the investments are rather robust to many changes.

7.2 Optimal Use of the EDVs with Regard to the Power System

Charging regimes in the Irish power system have shown that the more flexible the charging of the EDVs, the better integration of the EDVs with the power system. The EDVs are primarily used as a flexible demand, charging at optimal times for the integrated power and transport system.

The EDVs are used to remove some of the oscillations in electricity demand and production. This is evident when focusing on the electricity prices that evens out more and more with increasing storage capacities. The EDVs help getting a more stable electricity production from the base load plants, with less unit start-ups, as seen in the Irish power system. This reduction in start-ups also has an effect on the electricity prices. Furthermore, the EDVs can take over some of the production from CCGTs, removing some of the large power price increases, due to the high variable costs of the CCGTs.

The EDVs can take over some of the flexibility provided by the CCGTs. Including the EDVs in the capacity credit equation, can even exclude investments in CCGTs. Along with the integration of large amounts of wind power, the integration of EDVs does not result in overall electricity price increases. Only in Sweden increases are experienced in some scenarios, where the country needs more of the inland produced power themselves. Thus, more EDVs in particular situations result in electricity price increases in Sweden.

Furthermore, the simulations indicate that the EDVs can replace the use of heat storage and electric boilers in the northern European power systems, although inclusion of heat storage is optimal. However, EDVs cannot replace CCGTs or heat pumps, the latter due to the heat pumps not only proving flexibility to the power system, but also producing heat for the heat system. Both are needed especially in days or weeks without wind and at peak demand. Conclusions drawn from this are that EDVs can compete with the flexibility provided from heat storage and electric boilers and maybe also the flexibility provided by the heat pumps. However, the EDVs cannot compete with heat production from heat pumps, but if included as capacity during peak-load, the EDVs can compete with the CCGTs.

Using the EDVs as storage for later use, is optimal in some countries. V2G is used a lot in Germany, whereas, Norway has hydro power for flexibility and, thus, do not need the use of V2G at all. Hence, for some countries it is optimal to use the EDVs as storage with focus on later use of the power.

Discussion
The use of the EDVs is based on the hourly time steps in Balmorel. I expect the EDVs to be even more attractive, especially in terms of V2G if focusing on the intra-hour happenings in the power system. The need for reserves are often within the hour and, as shown in Chapter 2, EDVs are able to deliver most of these reserves.

Another reason for V2G not contributing with so much extra value is the great flexibility in charging the vehicles. When extra capacity is needed in the power system, the EDVs stop charging and, thus, can be regarded as *delivering* the capacity to the system.

7.3 Power System Benefit from the EDVs in Terms of Integrating more Renewable Energy/Wind in the Power System

Simulations indicate that the EDVs help integrate more wind power than needed for the EDVs in many power systems. Thus, these power systems benefit from the EDVs in integrating more renewable energy. The other systems also have the possibility of integrating more renewable energy in terms of, e.g. wind power. This is seen in the German power system with introduction of wind targets, where the flexibility needed for meeting the targets is already included in terms of the EDVs.

However, the system also benefits from the EDVs in terms of integrating more of the not so flexible base load plants. In Germany, most of the power production comes from coal steam turbines. Furthermore, V2G is used most aggressively in Germany, helping these steam turbines to a more stable production.

Discussion

Integrating smart charging for the EDVs help integrate more renewable energy in the power system. However, as can be seen from the charging regimes in Paper VI, the system costs are very dependent on the flexibility in the charging. I believe that dumb charging will lead to a need for huge investments in transmission capacity in the electricity distribution grid because it will lead to a large increase in demand in certain hours, especially in peak-load hours. Thus, if intelligence is not introduced in the system, I believe that the value of introducing EDVs will be negligible if not negative.

As was observed in the Finnish power system, investments in wind power reach the capacity limit, leading to large investments in coal powered plants to meet demand. Including other types of renewable energy sources in the analyses, such as photo voltaics, could result in decreases in investments in coal powered plants. For both Denmark, Finland, and Germany, inclusion of other types of renewable energy sources could be relevant. The Norwegian system and partly the Swedish system seem to have reached a maximum of interesting investments in renewable energy within the power system.

7.4 Consequences of Incorporating EDVs in a Power System Configured for Power Demand Excluding Transport

Renewable energy usually produces with a utilisation factor of 100% due to investment costs being high and variable costs close to zero. With renewable energy being used to the extend possible, introducing EDVs in a preconfigured power system can only increase power production on the remaining power plants. In the Irish case, the power system is characterised by a large penetration of wind power. However, with the capacity factor of 100% the power needed for the EDVs introduced is to a large extend produced on base load coal powered plants in Great Britain.

Thus, incorporating EDVs in a preconfigured power system results in an increase of power produced on fossil fuels. Overall system costs are decreasing, whereas the overall CO_2 emissions are increasing. However, incorporating the EDVs also brings benefits in terms of a more stable power production on the base load plants, with less start-ups.

The different charging regimes introduced show the importance of the integration of intelligent charging. The more intelligence, the lower the system costs and the better the integration of the EDVs.

The national effects of incorporating the EDVs are benefits, both in terms of system costs and CO_2 emissions. However, the international consequences are an increase in the CO_2 emissions.

Discussion
The flexibility brought by the EDVs is of importance to any power system. The more flexibility the better. Furthermore, a predefined power system can only support a certain amount of EDVs before expanding the capacity. This is illustrated in the Irish case where a large share of the increase in power production comes from Great Britain. If Great Britain was to introduce a corresponding share of EDVs, I am not sure the power system would be able to meet the demand.

I believe that integration of an increasingly electrified transport system has to enter the market parallel with the investments in charging infrastructure and increase in investments in electricity generation capacities. We cannot wait for the EDVs to enter the market before building the infrastructure and power generation capacity. However, building infrastructure and power system capacity is expensive if the EDVs do not take over considerable market shares. Thus, I believe it will be most profitable with simultaneous developments in the respective systems.

7.5 Consequences for the Energy System

All the analyses performed are socio-economic analyses. The optimal configuration of the energy system has been found without introducing, e.g. taxes and subsidies. However, analyses of introducing wind targets show that high penetrations of wind power are possible to integrate and the EDVs help the integration in terms of stabilizing the power production from other power generating plants.

Different support schemes or tax systems can be integrated depending on, e.g. political visions in terms of amount of renewable energy, nuclear power etc. Including taxes in, e.g. fossil fuels will change the optimal configuration of the integrated power and transport system.

Focusing on the climate changes, the energy system moves towards renewable energy production. Focusing on countries like Germany, either support schemes for the renewable energy or taxes targeted the fossil fuelled power plants are needed. Furthermore, the power systems with large amounts of renewable energy still need the flexibility or back-up power provided by the CCGTs and heat pumps. Thus, in order to turn the energy system into a 100% renewable energy system, a replacement for the CCGTs is still needed, e.g. in terms of including the EDVs as capacity to be used during peak-load hours.

As for the vehicles, introducing high vehicle taxes depending on, e.g. km/l, will charge the ICEs and even the PHEVs a lot more than the BEVs. This might change optimality to include a large amount of BEVs.

The overall consequences for the energy system are an introduction of a large flexibility, enabling an introduction of a large share of wind power. Integrating electricity in the transport system also enables better integration of other types of power plants in the energy system, as seen in the German case.

7.6 General Discussion

As mentioned in Section 3.1, there are many uncertainties concerning the development of the different technologies, e.g. the batteries. Based on previous research, a number of assumptions are made in order to be able to make the analyses in this PhD project. These assumptions are, of course, basis for a lot of questions including the validity of the results. Sensitivity analyses have been made on many of the parameters, finding the investments to be rather robust. However, not all parameters have been included. A series of factors developing in a different direction might result in changes in what is indicated as reasonable investments and operation.

The analyses have been limited to include road transport with passenger transport in light duty vehicles. As have been seen in Section 2.3, road transport counts for 77% of the total CO_2-emissions from transport. However, I believe that introduction of heavy duty vehicles will have a great effect on the power system, although the marginal value of adding extra battery capacity is decreasing. A benefit from heavy-duty vehicles can be that some are parked in large parking spot after working hours and are, thus, available as a large battery to the power system. These players can pool the battery capacity parked in the parking lot and act like the aggregators mentioned in Section 2.4.2. Hence, some of these parking lots can bid in to the power market as one player.

I believe that the transport patterns will change, with a shift in the means of transport. Thus, increasing BEVs will lead to a change in habits, due to the limited driving range. Some people could choose to have only a BEV and if needed they will rent a vehicle few times a year for the longer trips. Or, people would start travelling by public transport when going farther away. Changes in transport patterns as well as splitting the transport habits into different groups could change the value of the EDVs, making them more beneficial for the power system.

I have not focused on bio-diesel in this thesis. One reason is that I believe that the limited resources of bio-fuels will be used elsewhere, or in specific types of vehicles such as range extenders in busses, long-distance truks, or maybe in cabs. However, research is focused on second generation bio-fuels, and these might show to be relevant for broader use in the transport system. The inclusion of bio-fuels and investigations on the most optimal use of bio-fuels are left for future studies.

Mathematical models are not telling the whole truth, nor can they be considered fortune tellers. The models are good as decision support tools as long as the decision makers also are aware of the limitations of the models. A lot of refinements can be done, improving the model. However, the level of details seem to give rather valid results that are also very robust. Changes in input prices and other data can change the results, but with these data being based on results of leading researchers, I believe that the results in this thesis are trustworthy, keeping the assumptions in mind.

7.7 The Contribution of the PhD Project

The aim of contribution was in the introduction divided into four goals. In this section I comment on these four.

Introduction of decision support tools for the energy system including road transport system. These support tools help improving decision making on a national and international level.

A decision support tool has been provided in terms of a linear programming model for analysing future consequences of, e.g. changes in fuel or CO_2 prices. Through the optimisation model, optimality in operation and configuration of the integrated energy system is given. However, when using the decision support tool, one should beware of the limitations, e.g. assumptions about rationality. Furthermore, a mathematical model cannot predict the future but can be a very good tool to support decision making.

Integration of the power and road transport system by introducing an investment and operation model for vehicles to be integrated with existing investment models for the power system.

An investment and operation model has been developed for the road transport system working as an add-on to Balmorel, one of the existing energy system analysis models. However, only passenger road transport has been implemented so far. Including other types of road transport is a matter of data collection since the model can include all vehicle types, defined by data.

Improve the understanding of the effects of introducing EDVs in the power system, based on energy system analyses, primarily using the energy system model, Balmorel.

Different analyses have been made on the integrated power and transport system, as have analyses of the introduction of EDVs in a power system configured for power demand excluding transport. Through the analyses, an understanding of benefits and limitations when integrating EDVs in the power system has been reached. It has been surprising to see an optimum in Denmark being an increase in investments in wind power that exceeds the electricity demand from transport, when integrating the power and transport systems.

Furthermore, an improved understanding of the benefits of V2G has been reached. The V2G does bring benefits in some countries, however, it is expected that the model developed does not catch the largest benefits, due to the hourly time resolution.

Projection of technological development to 2030 and presentation of future vehicle configurations to be used in the interaction with the power system.

Data for the vehicle technologies used in the thesis has been projected to 2030. Different opinions are presented in the development of vehicles, and controversy is in particular present regarding the speed of development for FCEVs and the prices of the FCEVs. The projections made and presented are all based on expert knowledge.

Forecast of a driving pattern for the vehicles as well as a possible future plug-in pattern.

A forecast has been made on the driving patterns of the vehicles, to be used for a model with an hourly time resolution. Information from experts has been found on the different factors relevant to make the forecast. Based on the forecast of driving patterns, a plug-in pattern has been developed, assuming that the vehicles are plugged-in every time they are parked.

A plug-in pattern for vehicles parked only at home has also been developed. However, due to time restrictions and a large number of changes needed in the model to make the plug-in patterns independent of the driving patterns, analyses using the plug-in pattern have not been made - yet.

7.8 Future Research

Developing the road transport model has opened for numerous suggestions for further research. First of all, the model developed can be used in many different ways. The analyses made in this thesis are just a corner of the analyses made possible.

Using the transport model developed
Analyses for the interaction between the transport system and different power system technologies could be one example. Focusing on, e.g. different kinds of waste treatment in connection with storage possibilities in the transport system could be of interest.

Also, analyses of future electricity pricing is an interesting scope. Electricity pricing are in some regions based on the unit with the highest marginal cost of generating the electricity in action. With an increasing share of renewable energy, the marginal costs are decreasing as the marginal costs of generating electricity on, e.g. wind is zero. However, the high investment costs in renewable energy are to be covered, calling for a different pricing scheme in the future. Using the model for the integrated power and transport system for analyses of effects of different pricing schemes could be very relevant.

Another exciting analysis could be finding the marginal value of the EDVs at different levels of wind penetration. The value of different storage sizes is seen in Paper V in terms of different battery capacities. However, the contribution of the single EDV or the next hundred EDVs and the costs of integrating these has not yet been analysed. With the different wind penetrations, different marginal value of the EDVs are expected.

Besides the analyses with the existing model, refinements of the model could open for new research opportunities. As has been mentioned, integrating the possibility of using different plug-in patterns could be of interest, enabling analysis of costs changes and changes in benefits when the vehicles are not plugged-in as often.

Driving patterns and load factors

Dividing the vehicles into groups depending on their daily driving patterns, thus, all trips scheduled for the day gives a forecast of the power needed for the entire day. For some vehicles the battery capacities are large enough to cover the entire trips of the days resulting in only needing to charge at night time.

Furthermore, including the load factor as a variable instead of as a parameter is of great interest. Fixing the power and transport system, enables analysis of a variable load factor. A variable load factor is expected to give the EDVs even more credit than the model presented in this thesis. However, one could argue that restrictions should be incorporated with this as well, since perfect foresight for the next trips does not seem reasonable (length of trip, time of start, exact use of power etc.).

Introducing a new configuration of the load factor opens for analysis of more detailed driving patterns. The driving patterns used in this thesis are on an hourly basis, but using more detailed driving patterns for the first one or two hours could give different results. Thus, vehicles only commuting 5 km do not need as much stored electricity as the vehicles commuting 30 km, as is the case in the existing driving pattern. Research of the effects of introducing more detailed driving patterns could be interesting.

Integrating the road transport model in the stochastic energy systems analysis model, Wilmar, doing similar research studies as in Balmorel, could also be of future interest. Comparison of results from the two models could be interesting as could more detailed dispatch analyses. With the power system configuration being fixed in Wilmar, introducing a variable load factor is no problem. Thus, detailed analyses on consequences of a variable load factor could be of relevance in Wilmar.

Building new models or extending existing models

Another issue is focusing on the value of V2G. One aspect could be analysis of the value of V2G in different power system configurations. Some of these are seen in Paper IV and V, indicating that V2G is not relevant to use in Norway, whereas, V2G is used very much in Germany. For future decision making on the energy system development and the configuration of the vehicles and chargers/discharges in particular, analyses of many different configurations could be relevant. This could be done using the EnergyPLAN model, with the advantages of easily configuring many different energy systems.

Developing an intra-hour model to investigate the values of V2G in terms of delivering different reserves, could be of great interest. This model could be a stochastic model using different historical data on outages, demand variation, wind variations etc. Based on these variations, the demand for reserves could be modelled and analyses of the EDVs delivering the reserves can be made.

Integrating the vehicles as an active part of the power system demands for bids to be placed on the different power markets. Models for placing bids on the day-ahead market or the market for reserves are desired. With many small entities and some uncertainties, a stochastic model could be beneficial.

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Part II

Articles

CHAPTER 8

Paper I

Optimal configuration of future energy systems including road transport and vehicle-to-grid capabilities

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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 integration 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 power system and transport system including the competition between flexibility measures such as hydrogen storage, heat storage and plug-in electric vehicles.

Keywords: power system, transport system, vehicle-to-grid.

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 electric drive vehicles (EDVs) can lead to cleaner transportation. Incorporating the abilities to control when to charge the EDVs from the grid (grid-to-vehicle), as well as feed power back into the grid (vehicle-to-grid), 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 system and the customer, infrastructure, transition paths, and actually quantifying the impact and benefits. The contribution of this work is an optimisation model, enabling us to analyse the optimal investment path and operation of an integrated power and transport system, thereby calculating optimal investment in vehicle technologies and power system technologies. Bringing electrical power into the transport sector has consequences for the entire power system. These consequences along with consequences, such as introducing the concept of vehicle-to-grid (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 [10], 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 [12], and focus on potential benefits of particular services has been taken in terms of peak load shaving [8], and regulation and ancillary services [21]. [1] have looked into integration of battery electric vehicles (BEVs) in particular with focus on the benefits of the vehicles providing ancillary services. Cost comparisons of providing different kinds of services has been made in [18], comparing the different kinds of EDVs with the technologies providing the services today. [13] has provided a brief overview of potentials of grid-to-vehicle (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 [12] Kempton et al. have suggested infrastructure in terms of, e.g., connection standards and business models. Business models have also been touched upon in [11] as well as thoughts on dispatch of vehicles. Brooks and Gage have in their article [2] given a brief yet detailed introduction to the relevant factors in the system setup, and [9] 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 hybrid electric vehicles (PHEVs) and BEVs [11] and further all the way to fuel cell electric vehicles (FCEVs) [6, 15, 24].

Turton and Moura [23] have looked at the impacts of the availability of V2G in terms of benefits and changes in car technology market shares, focusing on different scenarios including climate policy scenarios. Analyses of retail and lifecycle costs have been made for PHEVs [14] and BEVs [4]. 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 [16]. 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 [17] McCarthy, Yang and Ogden have developed a simplified dispatch model for California's energy market to investigate the impacts of EDVs as part of the energy system. Short & Denholm have in their report [20] studied the impact on wind installations with more EDVs with G2V and V2G capabilities, and in [5] the impacts on the power system with optimal dispatch of EDV charging has been studied. However, 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 the interaction on future investments in far more detail and potentially provides more changes and benefits in the power system than in the papers mentioned above.

We start this article with a description of the Balmorel model. Section 3 provides a thorough description of the transport model as well as a description of the interactions with the existing power systems model, Balmorel. Application of the model is described in Section 4, including case description and expectations of the results.

2 The Balmorel model

The Balmorel model is a partial equilibrium model assuming perfect competition [19]. Based on input data the model (Figure 1) maximises social surplus subject to constraints including a) capacity restrictions, e.g., limits on generation and transmission, b) emission restrictions, e.g., on CO_2 emission, and c) balance equations. With fixed demands, maximising social surplus corresponds to minimising operation costs. The model can be run with either exogenous or endogenous investments. With endogenous investments, output is an economically optimal configuration 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.

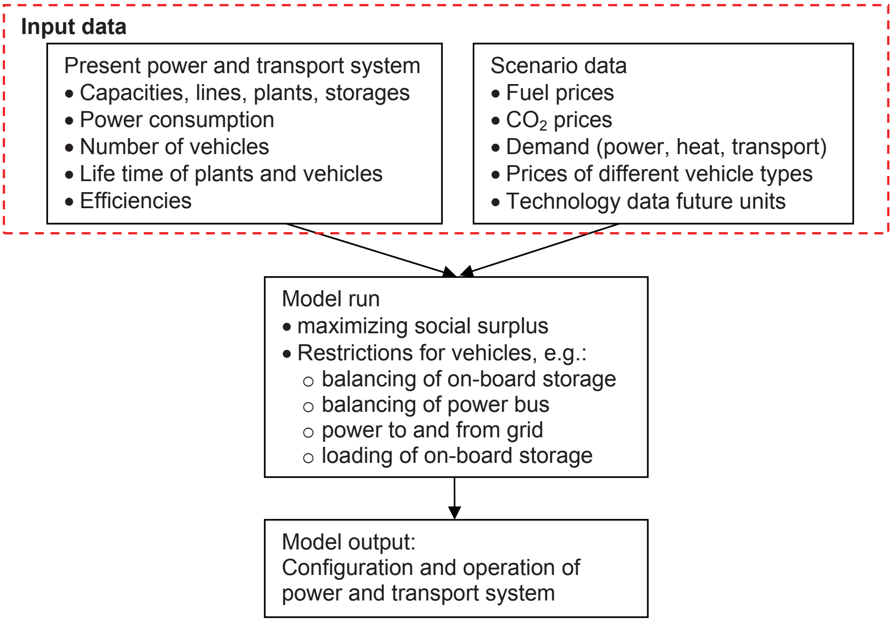

Figure 1 Sketch of the Balmorel model including transport

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 is balanced on area level.

Balmorel works with either yearly or weekly optimisation horizons. With a yearly optimisation horizon investment decisions are based on the demand and technology 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 vehicle-to-grid 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 electric drive vehicles (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., battery electric vehicles (BEVs) and plug-in series hybrid electric vehicles (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 is modelled using cars for persons transport and trucks for transport of goods. Inclusion of other types of transport services in the model is a matter of data availability and collection. Vehicles types included in the model are internal combustion engine vehicles (ICEs), and EDVs. Among others 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.

Figure 2 illustrates the transport model and the interactions with the Balmorel model. For illustrating purposes, the Balmorel model has been sketched as just one box. Based on input data, the model minimises total costs. The transport 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 energy and transport system. Each box of the transport model is explained in the following chapters. Nomenclature is given in Appendix 1.

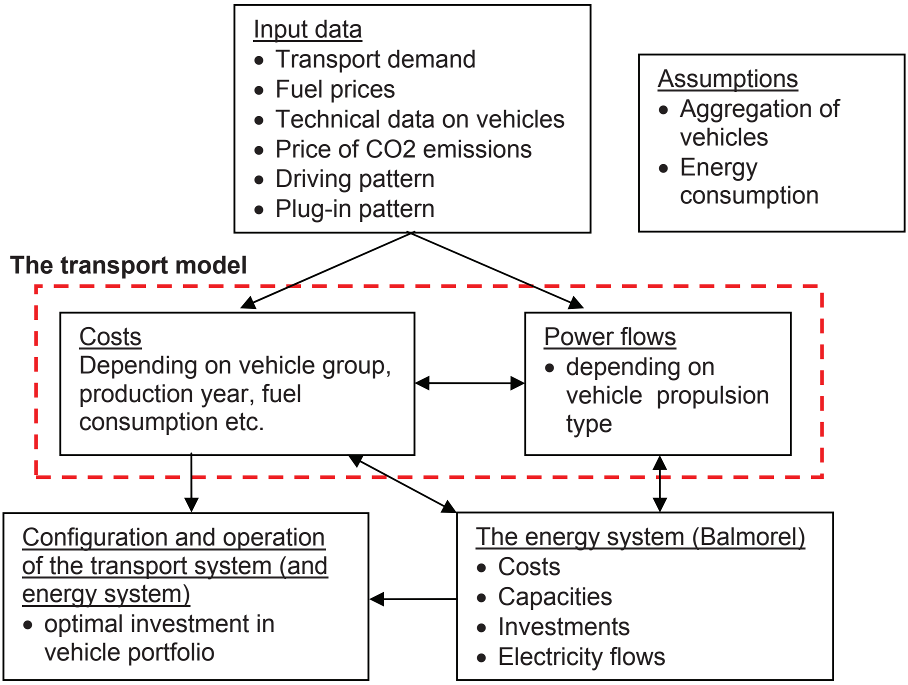

Figure 2 Sketch of the transport add-on in Balmorel

3.1.1 Terminology

Accessory loads: the energy consuming equipment such as compressors, pumps and fans, lights, power steering, and audio equipment in the vehicle not directly involved in propulsion of the vehicle.
Engine: the combustion engine of the vehicle.
Fuel Cell: the fuel cell of the vehicle.
Motor: the electric motor of the vehicle.
On-board storage: the electricity storage on board the vehicle.
Plug-in vehicles: vehicles that can be plugged in and charge from the electricity grid.
Power Bus: the power electronics in the vehicle inverting and converting AC/DC and DC/AC and directing the power to the subsystem.
Propulsion system: a certain configuration of engine, motor, on-board storage, and plug-in capability.
Transport service: could be either persons transport by cars or goods transport by trucks.
Vehicle group: a group of vehicles with the same propulsion system delivering the same transport service.
Vehicle technology: a vehicle characterised by type of propulsion system, transport service, fuel, and a specific set of technical and economic parameters.

3.1.2 Assumptions

- Vehicles are aggregated into vehicle groups depending on vehicle technologies, e.g., a limited number of BEVs are used to represent all types of BEVs.

- Grid-vehicles interactions are aggregated. The vehicles are aggregated into vehicle groups in relation to modelling of power to and from the grid. This implies that the on-board storage is treated on a vehicle group level.

- 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.

- Loading and unloading of electricity storage is dependent on number of vehicles plugged in.
- An average inverter loss is allocated to all power flows involving conversion from DC to AC and vice versa, except from the power flow from the fuel cell to the on-board electricity storage.
- CO_2 emissions are taken into account.
- 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.

3.1.3 Input data

Vehicle technology data, specified for each type of vehicle:

- Capacities of the engine, the electrical motor, the fuel cell, and capacities in relation to on-board storage, such as loading and unloading capacities.
- Average efficiencies during the driving pattern for the power bus, transmission, the generator, the engine, and the electrical motor.
- Costs covering annualised investment costs, and yearly operation and management costs.
- Average energy consumption during driving pattern (proportional to vehicle kilometres in each time step). For plug-ins average energy consumption covers consumption of accessory loads and consumption of mechanical propulsion power at driving wheel. For non-plug-ins it is an average energy consumption of the vehicle.
- Vehicle lifetime: average economical lifetime of the vehicle (number of years).
- Others: fuel type, propulsion system.

Vehicle utilisation data:

- Annual driving depending on vehicle technology.
- Average utilisation of vehicle technology (persons or tons of goods per vehicle km).

Transport pattern data:

- Driving distance: kilometres driven on each trip, depending on the duration of the trip.
- Plug-in pattern: percentages for each time step, representing the number of vehicles leaving at the particular time step, returning on j future time steps. One percentage for each combination of leaving and arrival within a 24 hour time horizon.

Each vehicle type is associated with a particular plug-in pattern.

3.1.4 Costs

Costs of transport are to be added to the Balmorel criterion function [2]. 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 and operations and management costs:

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

Fuel and CO_2 costs for non plug-ins, depend on, e.g., annual driving and fuel consumption:

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

Fuel and CO_2 costs for plug-ins depend on the use of engine as opposed to the use of motor.

$$\sum_{a,t} \sum_{v \in p,x} \left(\left(Pc_f^{Fuel} + Pc^{CO_2} \cdot Em_f^{CO_2} \right) \cdot \frac{O_{v,t}^{EnGen}}{\eta_v^{eng}} \right) \qquad (3)$$

All costs are added for the total costs of the configuration of the transport system. For electricity and hydrogen, fuel and CO_2 costs of are included through the increased fuel consumption of power plants. The costs of the FCEVs are described separately in Section 3.1.7.

