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Wind power integration with heat pumps, heat storages, and electric vehicles – Energy systems analysis and modelling

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- PhD thesis -

Wind power integration with heat pumps, heat storages, and electric vehicles
– Energy systems analysis and modelling

by
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Energy Systems Analysis

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Wind power integration with heat pumps, heat storages, and electric vehicles
– Energy systems analysis and modelling

PhD thesis

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Abstract

Wind power is in many countries considered a key renewable energy technology in achieving the goals of reducing greenhouse gas emissions and relieving the dependency on fossil fuels. However, the fluctuating and only partly predictable nature of wind challenges an effective integration of large wind penetrations. This PhD investigates to which extent heat pumps, heat storages, and electric vehicles can support the integration of wind power. Considering the gaps in existing research, the main focus is put on individual heat pumps in the residential sector (one-family houses) and the possibilities for flexible operation, using the heat storage options available. Several energy systems analyses are performed using the energy system models, *Balmorel*, developed at the former TSO, ElkraftSystem, and, *EnergyPLAN*, developed at Aalborg University. The Danish energy system towards 2030, with wind power penetrations of up to 60 %, is used as a case study in most of the analyses.

Both models have been developed further, resulting in an improved representation of individual heat pumps and heat storages. An extensive model add-on for Balmorel renders it possible to optimise investment and operation of individual heat pumps and different types of heat storages, in integration with the energy system. Total costs of the energy system are minimised in the optimisation. The add-on incorporates thermal building dynamics and covers various different heat storage options: intelligent heat storage in the building structure for houses with radiator heating and floor heating, respectively, heat accumulation tanks on the space heating circuit, as well as hot water tanks. In EnergyPLAN, some of the heat storage options have been modelled in a technical optimisation that minimises fuel consumption of the energy system and utilises as much wind power as possible.

The energy systems analyses reveal that in terms of supporting wind power integration, the installation of individual heat pumps is an important step, while adding heat storages to the heat pumps is less influential. As such, the installation of individual heat pumps can contribute significantly to facilitating larger wind power investments and reducing system costs, fuel consumption, and CO_2 emissions. This is first due to the high energy-efficiency and economic competitiveness of the heat pumps. Moreover, their electricity demand profile is well suited for integrating wind power, even when not operated intelligently. The political phase out of coal in Denmark by 2030 furthermore creates particularly good conditions for utilising wind power in meeting the electricity demand for the heat pumps.

When equipping the heat pumps with heat storages, only moderate system benefits can be gained. Hereof, the main system benefit is that the need for peak/reserve capacity investments can be reduced through peak load shaving; in Denmark by about 300-600 MW, corresponding to the size of a large power plant. This can be achieved when investing in socio-economically feasible heat storages complementing the heat pumps. The potential for reducing the required investments in peak/reserve capacities is crucial for the feasibility of the heat storages.

Intelligent heat storage in the building structure is identified as socio-economically feasible in 20-75 % of the houses with heat pump installations, depending on the cost of control equipment in particular. Investment in control equipment, enabling utilisation of existing hot water tanks for flexible heat pump operation, is found socio-economically feasible in about 20-70 % of the

houses. In contrast, heat accumulation tanks are not competitive, due to their higher investments costs.

Further analyses investigate the system effects of a gradual large-scale implementation of battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) in Denmark, Finland, Norway, Sweden, and Germany towards 2030. When charged/discharged intelligently, the electric vehicles can, in the long term, facilitate larger wind power investments, while they in the short term in many cases are likely to result in increased coal-based electricity generation. The electric vehicles can contribute significantly to reducing CO_2 emissions, while system costs are generally increased, due to assumed investments in the costly BEVs. The need for peak/reserve capacities can be reduced through the use of vehicle-to-grid capability.

Flexible operation will be more important for electric vehicles than for individual heat pumps. The reason is that in the situation without flexible operation, the electricity demand for charging of electric vehicles will typically be concentrated in the hours, where conventional electricity demand peaks, while individual heat pumps will have a more distributed load profile.