3.1.5 Transport demand

The first constraint is transport demand. Yearly demand for transport has to be equal to supply of transport during the year. Calculation of transport supply includes annual driving, and average utilisation of the vehicles.

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

3.1.6 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 yet included in the model. 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. 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 Figure 3. 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 vehicle-to-grid concept, with the ability to both load power to the vehicle from the grid and unload power from the vehicle to the grid.

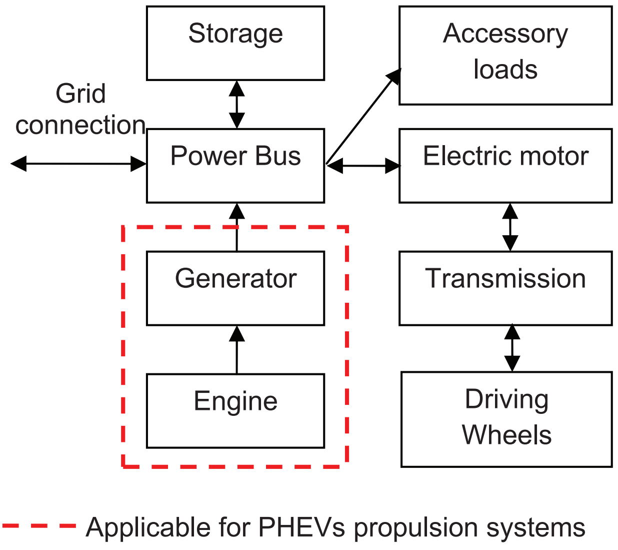

Figure 3 Propulsion system configuration of (series) electric drive vehicles

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.

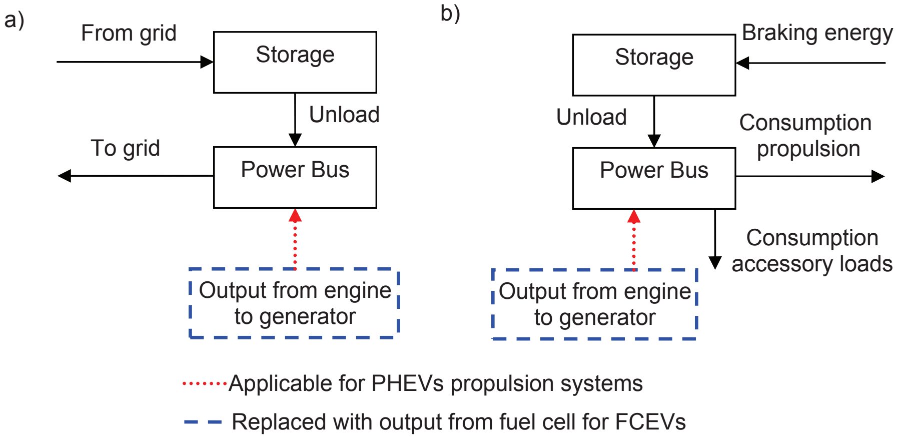

Figure 4 Power flow model of (series) electric drive vehicles for a) vehicles plugged in and b) vehicles not plugged in

Based on the propulsion system configuration, power flows are sketched in Figure 4. 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 power 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 (Figure 4a). For PHEVs and FCEVs optimising the use of electric motor versus use of fuel cell, or gasoline or diesel engine while driving, the model will always choose to use electric motor until depletion of storage, because of electricity being a cheaper fuel than diesel or hydrogen. Therefore, the power flow model for vehicles not plugged in as sketched in Figure 4b, is based on storage being depleted before using the engine. For the same reason, load from power bus to storage is set to 0.

Balancing on-board electric storage:
The electricity storage can be charged from the grid. The charging/discharging losses, L, are modelled as being proportional to the unloading of electricity storage:

$$L_{v,t} = S^{Unld}_{v,t} \cdot \left(\frac{1}{\eta^{Sto}_{v}} - 1 \right) \qquad (5)$$

On-board electricity storage capacity available for loading depends on last period's storage, power going into storage from grid, power going from storage to the power bus, charging/discharging losses, storage in vehicles leaving in period t. and storage in vehicles arriving in period t.

$$S^{PI}_{x,p,a,t+1} = S^{PI}_{x,p,a,t} - Gr^{Fr}_{x,p,a,t} \cdot \eta^{inv}_{p} - \sum_{v \in p} \frac{S^{Unld}_{v,t}}{\eta^{Sto}_{v}} - S^{Leav}_{x,p,a,t} + S^{Arr}_{x,p,a,t} \qquad (6)$$

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. Furthermore, it is assumed that all vehicles will be parked within a time horizon of 20 hours after leaving.

$$S^{Leav}_{x,p,a,t} = \sum_{v \in p} \sum_{j=t}^{t+20} PP_{v,tj} \cdot LF_{v} \cdot \gamma^{S}_{v} \qquad (7)$$

Storage level in vehicles arriving in period t depends on the storage in the vehicles when leaving, energy use for driving, E^{Dr}_{v}, and energy from braking, E^{brk}_{v}. A maximisation function is used, recognising that the storage well never be negative.

$$S^{Arr}_{x,p,a,t} = \sum_{v \in p} \sum_{j=1}^{t} \max\{ PP_{v,tj} \cdot$$

$$\left(LF_{v} \cdot \gamma^{S}_{v} - ((t-i) \cdot D_{v,1} + D_{v,0}) \cdot \left(\frac{E^{Dr}_{v}}{\eta^{sto}_{v}} - E^{Brk}_{v} \right) \right) ; 0\} \qquad (8)$$

Energy use for driving is based on consumption for propulsion and accessory loads, and motor and transmission efficiencies;

$$E^{Dr}_{v} = C^{Eacc}_{v} + \frac{C^{Eprp}_{v}}{\eta^{mot}_{v} \cdot \eta^{trs}_{v}}$$

Energy from braking depends on regenerated energy going to storage from braking and motor, power bus, and transmission efficiencies;

$$E_v^{brk} = RE_v^{brk} \cdot \eta_v^{mot} \cdot \eta_v^{PB} \cdot \eta_v^{trs}$$

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. Power into the power bus comes from either the engine or the on-board storage.

$$Gr_{x,p,a,t}^{To} = \sum_{v \in x,p} \left(\left(O_{v,t}^{EnGenPI} \cdot \eta_v^{gen} + S_{v,t}^{Unld} \right) \cdot \eta_v^{PB} \right) \tag{9}$$

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

Storage level:
The storage level is to stay between 0 and maximum capacity of the battery. $\sum_{i=1}^{t} \sum_{j=t}^{t+20} PP_{v,ij}$ is the sum of all vehicles not plugged in at time t.

$$0 \leq S_{x,p,a,t}^{PI} \leq \sum_{v \in x,p} \left(\left(N_{a,v} - \sum_{i=1}^{t} \sum_{j=t}^{t+20} PP_{v,ij} \right) \cdot \gamma_v^{S} \right) \tag{10}$$

Loading of on-board storage:
Power flow into storage at each time step is dependent on the load capacity of the storage.

$$Gr_{x,p,a,t}^{Fr} \cdot \eta_v^{inv} = \sum_{v \in x,p} \left(\left(N_{a,v} - \sum_{i=1}^{t} \sum_{j=t}^{t+20} PP_{v,ij} \right) \cdot \gamma_v^{SLd} \right) \tag{11}$$

Power to and from grid:
Power to and from grid is depending on the number of vehicles plugged in at each time step and the capacity of the grid connection. Power from grid:

$$Gr^{Fr}_{x,p,a,t} = \sum_{v \in x,p} \left(\left(O^{EnGenPI}_{v,t} \cdot \eta^{gen}_{v} + S^{Unld}_{v,t} \right) \cdot \gamma^{grd}_{v} \right) \qquad (12)$$

Power to grid:

$$Gr^{To}_{x,p,a,t} = \sum_{v \in x,p} \left(\left(O^{EnGenPI}_{v,t} \cdot \eta^{gen}_{v} + S^{Unld}_{v,t} \right) \cdot \gamma^{grd}_{v} \right) \qquad (13)$$

Unloading of on-board storage:
Unloading of storage is depending on the unloading capacity of storage.

$$S^{Unld}_{v,t} \leq \gamma^{SUnld}_{v} \qquad (14)$$

Maximum engine output:
Maximum output from the engine is restricted by engine capacity.

$$O^{EnGenPI}_{v,t} \leq \gamma^{En}_{v} \qquad (15)$$

$$O^{EnGenNPI}_{v,t} \leq \gamma^{En}_{v}$$

Where $O^{EnGenNPI}_{v,t} = O^{FCNPI}_{v,t}$ as well as $O^{EnGenPI}_{v,t} = O^{FCPI}_{v,t}$ for FCEVs.

Maximum annual driving:

$$\sum_{t=1}^{8760} \sum_{j=1}^{t} \left(PP_{v,jt} \cdot \left((t - j - 1) \cdot D_{v,1} + D_{v,0} \right) \right) \leq N_{a,v} \cdot Dr_{v} \qquad (16)$$

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.

$$+\sum_{a\in R(a)}\sum_{x,p}\left(Gr^{To}_{x,p,a,t} - Gr^{Fr}_{x,p,a,t}\right) \tag{17}$$

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 9. In order to calculate the output from engine to generator for vehicles not plugged in we find the time step when the vehicles start using the engine. This is done by calculating when

$$PP_{v,ij}\cdot\left(L_v\cdot\gamma_v^S - ((t-j-1)\cdot D_{v,1} + D_{v,o})\cdot\left(\frac{E_v^{Dr}}{\eta_v^{Sto}} - E_v^{brk}\right)\right)$$

We need to find the term $t-j$, which in this case indicates the number of hours before the storage is depleted and the vehicles start using the engine.

$$t-j = \frac{\frac{L_v\cdot\gamma_v^S}{E_v^{Dr}/\eta_v^{Sto} - E_v^{brk}} - D_{v,o}}{D_{v,1}+1}$$

This parameter can be calculated for each vehicle type, since all the other parameters are fixed on vehicle type level. Furthermore, the output from engine to generator is calculated separately for all combinations of vehicles leaving in period $i = 1, 2, ..., t$ and returning to the power grid in period $j = t, t+1, ..., t+20$. For each combination the return time is considered – that is the number of hours between i and j. If this exceeds $t-j$, then

$$O^{EnGenNPI}_{v,t,ij} = D_{v,1}\cdot\left(\frac{E_v^{Dr}}{\eta_v^{Sto}} - E_v^{brk}\right) \tag{18}$$

If the number of hours is equal to $t-j$, then:

$$O^{EnGenNPI}_{v,t,ij} = -PP_{v,ij}\cdot\left(L_v\cdot\gamma_v^S - D_{v,j-t}\cdot\left(\frac{E_v^{Dr}}{\eta_v^{Sto}} - E_v^{brk}\right)\right) \tag{19}$$

Finally, if the number of hours unplugged are less than $t-j$, then:

$$O_{v,t,ij}^{EnGenNPI} = 0 \qquad (20)$$

Summing for all i's and j's gives the total output from engine to generator in period t for vehicles not plugged in.

$$O_{v,t}^{EnGenNPI} = \sum_{i=1}^{t} \sum_{j=t}^{t+20} O_{v,t,ij}^{EnGenNPI} \qquad (21)$$

The total output from engine to generator then is:

$$O_{v,t}^{EnGen} = O_{v,t}^{EnGenPI} + O_{v,t}^{EnGenNPI} \qquad (22)$$

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

3.1.7 Interactions with hydrogen

The hydrogen add-on for Balmorel has been described in [7]. The cost of hydrogen is endogenous and is included through the increase in fuel consumption on hydrogen plants. To capture the cost, 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, and annual driving:

$$\sum_{a,v} \left(C_v^{H_2} \cdot N_{a,v} \cdot Dr_v \right) \qquad (23)$$

For plug-ins hydrogen demand is dependent on output from fuel cell and efficiency of the fuel cell:

$$\sum_{t} \sum_{v \in p,x} \frac{O_{v,t}^{FC}}{\eta_v^{FC}} \qquad (24)$$

Equations (23) and (24) are similar to Equations (2) and (3) without the fuel and CO_2 costs.

4 Application

To illustrate the model we plan to run a simple case, focusing on the power and transport system in Denmark in the year 2030. In this section we will describe the case and the expected results from running the model with this case.

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 [7]. With no electricity transmission between eastern and western Denmark the power system is essentially divided into two separate regions, requiring data, such as the demand data (Table 1), to be given for each region.

	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 1 Demand input data year 2030

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 allowed in only these few technologies to keep the case simple. For a more in depth analysis, further technologies should be included.

	Investment costs (M€/MW)	Variable costs (€/MW)	Annual costs (k€/MW)
Onshore wind	0.5	7	0
Offshore wind	1	4	4
CHP plant, biomass	1.3	2.7	25
Open cycle gas turbine	0.5	2	72
Heat storage	0.6	0	1
Solid oxide electrolysis	0.18	0	5.4
Heat pump	0.6	0	3
Combined cycle, natural gas	0.55	1.5	12.5
	Investment costs (M€/MWh storage capacity)		
Hydrogen storage, cavern	0.00058		

Table 2 Technology investment options in the simulation

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 approximately 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 approximately 5 km/kWh today as used by [3, 5, 20], the vehicle efficiency will reach 7 km/kWh by 2030.

Type of vehicle	Inv. costs (€) (yearly cost)	O & M costs (€/year)	Electric storage cap. (kWh)
ICE	11,766 (1,605)	1,168	0.8
BEV	19,078 (2,603)	1,101	50
PHEV	15,496 (2,114)	1,168	10
FCEV	80,204 (10,942)	1,101	10

Table 3 Vehicle technology investment options

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 [22]. Average plug-in patterns are derived from the driving patterns. Furthermore, average hourly travelling distance can be derived from the investigation on transport habits in Denmark.

Using the input data from above and an electricity price of approximately 54€/MWh, we have calculated the yearly fixed costs (investment and operations and management costs), the approximate fuel and CO_2 costs (depending on annual driving), and the differences between costs for ICEs and BEVs and PHEVs respectively (Table 4). The fuel and CO_2 costs for the PHEVs are calculated assuming one third is driven on diesel and two thirds on electricity. The difference in yearly costs, e.g., placing investments in BEVs instead of ICEs are 288€/vehicle. The increased cost could then potentially be found as benefits from the interaction with the power system, making the investments in EDVs worthwhile. We have excluded the FCEVs from the analysis because the fixed costs are very high compared to the other types of EDVs.

Type of vehicle	yearly costs (€/year)	Fuel and CO_2 costs (€/year)	Difference in costs relative to the ICE (€/year)
ICE	2,773	796	-
BEV	3,704	153	288
PHEV	3,282	294	6

Table 4 Benefits

4.2 Expectations

The model presented makes it possible to analyse many aspects of 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. From the price structure above it appears to be beneficial to invest in PHEVs instead of diesel ICEs.

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 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.

Results of the described hypotheses above, will be presented at the conference.

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Appendix A. Nomenclature

This appendix lists the indices (Table A.1), parameters (Table A.2), and variables (Table A.3) used in the equations of this article. The table consists of symbols, names, and units for all entries.

Table A.1

Indices used in equations in this article

Description	Symbol
Areas in which investments in vehicles can take place	a
Driving patterns of vehicle	d
Types of fuel used by vehicle	f
Types of propulsion systems	p
Regions	r
Time steps	t
Vehicle technologies	v
Transport service	x

Table A.2

Parameters used in equations in this article

Description	Symbol	Unit
Energy consumption of accessories of vehicle type v	C_v^{Eacc}	MWh/km
Propulsion system energy consumption, vehicle type v	C_v^{Eprp}	MWh/km
Fuel consumption of vehicle type v	C_v^{Fuel}	MWh/km
Hydrogen consumption of vehicle type v	$C_v^{H_2}$	MWh/km
Annualised vehicle investment costs	Co_v^{inv}	€/Vehicle
Yearly operation and maintenance costs excluding fuel costs	Co_v^{OM}	€/Vehicle
Distance driven between time i and j	$D_{v,j-1}$	km
Yearly demand for a transport service in region r	$D_{r,x}^{trp}$	km_{person}
Annual driving of vehicle type v	Dr_v	km
Energy left from braking when being stored	E_v^{brk}	MWh/km
Energy used for driving	E_v^{Dr}	MWh/km
CO_2 emission when using fuel type f	$Em_f^{CO_2}$	ton/MWh
Vehicle engine capacity	γ_v^{En}	MW
Capacity of the grid connection used by the vehicle	γ_v^{grd}	MW
Loading capacity of electricity storage	γ_v^{SLd}	MW
Storage capacity of electricity storage of vehicle type v	γ_v^{S}	MWh
Unloading capacity of electricity storage	γ_v^{SUnld}	MW
Average efficiency of engine in vehicle type v	η_v^{En}	
Average efficiency of fuel cell in vehicle type v	η_v^{FC}	
Average efficiency of generator converting the mechanical power output from the engine to electrical power	η_v^{gen}	
Average efficiency of inverter from grid to electricity storage for propulsion type p	η_p^{inv}	
Average efficiency of the electrical motor on-board vehicle type v	η_v^{mot}	
Average efficiency of power bus converting power on-board the vehicle	η_v^{PB}	
Average electric storage efficiency during loading/unloading cycle proportional to the unloading	η_v^{sto}	

Description	Symbol	Unit
Average efficiency of transmission from engine and/or electric motor to driving wheels	η_v^{trs}	
Fuel price of fuel type f	Pc_f^{Fuel}	€/GJ
Price of CO_2	Pc^{CO_2}	€/ton
Plug pattern - vehicles leaving at time i, returning at time j	$PP_{x,ij}$	
Amount of energy regenerated when braking	RE_v^{brk}	MWh/km
Minimum storage level of electricity storage as a fraction of storage capacity	S_v^{min}	
Utilisation of the capacity in vehicle type v	UC_v	km_{person}/ $\mathrm{km}_{vehicle}$

Table A.3

Variables used in equations in this article

Description	Symbol	Unit
Power loaded from the grid to the vehicle	$Gr^{Fr}_{x,p,a,t}$	MWh
Power loaded to the grid from the vehicle	$Gr^{To}_{x,p,a,t}$	MWh
Charging/Discharging losses	$L_{v,t}$	
Load factor for vehicles leaving	$LF_{v,t}$	
Number of vehicles of type v in area a	$N_{a,v}$	
Engine output going into the generator	$O^{EnGen}_{v,t}$	MWh
Engine output going into the generator for vehicles plugged in	$O^{EnGenPI}_{v,t}$	MWh
Engine output going into the generator for vehicles not plugged in at time t	$O^{EnGenNPI}_{v,t}$	MWh
Engine output going into the generator for vehicles not plugged in at time t; vehicles leaving at time i, returning at time j	$O^{EnGenPI}_{v,t,ij}$	MWh
Engine output going to propulsion of the vehicle	$O^{EnPrp}_{v,t}$	MWh
Fuel cell output going into the generator	$O^{FC}_{v,t}$	MWh
Fuel cell output going into the generator for vehicles plugged in	$O^{FCPI}_{v,t}$	MWh
Fuel cell output going into the generator for vehicles not plugged in	$O^{FCNPI}_{v,t}$	MWh
Storage level in on-board electricity storage	$S_{x,p,a,t}$	MWh
Storage level in vehicles leaving at time t	$S^{Leav}_{x,p,a,t}$	MWh
Storage level in vehicles arriving at time t	$S^{Arr}_{x,p,a,t}$	MWh
Storage level in vehicles plugged in	$S^{PI}_{x,p,a,t}$	MWh
Loading of on-board storage coming from engine	$S^{LdEn}_{v,t}$	MWh
Unloading of on-board storage	$S^{Unld}_{v,t}$	MWh

Chapter 9

Paper II

Transport and Power System Scenarios for Northern Europe in 2030

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Abstract

Increasing focus on sustainability affects all parts of the energy system. Integrating the power and transport system in future energy system planning, influences the economically optimal investments and optimal operation of the power system as well as the transport system. This work presents analysis of the optimal configuration and operation of the integrated power and transport system in Northern Europe. Optimal configuration and operation is obtained using the optimisation model, Balmorel [1], with a transport model extension. For electric drive vehicles with plug-in capabilities it is assumed that power can go both from grid-to-vehicle and vehicle-to-grid. Oil prices are assumed to be

\$120/barrel, and CO_2 price 40 €/ton. This results in an optimal investment path with a large increase in sustainable energy; primarily wind energy, as well as an increase in the electric drive vehicles fleet. Furthermore, the increase in wind power production exceeds the required increase in power production.

1 Introduction

Moving towards 100% renewables in the energy system is a challenge for both the power and transport system. Sustainable energy sources like solar and wind are stochastic by nature and call for a larger flexibility in the remainder of the energy system. Moving the means of transportation towards electric drive vehicles (EDVs) with plug-in facility leads to cleaner transportation provided the power used is produced on renewables. Furthermore, the charging of EDVs from the grid (G2V) and even loading of power back to the grid (V2G), can deliver some of the desired flexibility.

Based on the model of the integrated power and transport system described in [2], scenarios are analysed for the northern European power system. The contribution of this article is a study of means for providing an energy system with a large share of renewables that is economically optimal, and whether the economically optimal investments support a move towards 100% renewables in the energy system. Also, competition between the different vehicle types is studied as well as competition between sources of flexibility, e.g., EDVs versus heat storage in combination with electric heat boilers.

Research has been done within various fields related to the integrated power and transport system, i.e., infrastructure, transition paths, potential benefits for both the power system and the customer, and quantifying the impact and benefits. The contribution of this work is analyses of differences in optimal investment paths and configuration of the power and transport system for various scenarios for northern Europe in 2030, and, thereby, finding key drivers contributing to the path towards a 100% renewable energy system. Using electrical power in the transport system has consequences for the entire energy system as does the introduction of, e.g., V2G and control of the loading and unloading of the batteries.

Kempton and Tomic [3] explain the concept of V2G and touch on the potential benefits of V2G. Details on the economics of services provided to the power system by the EDVs have been analysed by Kempton et al. [4]. Potential benefits of providing particular services have been studied in terms of peak load shaving [5], and regulation and ancillary services [6]. Integration of battery electric vehicles (BEVs) with particular focus on benefits of vehicles providing ancillary services has been looked into by Brooks [7]. Moura [8] has made cost comparisons of providing the different services, comparing the EDVs with the different technologies providing the same services today. A brief overview of potentials of the G2V and V2G capabilities is given in [9].

Integration of the power and transport systems requires a number of changes and additions, e.g., monitoring and metering of the vehicles, aggregators dealing with the system operator, connection standards, communication with the vehicles etc. In order to control the use of the EDVs in the model, all these changes and additions are assumed to have taken place. Possible infrastructure solutions and system needs have been the focus of several articles. Kempton et al. [4] have suggested an infrastructure in terms of, e.g., business models and connection standards. Business models are also a subject of [10] as are thoughts on dispatch of vehicles. Brooks and Gage [11] have given an introduction to relevant factors in the system setup, and Kempton and Letendre [12] include suggestions on computer functionalities. Regarding the transition path, studies have focused on how to ensure a smooth transition path from today's vehicle fleet to a fleet of plug-in hybrid electric vehicles (PHEVs) and BEVs [10] and further on to fuel cell electric vehicles (FCEVs) [13], [14], [15].

The impacts of availability of V2G in terms of benefits and changes in the vehicles technology market shares, has been looked into by Turton and Moura [16], focusing on scenarios including climate policy scenarios. Retail and lifecycle cost analyses have been made for BEVs [17] and PHEVs [18]. Furthermore, an advanced model returning, e.g., energy usage for different vehicles types, divided on different parts of the vehicles has been developed (ADVISOR) [19]. For optimising future configuration and operation of the integrated power and transport system, assumptions and calculations are made in terms of, e.g., costs of vehicles, availability, and energy usage as studied above.

Integration of the power and transport systems influences the power production. This impact has been quantified by few so far. McCarthy, Yang and Ogden [20] have for California's energy market developed a simplified dispatch model to investigate the impacts of EDVs being part of the energy system. Short & Denholm [21] have studied the impact on wind installations with the introduction of EDVs with G2V and V2G capabilities, and Denholm and Short [22] have studied the power system impacts with optimal dispatch of EDV charging. However, investment analysis has not been included in any of these studies, i.e. configuration of both the power system and the vehicle fleet was inputs in the analyses. In this article the power and transport systems are integrated in a way that allows us to analyse the effects the changes in one system has on both the power and transport system.

In Section 2 we give a presentation of the model used for the analyses, followed by a touch on some of the assumptions in Section 3. The model is applied to a number of cases presented in Section 4 and results from running the model are presented in Section 5. Finally, discussions about the model, results, and the assumptions are given in Section 6. Section 7 concludes.

2 Balmorel with transport

The model of the integrated power and transport system is a partial equilibrium model [1], [2], [23] assuming perfect competition. The model (Figure 1) maximises social surplus subject to constraints, including technical restrictions, renewable energy potentials, balancing of electricity and heat production, and restrictions on the vehicles. Maximising social surplus in a case with price inelastic demand corresponds to minimising operational costs. Investments are generated resulting in an economically optimal operation and configuration of the power system. Electricity prices are derived from marginal system operation costs.

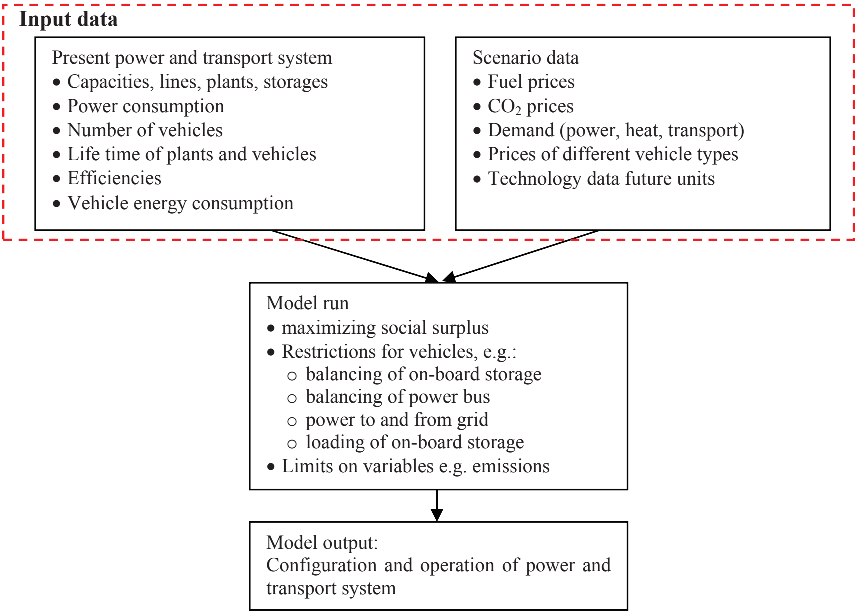

Figure 1 Sketch of the Balmorel model including transport

Balmorel works with three geographical entities: countries, regions and areas. Countries are divided into regions connected with transmission lines. The regions are then divided into areas. Balancing of electricity and transport supply and demand is done on regional level, whereas balancing of supply and demand for district heating is on area level.

The optimization horizon is yearly and the investment decisions are based on demand and technology costs. Balmorel works with an hourly time resolution that can be aggregated into fewer time steps. Time aggregation is typically used for long term investments. For some cases the hourly time resolution is important, then, a cut down in the number of weeks calculated is also a possibility.

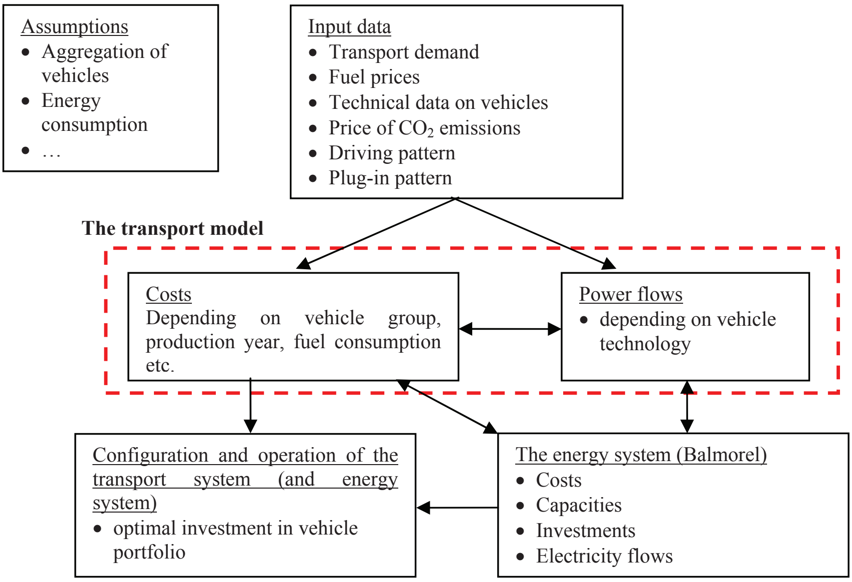

Figure 2 The transport add-on in Balmorel

For including transport in Balmorel a transport add-on has been developed [2] (Figure 2). The transport model includes electricity balancing in the transport system as well as electricity balancing in the integrated power and transport system, investment and operation costs, and demand for transport services. In the model we have included the following vehicle technologies; internal combustion engine vehicles (ICEs), and EDVs, where EDVs cover BEVs, PHEVs, and FCEVs. Vehicles that are non-plug-ins do not provide flexibility to the power system and are, therefore, treated in a simplified way.

3 Assumptions

The transport model is based on a number of assumptions also described in [2]. In this section we will mention a few assumptions crucial for the results of the model runs. First of all, all EDVs vehicles are assumed to leave the grid with a vehicle dependent amount of power on the battery, restricting the loading and unloading to meet this load factor.

Furthermore, the plug-in hybrids are assumed to use the electric storage until depletion (of the usable part of the battery) before using the engine. This assumption seems reasonable due to the high difference in prices on fuels and electricity as well as the high difference in efficiencies of the electric motor and the combustion engine or fuel cell. Also, the batteries have no loss of effect before almost depleted, leaving the motor able to perform as demanded until down to the minimum state of charge.

4 Application

The model is applied to a northern European case introducing different scenarios to analyse the consequences of the optimal operation and configuration of the integrated power and transport system. In this section we start with a case description. Then, an outline of the scenarios is presented and finally we present and analyse the results from running the model with the different scenarios.

4.1 Base case

Balmorel is run for the year 2030 for the northern European countries including the Scandinavian countries and Germany. In order to be able to run the model within reasonable computation time for Norway, Sweden and Finland each country is aggregated into one region. For Germany we have aggregated the regions into two in order to represent the transmission bottlenecks between northern Germany with a large share of wind power and the consumption centres in central Germany. Denmark is split into two regions representing western Denmark being synchronous with the UCTE power system and eastern Denmark being synchronous with the Nordel power system.

A number of inputs are required for running the model, e.g., fuel prices, CO_2 prices, demand data, and vehicle and power system technology data, which are all given exogenously. In the base case, oil prices are assumed to be \$120/barrel, assuming constant price elasticities as in [23]. CO_2 prices are assumed to be €40/ton. Data, such as the demand data, is to be given on a regional level (Table 1). Currently, there is no transmission between the two regions in Denmark, but for the year 2030 we have assumed a transmission capacity of 1.2 GW and a transmission loss of 1%.

Table 1 Demand input data year 2030 (source for all but Norway [25])

	Denmark East	Denmark West	Sweden	Norway	Finland	Germany
Electricity demand (TWh/yr)	16	24	153	145	104	620
District heat demand (TWh/yr)	12	15	46	9	56	102
Transport demand (b. persons km/yr)	31	41	148	69	86	1262

In order for Balmorel to balance power demand and power supply, new technologies must be available for investment. Table 2 shows the technologies we have made available for investment in 2030 for the base case. With the analysis focusing on competition between technologies and incorporating more renewables, we find this list of technologies to be a good basis.

Table 2 Technology investment options in the simulation (all data except data on Electric boiler are from the Danish Energy Authority [26]). Investment costs for heat storage and hydrogen storage are given as M€/MWh storage capacity.

	Inv. costs (M€/MW)	Var. 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
Combined cycle gas turbine, condensing	0.54	0.67	13.39	0.55
Combined cycle gas turbine, extraction	0.55	1.5	12.5	0.56
Heat storage	0.6	0	1	1
Heat pump	0.6	0	3	3.9
Electric boiler	0.04	0	1.2	0.98
Coal extraction	1.2	1.8	16	0.5
Heat boiler, biomass	0.32	4.02	19.28	0.85
Heat boiler, natural gas	0.05	0.67	0.54	0.95
Nuclear	1.89	1.37	37.75	0.35
Solid oxide electrolysis	0.18	0	5.4	0.93
Hydrogen storage, cavern	0.00058	0	0	0.83

As for the power system, balancing the transport supply and demand requires investment opportunities in different technologies. With focus on incorporating more renewables through the introduction of different EDVs we have decided to consider four different vehicles technologies; Diesel ICE, series PHEV (diesel), series plug-in FCEV (from now on referred to as FCEV), and BEV. The four technologies compete both in cost and in delivering benefit for the power system. The cost and electric storage capacity for the four vehicle technologies included in the base case are given in Table 3. The size of the electric storage capacity, shown in the table, reflects the usable size of the battery. Today the electric vehicle efficiency used is approx. 5 km/kWh [21], [22], [24], leading us to believe that the efficiency will reach approx. 7 km/kWh by 2030. We believe that the battery size for BEVs by 2030 will provide a driving range of approx. 350 km. For both FCEVs and PHEVs the batteries could be almost as large as for BEVs, but additional weight as well as trade-off between additional driving range and additional cost leads us to believe that a battery covering a driving range of approx. 65 km is reasonable for everyday purpose.

Table 3 Vehicle technology investment options [27]

Type of vehicle	Annualised investment costs (€)	O & M costs (€/year)	Electric storage cap. (kWh)
ICE	1,572	1,168	0.8
BEV	2,185	1,101	50
PHEV	2,133	1,168	10
FCEV	2,597	1,101	10

Plug-in patterns has been derived from driving patterns obtained from the investigation of transport habits in Denmark [28].We have assumed that driving habits are the same for all the countries in Northern Europe, since we believe that the difference is minor and, therefore, will not have great effects on the results. Changing the plug-in patterns in the model will give an illustration on whether this assumption should be relaxed.

4.2 Scenarios

In this article we provide an investigation of the EDVs and their ability to provide some of the benefits for the power system needed in order to reach a level of 100% renewables in the entire energy system. We focus on investigation of:

1) The optimal configuration of the power system depending on flexibility of the vehicles. What is the influence of introducing V2G, sensitivity of changing the plug-in patterns etc? We believe that V2G has some influence on the configuration of the power system since being able to deliver power back to the grid delivers a greater flexibility than just flexible demand. We believe that this very well could mean introduction of more wind in the cases with V2G facilities available.

2) What is the economic value of the EDVs, e.g., a) at what price do they appear to be competitive with the ICE, b) what is the marginal benefit of the EDVs, and c) how does changes in the fuel and CO_2 prices affect the value of the EDVs. We believe that the EDVs have the benefit that they do provide some flexibility to the power system, and expect the EDVs being quite competitive both when it comes to vehicle prices and changes in the fuel prices.

3) How do the EDVs compete with other flexible technologies, e.g., heat pumps, heat storage, electric boilers, and OCGTs. We believe that being forced to invest in one vehicle technology or the other, the EDVs will do quite good because of the benefits they provide to the power system.

In order to investigate the above, a number of scenarios have been set up. First of all, we will be running the base case and analyse the results. Based on this we will change the following separately – subsequently some of them simultaneously, creating many different scenarios:

- The inclusion of the V2G facility
- Fuel prices
- CO_2 prices
- Inclusion of different technologies
- Prices of the vehicles technologies
- Price differences between the vehicles technologies
- Plug-in patterns from only plugging-in when parked at home to plugging in every time the vehicle is parked

5 Results

The model has yet to be run for the Nordic case. For illustrative purposes we will present some results from the Danish case. In this model run the oil prices have been set to only \$100/barrel, and no transmission between countries is allowed.

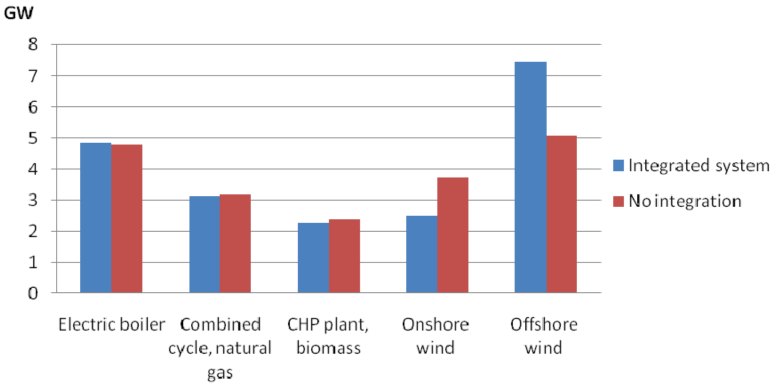

Figure 3 Optimal investments in power plants (2030)

If there is no interaction between the power and transport system, the investments in vehicles are of course in ICEs, because the model in this case do not include the option to charge vehicles from the grid. Integrating the power and transport system and allowing for both G2V and V2G results in investments in PHEVs to be the most optimal. The investments in power plants are shifted most notably from onshore wind to offshore wind, and secondly a slight reduction in investments in thermal power plants is seen when going from no integration with the transport system to the integrated system (Figure 3). Furthermore, the total costs of the system amounts to 74 million more if the power and transport systems are not integrated.

Excluding the V2G facilities does not change much for neither the power nor the transport system. Running the system becomes more expensive – a prices difference of 1.8 million Euros. We get a power system with less renewables and more of regular production, although the change is only barely visible. Investment in vehicles remains the same.

As for electricity generation it is easily seen from Figure 4, that the extra electricity generation needed due to the electricity consumption of electric vehicles is delivered from wind power. Furthermore a reduction in power production using natural gas is observed. The increase in wind power production exceeds the demand for power from the transport sector. This large increase in power production is a good indication of the benefits of the integration of the power and transport system.

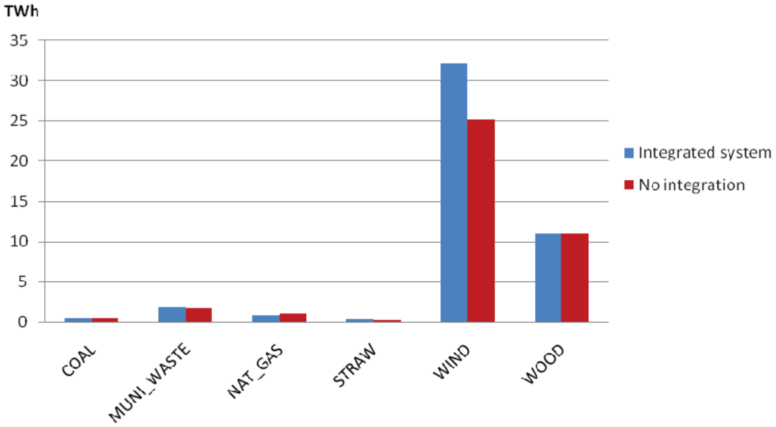

Figure 4 Power production based on fuel type (2030)

Looking at the use of energy over the day, we see the major part of the loading is done during night time, although there is more than expected in the day time

(Figure 5). This is due to the rather strict assumptions about the load factor of the vehicles leaving the grid. We have set the load factor of the PHEVs to 80% in order for the vehicles to be able to drive quite far on electrical power. If all EDVs leave the grid with a load factor of 80% the charge during the day is also required to meet the restrictions and thereby fixed to be rather high. This does not leave much flexibility to the power system to optimise. From looking at the figure we also get an indication of the rather small usage of the V2G facility, placed at the times of high demand followed by higher prices for electricity.

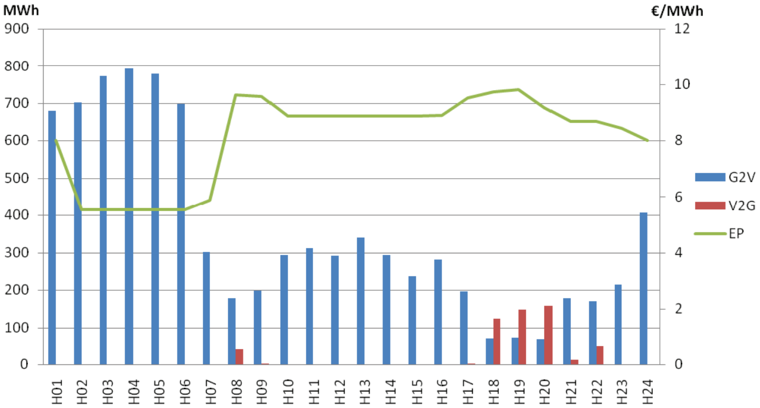

Figure 5 Grid-vehicle interactions vs. electricity price (week 46)

For driving the vehicles the gross use of power amounts to a battery use of 6.7 TWh and use of engine worth 2.2 TWh summing to a total energy use of 8.9 TWh for 2.5 million vehicles. Changing prices of fuel shows that a fall in the fuel price to $90/barrel or the CO_2 prices to €30/ton results ICEs becoming competitive and we get an investment split in the two vehicle types; ICEs and PHEVs. Increasing the prices of the EDVs of approx. 11% results in optimal investments being in ICEs. Alas, results from the model are quite sensitive to pricing of both fuel, CO_2, and the EDVs.

6 Discussion

The results are an indication of the optimal investment in the situation where all people are rational and acting according to the overall optimum. This is of course not the case and the modelling cannot capture all individual thinking and acting, but only give a good indication to act upon. Some improvements could be made for the model to be more representative, though. For example would an inclusion of different customer types through different driving patterns be a way to capture the different types of driving demands. This could result in, e.g., the BEVs being more attractive for customer groups like the people with a second vehicle only used for commuting. Also, one could consider including different plug-in patterns based on the different driving patterns.

Exclusion of the transmission lines as in the illustrative case above does leave out some of the positive effects of, e.g., hydro in Norway. The availability of hydro as a flexibility could make the EDVs less attractive and it could be interesting to see if the two technologies compete.

The model works with a capacity balance restriction ensuring enough production capacity to meet peak demand. One could argue that EDVs would have a capacity value and hence should be able to contribute to the capacity balance. How much of their total capacity they can contribute with is yet to be looked into and is a subject for future research.

Finally, as mentioned the assumption about load factor fixes the possible loading of power to the vehicles somewhat. The load factor could, for later versions of the model, very well be part of the optimisation problem, leaving the problem somewhat bigger and calculation time higher. It could be interesting to see, if making the load factor a decision variable changes the optimal loading pattern. We would expect to see results more dependent on the electricity prices and driving distances than the results of these model runs.

7 Concluding remarks

From running the model on an illustrative case of the Danish power and transport system it is obvious that investments in EDVs are optimal and beneficial for the power system as well. They provide flexibility in terms of resembling flexible demand and with inclusion of V2G they are an even greater benefit although the overall costs savings are small compared to the total cost of the system.

The results from the model are sensitive to the price settings, and it is yet to be investigated whether it is also sensitive to which technologies are included. Furthermore, the optimal configuration of the power system given specific configurations of the vehicle fleet is of great interest – and whether the costs of the systems increase or decrease with different vehicle fleet configurations.

In this model the wind power production is predictive and not stochastic. Making the wind power stochastic would probably change the results quite a lot and is a subject for future research. With unknown actual production the need for reserves will be different and we would expect the value of the EDVs to rise. Future research also includes transforming the load factor into a decision variable, creating different customer profiles, having EDVs provide capacity credit, as well as vehicles with different features for each vehicle technology.

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Chapter 10

Paper III

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.

Keywords: power system; transport system; plug-in vehicles; vehicle-to-grid.

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 electric drive vehicles (EDVs) 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 [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 [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 battery electric vehicles (BEVs) in particular focusing on the benefits of the vehicles providing ancillary services. Cost comparisons of providing different kinds of services has been made in [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 [2] Kempton et al. have suggested infrastructure in terms of, e.g., connection standards and business models. Business models have also been touched upon in [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 hybrid electric vehicles (PHEVs) and BEVs [8] and further all the way to fuel cell electric vehicles (FCEVs) [11], [12], [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, focusing 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 [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. [20] has analysed the contributions of flexibility to the Danish energy system, provided by EDVs and heat pumps, focusing 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 [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 [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 [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 (Figure 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 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 internal combustion engine vehicles (ICEs), 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.

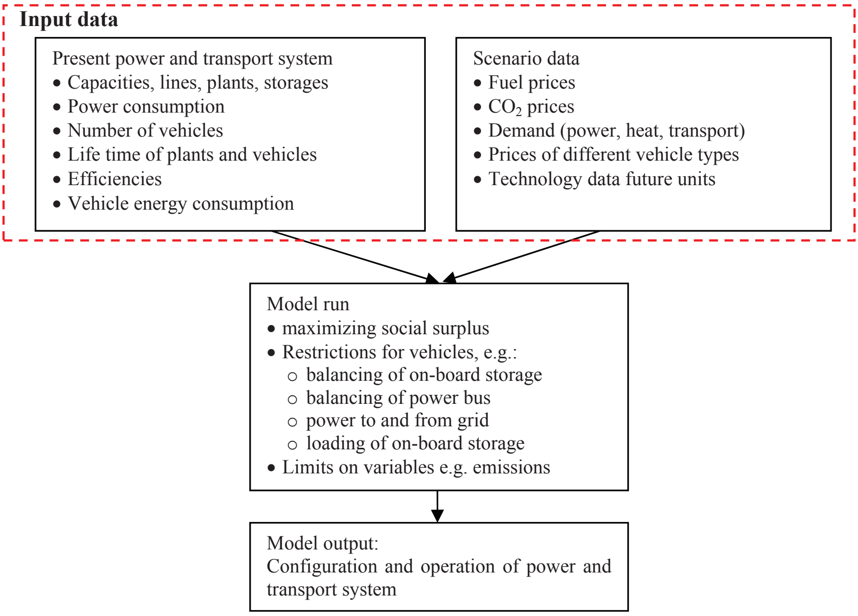

Figure 1 Sketch of the Balmorel model including transport

Based on input data (Figure 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 hour time horizon. In a first step the EDVs are assumed to be plugged in when not driving.

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:

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

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}:

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

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.

$$\sum_{a,t} \sum_{v \in p,x} \left(\left(Pc_f^{Fuel} + Pc^{CO_2} \cdot Em_f^{CO_2} \right) \cdot \frac{O_{v,a,t}^{EnGen}}{\eta_v^{eng}} \right) \tag{3}$$

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 Figure 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.

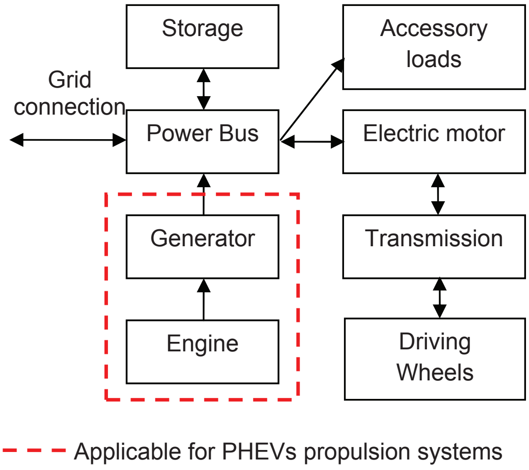

Figure 2 Propulsion system configuration of (series) electric drive vehicles.

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.

Based on the propulsion system configuration, power flows are sketched in Figure 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.

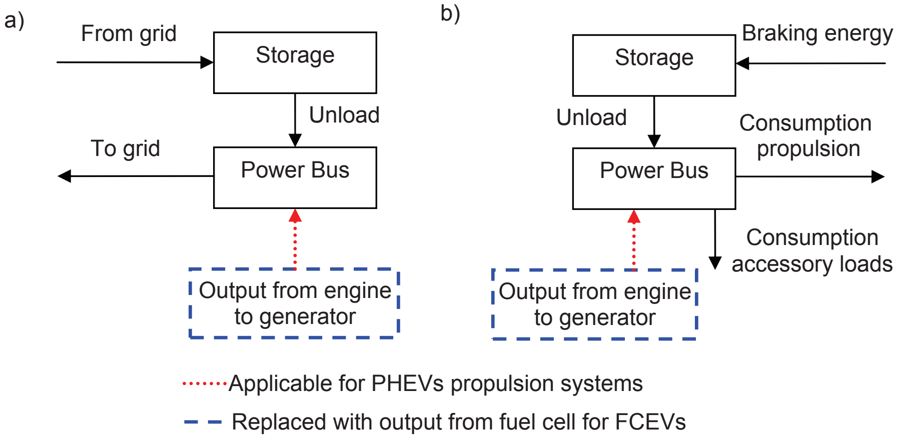

Figure 3 Power flow model of (series) electric drive vehicles for a) vehicles plugged in and b) vehicles not plugged in.

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 (Figure 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 Figure 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.

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, $S_{v,t}^{Unld}$. On-board electricity storage capacity, $S_{p,a,t}^{PI}$, available for loading depends on last period's storage, power going into storage from grid, $Gr_{p,a,t}^{Fr}$, power going from storage to the power bus, $S_{v,t}^{Unld}$, charging/discharging losses, storage in vehicles leaving in period t, $S_{p,a,t}^{Leav}$, and storage in vehicles arriving in period t, $S_{p,a,t}^{Arr}$.

$$S_{p,a,t+1}^{PI} = S_{p,a,t}^{PI} - Gr_{p,a,t}^{Fr} \cdot \eta_p^{inv} - \sum_{v \in p} \frac{S_{v,t}^{Unld}}{\eta_v^{Sto}} - S_{p,a,t}^{Leav} + S_{p,a,t}^{Arr} \qquad (5)$$

$$\forall v \in V^{GC}; a \in A; t \in T$$

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 hours after leaving, thus the plug-in pattern, $PP_{v,t,j}$, is derived from these data.

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

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.

$$S_{p,a,t}^{Arr} = \sum_{i=t-11}^{t} \max\{PP_{v,i,t}$$

$$\cdot \left(LF_v \cdot \gamma_v^S - ((t-i) \cdot D_{v,1} + D_{v,0}) \cdot \left(\frac{E_v^{Dr}}{\eta_v^{sto}} - E_v^{Brk} \right) \right); 0\} \qquad (7)$$

$$\forall v \in V^{GC}; a \in A; t \in T$$

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};

$$E_v^{Dr} = C_v^{Eacc} + \frac{C_v^{Eprp}}{\eta_v^{mot} \cdot \eta_v^{trs}} \qquad \forall v \in V^{GC}$$

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;

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

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, $Gr_{p,a,t}^{To}$. Power into the power bus comes from either the engine, $O_{v,a,t}^{EnGenPI}$, or the on-board storage, $S_{v,a,t}^{Unld}$.

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

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.

Output from engine to generator:

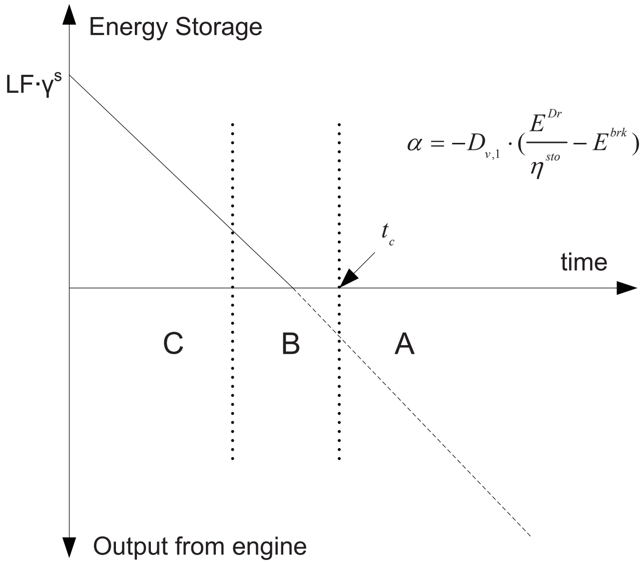

Figure 4 Use of energy storage versus engine depending on time. α is the slope of the line and $LF_v \cdot \gamma^S$ the storage level when the vehicle is leaving the grid. t_c is the time period where the on-board storage is depleted.