Competing flexibility measures, such as large heat pumps, electric boilers, and thermal storages in the district heating system, have also been included in the energy systems analyses. These technologies can together facilitate increased wind power investments and reduce CO_2 emissions in the same order of magnitude as a large-scale implementation of electric vehicles. The connection between large heat pumps/electric boilers and the large district heating storages allows for storing electricity as heat during longer periods when needed. This is an advantage compared to individual heat pumps and electric vehicles, which will mainly be able to provide power balancing intra-day and intra-hour, due to smaller storage capacities.

Overall, it is concluded that individual heat pumps, flexibility measures in the district heating system, and PHEVs, can provide significant contributions to a cost-effective integration of wind power towards 2030. Heat storages complementing individual heat pumps can contribute only moderately in this regard.

Resume

Vindkraft betragtes i mange lande som en vigtig vedvarende energikilde i forhold til at nå målsætningerne om at reducere drivhusgasemissioner og afhængigheden af fossile brændsler. Imidlertid er vinden fluktuerende og kun delvis forudsigelig, hvilket vanskeliggør en effektiv integration af store mængder vindkraft. Denne Ph.d.-afhandling undersøger i hvilket omfang varmepumper, varmelagre og elbiler kan fremme integrationen af vindkraft. Hovedfokus er på individuelle varmepumper i boligsektoren (enfamilieshuse) og deres muligheder for fleksibel drift ved brug af varmelagring, da dette område hidtil har været mangelfuldt belyst i et energisystemperspektiv. Adskillige energisystem-analyser er foretaget ved brug af energimodellerne, *Balmorel*, udviklet ved den tidligere TSO ElkraftSystem, og *EnergyPLAN*, udviklet ved Aalborg Universitet. Det danske energisystem mod 2030 med vindkraft-andele på op mod 60 % er anvendt som case i de fleste af analyserne.

Begge modeller er blevet videreudviklet til at give en forbedret repræsentation af individuelle varmepumper og varmelagre. Et omfattende model add-on til Balmorel gør det muligt at optimere investeringer og drift af individuelle varmepumper og forskellige typer varmelagre i integration med energisystemet. De samlede omkostninger for energisystemet minimeres i optimeringen. Modellen inkorporerer bygningers termiske forhold og omfatter en bred vifte af forskellige varmelagre: Intelligent varmelagring i bygningskonstruktionen for hhv. radiator- og gulvvarmesystemer, varmeakkumuleringstanke på rumvarmekredsløbet samt beholdere til varmt brugsvand. I EnergyPLAN er nogle af varmelagerteknologierne modelleret i en teknisk optimering, der minimerer brændselsforbruget i energisystemet og udnytter så meget vindkraft som muligt.

Energisystemanalyserne viser, at med hensyn til at understøtte integration af vindkraft, er implementering af selve varmepumperne et vigtigt skridt, mens det har mindre betydning at koble varmelagre til varmepumperne. Således kan varmepumperne bidrage betydeligt til at fremme vindkraftinvesteringer og reducere systemomkostninger, brændselsforbrug og CO_2-emissioner. Det skyldes dels, at varmepumperne har en høj energieffektivitet og er økonomisk konkurrencedygtige. Derudover har de selv uden fleksibel drift en elbehovsprofil, som er velegnet til at integrere vindkraft. Den politiske udfasning af kul i Danmark mod 2030 giver desuden særligt gode muligheder for at anvende vindkraft til at dække elforbruget til varmepumperne.

At udstyre varmepumperne med varmelagre giver kun moderate systemgevinster. Heraf er den største systemfordel, at behovet for spids- og reservelastkapacitet kan reduceres ved at udglatte spidserne i elforbruget; i Danmark med 300-600 MW svarende til et stort kraftværk. Dette kan opnås ved samfundsøkonomisk rentable investeringer i varmelagre til varmepumperne. Potentialet for at reducere investeringer i spids- og reservelastkapacitet er afgørende for rentabiliteten af varmelagrene.