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 (Figure 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 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:

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

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

$$LF_v \cdot \gamma_v^S - ((t_c - i - 1) \cdot D_{v,1} + D_{v,0}) \cdot \left(\frac{E_v^{Dr}}{\eta_v^S} - E_v^{Brk} \right) = 0 \qquad (9)$$

$$\forall v \in V^{GC}$$

If t$_c$ ¡ j

$$LF_v \cdot \gamma_v^S - (t_c - i - 1) \cdot D_{v,1} \cdot \left(\frac{E_v^{Dr}}{\eta_v^S} - E_v^{Brk} \right) = 0 \qquad \forall v \in V^{GC} \qquad (10)$$

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 equation (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 $i = 1, 2, ..., t$ and returning to the power grid in time period $j = t, t+1, ..., t+11$. $\sum_{i=1}^{t} \sum_{j=t}^{t+11} PP_{a,v,i,j}$ 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 Figure 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

$$O^{EnGenNPI}_{v,a,t>t_c} = \sum_{i=1}^{t} \sum_{j=t}^{t+11} (N_{a,v} \cdot PP_{a,v,i,j} \cdot D_{v,1} \cdot \left(\frac{E^{Dr}_v}{\eta^S_v} - E^{Brk}_v \right) \tag{11}$$
$$\forall v \in V^{GC}; t \in \{t \in T \wedge t > t_c\}$$

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

$$O^{EnGenNPI}_{v,a,t=t_c} =$$
$$-N_{a,v} \cdot \sum_{i=1}^{t} \sum_{j=t}^{t+11} \left(PP_{a,v,i,j} \cdot \left(LF_v \cdot \gamma^S_v - D_{v,1} \cdot \left(\frac{E^{Dr}_v}{\eta^S_v} - E^{Brk}_v \right) \right) \right) \tag{12}$$
$$\forall v \in V^{GC}; t \in \{t \in T \wedge t > t_c\}$$

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:

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

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

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

$$0 \leq S^{PI}_{v,a,t} \leq N_{a,v} \cdot \left(1 - \sum_{i=t}^{t} \sum_{j=t}^{t+11} \mathrm{PP}_{a,v,i,j} \right) \cdot \gamma^S_v \qquad \forall v \in V^{GC}; a \in A; t \in T \tag{14}$$

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

$$Gr^{Fr}_{v,a,t} \cdot \eta^{inverter}_{v} \leq N_{a,v} \cdot \left(1 - \sum_{i=1}^{t} \sum_{j=t}^{t+11} PP_{a,v,i,j}\right) \cdot \gamma^{Sld}_{v} \qquad (15)$$

$$\forall v \in V^{GC}; a \in A; t \in T$$

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

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.

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

3.1.5 Interactions with hydrogen

The hydrogen add-on for Balmorel has been described in [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, $C^{H_2}_{v}$, and annual driving:

$$\sum_{v,a} \left(C^{H_2}_{v} \cdot N_{a,v} \cdot Dr_{v}\right) \qquad (17)$$

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

$$\sum_{v,a,t} \left(\frac{O^{FC}_{v,a,t}}{\eta^{FC}_{v}} \right) \qquad (18)$$

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, focusing on the power and transport system in Denmark in the year 2030. The model presented makes it possible to analyse many aspects of 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 [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% .

	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 1 Demand input data year 2030

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.

	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

Table 2 Technology investment options in the simulation (all data except for Electric boiler are from the Danish Energy Authority [24])

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 approximately 5 km/kWh today as used by [19], [21], [28], the vehicle efficiency will reach 7 km/kWh by 2030.

Type of vehicle	Inv. costs (€) (yearly cost)	O & M costs (€/year)	Electric storage cap. (kWh)
ICE	11,528 (1,086)	1,168	0.8
BEV	17,797 (1,760)	1,101	50
PHEV	17,372 (1,430)	1,168	10
FCEV	21,154 (1,952)	1,101	10

Table 3 Vehicle technology investment options [26]

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 hours.

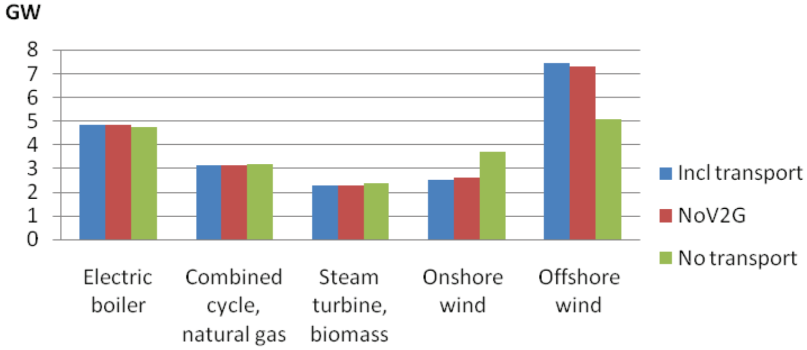

Figure 5 Investments in plants.

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 (Figure 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 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.

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

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

	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

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

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.

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

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

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

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.

Type of vehicle	yearly costs (€/year)	Fuel and CO_2 costs (€/year)	Difference in costs relative to the ICE (€/year)
ICE	2,254	796	-
BEV	2,861	76	112
PHEV	2,598	229	223

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

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.

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 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. 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.

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.

7 Acknowledgements

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Appendix A. Nomenclature

This appendix lists the indices (table A.1), parameters (table A.2), and variables (table A.3) used in the equations of this article. The table consists of symbols, names, and units for all entries.

Table A.1

Indices used in equations in this article

Description	Symbol
Areas in which investments in vehicles can take place, set of areas	a, A
Fuel types used by vehicle, set of fuel types	f, F
Regions, set of regions	r, R
Time steps, set of time steps	t, T
Time period where vehicles leave the grid	i
Time period where vehicles return to the grid	j
Time period when storage is depleted and use of engine starts	t_c
Vehicle technologies, set of vehicle technologies	v, V
Set of vehicle technologies without grid connection capability, set of vehicle technologies with grid connection capability	V^{NGC}, V^{GC}
Transport service, set of transport services	x, X

Table A.2

Parameters used in equations in this article

Description	Symbol	Unit
Energy consumption of accessories of vehicle type v	C_v^{Eacc}	MWh/km
Propulsion system energy consumption, vehicle type v	C_v^{Eprp}	MWh/km
Fuel consumption of vehicle type v	C_v^{Fuel}	MWh/km
Hydrogen consumption of vehicle type v	$C_v^{H_2}$	MWh/km
Annualised vehicle investment costs	Co_v^{inv}	€/Vehicle
Yearly operation and maintenance costs excluding fuel costs	Co_v^{OM}	€/Vehicle
Average distance driven in the hour of return from the trip	$D_{v,0}$	km/h
Average hourly distance driven when on the road for the full hour	$D_{v,1}$	km/h
Distance driven between time i and j	$D_{v,j-1}$	km
Yearly demand for a transport service in region r	$D_{r,x}^{trp}$	km_{person}
Annual driving of vehicle type v	Dr_v	km
Energy left from braking when being stored	E_v^{brk}	MWh/km
Energy used for driving	E_v^{Dr}	MWh/km
CO_2 emission when using fuel type f	$Em_f^{CO_2}$	ton/MWh
Loading capacity of electricity storage	γ_v^{SLd}	MW
Storage capacity of electricity storage of vehicle type v	γ_v^S	MWh
Storage load factor for vehicles leaving	LF_v	
Average efficiency of engine in vehicle type v	η_v^{Eng}	
Average efficiency of fuel cell in vehicle type v	η_v^{FC}	
Average efficiency of generator converting mechanic power output from the engine to electric power	η_v^{gen}	
Average efficiency of inverter from grid to electricity storage for propulsion type p	η_p^{inv}	
Average efficiency of the electrical motor on-board vehicle type v	η_v^{mot}	
Average efficiency of power bus converting power on-board the vehicle	η_v^{PB}	
Average electric storage efficiency during loading/ unloading cycle proportional to the unloading	η_v^{sto}	

Description	Symbol	Unit
Average efficiency of transmission from engine and/or electric motor to driving wheels	η_v^{trs}	
Fuel price of fuel type f	Pc_f^{Fuel}	€/kWh
Price of CO_2	Pc^{CO_2}	€/ton
Plug pattern - vehicles leaving at time i, returning at time j	$PP_{x,ij}$	
Amount of energy regenerated when braking	RE_v^{brk}	MWh/km
Minimum storage level of electricity storage as a fraction of storage capacity	S_v^{min}	
Utilisation of the capacity in vehicle type v	UC_v	km_{person}/ $\mathrm{km}_{vehicle}$

Table A.3

Variables used in equations in this article

Description	Symbol	Unit
Power loaded from the grid to the vehicle	$Gr^{Fr}_{p,a,t}$	MWh
Power loaded to the grid from the vehicle	$Gr^{To}_{p,a,t}$	MWh
Number of vehicles of type v in area a	$N_{a,v}$	
Engine output going into the generator	$O^{EnGen}_{v,a,t}$	MWh
Engine output going into the generator for vehicles plugged in	$O^{EnGenPI}_{v,a,t}$	MWh
Engine output going into the generator for vehicles not plugged in at time t	$O^{EnGenNPI}_{v,a,t}$	MWh
Engine output going to propulsion of the vehicle	$O^{EnPrp}_{v,a,t}$	MWh
Fuel cell output going into the generator	$O^{FC}_{v,a,t}$	MWh
Fuel cell output going into the generator for vehicles plugged in	$O^{FCPI}_{v,a,t}$	MWh
Fuel cell output going into the generator for vehicles not plugged in	$O^{FCNPI}_{v,a,t}$	MWh
Storage level in vehicles leaving at time t	$S^{Leav}_{p,a,t}$	MWh
Storage level in vehicles arriving at time t	$S^{Arr}_{p,a,t}$	MWh
Storage level in vehicles plugged in	$S^{PI}_{p,a,t}$	MWh
Unloading of on-board storage	$S^{Unld}_{v,a,t}$	MWh

Chapter 11

Paper IV

Road Transport and Power System Scenarios for Northern Europe in 2030

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ABSTRACT

Increasing focus on sustainability affects all parts of the energy system. The future integration of the power and road transport system due to the introduction of electric drive vehicles influences the economically optimal investments and optimal operation of the power system. This work presents analysis of the optimal configuration and operation of the integrated power and road transport system in Northern Europe, i.e. Denmark, Finland, Germany, Norway, and Sweden using the optimization model, Balmorel, with a transport model extension.

A number of scenarios have been set up, including sensitivity on CO_2 and oil prices, inclusion/exclusion of electric drive vehicles, and change in investment possibilities in flexible power plants. The optimal investment path in the Nordic countries results in an increase in sustainable energy; primarily wind energy, as well as an increase in the electric drive vehicles fleet. The increase in wind power depends on the country and resources of this. Thus, the vehicles will drive on, wind, coal, or lignite depending on the country in which they are situated.

Keywords: Energy system, vehicle-to-grid, plug-in hybrid, transport model

1 INTRODUCTION

Moving towards 100% renewables in the energy system is a challenge for both the power and transport system. Sustainable energy sources like solar and wind are stochastic by nature and call for larger flexibility in the remainder of the energy system. Moving the means of transportation towards electric drive vehicles (EDVs) with plug-in facility leads to cleaner transportation provided the power used is produced on renewables. Charging of EDVs from the grid (G2V) and even loading of power back to the grid (V2G), can deliver some of the desired flexibility. The short driving range and high costs associated with driving on electricity, due to the low energy and power densities and high costs of batteries constitute significant challenges for the large scale introduction of EDVs.

Research has been done within various fields related to the introduction of EDVs, i.e., infrastructure, transition paths, potential benefits for both the power system and the customer and quantifying the impacts. The contribution of this work is analyses of differences in optimal investment paths and configuration of the power and road transport system for various scenarios for northern Europe in 2030. Thereby, key drivers contributing to the path towards a 100% renewable energy system can be found. Based on the model of the integrated power and transport system described in [1] and [2], scenarios are analyzed for the Northern European energy system. Using electrical power in the transport system has consequences for the entire energy system as does the introduction of, e.g., V2G and control of the loading and unloading of the batteries. Competition between the different vehicle types is studied as well as competition between sources of flexibility, e.g., EDVs versus heat storage in combination with electric heat boilers.

Integration of the power and transport systems requires a number of changes and additions, e.g., monitoring and metering of the vehicles, aggregators dealing with the system operator, connection standards, communication with the vehicles etc. In order to control the charging and discharging of the EDVs in the model, all these changes and additions are assumed to be in place.

Kempton and Tomic [3] initially defined and explained the concept of V2G and potential benefits of V2G. Details on the economics of services provided to the power system by the EDVs have been analyzed by Kempton et al. [4]. Potential benefits of providing particular services have been studied in terms of peak load shaving [5], and regulation and ancillary services [6], [7].

Integration of the power and road transport systems influences the power production. This impact has been quantified by few so far. McCarthy, Yang and Ogden [8] have for California's energy market developed a simplified dispatch model to investigate the impacts of EDVs being part of the energy system. Short & Denholm [9] have studied the impact on wind installations with the introduction of EDVs with G2V and V2G capabilities, and Denholm and Short [10] have studied the power system impacts with optimal dispatch of EDV charging. [11] is comparing power system investments and CO2-emissions in scenarios with different amounts of wind, heat pumps, and PHEVs in the Finnish power system. In [12] Lund and Kempton have made a rule based model of the integrated power and transport system, focusing on the value of V2G in different scenarios of wind penetration. Though, calculation of investments in different vehicle types has not been included in any of the above, but has been introduced in [2] and [13] in terms of illustrative cases. Investment decisions regarding vehicle types and power system configuration are co-optimized in this article. Hence the benefits for both the power and road transport system are taken into consideration.

In the next section a presentation of the model, Balmorel, and the transport add-on used for the analyses is given, crucial assumptions will be presented in Section 3. The integrated power and road transport model is applied to a reference case and a number of corresponding scenarios all described in Section 4. Results from running the model and analyzing output is presented in Section 5. Finally, discussions concerning results, the model, and assumptions are found in Section 6. Section 7 concludes.

2 BALMOREL WITH TRANSPORT

The model of the integrated power and road transport system is a partial equilibrium model [1], [2], [11] assuming perfect competition. The model (Figure

1) minimizes investment and operational costs subject to constraints, including technical restrictions, renewable energy potentials, balancing of electricity and heat production, and restrictions on the vehicles. Investments are generated resulting in an economically optimal operation and configuration of the power system. Electricity prices are derived from marginal system operation costs.

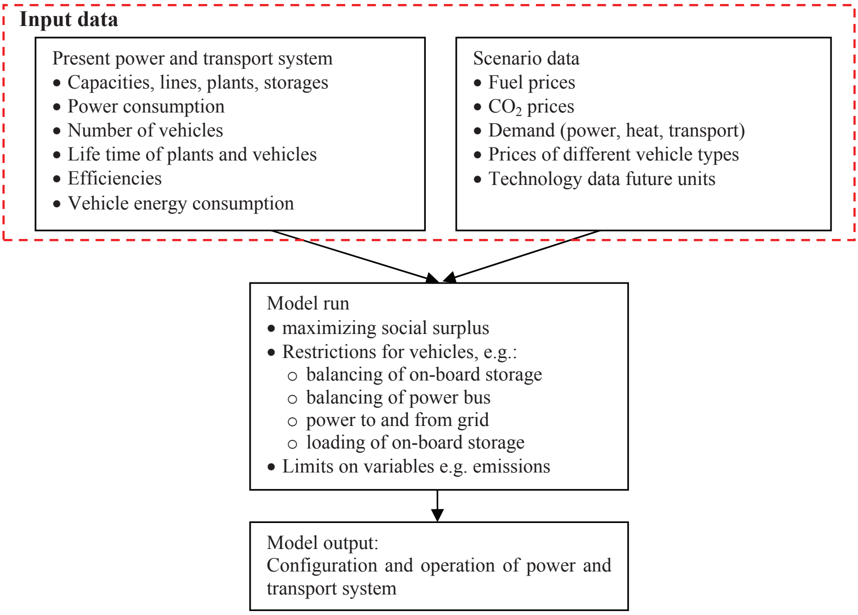

Figure 1 Sketch of the Balmorel model including road transport [2]

Balmorel works with three geographical entities: countries, regions and areas. Countries are divided into regions connected with transmission lines. The regions are then divided into areas. Balancing of electricity and road transport supply and demand is done on regional level, whereas balancing of district heating is on area level.

The optimization horizon is yearly and the investment decisions are based on demand and technology costs. Balmorel works with an hourly time resolution that can be aggregated into fewer time steps. Time aggregation is typically used for long term investments. For some cases the hourly time resolution is important, then, a cut down in the number of weeks calculated is also a possibility.

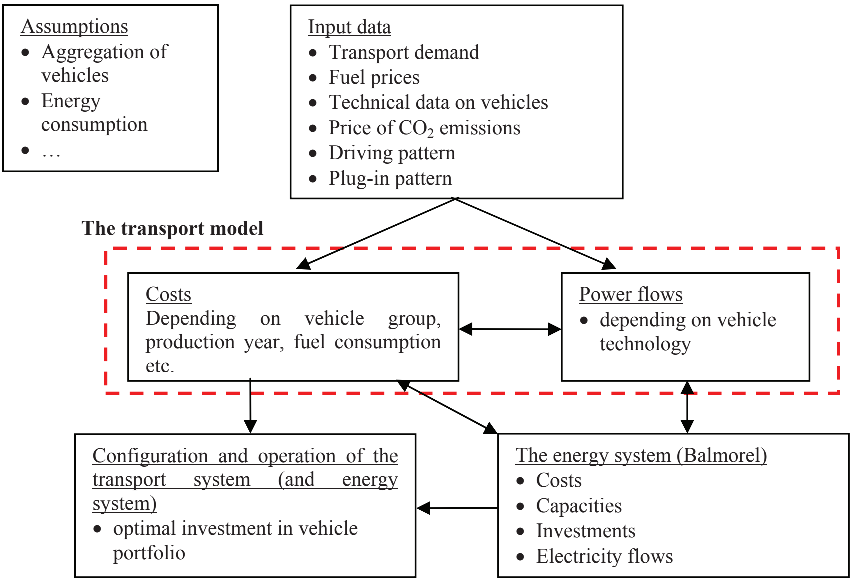

Figure 2 The transport add-on in Balmorel

For including road transport in Balmorel, a transport add-on has been developed [2] (Figure 2). The transport model includes electricity balancing in the road transport system as well as electricity balancing in the integrated power and transport system, investment and operation costs, and demand for transport services. Thus, benefits from the interaction between the power and road transport systems are taken into account. In the model, following vehicle technologies are included;

- internal combustion engine vehicles (ICEs): vehicles driving on gasoline, diesel, bio-diesel or the like
- EDVs including:
  - Battery electric vehicles (BEVs): vehicles driving on electricity only
  - Plug-in hybrid electric vehicles (PHEVs): Plug-in vehicles driving both on electricity and gasoline, diesel, or the like. Thus, electric vehicles with range extenders using internal combustion engines
  - Fuel cell electric vehicles (FCEVs): plug-in vehicles driving both on electricity and hydrogen or the like. Thus, electric vehicles with range extenders using fuel cells. In this article the FCEVs are only treated as plug-ins.

Vehicles that are non-plug-ins do not provide flexibility to the power system. Hence, these are treated in a simplified way.

2.1 Assumptions

The road transport model is based on a number of assumptions also described in [2]. In this section a few assumptions crucial for the results of the model runs are mentioned. First, all EDVs are assumed to leave the grid with a fixed amount of power on the battery, restricting the loading and unloading to meet this load factor. Dealing with an investment model does not allow for the load factor to be variable, without introducing a nonlinearity that makes solving the model intractable.

Furthermore, the plug-in hybrids are assumed to use the electric storage until depletion (of the usable part of the battery) before using the engine. This assumption seems reasonable due to the high difference in efficiencies of the electric motor and the combustion engine or fuel cell, as well as the prices differences on fuels and electricity (by 2030 the price of diesel is assumed to be €61/MWh, based on an oil price of $120/barrel and the price of electricity is approx. €50/MWh, based on numerous calculations). Furthermore, the batteries have no loss of effect before almost depleted, leaving the motor able to perform as demanded until down to the minimum state of charge.

3 APPLICATION

The model is applied to a northern European case. Introducing different scenarios allows analyses of consequences of the optimal operation and configuration of the integrated power and transport system. This section starts with a description of the base case. An outline of the scenarios is presented and, finally, the results from running the model with the different scenarios are analyzed.

3.1 Base case

Balmorel is run for the year 2030 for the northern European countries including the Scandinavian countries and Germany. In order to be able to run the model within reasonable computation time, Norway, Sweden and Finland are aggregated into one region each. Germany is aggregated into two regions in order to represent the transmission bottlenecks between northern Germany with a large share of wind power and the consumption centers in central Germany. Denmark is split into two regions representing western Denmark being synchronous with the UCTE power system and eastern Denmark being synchronous with the Nordel power system.

A number of inputs are required for running the model, e.g., fuel prices, CO_2 prices, demand data, and vehicle and power system technology data, which are all given exogenously. In the base case, oil-prices are assumed to be \$120/barrel, assuming constant price elasticities as in [11]. CO_2-prices are assumed to be €40/ton. Data, such as the demand data, is to be given on a regional level (Table 1). Currently, the transmission between the two regions in Denmark is at 600 MW, but for the year 2030 a transmission capacity of 1.2 GW and a transmission loss of 1% are assumed.

Table 1 Demand input data year 2030 (for EU countries the source is [14] - for Norway, Swedish demand have been scaled according to the situation today)

	Denmark east	Denmark west	Sweden	Norway	Finland	Germany
Electricity demand (TWh/yr)	16	24	153	133	104	620
District heat demand (TWh/yr)	12	15	46	3	56	102
Transport demand (b. persons km/yr)	31	41	148	69	86	1,262

In order for Balmorel to balance power supply and demand, new technologies must be available for investment. Table 2 shows the technologies available for investment in 2030 in the base case. With the analysis focusing on competition between technologies and incorporating more renewables, this list of technologies is thought of as a good basis.

As for the power system, balancing the transport supply and demand requires investment opportunities in different technologies. With focus on incorporating more renewables through the introduction of different EDVs, it is decided to consider four different vehicles technologies; Diesel ICE, series PHEV (diesel), series plug-in FCEV (referred to as FCEV), and BEV. The four technologies compete both in costs and in delivering benefits for the power system.

Table 2 Technology investment options in the simulation. Investment costs for heat storage and hydrogen storage are given as M€/MWh storage capacity.

Technology	Source	Fuel	Inv costs* (M€/MW)	V O& M cost (€/MWh)	F O& M cost (k€/MW/yr)	Efficiency**
Onshore wind	[15]	-	1.22	11.5	-	1
Offshore wind	[15]	-	2.2	15	-	1
Coal extraction, Steam Turbine	[15]	Coal	1.1	-	34	0.51
Open cycle gas turbine	[15]	Natural gas	0.57	3	8.6	0.42
Combined cycle gas turbine, condensing	[18]	Natural gas	0.56	3.4	21.4	0.58
Combined cycle gas turbine, extraction	[15]	Natural gas	0.47	4.2	-	0.61
Solid oxide fuel cells	[15]	Hydrogen	0.5	-	25	0.6
Solid oxide electrolysis	[15]	Electric	0.57	-	14	0.98
Hydrogen storage, cavern	[16]	Hydrogen	0.00058	-	-	0.83
CHP plant, biomass (medium)	[15]	Wood	1.6	3.2	23	0.485
CHP plant, biomass (small)	[15]	Wood-waste	4		140	0.25
Nuclear	[18]	Uranium	2.81	7.7	55.5	0.37
Heat storage	[17]	-	0.00178	-	-	0.99
Heat pump	[15]	Electric	0.55	-	3	3
Electric boiler	[15]	Electric	0.06	0.5	1	0.99
Heat boiler, biomass	[15]	Wood	0.5	-	23.5	1.08
Heat boiler, natural gas	[15]	Natural gas	0.09	-	0.32	1

* For heat pumps coefficient of performance (COP)

* Investment costs will be annualised with a discount rate of 3% (low rate is due to fixed prices)

The cost and electric storage capacity for the four vehicle technologies included in the base case are given in Table 3. The size of the electric storage capacity, shown in the table, reflects the usable size of the battery. Today the electric vehicle efficiency used is approx. 5 km/kWh [9], [10], [18], leading us to believe that the efficiency will reach approx. 7 km/kWh by 2030. The battery size for BEVs by 2030 is believed to provide a driving range of approx. 350 km. For both FCEVs and PHEVs the batteries could be almost as large as for BEVs, but additional weight as well as trade-off between additional driving range and additional cost leads us to believe that a battery covering a driving range of approx. 65 km is reasonable for everyday purpose.

Table 3 Vehicle technology investment options [16]

Type of vehicle	Annualised inv costs (€)	O& M costs (€/year)	Electric storage cap. (kWh)
ICE	1,065	1,168	0.8
BEV	1,513	1,101	50
PHEV	1,484	1,168	10
FCEV	1,893	1,101	10

Plug-in patterns have been derived from driving patterns obtained from the investigation of transport habits in Denmark [19]. In deriving the plug-in patterns it has been assumed, that the EDVs are plugged-in at all times when parked. Furthermore, it is assumed that driving habits are the same for all the countries in Northern Europe.

3.2 Scenarios

In this article, an investigation of the EDVs and their ability to provide some of the benefits for the power system needed in order to reach a level of 100% renewables in the entire energy system is provided. Focus is on the investigation of:

- 1) The optimal configuration of the power system depending on flexibility of the vehicles. What is the influence of introducing V2G and what are the consequences/benefits of introducing a percentage of BEVs? It is believed that V2G has some influence on the configuration of the power system since being able to deliver power back to the grid delivers a greater flexibility than just flexible demand. This could very well mean introduction of more wind in the cases with V2G facilities available.
- 2) What is the economic value of the EDVs, e.g., what is the benefit of the EDVs, and how does changes in the fuel and CO_2 prices affect the value of the EDVs? The EDVs are believed to have the benefit that they provide flexibility to the power system, and the EDVs are expected to be competitive both when it comes to vehicle prices and changes in the fuel prices.
- 3) How do the EDVs compete with other flexible technologies, e.g., heat pumps, heat storage, electric boilers, and OCGTs/CCGTs. Being forced to invest in one vehicle technology or the other, it is believed that the EDVs will do quite good because of the benefits they provide to the power system.

Table 4 Scenarios

Scenario	V2G	G2V	BEV	Oil	CO_2	Wind target	Heat Sto	Boiler	El-HP	OCGT/ CCGT
Base	+	+		+	+		+	+	+	+
NoV2G		+		+	+		+	+	+	+
NoV2GG2V				+	+		+	+	+	+
BEV	+	+	+	+	+		+	+	+	+
LoadFac50%	+	+		+	+		+	+	+	+
HighOil	+	+		high	+		+	+	+	+
HighCO_2	+	+		+	high		+	+	+	+
HighOilCO_2	+	+		high	high		+	+	+	+
LowOil	+	+		low	+		+	+	+	+
LowCO_2	+	+		+	low		+	+	+	+
LowOilCO_2	+	+		low	low		+	+	+	+
MedWind	+	+		+	+	med.	+	+	+	+
HighWind	+	+		+	+	high	+	+	+	+
NoHeatSto	+	+		+	+			+	+	+
BEV_NoHeatSto	+	+	+	+	+			+	+	+
BEV_HighWind	+	+	+	+	+	high	+	+	+	+
NoElBoiler	+	+		+	+		+		+	+
NoHP	+	+		+	+		+	+		+
NoCCGT/OCGT	+	+		+	+		+	+	+	

In order to investigate the above, a number of scenarios have been set up. First of all, the base case, described in the previous section, will be run and the results analyzed. Based on this, the following will be changed separately – subsequently some of them simultaneously, creating many different scenarios (Table 4):

- The inclusion of the G2V and V2G facility
- Fuel prices: These are set to low at \$90/barrel and high at \$130/barrel
- CO_2 prices: These are set to low at €10/ton and high at €50/ton
- Exclusion of different energy technologies (heat pumps, heat storage, electric boilers, and OCGTs & CCGTs)
- Having a BEV as the 2^{nd}, 3^{rd} etc. vehicle in the house: Danish statistics [20] show that 25% of all trips are driven with these vehicles in Denmark, thus 25% of all trips will be covered by BEVs in this model run.

It will probably be a political decision, how much wind to include in the national power systems. Based on these observations, wind targets are implemented.

Wind targets are minimum required investments in wind power plants. Both a medium and high wind target is used as shown in Table 5.

Table 5 Medium and high wind targets (MW) [21]

Wind target	Denmark	Sweden	Norway	Finland	Germany
Medium	7,291	10,000	5,980	3,200	54,244
High	8,020	17,000	11,970	6,000	63,587

Finally, in order to test the influence of the assumption of having a load factor of 100%, a scenario has been run with a load factor of 50%. Thus, the sensitivity of the load factor is tested, including changes in the charging pattern of the vehicles.

4 RESULTS

The model has been run on a computer with a 2.99 GHz processor and 7.8 GB RAM. Calculation time for running 7 weeks with 168 time steps is approximately 52 hours. Initial runs show that investments in hydrogen plants and FCEVs are too expensive and, thus, will never be used. Hence, for the remainder of the model runs, the hydrogen based technologies have been excluded in order to improve calculation time (down to 31 hours)

4.1 Costs

The total costs of the integrated power and road transport system varies with the different scenarios (Figure 3). For the base scenario it amounts to €203 bill. Forcing BEVs into the system increases the costs the most, due to the battery costs. Furthermore, changing the load factor from 100% to 50% when the vehicles leave the electricity grid creates a cost increases. This is primarily due to the increase in use of diesel for transportation.

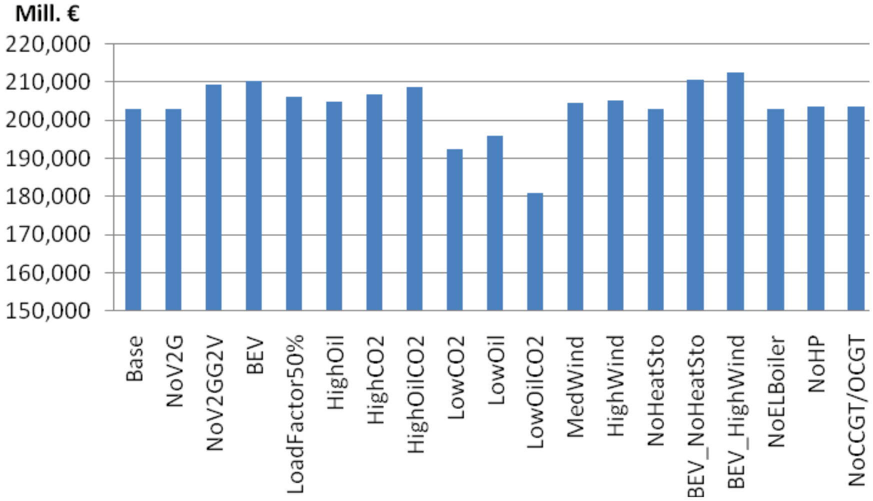

Figure 3 Total costs (mill. €) for optimal investments and operation of the integrated power and transport system under the different scenarios

No interaction between the power and transport system, of course, results in investments in ICEs. Introducing G2V (the possibility of investing in EDVs) saves €6.2 bill. Introducing V2G saves another €18 mill. (Figure 3).

4.2 Investments and production

Optimal investments in vehicles are in all scenarios except for three in PHEVs. In the other three scenarios all or almost all investments are placed in ICEs. The first scenario is when forced (no interaction between the vehicles and the power grid), and the others are the low oil costs scenario and the low oil & CO_2 costs scenario.

Power plant investments, on the other hand, vary depending on the scenarios. For Denmark, introducing PHEVs result in higher investments in and generation on wind power (Figure 4 and Figure 5) – an increase in production on 5.9 TWh. The increase in wind power production more than exceeds the power supply for the PHEVs (5.4 TWh/year). Thus, in the Danish system the vehicles will be sustainable to the degree that they drive on electricity from wind power.

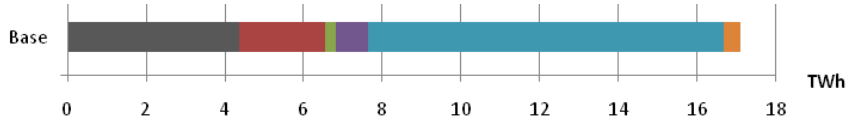

Figure 4 Base case yearly power generation based on fuel type, Danish power system.

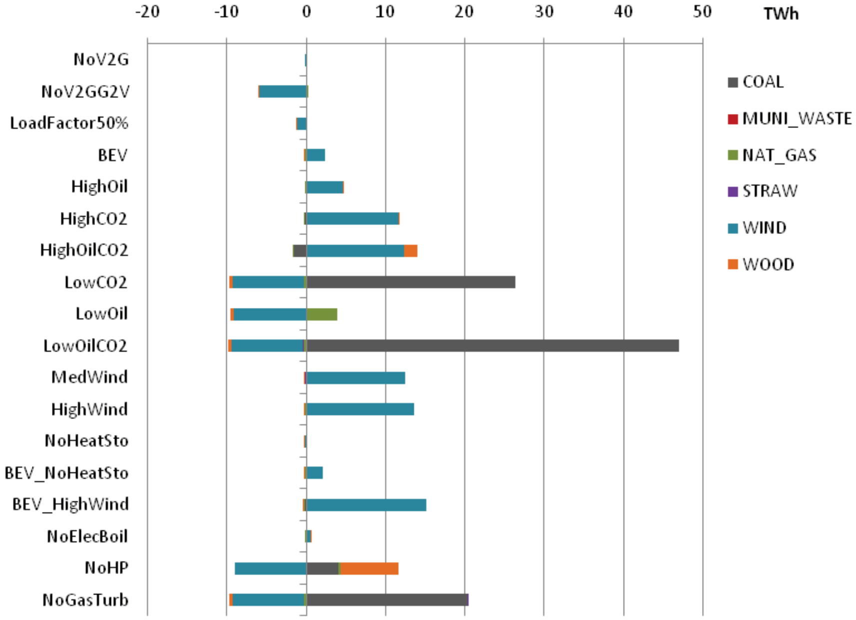

Figure 5 Deviations from base case power generation based on fuel types, Danish power system.

Focusing on the German power system, investments and generation are in coal, except for the scenarios where wind targets are set and the low oil scenario (Figure 6 and Figure 7). Power production in Germany is characterized by a fixed level of Nuclear power on 129 TWh, and varying levels of production on coal and lignite (431 and 150 TWh respectively in the base case). Hence, in Germany the PHEVs are driving on coal and lignite (95.1 TWh/year).

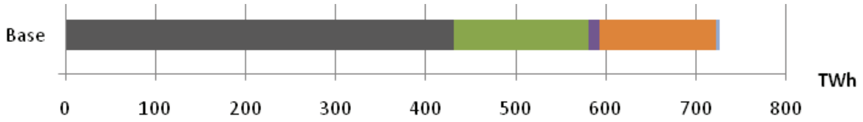

Figure 6 Base case yearly power generation based on fuel type, German power system.

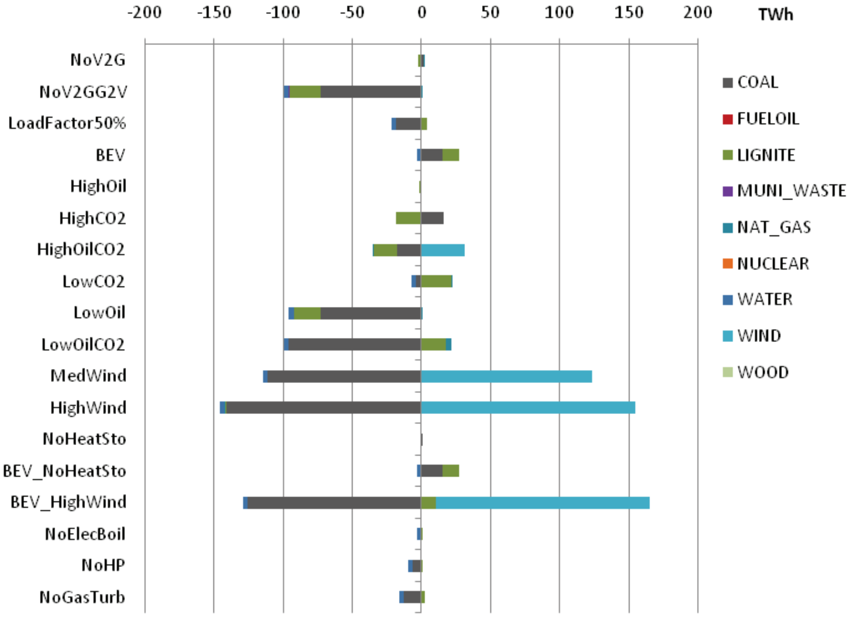

Figure 7 Deviations from base case power generation based on fuel types in the German power system.

For Norway, investments are primarily in wind power, whereas generation primarily is on hydro (Figure 8 and Figure 9). The investments and electricity production using wind varies according to the scenarios, due to varying import and export to the neighboring countries depending on the prices of alternative power generation in these countries. Furthermore, the use of hydro power in Norway is stable around 128 TWh, equivalent to 72% of the total power production in the base case. The facilities of hydro power plants with reservoirs help integrate the high amount of wind power – both in Norway and in the neighboring countries. In Norway the PHEVs use 5.2 TWh for electric transportation.

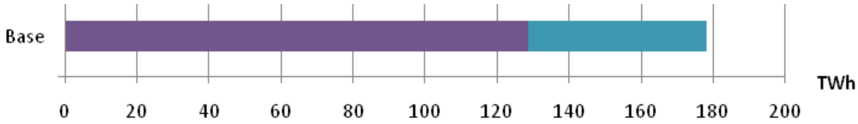

Figure 8 Base case yearly power generation based on fuel type, Norwegian power system.

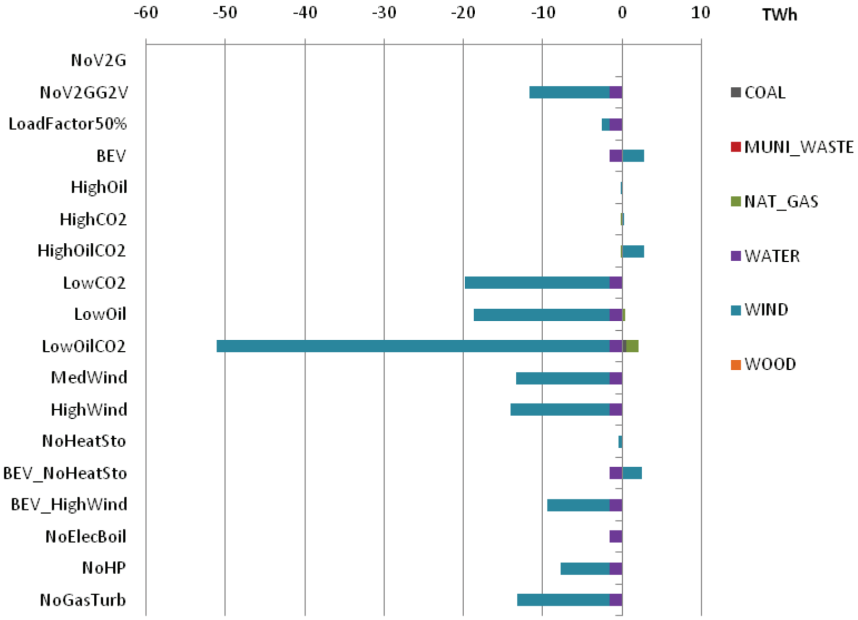

Figure 9 Deviations from base case power generation based on fuel types, Norwegian power system.

For Sweden most investments are in wind power, and some in gas turbines and heat pumps for most scenarios. Interesting for Sweden, as for Norway, is the almost non-existing difference in the power system no matter if PHEVs, using 11.1 TWh, are included or not (Figure 10 and Figure 11). Again this is due to changes in import and export of power. Sweden and Norway being net exporters due to the large hydro resources, makes it cheaper for them to cut down on export before investing in more power generating capacity.

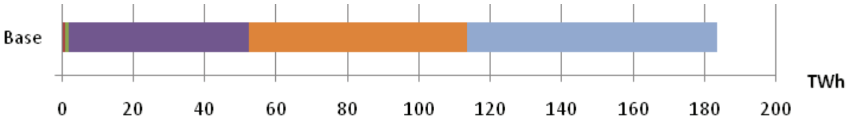

Figure 10 Base case yearly power generation based on fuel type, Swedish power system.

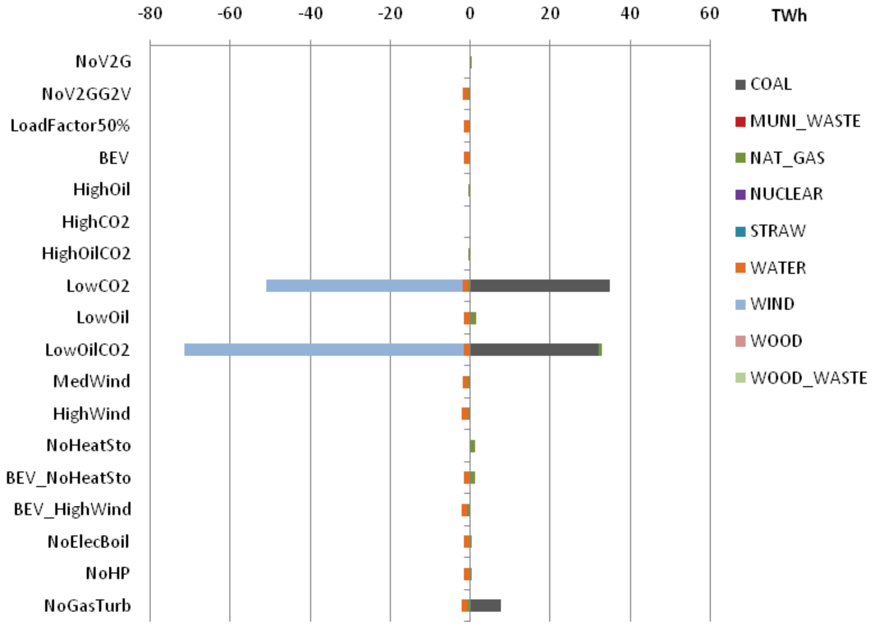

Figure 11 Deviations from base case power generation based on fuel types, Swedish power system.

The Finnish power system is characterized by high wind power investments in most scenarios, except for those with either low oil or low CO_2 costs (or both) and those without heat pumps or no gas turbines. Introducing PHEVs (using 6.4 TWh) in this system increases the use of coal by 9 TWh and slightly decreases investments in both gas turbines and heat pumps. The latter indicating that some of the flexibility provided by gas turbines and heat pumps is replaced by the flexibility provided by the PHEVs.

4.3 Including EDVs

Excluding EDVs from the power system (no V2G and no G2V), the electricity prices are fluctuating a lot (Figure 12). Introducing G2V, and thus PHEVs, removes a lot of the fluctuation in electricity prices indicating that electricity production is more stable. Thus, the PHEVs supply the flexibility needed in order to meet demand. Further, introducing V2G cut off some peaks in the electricity prices in the German power system. It is interesting, that the prices of electricity do not increase with the introduction of PHEVs in the energy system (except for Sweden). This is due to better utilization of the base load power plants being able to produce more constantly. Hence, besides the power system being cheaper, the PHEVs do provide benefits to the electricity system, no matter if they make the power system more sustainable or not.

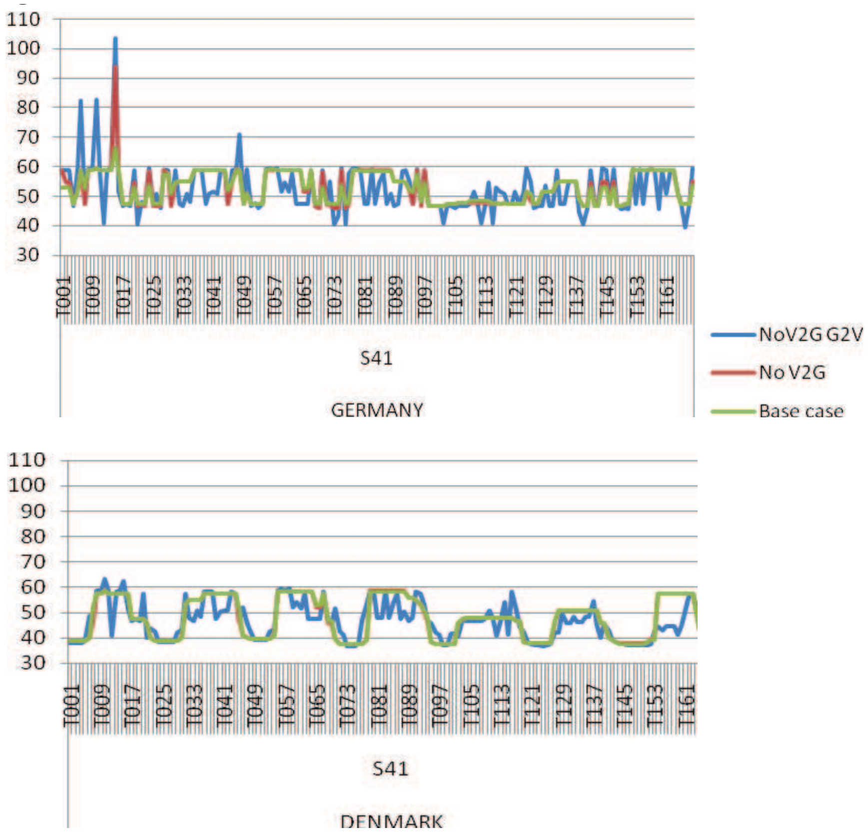

Figure 12 Electricity price fluctuations.

Introducing 25% BEVs changes investments in the power system as well as generation. Generally, investments and use of gas turbines decreases. For Denmark and Norway, investments and use of wind power increases (Figure 5 and Figure 9), for Germany (Figure 7) and Finland (Figure 13 and Figure 14) the increase is in coal steam turbine. Electricity prices smooth out and stay at the same level as without BEVs for all countries but Sweden. Hence, BEVs provide flexibility to the power system enabling higher wind or coal penetration and more stable production.

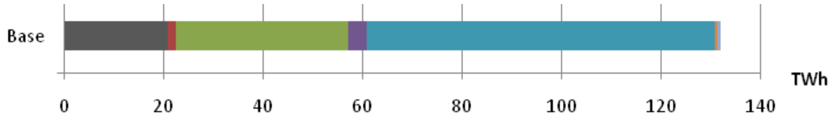

Figure 13 Base case yearly power generation based on fuel type, Finnish power system.

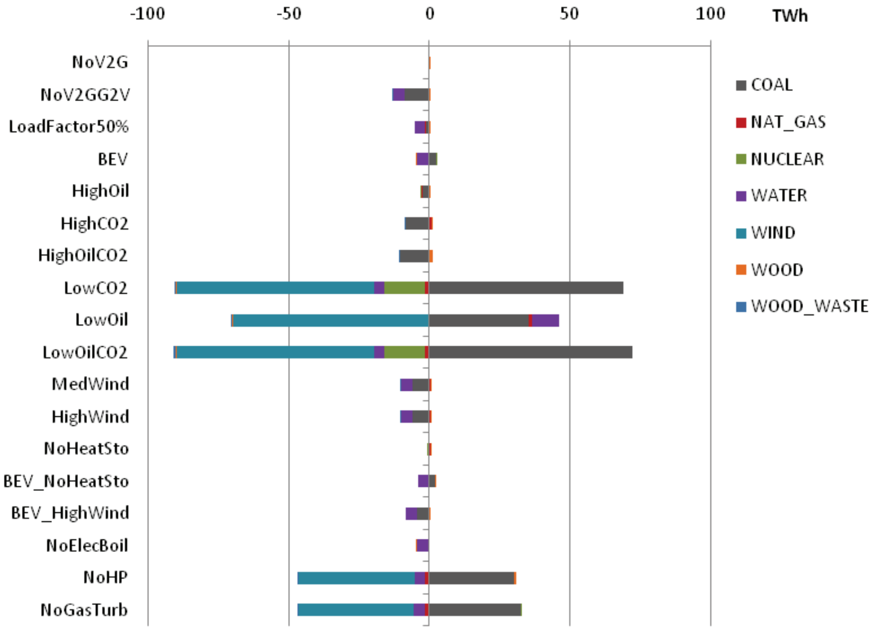

Figure 14 Deviations from base case power generation based on fuel types, Finnish power system.

4.4 CO_2 and Oil prices

High Oil and CO_2 prices generally result in increased investment in wind power (Figures 4-9 and 11-12). Even for Germany, high prices on both oil & CO_2 results in some investments in wind power being optimal. On the other hand, lowering oil and CO_2 prices decreases total wind power investments in the Northern European countries. Low CO_2 prices (also along with low oil prices) have great influence on investments in and generation on coal in Denmark. Generation increases to 31 (36) TWh on coal as opposed to 4 TWh in most other scenarios. Low CO_2 prices results in a shift in investments in most power systems from wind to coal. Low oil prices also results in a shift from wind to coal although the shift is not as pronounced. Alas, results from the model are quite sensitive to pricing of both fuel and CO_2.

4.5 Competition between flexible technologies

Eliminating heat storage and electric boilers from the investment possibilities do not influence on the configuration and operation of the rest of the power system very much. Looking at the power system use of the EDVs, they are used more actively when heat storage and electric boilers are excluded. This is especially the case with BEVs included in the system. Thus, the EDVs can replace, end hence be in competition, with the heat storage and the electric boilers.

Eliminating heat pumps and gas turbines, on the other hand, have massive influence on the investments in wind power and coal steam turbines. For Denmark, Norway and especially Finland, investments in wind power decrease in these scenarios. For Denmark no wind power is invested in. For Norway the decrease is by 2 and 4 GW respectively (NoHP and NoGasTurbines), and for Finland the decrease is 15 GW. On the other hand, investments increase for in coal steam turbines for Denmark by 0.5 and 6.6 GW respectively and for Finland by 5 and 6 GW respectively. The use of the PHEVs by the power system also reflects this observation, since no significant changes are to be found. Thus, PHEVs cannot replace all of the flexibility provided by neither heat pumps nor gas turbines.

Looking at the electricity prices the most significant change is seen when excluding gas turbines. In this scenario electricity prices tend to be less fluctuating than in the remaining scenarios. This is due to the marginal cost of gas and the decreased use of the fluctuating power generation, wind.

4.6 Wind targets

The wind targets are met in Finland, Norway and Sweden by optimality in the base case. For Denmark and Germany the situation is different. In Denmark, the wind targets reduce investments in gas turbines 700-800 MW and increases investments in heat pumps by approx. 200 MW. Total investments in power generating technologies, in Northern Europe, increase with 64-66 GW depending on the wind target, thus, almost the amount of increase in wind power investments (55-65 GW depending on wind target). Although, the use of wind increases, the remaining power generating technologies are used as much as without the wind, indicating that the net export increases. For Germany, wind targets results in a decrease in investment in and generating with coal power plants on approximately 15 GW and a slight increase in investments in heat pumps and electric boilers. Thus, even though introduction of wind target cost €1.5 and €2.2 bill respectively, they do generate the desired effect towards sustainability.

4.7 Charging the PHEVs

Looking at the use of energy over the day, part of the loading is done during night time, although there is more than expected in the day time (Figure 15). This is due to the rather strict assumptions about the load factor of the vehicles leaving the grid. The load factor of the PHEVs is set to 100% in order for the vehicles to be able to drive as far as possible on electrical power. If all PHEVs leave the grid with a load factor of 100%, charge during the day is required to meet the restrictions and, thereby, fixed to be rather high. This does not leave much flexibility to the power system to optimize. Reducing the load factor to 50% does reduce the charging throughout the 24 hour period. Furthermore, the reduced load factor increases the total costs of the system by €3.3 bill. because of the increased use of diesel for some vehicles.

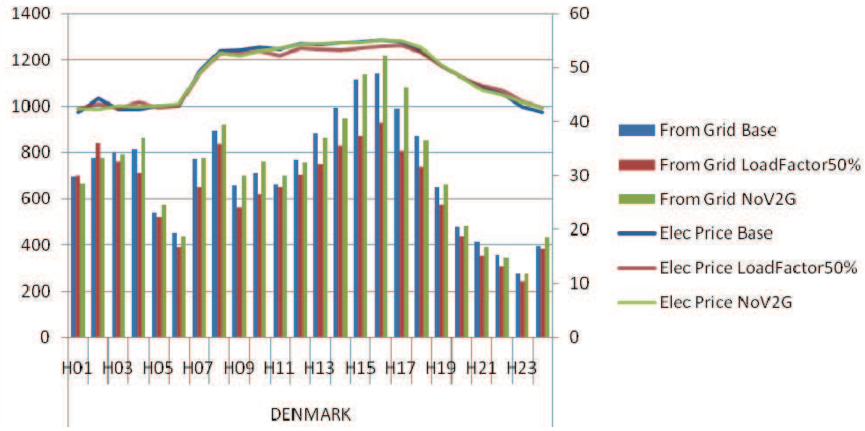

Figure 15 Power from grid to vehicles (MWh) and average electricity prices.

5 DISCUSSION

The results are the optimal investments in the situation where all people are rational and acting according to the overall optimum. This is of course not the case and the modeling cannot capture all individual thinking and acting, but only give an indication to act upon. Some improvements could be made for the model to be more representative, though. As an example, inclusion of different customer types through different driving patterns and, thus, plug-in patterns, would be a way to capture the different types of driving demands. Although, investments in electricity and heat generating plants are somewhat rational or to be decided politically, investments in vehicles are not always rational. Thus, the assumption of rationality counts when modeling the power system, but is not as reliable when modeling the road transport system.

Optimally the load factor is variable and to be decided by the model, although this creates non-linearity in the investment model. Thus, the influence of a variable load factor will have to be studied in a situation where investments in vehicles are fixed. As the driving patterns used are on an hourly basis the shortest trip driven is approx. 36 km, supporting a load factor of around 75-100% when leaving the grid in order to be able to cover the entire trip with electricity. Including driving patterns with intra-hour patterns enabling shorter driving distances for the first hour driven, would allow for the load factor providing better benefit if it is transformed into a decision variable. This is all subject for future research. It is expected to see results more dependent on the electricity prices and driving distances than the results of these model runs.