Intelligent varmelagring i bygningskonstruktionen er identificeret samfundsøkonomisk rentabelt i 20-75 % af husene med varmepumper afhængig af især omkostningerne til kontroludstyr. Det er desuden fundet samfundsøkonomisk rentabelt at investere i kontroludstyr, der understøtter anvendelse af eksisterende varmtvandsbeholdere til fleksibel drift af varmepumperne i omkring

20-70 % af husene. Derimod er varmeakkumuleringstanke pga. deres højere investeringsomkostninger ikke konkurrencedygtige.

Yderligere analyser undersøger systemeffekterne af en gradvis storskala-implementering af batteri-elbiler og plug-in hybrid-elbiler i Denmark, Norge, Sverige, Finland og Tyskland mod 2030. Ved intelligent ladning/afladning kan elbilerne fremme større vindkraftinvesteringer, mens de på kort sigt i mange tilfælde sandsynligvis vil øge den kulbaserede elproduktion. Elbilerne bidrager betydeligt til at reducere CO_2-udledningerne, mens de samlede systemomkostninger øges pga. en antaget implementering af de investeringstunge batteri-elbiler. Behovet for spids- og reservelastkapacitet kan reduceres ved at sørge for, at elbilerne kan levere elektricitet tilbage til elsystemet.

Fleksibel drift vil være vigtigere for elbiler end for individuelle varmepumper. Det skyldes, at i en situation uden fleksibel drift vil elforbruget til opladning af elbilerne typisk være koncentreret i spidslasttimerne for det konventionelle elforbrug, mens individuelle varmepumper vil have en mere fordelt elbehovsprofil.

Konkurrerende fleksible energiteknologier, så som store varmepumper, elkedler og varmelagre i fjernvarmesystemet, er også inkluderet i energisystemanalyserne. Disse teknologier kan tilsammen øge vindkraftinvesteringer og reducere CO_2-emissioner i samme størrelsesorden som en storskala-implementering af elbiler. Forbindelsen mellem de store varmepumper/elkeder og de store fjernvarmelagre gør det muligt at lagre el som varme igennem længere perioder, når der er behov for det. Dette er en fordel i forhold til individuelle varmepumper og elbiler, som pga. mindre lagre primært vil kunne yde fleksibilitet inden for døgnet og timen.

Samlet set kan det konkluderes, at individuelle varmepumper, fleksible teknologier i fjernvarmesystemet samt plug-in hybrid-elbiler kan bidrage betydeligt til en omkostningseffektiv integration af vindkraft mod 2030. Varmelagre til individuelle varmepumper kan kun bidrage moderat hertil.

Publications

Primary publications

Paper I
Wind power impacts and electricity storage – A time scale perspective.
Hedegaard, K., Meibom, P.
Published in Renewable Energy. vol. 36, issue 1, pp. 318-324. January, 2012.

Paper II
Effects of electric vehicles on power systems in Northern Europe.
Hedegaard, K., Ravn, H., Juul, N., Meibom, P.
Published in Energy. vol. 48, issue 1, pp. 356-368. December, 2012.

Paper III
Wind power integration using individual heat pumps – Analysis of different heat storage options.
Hedegaard, K., Mathiesen, BV, Lund, H., Heiselberg, P.
Published in Energy. vol. 47, issue 1, pp. 284-293. November, 2012.

Paper IV
Energy system investment model incorporating heat pumps with thermal storage in buildings and buffer tanks.
Hedegaard, K., Balyk, O.
Accepted for publication in Energy. September, 2013.

Paper V
Influence of individual heat pumps on wind power integration – Energy system investments and operation.
Hedegaard, K., Münster, M.
Published in Energy Conversion and Management. vol 75. pp. 673-684. November, 2013[1].

Paper VI
District heating versus individual heating in a 100 % renewable energy system by 2050.
Karlsson, K., Balyk, O., Zvingilaite, E., Hedegaard, K.
Peer reviewed conference proceeding published at the 6th Dubrovnik Conference on Sustainable Development of Energy Water and Environment Systems, September 25-29, 2011.

Report chapter
Electricity for Road Transport, Flexible Power Systems, and Wind power.
Chapter 9: Balmorel model results – EVs and power system investments.
Hedegaard, K., Ravn, H., Juul, N., Meibom, P.
Risø-Report, Risø-R-1804 (EN), December 2011. Systems Analysis Department, Risø DTU National Laboratory for Sustainable Energy

[1] Published online: September 11, 2013.

Secondary publications

Conference proceedings later expanded and submitted to international scientific journals
Effects of electric vehicles on power system investments and operation.
Hedegaard, K., Ravn, H., Juul, N., Meibom, P.
Peer reviewed conference proceeding. 6th Dubrovnik Conference on Sustainable Development of Energy Water and Environment Systems, September 25-29, 2011.

Wind power impacts, electricity storage, and heat measures – A time scale perspective.
Hedegaard, K., Meibom, P.
Conference proceeding, Risø International Energy Conference, May 10-12, 2011.

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Abbreviations

Energy and monetary units

DKK	Danish kroner
€, EUR	Euro
M€	Million euro
MW	Mega watt
MW-e	Mega watt electricity
MW-th	Mega watt thermal
TWh	Tera watt hours (3.6 Peta joule)
USD	US dollar

Other abbreviations

BEV	Battery electric vehicle
DH	District heating
CO_2	Carbon dioxide
CHP	Combined heat and power
EV	Electric vehicle
Flex	Flexibility
HP	Heat pump
iHP	Individual heat pump
inv.	Investment
O&M	Operation & maintenance
PHEV	Plug-in hybrid electric vehicle
TSO	Transmission System Operator

Nomenclature

Indices

a, A	heating area, set of heating areas in simulation
h, H	time period (hour), set of time periods in simulation
g, G	generation technology/storage, set of generation technologies/storages in simulation
G^{El}	set of electricity generation technologies in simulation
r, R	region, set of regions in simulation

Parameters

cc	capacity credit of electricity generation unit ( )
C^B	effective heat capacity of building structure (Wh/°C/m^2 floor area)
C^I	heat capacity of indoor air, furniture and for radiator heating systems, also water in radiators (Wh/°C/m^2 floor area)
C^F	heat capacity of concrete floor heating system, incl. concrete and water in tubes (Wh/°C/m^2 floor area)
C^L	effective heat capacity of walls/ceiling (Wh/°C/m^2 floor area)
D^{ElConv}	conventional electricity demand, i.e. excl. heat pumps, electric boilers, and electricity storage (MW)
KE	capacity of existing generation technologies (MW) and storages (MWh)
T^O	ambient (outdoor) air temperature (°C)
Q^{Pel}	heat contribution from persons and electrical appliances (W/m^2 floor area), (MW)

Variables

KN	capacity of new generation technologies (MW) and storages (MWh)
D^{ElFlex}	electricity consumption for heat pumps/electric boilers and loading of electricity storages (MW)
LD^{ACT}	loading of heat accumulation tanks (MW)
T^B	temperature of building structure (°C)
T^F	temperature of floor (°C)
T^I	temperature of indoor air (°C)
T^L	temperature of walls/ceiling (°C)
Q^{Cool}	cooling (MW)
Q^{SH}	space heating from existing and new heating installations and unloading from heat accumulation tanks (MW)
Q^{Ven}	ventilation loss through building envelope (MW)
Q^{IB}	heat transfer from indoor air to building structure (MW)
Q^{BO}	heat transfer from building structure to ambient air (MW)
Q^{FI}	heat transfer from floor to indoor air (MW)
Q^{IL}	heat transfer from indoor air to walls/ceiling (MW)
Q^{LO}	heat transfer from walls/ceiling to ambient air (MW)
Q^{TLos}	heat loss from heat accumulation tanks contributing to space heating (MW)

1 Introduction

1.1 Challenges of wind power integration

Our energy systems face serious challenges of reducing greenhouse gas emissions and relieving the dependency on fossil fuels [1]. Wind power is considered an important renewable energy source, due to its high economic competitiveness [2]. This is reflected in the significant increases in wind power capacities planned in many countries [3]. However, wind power is not dispatchable like e.g. biomass fired power plants, but expresses significant fluctuations depending on wind variations [4]. This challenges an efficient integration of large amounts of wind power. As such, in high wind systems, wind generation will often exceed electricity demand, resulting in forced electricity export (see Figure 1).