The model works with a capacity credit restriction ensuring enough production capacity to meet peak demand. One could argue that EDVs would have a capacity value and, hence, should be able to contribute to the capacity credit equation. How much capacity they can contribute with is yet to be looked into and is a subject for future research. Furthermore, it is still to be analyzed how sensitive the results are to battery prices and capacities. Future research also includes introduction of vehicles with different features for each vehicle technology.

6 CONCLUDING REMARKS

From running the model on the Nordic power and road transport system it is obvious that investments in PHEVs are optimal except in the scenarios with a low oil price. Furthermore, the PHEVs are beneficial for the power system in all the countries no matter the configuration of the power system. They provide flexibility in terms of flexible charging and introduce large savings in the power and transport system. With inclusion of V2G they are an even greater benefit although the overall costs savings on €18 mill are small compared to the savings of €6.2 bill from introducing G2V. The benefits of the flexibility are also reflected in the electricity prices.

Making the road transport more sustainable depends on the power system. The German system influences the overall picture with PHEVs driving on coal instead of diesel. Although, the great majority of the Nordic road transport systems are sustainable. Furthermore, the results from the model are sensitive to oil and CO2 prices.

Important to notice, is the fact that introducing EDVs is beneficial for both fluctuating production and base load, as seen in the results from Germany. Furthermore, introducing EDVs along with targets for sustainable energy is a good way to ensure more sustainability in the energy system as a whole.

In this model the wind power production is predictive and not stochastic. Making the wind power stochastic does change the results towards reality. Furthermore, the value of V2G is rather low in the model results shown here. This is probably due to the fact that the model works on an hourly time basis. In future research, it could be interesting to see the value of V2G in an intra hour model, capturing the effects from PHEVs being able to deliver ancillary services to the power system. Ancillary services are very likely the most beneficial area of V2G as for the power system.

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Chapter 12

Paper V

Sensitivity on Battery Prices and Battery Capacity on Electric Drive Vehicles and the Effects on the Power System Configuration

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ABSTRACT

The need for reserves is increasing with increasing fluctuating production capacities in the power system. For flexible reserves, either reserves with a fast response time like gas turbines are needed, or storage options are to be investigated. In the transport system, the expectation for electric drive vehicles, including both battery electric vehicles and plug-in hybrids, is that they will be taking over parts of the market within the next decade or two. The electric drive vehicles can provide some of the flexibility needed in the power system both in terms of flexible demand and electricity storage. The question is how much reserve capacity in terms of batteries is interesting for the power system? To answer that question, the optimal capacity of the battery in a vehicle is to be found, given the use of the battery for both driving and storage in the power system. Likewise, the prices at which the electric drive vehicles are interesting in a cost minimisation problem are to be found. This article presents an analysis of the integrated power and transport system focusing on the sensitivity in the power system according to battery capacity and price, in a situation where the vehicles use smart charge and are able to deliver power back to the grid (vehicle-to-grid). The analyses show that it is very beneficial to introduce the flexibility of the battery, and the larger the battery, the more benefits are included, although, the marginal benefit decreases. For very high battery prices, large batteries imply that investments in diesel vehicles are preferred.

Keywords: vehicle-to-grid (V2G), electric vehicles, power system, renewables, vehicle batteries

1 Introduction

Electric drive vehicles (EDVs) are of increasing interest in a world with intensified focus on the climate and CO_2-emissions. Electrification of the transport system also influences the power system. Integration of the two systems has great potentials in terms of synergies between variable renewables and the possibility of storing electricity on the vehicles' batteries. For configuring the power system, the value of the batteries depends on the price, whereas, for operating the power system, the value of the batteries depends on the capacities. If the batteries are too expensive and large, it becomes more beneficial to invest in other vehicles.

This article is analysing of the consequences on the power system operation and configuration given various battery prices and capacities. This is done by a sensitivity analysis of battery price vs. battery capacity in the EDVs finding the situations where the EDVs are to be most beneficial for the power system. Based on a model of an integrated power and transport system described in [2], scenarios are analysed for the Northern European power system.

Previous research has focused on various fields within energy systems and transport. The vehicle-to-grid (V2G) concept was touched on and described by Kempton and Tomíc [3], followed by another article [14] on the transition path to V2G and how to integrate the energy and transport systems. An overview of potentials of grid-to-vehicle (G2V) and V2G capabilities is given in [12] and [22], the latter also touching on the transition path. Regulation, operating reserves, etc. provided by the EDVs to the power system has been analysed by a number of researchers. Kempton et al. [4] have analysed details on the economics of providing the services. Providing particular services has potential benefits studied in terms of a Japanese study of peak load shaving [5] and regulation and ancillary services [6], [7], [8], and [9]. Integration of battery electric vehicles (BEVs) with focus on benefits of providing ancillary services has been studied by Brooks [10]. Moura [11] has compared costs of providing different services comparing the EDVs and other technologies providing these services today. In [13] the value of V2G providing different reserves has been studied. Brooks and Gage [15] have tested the use of BEVs for regulation and plug-in hybrid electric vehicles (PHEVs) for generation of power to the grid.

Power and transport systems integration influences the power production. The impact of the integration has been quantified by few researchers so far. For California's energy market, McCarthy, Yang and Ogden [24] have developed a simple dispatch model. Lund & Kempton [27] have looked into the value of V2G with different wind penetrations and how the EDVs can help integrate more wind. An investment analysis and optimal operation of the power system has been introduced in [2] and in [28] in terms of an illustrative case. Fast charge versus slow charge and the impacts on the power system – and thus the electricity price – has been studied by Shortt and O'Malley [18].

How to control the charge of the EDVs and impacts of different charging regimes have been studies by many. Hadley and Tsvetkova [21] have studied the impacts of different strategies for battery loading. Different charging control algorithms have been studied in [19] and [20]. Battery types for EDVs have been analysed and compared in [37] and [36]. The technological innovation of batteries and EDVs has been touched upon by Lipman and Hwang [17] and lifecycle costs of EDVs by Delucchi and Lipman [23]. In [16] Kempton and Letendre studies the characteristics for different types of EDVs with different types of batteries, their potentials and requirements. Change in vehicle efficiency depending on battery weight has been focused on by Shiau et al. [41].

Despite the broad research, not many researchers have looked into the benefits or costs of changing the size or price of the battery in the EDVs. For valuing a change in battery capacity, Lemoine [38] has used real options, capturing the uncertainty of the electricity prices. In this article a model of the integrated power and transport system [2] for Northern Europe is used to analyse consequences of varying battery prices and capacities for the power system.

The integrated power and transport model is briefly described in the next section followed by a touch on the most relevant assumptions. A description of the base case is presented in Section 4 while Section 5 presents the scenarios and gives an argumentation for the choice of variation in battery capacities and prices. Results of the model runs are presented in Section 6 and both method and results are discussed in Section 7. Section 8 concludes the paper.

2 Balmorel with road transport

Balmorel is a partial equilibrium model [1] assuming perfect competition. The model (Figure 1) minimises operational costs subject to constraints including renewable energy potentials, balancing of electricity and heat production, and technical restrictions. An economically optimal operation and configuration of the power system is found through investment generation and electricity prices are derived from marginal system operation costs.

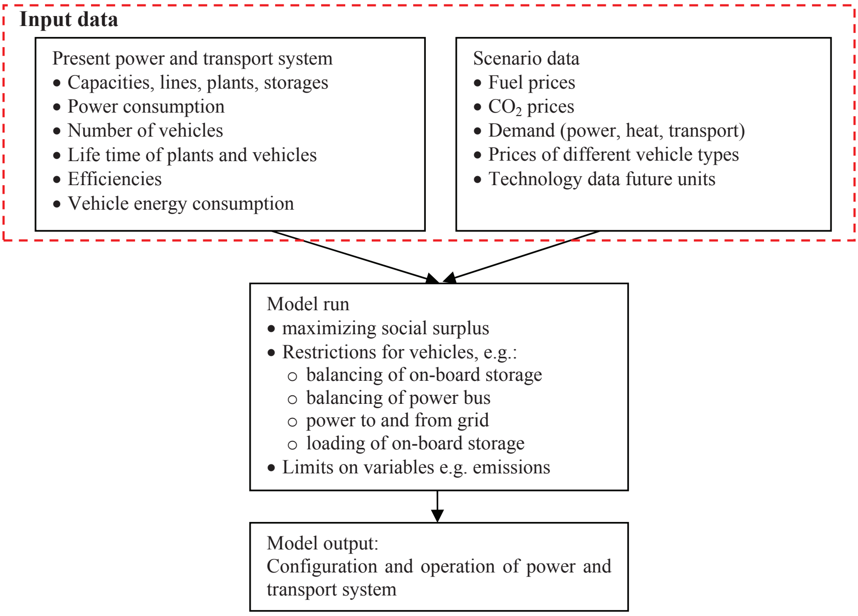

Figure 1 Sketch of the Balmorel model including road transport [2]

Balmorel was originally developed for modelling the power system in the Baltic region [35]. The model works with three geographical entities: countries, regions, and areas. Countries are divided into regions which are then divided into areas. Regions are connected with transmission lines as are some regions between countries. Balancing of electricity and transport supply and demand is on regional level, whereas balancing of supply and demand for district heating is on area level.

The optimisation horizon in Balmorel is one year and the investment decisions are based on technology costs and demand. The model works with an hourly time resolution that can be aggregated into fewer time steps if calculation time is too heavy. Time aggregation is typically used for long term investments. Cutting down the number of weeks calculated is another possibility in situations where hourly time resolution is important, but calculation time is critical.

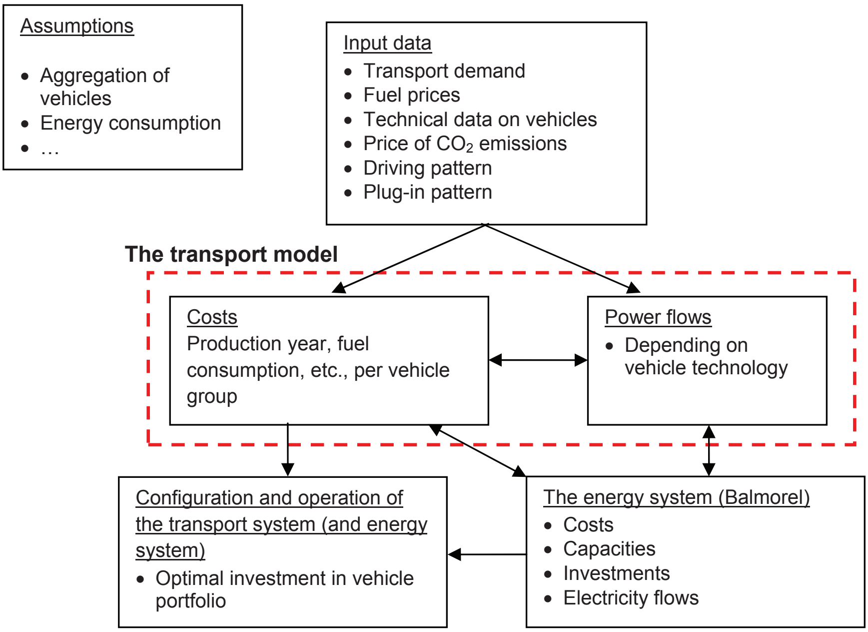

Figure 2 The transport add-on in Balmorel [2]

Including passenger road transport in Balmorel requires activation of the transport add-on [2], resulting in an analysis of the integrated power and transport system. The transport model includes electricity balancing in the transport system and the power system as well as electricity balancing in the integrated power and transport system (Figure 2). Investment and operation costs, demand for transport services, and restrictions on the vehicles are included as well. In the model, internal combustion engine vehicles (ICEs) and EDVs (BEVs, PHEVs, and Plug-in hybrid fuel cell electric vehicles (FCEVs)) are covered. Vehicles that are non-plug-ins are treated in a simplified way, since they do not provide flexibility to the power system. Including other types of road transport in the model is a question of data availability.

Modelling storage is done on an hourly time resolution with the restriction of having the first and last time step equal each other on a weekly basis. For further information about the transport add-on, see [2].

2.1 Assumptions

Balmorel and the transport add-on are based on a number of assumptions to be found in [2], [35]. In this section we mention two assumptions particularly relevant for the analyses made in this article.

First, PHEVs are assumed to use the battery until depletion before using the engine. Due to the price differences between electricity and diesel, and the differences in efficiency between an electric motor and a diesel engine, this assumption does seem reasonable.

Secondly, the load factor of the battery is fixed for every vehicle group, meaning that all vehicles in each group leave the grid with the same battery state-of-charge (SOC). Inclusion of optimisation of the SOC of the batteries would introduce non-linearity to the model.

3 Application

The model is applied to a case of the northern European power system in the year 2030. A base case has been developed based on scientific data, as presented. With offset in the base case, scenarios with different battery prices and capacities have been developed. Both base case and scenarios are described in the following.

3.1 Base case

Balmorel is run for the northern European energy system including the Scandinavian countries and Germany. In order to reach a reasonable computation time each country is modelled as one region except from Denmark consisting of an eastern and a western region and Germany consisting of a northern and a southern region. These regions are included due to poor interconnection and, thus, bottlenecks in the system.

Table 1 Demand input data year 2030 (source [30])

	Denmark east	Denmark west	Sweden	Norway	Finland	Germany
Electricity demand (TWh/yr)	16	24	153	133	104	620
District heat demand (TWh/yr)	12	15	46	3	56	102
Transport demand (b. persons km/yr)	31	41	148	69	86	1,262

Power and transport demand is set according to [30] (Table 1). The source only includes EU-countries, thus, for estimating Norwegian demand, the Swedish demand has been scaled according to historical demand.

Table 2 Technology investment options in the simulation. Investment costs for heat storage is given as M€/MWh storage capacity.

Technology	Source	Fuel	Inv costs* (M€/MW)	V O&M cost (€/MWh)	F O&M cost (k€/MW/yr)	Efficiency*
Onshore wind	[31]	Wind	1.22	11.5	-	1
Offshore wind	[31]	Wind	2.2	15	-	1
Coal extraction, Steam Turbine	[31]	Coal	1.1	-	34	0.51
Open cycle gas turbine	[31]	Natural gas	0.57	3	8.6	0.42
Combined cycle gas turbine, condensing	[33]	Natural gas	0.56	3.4	21.4	0.58
Combined cycle gas turbine, extraction	[31]	Natural gas	0.47	4.2	-	0.61
CHP plant, biomass (medium)	[31]	Wood	1.6	3.2	23	0.485
CHP plant, biomass (small)	[31]	Wood-waste	4		140	0.25
Nuclear	[33]	Uranium	2.81	7.7	55.5	0.37
Heat storage	[34]	Heat	0.00178	-	-	0.99
Heat pump	[31]	Electric	0.55	-	3	3
Electric boiler	[31]	Electric	0.06	0.5	1	0.99
Heat boiler, biomass	[31]	Wood	0.5	-	23.5	1.08
Heat boiler, natural gas	[31]	Natural gas	0.09	-	0.32	1

* Electricity efficiency

Balancing supply and demand in the power system requires investment possibilities in new plants. Investments are made possible in the technologies shown in Table 2. Hydrogen is not included in the investment options because preliminary analyses show that hydrogen is too expensive and will never be invested in. Furthermore, including hydrogen is very time consuming when running the model (adds approx. 12 hours to the computation time).

In order to do a sensitivity analysis of battery price and capacity, the focus in this article will be on only diesel vehicles, diesel series PHEVs and BEVs, the latter two with varying battery sizes. Today the electric vehicle efficiency used is approx. 5 km/kWh [25], [26], [29]. Based on these efficiencies and the assumed evolution, we are lead to believe that the efficiency will reach approx. 7 km/kWh by 2030. Based on [39], the base case battery size for PHEVs by 2030 will provide a driving range of 50 km and for BEVs a driving range of 200 km.

The vehicles are assumed to be plugged-in when parked; hence, the batteries are available to the transmission system operator (TSO) or aggregator while parked. The plug-in patterns and driving patterns are derived from the investigation of transport habits in Denmark [32]. Driving habits are assumed to be the same for all the Nordic countries. The grid capacity is set to a 3 phase 10 Amp connection resulting in 6.9 kW with a 230V cable.

3.2 Scenarios

The battery evolution is uncertain and so are the battery prices. Expectations are based on the technology roadmap from IEA [39] (Table 3). For the PHEVs, the battery capacity is expected to support a driving range between 20km and 100km, hence, battery capacity should be in the range of approx. 3kWh to 15 kWh. For the BEVs the driving range is between 100km and 500km, a battery capacity between 15kWh and 72kWh.

Table 3 Vehicle battery range options (figures based on [39] and [40])

Type of vehicle	Battery max costs (€/kWh)	Battery min costs (€/kWh)	Electric storage cap. max (km)	Electric storage cap. min (km)
BEV	400	100	500	100
PHEV	600	150	100	20

Depending on the size of the battery, one could argue that the weight is increasing with increasing power capacity. Considerations have been made on varying the battery weight and vehicle efficiencies based on [41]. It has been decided not to include the battery weight both because of the high uncertainty and because of the belief that the size of the battery will somehow be negatively correlated with the weight. That is, the lighter the battery per kWh, the larger the capacity is incorporated in the EDV – approximately reaching the same driving efficiency. Thus, the final weight of the vehicle is believed to end up more or less the same.

Two analyses are made:

1. Analysis of the influence of the battery capacity. In this analysis it is assumed that 25% of the vehicle fleet is BEVs and 75% PHEVs. These assumptions are based on data from DST about the primary vehicles in the families account for 75%, whereas, the share of 2^nd, 3^rd, etc. vehicle in the household summing up to 25%. The idea is, that only one vehicle per family needs to be able to take the very long trips, thus, longer than can be driven with a BEV.

2. Analysis of the influence of battery pricing. This is done by changing the price for different battery capacities. The model then invests in the most optimal vehicle fleet as well as the optimal heat and power system.

An overview of the scenarios tested for analysis 1 is shown in Table 4. The table leaves out the combinations that seem unrealistic such as an extremely small battery in the BEVs and a very large battery in the PHEV.

Table 4 Scenarios run for analysing the influence of the battery capacity

Type		BEV	BEV	BEV	BEV	BEV
	kWh	15	29	43	58	72
PHEV	3	x				
PHEV	4.5	x	x			
PHEV	6	x	x			
PHEV	7.5	x	x	x	x	
PHEV	9		x	x	x	x
PHEV	11.5		x	x	x	x
PHEV	15			x	x	x

In order to analyse the influence of the battery prices many scenarios are run as shown in Table 5.

Table 5 Annual vehicle price depending on the battery price (€/year)

Battery Price	kWh	€150/kWh	€250/kWh	€300/kWh	€500/kWh	€600/kWh
PHEV	3	1122	1150	1177	1219	1247
PHEV	4.5	1143	1184	1226	1288	1330
PHEV	6	1164	1219	1274	1357	1413
PHEV	7.5	1184	1253	1323	1426	1496
PHEV	9	1205	1288	1371	1496	1579
PHEV	11.5	1240	1346	1452	1611	1717
PHEV	15	1288	1426	1496	1772	1911

Based on the scenarios, the expectation is to have increasing benefits the larger the battery, although, the marginal benefit is expected to decrease.

4 Results

The model is run on a computer with 7.8 GB RAM and a 2.99 GHz processor. Computation time is approximately 35 hours for each model run. Results from running the scenarios are presented below.

4.1 Battery capacity change

Changing the capacity of the battery in a vehicle fleet of 75% PHEVs and 25% BEVs changes a lot of different things in the power system. Generally, costs are decreasing with increasing battery sizes due to the decrease in use of diesel.

4.1.1 Investments and electricity generation

In Denmark investments in wind are increasing and a slight decrease in combined cycle gas turbine (CCGT) and heat pumps is experienced with increasing battery capacities. As can be seen from Figure 3, a decrease in electricity generation on coal is experienced with battery capacity increase for PHEVs up until 7.5 kWh. After that, the usage of coal is almost the same with a slight increase except for BEVs with 29kWh batteries that experience a larger increase than the others. The increases are not due to increases in investment, but rather an indication that increased use of existing plants are more beneficial than investment in other plant types. The changes are very small, as can be seen from the figure.

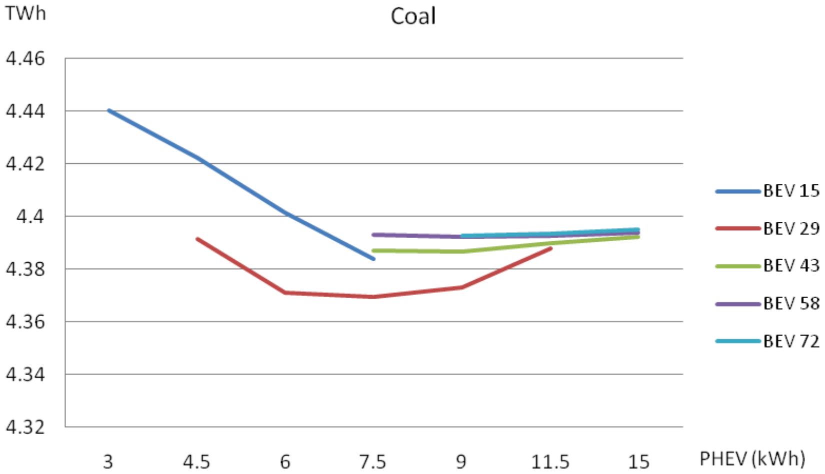

Figure 3 Electricity generation on coal in Denmark, 2030 (TWh)

For natural gas, an increase in consumption is experienced with increasing battery capacity in the PHEVs when batteries are small (Figure 4). However, after a level of 7.5 kWh is reached, the usage is decreasing. For BEVs the electricity generation on natural gas is decreasing with increasing battery capacity except for one situation with extremely large batteries in both PHEVs and BEVs, where the change is almost invisible. Thus, for the natural gas generation the largest benefits are found reaching a level of 43-58 kWh for the BEV and 9-15 for the PHEVs.

An explanation for the large increase when going from a battery capacity of 3kWh to 4.5kWh for PHEVs (15kWh for the BEVs), can be that increased amounts of renewables are incorporated in the energy system. The battery sizes in the EDVs are not very large, thus, more reserve capacities than can be provided with the EDVs are needed. However, investments in CCGT have decreased, indicating that the increased use is more spread over time.

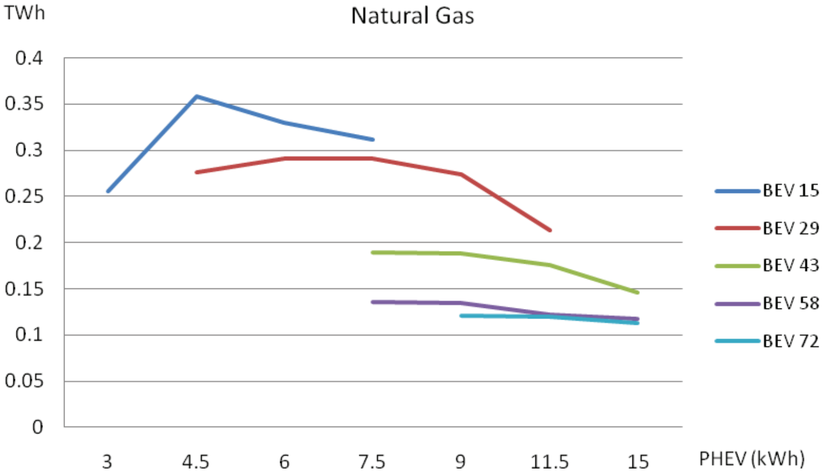

Figure 4 Electricity generation on natural gas in Denmark, 2030 (TWh)

The increase in electricity on wind power is large and continuous with increasing battery capacities (Figure 5). Although, increasing the battery capacities for the BEVs do not change much in the wind power generation. The exception is in the cases with either very low battery capacity or very high battery capacity, where the change is more visible. The total share of renewable energy in the electricity generation in the Danish power system is increasing along with the wind.

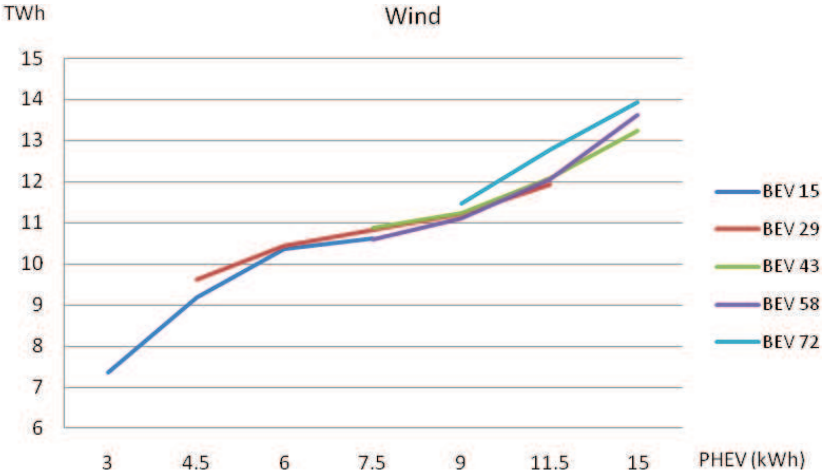

Figure 5 Electricity generation on Wind in Denmark, 2030 (TWh)

For Finland the situation is quite different. Investments in wind power has reached the limit even with the lowest batteries, leaving changes in investments to be on fossil fuelled power plants. Both investments in and generation from coal power plants increases with increasing battery capacities (Figure 6) and the share of renewables is decreasing (Figure 8). Investments in Finland do include a maximum investment in wind power of 25,000 MW in all scenarios. Furthermore, a slight decrease in the use of natural gas and heat pumps with increasing battery capacity is experienced.

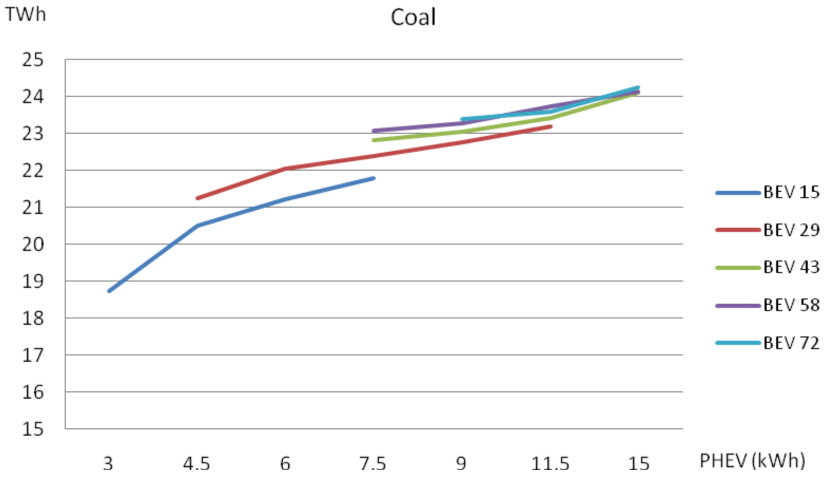

Figure 6 Electricity generation on coal in Finland, 2030 (TWh)

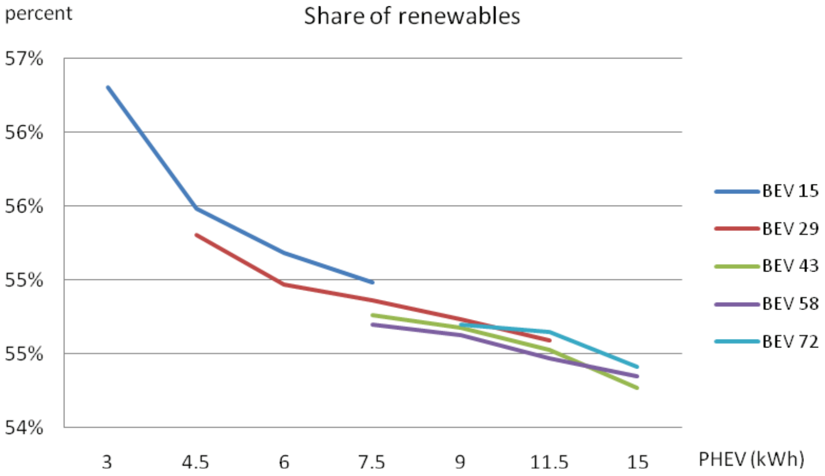

Figure 7 Share of renewables in the Finnish power system, 2030

In Germany investments are in coal plants only. For generation the majority is on nuclear coal and lignite. Both coal and lignite is increasing with increasing battery capacities. It is interesting though, that with an increase in the BEVs battery capacity, the electricity generation on coal is decreasing as can be seen from Figure 8. Furthermore, the largest increase is experienced with the increase from 3 to 6 kWh batteries in the PHEVs.

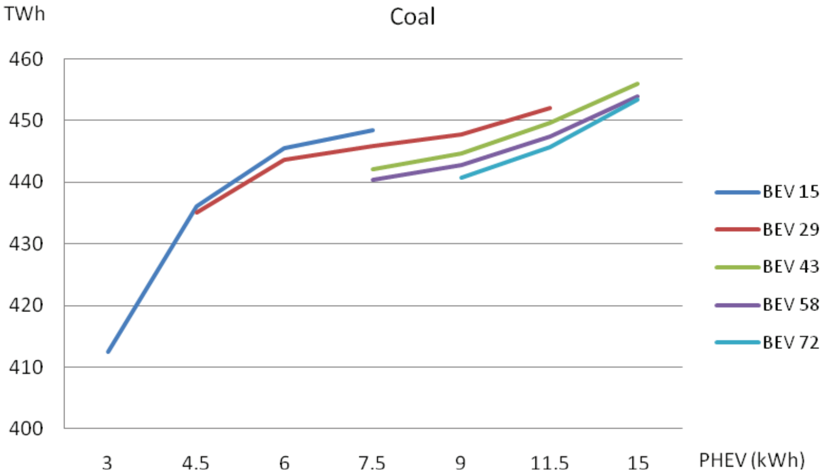

Figure 8 Electricity generation on coal in Germany, 2030 (TWh)

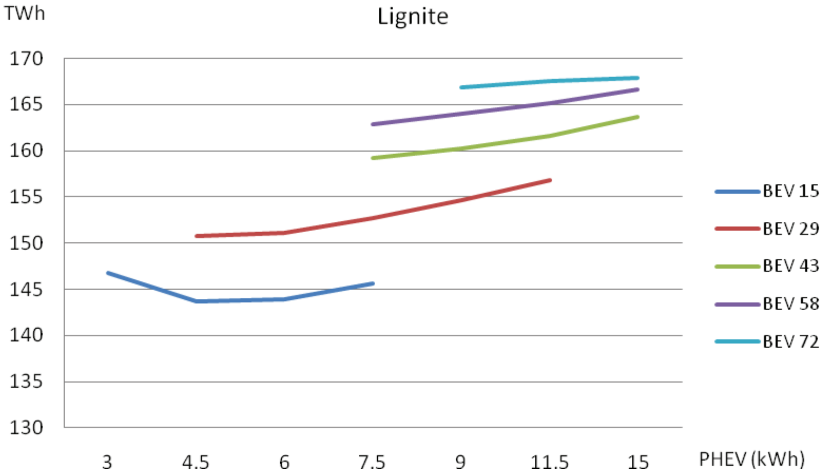

Figure 9 Electricity generation on lignite in Germany, 2030 (TWh)

It is not the same picture for lignite for which there is a decrease in usage until a battery level of 4.5 kWh for the PHEVs and the increase with battery capacity increase for both the PHEVs and BEVs (Figure 9). In Germany the level of renewable energy is 0% , due to resources and maybe also because of Germany only being allowed transmissions with the other Nordic countries.

Norway is atypical with a rather stable electricity production on water and an increasing investment and production on wind power with increasing battery capacities. Hydro power accounts for the majority of the power production in Norway.

In Sweden power production is primarily on wind, water and nuclear. Investments are almost non-changing, although a small increase in heat pumps is experienced. Changes in the use of natural gas are experienced (Figure 10). A small increase is seen until a level of 6 kWh in the PHEVs and after that, the use of natural gas is generally decreasing. Furthermore, the use is decreasing with increasing battery capacities in the BEVs. All of this is resulting in a level of approximately 71% of renewable energy in Sweden in all scenarios.

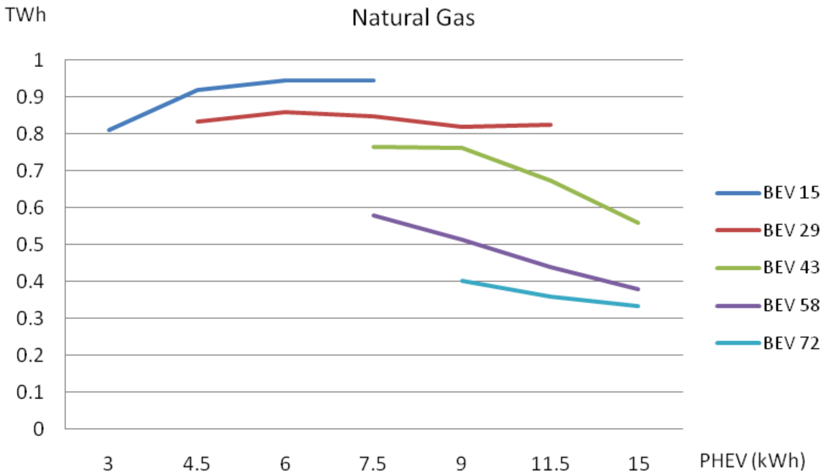

Figure 10 Electricity generation on natural gas in Sweden, 2030 (TWh)

Thus, increasing battery capacity results in increasing shares of renewable energy in Denmark, Norway and Sweden, whereas, the shares are decreasing in Finland and Germany. The latter two experiencing an increase in the share of coal fuelled power plants.

4.1.2 CO_2 emissions from electricity generation

An affect of the results of investments and generation is an increase in CO_2 emissions for Germany and Finland with increasing battery capacity, a decrease in Denmark and Sweden and a stable CO_2 emission in Norway. The largest changes are seen from 3kWh to 7.5kWh battery capacity for the PHEVs and all the way up to the 58kWh battery capacity for the BEVs.

4.1.3 Charging and discharging of the vehicles (net from grid)

Night time charging increases with increasing battery capacity for both BEVs and PHEVs. Slight trend of less charge during the day for the BEVs, the larger the battery.

Discharging – or V2G – is used very differently from country to country. In Norway the V2G is not used at all – probably due to the availability of hydro storage and flexibility enabling large integrations of wind power. For Denmark the BEVs are used for V2G around 6 p.m. for large batteries and with 72kWh batteries V2G is widely used during the day (btw 8 am and 3pm). PHEVs are used some, although not very much V2G. For Sweden and Finland V2G is widely used for the BEVs with the large battery capacities (58kWh and 72kWh) between 8am and 7pm, whereas, it is rarely used for the PHEVs. In Germany, V2G is heavily used for all battery sizes and for both PHEVs and BEVs all times of day. This is due to the batteries enabling a more stable production on the remaining fossil power plants.

4.1.4 Electricity prices

In Denmark, Norway and Germany the electricity prices are more even the larger the batteries. Thus lower peaks and higher downs in the prices are experienced. In Finland the electricity prices are increasing slightly with larger battery capacities, although, still with less distinct peaks and downs. Finally, Sweden experiences increasing prices with increasing battery capacities. The stable production and, thus, less export make the power prices increase.

4.2 Battery price change

Investments are in either PHEVs or diesel vehicles when optimising investments in vehicles. Interestingly, battery prices as well as battery capacity have to be very high before EDVs are not optimal for the integrated power and transport system. ICEs are optimal only in situations with battery capacity of 11.5kWh and a battery price of 600€/kWh or battery capacity of 15 kWh and a battery price of either 500€/kWh or 600€/kWh. This counts both for countries with primary investments in coal and countries with primary investments in wind.

Thus, investments in EDVs are not very sensitive to changes in the battery prices except when batteries both become expensive and large. This situation is not very likely though. In case the batteries are very expensive, the sizes will most likely be smaller, and thus still beneficial.

5 Discussion

The analyses presented are based on an optimisation model assuming rational behaviour. As for the heat and power system this assumption seems reasonable with all the players minimising costs. For investments in private vehicles, however, people act less rational, and choices are often based on both preferences and wealth. Although the results shown are optimal, investments in vehicles will most likely differ from this, yet, incentives could still be considered in order to move towards the optimum for the integrated power and transport system.

Furthermore, optimising the load factor is of interest for future analyses. This could be done in situations where investments are not included. Optimising the load, when leaving the grid, is expected to increase the value of the EDVs and might result in EDVs being beneficial in all the scenarios investigated in this paper.

6 Concluding remarks

As has been showed in this paper, optimal investments are in most cases in EDVs. Only with very large batteries and high battery costs, optimum changes to investments in diesel vehicles. Thus, optimum is not as sensitive to the battery prices as expected.

However, configuring the power system and generating electricity is sensitive to the battery capacity. The most drastic changes happen from the 3kWh to 6kWH batteries in the PHEVs, with large increases in coal use in Germany and Finland and decrease in coal in Denmark. The use of wind power also increases most significantly with the small batteries in both Denmark and Norway. Furthermore, the need for natural gas is increasing in with the scenarios with small batteries, whereas, the larger batteries seem to be able to take over some of the need for natural gas.

As for the BEVs the greatest benefits are also experienced up until the 43kWh battery capacity. Afterwards, the marginal benefits are decreasing. As for the CO_2 emissions, the BEVs should reach a level of 58kWh before the marginal benefits to almost reach a level of zero.

Hence, in an environmental perspective the BEVs should have a 58kWh battery and the PHEVs a 7.5kWh, which is also a beneficial choice for the investment and electricity generation perspective.

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CHAPTER 13

Paper VI

Influences on dispatch of power generation when introducing electric drive vehicles in an Irish power system year 2020.

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ABSTRACT

Increased focus on global heating and CO_2 emissions imply increased focus on the energy system, consisting of the heat, power, and transport systems. Solutions for the heat and power system are increasing penetrations of renewable heat and power generation plants such as wind power and biomass heat plants. For the future transport system, electric drive vehicles are expected to be one of the solutions. However, electrification of the transport system influences the heat and power system. Introducing different electric drive vehicle penetrations in a power system with a large amount of wind power, changes the usage of the predefined power system. This work presents investigations of different charging regimes' influence of the power dispatch in the Irish power system. Analyses show an overall cost and CO_2 emission decrease in the national heat and power system with the introduction of electric drive vehicles. However, focusing on the international costs and CO_2 emissons results are an overall cost decrease and CO_2 emission increase. Hence, the decisions on how to proceed with electrification of the transport system will be different whether it is a national or international level decision.

INTRODUCTION

The energy system faces a large change towards renewables in terms of both heat and power generation and a sustainable transport system. A challenge for the power system is the fluctuating nature of many renewables, e.g. wind power. Larger penetrations of wind call for more flexibility in the system. Flexibility comes from, e.g. storage, and flexible demand. Introducing electric drive vehicles (EDVs) brings along not only a possibly flexible demand, but also storage possibilities if charging and maybe even discharging is made intelligent. Although, electrifying transport also brings along an increased demand to be covered. The contribution of this work is analyses of how different charging regimes change the operation of an all-island power system predefined for the year 2020 – a power system configured for power demand excluding transport.

In a CO_2 perspective, electrifying the transport system makes sense as long as the increased power demand is supplied from power units having a lower CO_2 emission per kilometre driving distance than the corresponding CO_2 emission from a conventional diesel vehicle. Hence the efficiency of the EDVs compared to the conventional vehicles is very important. Assuming electric vehicle energy efficiency in the range of 4-6 km/kWh and diesel vehicle efficiency of 20 km/l, this applies to high efficiency combined cycle gas turbine plants, nuclear power and renewable power, but not for coal fired power plants.

Many researchers have focused on the fields of introduction of EDVs, i.e., infrastructure, potential benefits, and quantifying the impacts in the power system. EDVs are capable of providing different services to the power system. The economics of providing different services have been analysed in Kempton et al. (2001). Kempton and Kubo (2000) studies the services of peak load shaving, concluding that it is not profitable for the EDVs, unless the rate schedules change. Regulation and ancillary services have been studied in (Tomic and Kempton, 2007) and Brooks (2002) has looked on the integration of battery electric vehicles (BEVs) with particular focus on the vehicles providing ancillary services. Moura (2006) has made costs comparisons of providing the different services, comparing the different kinds of EDVs to the technologies providing the services today. In general, the papers find that it is beneficial to introduce EDVs except for the peak load shaving.

Integrating the heat, power, and transport systems influences the power production. Lipman (2005) has provided an overview of the potentials of the grid-to-vehicle (G2V) and vehicle-to-grid (V2G) capabilities. A simplified dispatch model of California's energy market has been developed by McCarthy et al. (2008) in order to investigate the impacts of EDVs being part of the energy system. Analyses of the flexibility contributions provided by EDVs and heat pumps to the Danish energy system are provided in (Østergaard, 2010), focusing on forced export.

Consequences of having flexibility provided by PHEVs on power system investments have been analysed in the energy system analysis model, Balmorel, by Kiviluoma and Meibom (2010). They use an exogenously given EDV fleet and optimise investments in the power system accordingly. Juul and Meibom (2009) have developed a road transport model for analysing the optimal configuration and operation in the integrated power and road transport system in Balmorel, including investments in vehicles. Lund and Mathiesen (2009) have analysed the power system needs for reaching a 100% renewable energy system, including transport on non-fossil fuels. In the paper they set up a scenario for Denmark to reach 100% renewables, finding that it is possible even on domestic resources.

The transition path from today towards a sustainable transport system has been studied in (Tomic and Kempton, 2007), where the focus is how to ensure a smooth transition path going from today's vehicle fleet to PHEVs and BEVs. The main focus in these papers is when and in which penetrations to include the EDVs in the respective years. However, none of the above has focused on how to include the EDVs in an existing power system and analysed the consequences on this power system, thus how to make the transition work. Thus, they do not focus on how to integrate EDVs in a power system not configured to include the transport system. This paper contributes with analyses of the influence on the power system when introducing different penetrations of EDVs with different charging regimes, focusing on a predefined 2020 Irish power system.

The methodology used for the analyses is described in the next section. A base case and four scenarios has been defined in order investigate the influences on the power system from introducing EDVs. These are all described in Section 3. Section 4 elaborates on the results from running the model. Finally, discussions are found in Section 5 and Section 6 concludes.

METHODOLOGY

An advanced hourly dispatch model is used to investigate the operating of the all-island power system for the entire 2020 with an assumed CO_2 price of €30/ton. A base case is set up as in (Denny et al., 2010). To investigate effects of different EDV charging schemes on the base load, mid merit and peak load plants, 4 scenarios have been developed and run in the unit commitment and dispatch model, Wilmar. The system impact of various EDV penetrations is examined by examining various system metrics relative to a base system configuration. A superficial description of the Wilmar model is provided in this section. For a more thorough description see (Meibom et al., 2007) and (Meibom et al., 2010). Presentations of the base case and the 4 scenarios are given in the next section.

Wilmar

Wilmar is a stochastic unit commitment and dispatch model optimising the operation of a given power system. The model is stochastic in three elements; the forecasts of electricity demand, wind power production, and demand for replacement reserves. Thus, a scenario tree representing these three elements is implemented. Replacement reserves represent reserves with activation times longer than five minutes. They can be provided by on-line power plants and off-line power plants that are able to start up in time to provide the reserves in the hour in question.

The model is a stochastic multi-stage linear model with recourse. The model uses an hourly time resolution and rolling planning in 3 hours steps, thus, 8 loops a day (Figure 1). The figure illustrates three stages, stage 1 resembling the first three hours, stage 2 hours 4-6, and stage 3 the remaining period in the planning horizon. Perfect foresight is assumed for the first three hours, but to get a more realistic picture, forecast errors are introduced in terms of replacement reserves.

The root decision is the production plans for the day-ahead market (stage three), where the forecast of electricity demand, wind power production, and replacement reserve demand are all uncertain. The recourse decision is taken after knowing the uncertain outcome, thus, when planning the first three hours. Hence, the recourse decision consists of up and down regulations of power production relatively to the production plan determined day-ahead.

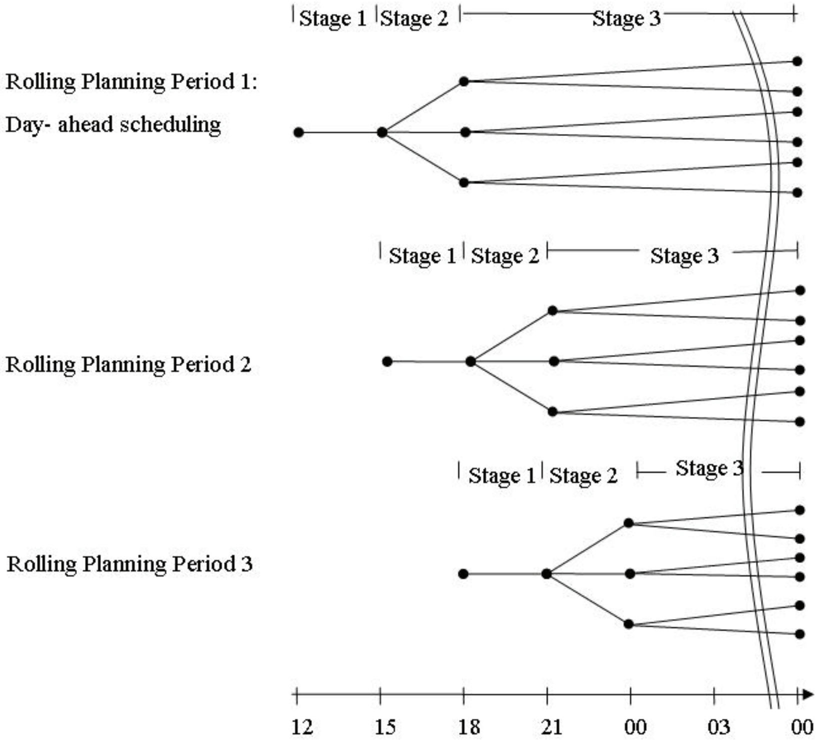


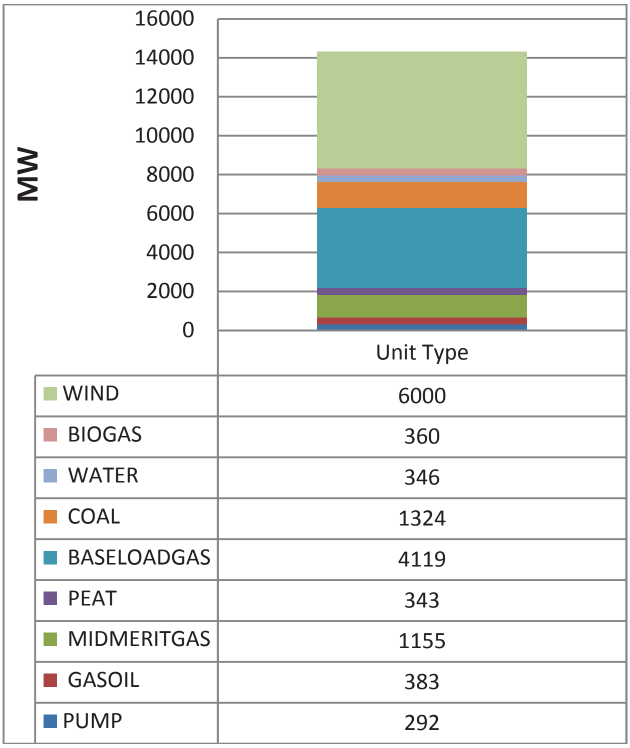
Figure 1: Illustration of the rolling planning and decision structure in each planning period (Meibom et al., 2007).

APPLICATION

In this section the base case is defined, followed by the definition of the 4 scenarios.

Base Case

A 2020 power system with 6000MW of wind generation has been defined for the Irish power system. This is based on portfolio 5 used in the All Island Grid study (Meibom et al., 2010). The portfolio consists of a total of 47% renewable share of total capacity. The total capacities of the various units used in the base case are shown in Figure 2.



	Unit Type
🟩 WIND	6000
🟥 BIOGAS	360
🟦 WATER	346
🟧 COAL	1324
🟦 BASELOADGAS	4119
🟪 PEAT	343
🟩 MIDMERITGAS	1155
🟥 GASOIL	383
🟦 PUMP	292

Figure 2: Ireland unit capacities by type

An interconnection with Great Britain of 1000MW is assumed to exist. The total conventional generation assumed in the Great Britain system is shown in Figure 3. It can be seen that base load gas, coal and nuclear comprise the vast majority of conventional generation in Great Britain. The power system in Great Britain is kept fixed for all the scenarios.

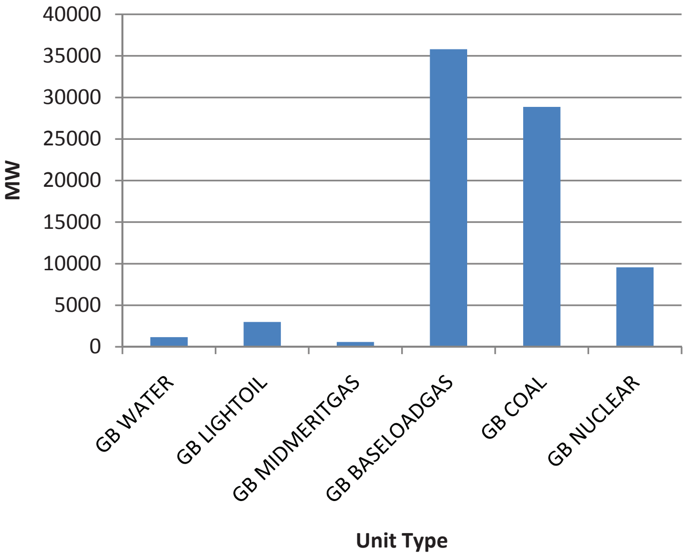


Figure 3: GB unit capacity by type

Fuel prices differ depending on the area. The fuel prices used for this study are seen in Table 1.

Area	Fuel	Price (€/GJ)
Great Britain	Baseloadgas	6.71
	Coal	1.75
	Gasoil	9.64
	Lightoil	5.22
	Midmeritgas	6.90
	Nuclear	0.4
Northern Ireland	Baseloadgas	7.06
	Coal	2.11
	Gasoil	8.33
	Lightoil	4.83
	Midmeritgas	7.27
	Peat	3.71
Republic of Ireland	Baseloadgas	7.06
	Coal	1.75
	Gasoil	9.64
	Lightoil	5.22
	Midmeritgas	7.27
	Peat	3.71
Ireland	Diesel	14

Table 1: Fuel Prices used in the study

The Irish vehicle fleet

Table 2 shows the three classes of vehicles that were identified as realistic candidates for future replacement by equivalent PHEVs and/or BEVs (SEI2004).

Vehicle Type	Number
Private car fleet	1,882,901
Goods Cars/light vans<3.5T fleet	292,604
Bus fleet	6,480

Table 2: Irish vehicle fleet, 2007 (Department of Transport, 2007)

	PHEV Battery kWh	PHEV charging capacity kW	Charging point
Private car	10	3	Single phase 15A supply
Goods Cars/light vans<3.5T	25	3	Single phase 15A supply
Bus	120	12.5	3 Phase 32A supply

Table 3: PHEV battery and charging data

	BEV Battery kWh	BEV charging capacity kW	Charging point
Private car	40	3	Single phase 15A supply
Goods Cars/light vans<3.5T	100	12.5	3 phase 32A supply
Bus	480	60.0	Required capacity exceeds 3 standard 3 phase supplies

Table 4: BEV battery and charging data

Diesel	
CO_2 emission (kg/GJ)	76.5
km/litre (passenger veh.)	20
km/litre (others)	12
MJ/l	38.6

Table 5: Diesel data and assumed energy consumption of a private car driven on diesel.

It can be seen from Table 2 and Table 3 that the proposed PHEVs and BEVs may be charged at standard residential/commercial and industrial outlets. The

60kW charging requirement of the BEV bus was assumed to exceed the electrical capacity of standard installations, thus, BEV buses are not considered. Table 4 shows the data for diesel used to calculate the effect on CO_2 emissions and total system cost increase of moving from a diesel to an EDV fleet. The usable part of the battery is assumed to be 60%. The average use of energy is 4 km/kWh when driving on electricity.

Scenarios

Each of the four scenarios defined can be characterized as consisting of either a low or high EDV fleet.

LOW EDV FLEET

The low fleet assumes the percentages of PHEVs and BEVs along with the total daily electrical consumption for each vehicle class shown in Table 5.

Diesel	PHEV %	BEV %	# PHEV	# BEV	Total daily consumption (MWh)
Private car fleet	5	1	94,145	18,829	1,016.77
Goods Cars/light vans<3.5T fleet	20	1	58,521	2,926	1,053.38
Bus fleet	6	0	389	0	28.01

Table 6: Low vehicle fleet

HIGH EDV FLEET

The high fleet assumes the percentages of PHEVs and BEVs along with the total daily electrical consumption for each vehicle class shown in Table 6.