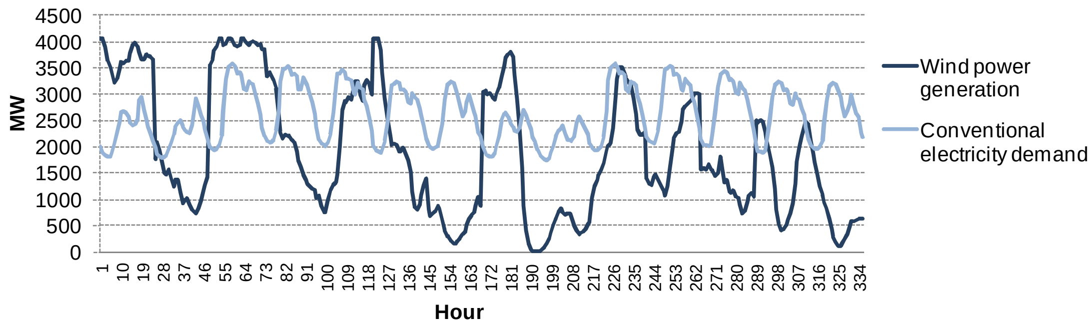


Figure 1. Wind power generation and conventional electricity demand in Western Denmark by 2020 for a wind power share in Denmark of around 50 % of annual electricity demand [5]. A two week period in March is illustrated.

High excess electricity production combined with bottlenecks in the transmission lines can have a substantial effect on electricity prices [6] and even negative electricity prices can occur, as could be observed for single instances during the last years [7]. The variability of wind moreover creates a need for dispatchable power plants to back it up in low wind periods, as also illustrated in Figure 1. Additionally, wind power is only partly predictable, which can create a costly need for reserve capacity investment and operation, responding to forecasts errors [8].

Denmark is among the countries in the world with the highest share of wind power in the system, currently around 30 % of annual electricity demand [9], and this share is planned to increase to 50 % by 2020 [10]. The Danish energy system thus forms an interesting case for analysing the challenges of integrating large amounts of wind power. Moreover, the Danish energy system is characterised by a large share of district heating (46 % [11]) and combined heat and power (CHP, 55% of thermal power production [12]). The high share of CHP increases the energy efficiency of the system but can also contribute to generating excess electricity production, due to constraints between heat and power generation [7, 13]. Analyses of the Danish system are therefore particularly relevant for other countries, which strive to integrate large amounts of wind power and at the same time ensure a high efficiency of the energy system.

In the context of wind power integration, Denmark benefits from the electrical interconnections with Norway and Sweden, which give access to vast hydro power reservoirs. These reservoirs function as large scale electricity storages, since water intake to the reservoirs can be stored in high wind periods and then used for hydro power generation in low wind periods. This contributes to improving the possibilities of integrating large amounts of wind power in the Danish energy system [14]. Furthermore, Denmark has benefited from the option of exporting excess electricity to Germany [15].

1.2 The role of heat pumps, heat storages, and electric vehicles

As described above, electrical interconnections to neighbouring countries can contribute significantly in meeting the challenges of integrating wind power. However, significant wind power expansions are also expected in neighbouring regions, particularly German wind power installations in the North Sea, and wind power production from these sites is highly correlated to production from wind turbines in Western Denmark. This will reduce the benefit of exporting electricity to Germany in high wind periods, in the future [14, 15]. Similar tendencies are expected for other neighbouring regions to Denmark [14]. Flexible electricity demand technologies are therefore considered a valuable contribution in supporting an effective integration of wind power in Denmark [14]. In this regard, large heat pumps in the district heating system, individual heat pumps in the residential sector, and electric vehicles in the transport sector are expected to play an important role [6, 14, 16].