Diesel	PHEV %	BEV %	# PHEV	# BEV	Total daily consumption (MWh)
Private car fleet	15	5	282,435	94,145	3,954.09
Goods Cars/light vans<3.5T fleet	40	5	117,042	14,630	2,633.43
Bus fleet	10	0	648	0	46.66

Table 7: High vehicle fleet

Furthermore, the scenarios have different charging regimes. The four scenarios, EV1-EV4, are described in the following.

EV1

The demand in the base case is modified to introduce the low EDV fleet having a daily charging target of 2,098 MWh. Fleet charging is spread over the night hours of 9pm – 3am, thus, no daytime charging takes place. The extra demand during charging hours is 300 MW per hour.

EV2

The demand in the base case is modified to introduce the high fleet having a daily charging target of 6,634 MWh. Fleet charging is spread over the night hours of 9pm – 3am. The extra demand during charging hours is 1,000 MW per hour.

EV3

In EV3, the demand is modified to introduce the high fleet. Fleet charging is set to begin at 7pm but is configured to ensure that 1,200 MW of spare conventional and wind capacity is available during all charging hours. Modelling the charging in this manner has the effect of ensuring that the EDVs will be charged at times of high wind. This results in a reduction of the night time consumption (relative to EV2) and a spreading of the extra demand into the early morning hours. The connection between wind and vehicle charging is illustrated in Figure 4 where it can be seen that during the period of low wind early in the month night time fleet charging is reduced, whereas, during the period of high wind later in the month night time charging increases.

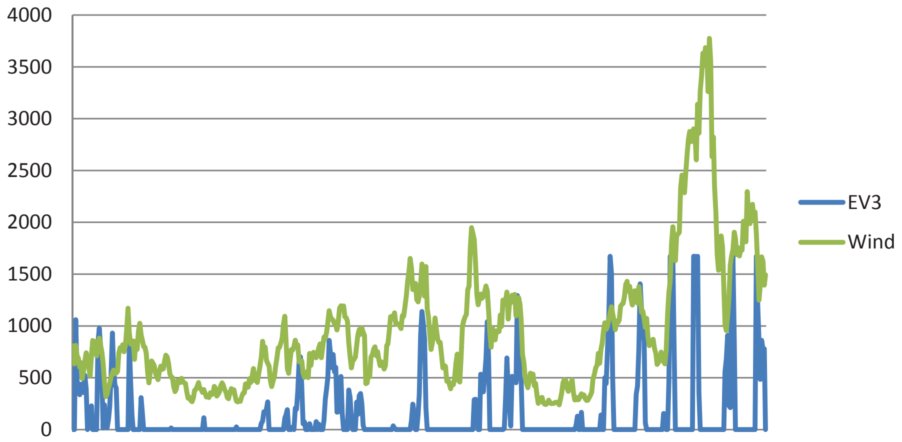


Figure 4: Hourly wind and fleet charge during May 2020, EV3

EV4
The demand in the base case is modified to introduce the high fleet. The maximum additional demand due to the electrical vehicle fleet is limited to 400MW and the case is configured such that 1,000MW of spare conventional and wind capacity is available at all times. These restrictions have the effect of spreading the additional demand due to the EDVs across the day. The majority of charging takes place during the evening and night hours but significant levels of charging also occur during daylight hours.

The average additional system demands due to the four scenarios chosen for this study are shown in Figure 5.

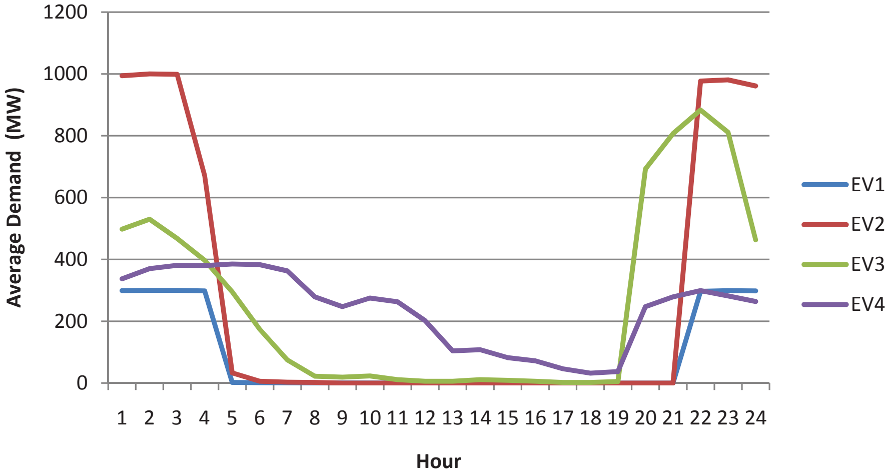


Figure 5: Average additional load (above base case) due to electric vehicles

Figure 6 shows the effect of the additional demand for each of the EDV scenarios on the average daily demand of the Irish system. It can be seen that EV4 has the effect of increasing the demand across the whole day while scenarios EV1-3 have the effect of increasing demand to various degrees during the evening and night hours.

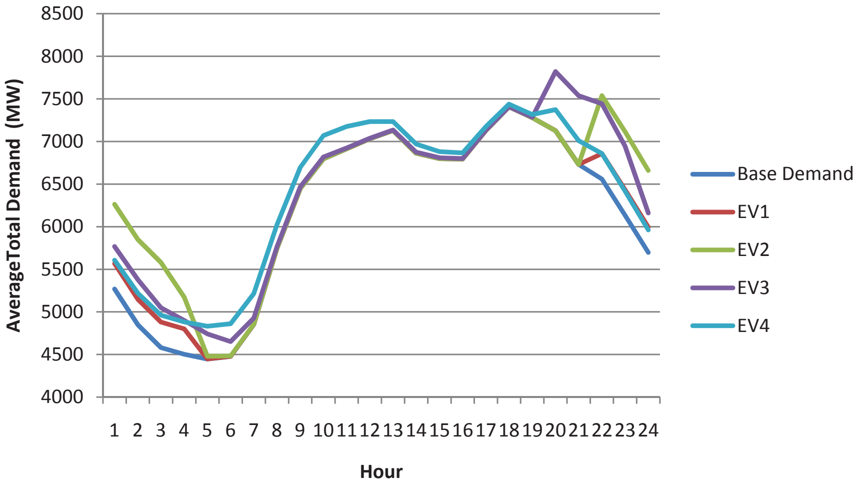


Figure 6: Average Ireland daily system load

Based on the scenarios, the expectations of the results are that the EV4 scenario will be the best of the high EDV fleet scenarios, when it comes to system costs and CO2-emissions, due to the better correlation with wind power production. The number of start-ups are expected to increase the more fixed the charging of the EDVs are.

RESULTS

CHANGE IN UNIT STARTS

A key consideration for generator owners and operators is the effect that wind and EDVs have on the dispatch of units. In this regard the number of unit starts per year or the change in the number of unit starts due to EDVs will have a large impact on the operation and maintenance costs of units. The change in the number of unit starts for EV1-EV4 is shown in Figure 7.

It is seen from the figure, that the increased demand in low load periods from the EDV fleet reduces the number of starts required by the base load units (baseload gas, coal, and peat). With the large wind penetration, number of base load starts is quite high in the base case. Therefore, the EDVs could be of great benefit when integrating larger shares of wind power in existing power systems.

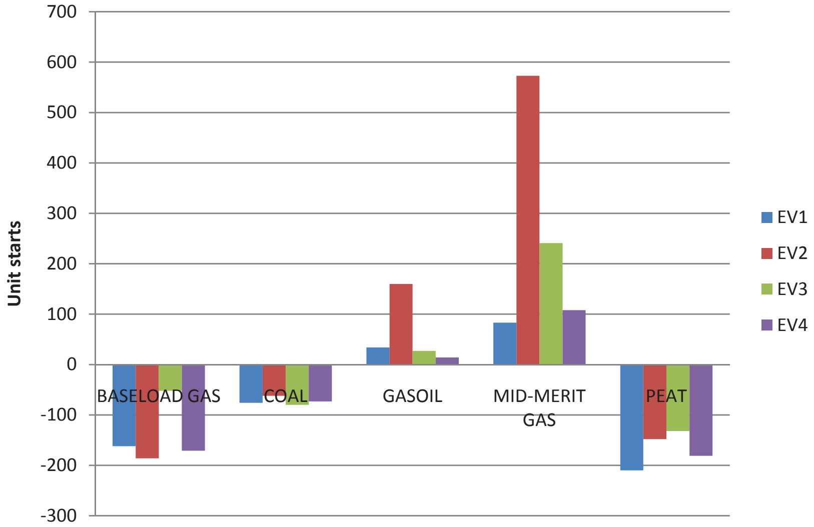


Figure 7: Change in number of starts per year relative to base case for Ireland

The number of start-ups required by mid-merit and peaking units to accommodate the EDV fleet is seen to be increasing. This is due to the inflexibility in the charging regimes creating rapid changes in the demand profile as illustrated in the large increase in mid-merit and peak load start-ups in EV2 compared to EV3 and EV4. From these results it is evident, that some kind of intelligence in the charging of the vehicles is needed.

UNIT PRODUCTION

Unit production is the amount of electricity produced on a specific power plant. The change in unit production reflects the change in how big a share of the available capacity is used for each power plant, also known as change in the capacity factor. With a predefined power system configuration the unit production will be increasing with the introduction of another load, the EDVs.

Figure 8 illustrates an important finding. It can be seen that the majority of energy required to charge the EDVs comes from coal plant in Great Britain (GB COAL) followed by base load gas in Ireland (BASELOADGAS) and nuclear energy in Great Britain (GB NUCLEAR). For the low fleet scenario, EV1, the charging energy comes predominantly from units in Great Britain. This finding suggests that a growing EDV fleet in Ireland will be powered mainly from Great Britain plants and it is only at higher fleet penetrations that base load gas plants on the all-island system will begin to dominate. The primary reason for this is that, in this study, generation is cheaper in Great Britain and the large amount of interconnection is sufficiently flexible to allow import at the appropriate times.

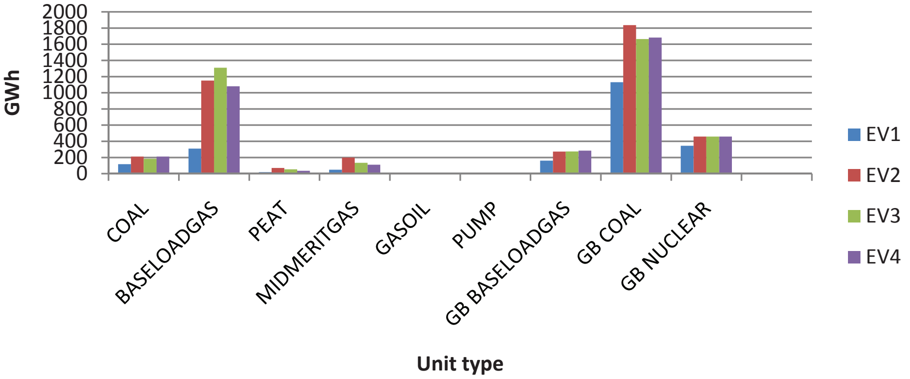


Figure 8: Total change in yearly production relative to base case by unit type

COSTS

The change in system costs of operating the all-island power system for the four EDV scenarios is shown in Table 7. The table shows an increase in operating cost with increasing fleet size and a reduction (relative to EV2 & EV3) in the operating cost of the high fleet scenarios when charging is spread throughout the day in EV4.

In order to compare the systems, the decrease in diesel costs needs to be taken into account. The system cost savings and emissions savings for EV1-EV4 due to the displacement of a diesel only fleet by a BEV/PHEV fleet are shown in Table 7. The decrease in diesel costs more than exceeds the increase in system costs in both the all-island power system and the total power system (both Great Britain and Ireland).

	EV1		EV2		EV3		EV4	
	Cost (M€)	CO_2 (Mton)	Cost (M€)	CO_2 (Mton)	Cost (M€)	CO_2 (Mton)	Cost (M€)	CO_2 (Mton)
Increase Ireland	27.7	0.41	90.8	1.14	91.9	0.95	75.3	0.86
Increase GB	60.3	1.36	97.7	1.79	90.1	1.63	91.4	1.65
Decrease diesel	111.2	0.61	332.2	1.82	332.2	1.82	332.2	1.82
Total Ireland	-83.5	-0.20	-241.4	-0.68	-240.3	-0.87	-256.9	-0.96
Total GB & Ireland	-23.2	1.16	-143.7	1.11	-150.2	0.76	-165.5	0.69

Table 8: Yearly changes in system costs and CO_2 emissions

When comparing the costs of EV3 and EV4 it can be seen that while a decrease in cost is observed in Ireland, the operating cost of the Great Britain system increase by €1.2M.

CO_2 EMISSIONS

An important consideration when evaluating the emissions benefits of moving from a diesel based to an EDV or part EDV fleet may be stated as follows. Do the emissions which are saved by the transport system outweigh the increased power system emissions which will occur when charging the EDVs?

Table 8 shows the levels of decrease of transport system emissions together with the levels of increase in power system emissions (relative to the base case) for each of the EDV scenarios. It is evident, that the decrease in transport system emissions is proportional to the size of the EDV fleet. The increase in power system emissions depends on the charging regime. Based on this, a saving in overall CO_2 emissions in Ireland is achievable when moving from a diesel to BEV/PHEV fleet. The magnitude of this saving is, of course, dependent on the emissions characteristics, usage of the existing vehicle fleet, the power system plant mix, and the charging regime of the EDV fleet.

However, including the CO_2 emissions from Great Britain changes the net decrease in CO_2 emissions to a net increase. So what would is obviously good nationally is bad in an international perspective in this case. Thus, it is of great importance to remember to consider the international aspects.

CONCLUSIONS

This paper investigates the influence of different charging regimes on a predefined power system. A simple analysis of the transport sector was used to provide data inputs while a detailed power system model was used. Despite the simple transport analysis performed, the range of cases examined is sufficient to provide a clear insight to the effects on the cost, emissions and operation of the all-island power system.

The number of base load starts decreases with the introduction of the EDV fleet, probably due to the demand increase during the night. However, the number of mid-merit starts increases with the introduction of the EDV fleet, indicating that load/demand is still fluctuating.

Nationally
Focusing nationally on Ireland, the introduction of a low EDV fleet comprising 174,810 BEVs or PHEVs results in an increase to the all-island power system costs of 28M€ and a decrease in the diesel costs of 111M€. Hence, a total decrease of 84M€ in Ireland for the year 2020 examined.

Introducing a high EDV fleet comprising 508,900 BEVs or PHEVs results in an increase to the all-island power system costs of between 75M€ - 92M€ depending on the fleet charging regime. A decrease in diesel costs of 332M€ results in a total cost decrease of between 240M€ - 257M€ for Ireland for the year 2020.

Furthermore, power system CO_2 emissions increase with the introduction of an EDV fleet. The primary contributors to the increased emissions are the base load units. The net effect on emissions for the transport and power systems due to the EDV fleet is a reduction in CO_2, though. A significant proportion of the achievable reduction is due to sensible choice of charging regime.

Internationally
Focusing on both Ireland and Great Britain, changes the positive results. The cost decrease we saw nationally is still a cost decrease in the international aspect; of 23M€ in EV1 and between 143M€ and 166M€ in the other scenarios. The same is the case with the CO_2 emissions, where the saving in CO_2 emission on a national turns into a large increase in CO_2 emissions on the international level.

These results show how important it is to take decisions about the future power and transport system on an international level or at least focus on the international perspective before taking the decisions.

Future research

The combined effect of increased start-ups due to wind coupled with decreased base-load start-ups due to EDVs was not examined. A detailed investigation of this interaction is of interest for future research.

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Chapter 14

Paper VII

Favorabelt at satse på strøm

Samfundsmæssigt kan det betale sig at investere i plug-in hybridbiler/elbiler og masser af vedvarende energi i Danmark i 2030. Men hvad er det, der gør de eldrevne biler så interessante?

Analyse

Af Nina Juul, ph.d. stipendiat, Risø DTU

Med det stadig stigende fokus på miljø og klima, rettes blikket mod energisystemet og herunder også transportsektoren. Inden for energisystemet er målsætningen, at mere og mere bliver produceret med vedvarende energi. Vedvarende energi i Danmark er primært vindmøller. Vindmøller giver strøm når det blæser, men hvad så når det blæser for meget eller slet ikke blæser?

Fokus i denne forskningsanalyse er at skabe mest mulig værdi i energisystemet, dvs. at undersøge hvordan vi udnytter systemet mest effektivt. Vi må tænke i energilagre, og det er her, at de eldrevne biler kommer ind.

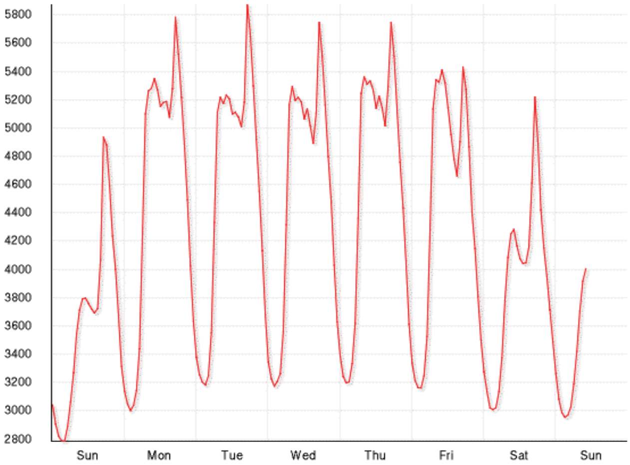
Eldrevne biler, der kan kobles til elnettet (plug-in), svarer til en masse små batterier, som står parkeret en stor del af tiden. Hvorfor ikke gøre brug af dette på intelligent vis? Det kan gøres på mange måder - alle dog med den forudsætning, at ejeren af bilen selvfølgelig altid skal kunne komme ud til en bil, der kan køre den tur, hun skal ud på.

Eldrevne biler består af a) elbiler som udelukkende kører på batteri, b) plug-in hybridbiler som kører på batteri med en 'afstandsforlænger' i form af enten benzin- eller dieselmotor eller en brændselscelle eller c) hybridbiler med mindre batterier, som hverken kan oplade fra eller aflade til elnettet. De interessante for elsystemet er selvfølgelig elbiler og plug-in hybridbiler.

Midt i madlavningen

Lad os antage, at alle biler skiftes ud til plug-in hybrider (med dieselmotor). Hvis alle kommer hjem efter arbejde, sætter bilen til opladning og derefter går ind og laver mad, vil elnettet bryde sammen. For at kunne levere så meget strøm på en gang, kræves en betydelig udbygning af elnettet.

I stedet forventes det at indføre intelligent opladning og muligvis også afladning af bilerne. Således vil man kunne oplade biler ved situationer, hvor vi alternativt eksporterer strøm, og aflade dem i situationer, hvor vi importerer strøm.



Figur 1. En typisk uges elforbrug, Østdanmark (Nord Pool)

Ser man på elforbruget i Østdanmark i dag, ser en typisk uge ud som på figur 1. Her kan vi se højt forbrug i løbet af dagen og specielt om aftenen under madlavning. Lavest forbrug findes i løbet af natten. Her vil vi altså gerne have, at biler for eksempel lader jævnt i løbet af natten. Og hvad med at nogle af dem måske aflader under madlavningen – når eller hvis der er strøm nok på batteriet til det?

Ok, så bliver forbruget udjævnet, men kører bilerne ikke bare på kul i stedet for diesel? Nej, der sker det, at de eldrevne biler giver stor fleksibilitet i energisystemet. Det bliver altså økonomisk favorabelt at producere meget mere strøm fra bl.a. vind.

Vores analyser viser, at det kan betale sig at investere i så meget vindenergi, at det mere end dækker det merforbrug af strøm, der kommer, givet bilernes efterspørgsel. Vi kan derfor roligt sige, at optimalt set kommer bilerne snarere til at køre på vind end på kul. Miljømæssigt er det altså en stor fordel.

Sund økonomi

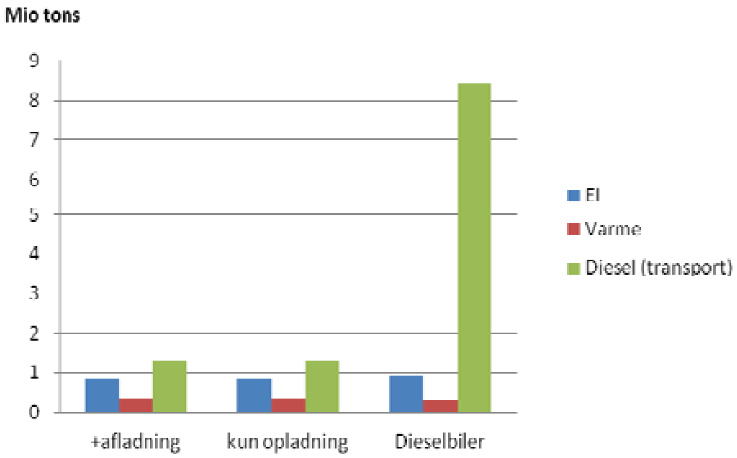
Ser vi på de økonomiske aspekter, gør elpriserne i dag det yderst fordelagtigt at køre så meget på el som muligt. Når opladning og afladning af batteriet styres fra centralt hold, kan bilerne oplades og aflades på de, for alle, mest favorable tidspunkter. Lav efterspørgsel giver nemlig lave priser og omvendt. Dvs. det kan betale sig for både forbrugerne og el-operatørerne at oplade bilerne, når der er lav efterspørgsel - og aflade når efterspørgslen er høj.

Vores analyser fokuserer på dieselbiler, diesel plug-in hybridbiler og rene elbiler. Diesel er valgt frem for benzin, da brændstoføkonomien er bedre for dieselbiler. Vi antager selvfølgelig, at alle bilerne har partikelfiltre.

Vores beregninger viser, at indførsel af plug-in hybrider for personbilstransporten i Danmark giver en besparelse på 4,532 mia. kr. i det danske energisystem i 2030 i forhold til, hvis investeringen udelukkende var i konventionelle dieselbiler. Det skyldes både besparelser ved at anvende hybridbiler frem for dieselbiler, men afspejler også besparelser i forbindelse med investeringer og drift af energisystemet.

Tilføjer vi mulighed for at aflade bilerne og dermed levere strøm tilbage til nettet, giver det en besparelse på yderligere 13 mio. kr. Der er også omkostninger ved for eksempel at indføre mulighed for afladning, hvorfor det selvfølgelig er en overvejelse værd, hvad der er mest rentabelt.

Effekterne på miljøet fremgår tydeligt af CO_2-besparelserne i systemet (figur 2). Som følge af skift fra rene dieselbiler til diesel plug-in hybridbiler falder CO_2-udledningen med godt 7 mio. tons - bare indenfor privattransporten.



Figur 2. CO_2-udledning i Danmark i 2030

Vedvarende energi

76 procent af den energi, der skal bruges på personbilstransport, kommer fra el. Dette svarer altså til, at tre fjerdedele af vores transportbehov i Danmark, vil kunne erstattes af elbiler. Muligvis er det mere, da elbiler har væsentligt større batterikapacitet end plug-in hybriderne.

Andelen af energi produceret på vind stiger til 52 procent af den samlede energiproduktion mod kun 31 procent i situationen med dieselbiler. Forskellen i produceret vindenergi mere end dækker den energiefterspørgsel, der er på personbilstransporten. Elektrificering af transporten afhjælper en integration af mere vedvarende energi, og hele systemet drager nytte af indførsel af eldrevne biler.

Læs mere på www.risoe.dtu.dk

Bag om beregningerne

Bag konklusionerne i denne samfundsøkonomiske analyse ligger en række modelberegninger uden afgifter (dog med CO_2-afgifter). Analysens formål er at vise, hvad der er fordelagtigt i en situation uden incitamentsstruktur. Indføres de afgifter, vi har i transport- og energisystemet i dag, vil disse være til fordel for rene elbiler. Derudover er der lagt en række forudsætninger - for eksempel:

* Årlig kørsel: 20.000 km for elbiler og 25.000 km for andre.

* Effektivitet: 7 km/kWh på batteri. 2 km/kWh på dieselmotor

* Batteristørrelser: Der er forskellige meninger om, hvor stor en del af batteriet, der kan anvendes. Kun den anvendelige del er med i analysen, og det er 50 kWh (350 km) for rene elbiler og 10 kWh (65 km) for plug-in hybrider.

* Kørselsmønster: Der er taget udgangspunkt i historiske kørselsmønstre. Det forventes, at de vil ændre sig med sammensætningen af bilparken. Således kan der for eksempel være flere, der køber elbiler og benytter offentlig transport til de lange ture.

* Ladeinfrastruktur: Det er antaget, at infrastrukturen omkring ladestationer er til stede. Det vil være naturligt, at plug-in-hybrider vil være de

primære eldrevne biler under op- og udbygning, og at rene elbiler bryder mere frem senere.

* Danmark isoleret: I analyserne er der set på Danmark isoleret. Det kan skabe øget værdi af elbiler som lager, idet transmission til for eksempel Norge og dermed også adgang til energilagre i form af vandreservoirer er udeladt.

* Sidegevinster: I modellen bliver investeringer og driftsomkostninger kvantificeret. Andre værdier såsom helbredseffekter, støj og andre eksternaliteter er ikke. Mange af disse tæller imidlertid som yderligere fordele ved elektrificering af transporten.

Climate change and CO2 emissions are important issues on the agenda of many politicians. A CO2 emissions decrease influences transportation, power production etc. The power system is characterised by an increasing amount of wind. Wind energy is fluctuating by nature, calling for increasing flexibility elsewhere in the energy system. Flexibility could come from the road transport system, e.g. electric drive vehicles. With intelligent charging of the vehicles, the electric drive vehicles can be of great benefit providing flexible demand and charging at night time. Furthermore, discharging of vehicles can provide services to the power system.

This PhD project focus on modelling and analysis of a future integrated transport and power system. An integrated power and transport system enables analyses of the interactions between different parts of the energy system. The object of interest is an optimal configuration of an integrated power and transport system as well as focus on drawbacks and benefits for the power system incorporating an electrified transport system. Analyses are performed in terms of integrating more renewable energy, for both Denmark as an isolated system and for the northern European countries including Denmark, Sweden, Norway, Finland, and Germany. The analyses are performed using the deterministic energy systems analysis model, Balmorel. Different analyses have been made for the Irish power system on the influence of introducing electric drive vehicles in a predefined power system, using the stochastic energy systems analysis model, Wilmar.

Interesting is, that it turns out to be most profitable to invest in enough wind to more than cover the electrified transport in Denmark. This holds, both when modelling Denmark as an isolated country, and when including the interactions between the Nordic countries. Furthermore, analyses show that fuel cell electric vehicles are not yet ready for competing with the other vehicle types. This is, among other things, due the technologies not being cheap enough, thus, the development is not expected to have reached a competitive stage.

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