Due to the high efficiency of these technologies compared to the technologies they displace, e.g. individual boilers, and combustion engines in conventional vehicles, they can reduce the fuel consumption of the energy system [6, 11]. By displacing fossil fuels, particularly the use of oil products in individual boilers and in the transport sector, they can moreover increase security of supply [14]. The heat pumps and electric vehicles also contribute in making a larger part of society's energy demands electricity based. This improves the possibilities for using wind power and other renewable energy sources to cover the energy demands of the system. This can in itself support the integration of renewable energy and increase security of supply. The use of heat pumps for integrating wind power furthermore benefits from the fact that both wind power and heat demand are typically high in the cold periods [14].

As illustrated in Figure 2, the Danish Transmission System Operator (TSO), Energinet.dk, expects that individual heat pumps and large heat pumps will comprise a significant part of the Danish electricity demand by 2030.

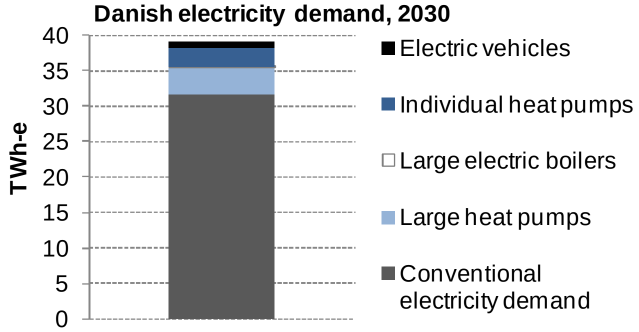


Figure 2. Danish electricity demand in 2030 as expected by Energinet.dk (incl. grid losses) [5].

Energinet.dk expects that electric vehicles will constitute a relatively low part of the electricity demand towards 2030, based on the challenges of competing with conventional vehicles; but also stresses the uncertainty associated with the projection. Large electric boilers are here estimated to represent a very low electricity demand annually since they, due to their low efficiency, will typically be operated in relatively few hours of the year, when electricity prices are sufficiently low[2].

Apart from contributing in electrifying the energy system and increasing its energy efficiency, heat pumps and electric vehicles can provide flexibility to the system, if utilising the storage options available. Large heat pumps can be connected to thermal storages used in the CHP system, individual heat pumps can store heat in the building structure and/or in thermal storage tanks, and electric vehicles can utilise their batteries. As a result, heat pumps and electric vehicles can be integrated as a flexible electricity demand in the system. Electric vehicles can with vehicle-to-grid capability moreover deliver power back to the system when needed [2, 17, 18].

A variety of dedicated electricity storage technologies also exists, e.g. pumped hydro storage, compressed air energy storage (CAES), electrolysis combined with fuel cells, and batteries/flow batteries, which can provide system flexibility. Hereof, pumped hydro is today the most developed and cost-effective technology for large scale electricity storage [19, 20]. However, this is not an immediate option to utilise locally in Denmark, due to the lack of suitable topography [20]. The other electricity storage technologies are known to be expensive and some still require significant technology development [2, 13, 20-23]. This is also reflected in the fact that Energinet.dk, together with expansion of electrical interconnections, considers heat pumps and electric vehicles (not electricity storage technologies) as the most important wind integration measures in a near term perspective [14].

Overall, heat pumps, heat storages, and electric vehicles can potentially play an important role in supporting the integration of wind power in near future. Analyses are needed to improve the understanding of the potentials and limitations of these technologies. The technologies have different technical and economic properties and will compete with each other in providing flexibility to the system. Moreover, they will affect the operation of the energy system and can also affect energy system investments. These complex interactions can be captured in the use of energy system models.

1.3 Goals and research question

The above arguments form the background for the PhD project, which has the goals to:

1. *Contribute to the national decision-making with regard to using heat pumps, heat storages, and electric vehicles in supporting wind power integration*
2. *Improve the modelling of some of the wind integration technologies enabling a better representation and understanding of their potentials and limitations.*

[2] Efficiency: 1 kWh-e converted to approx. 1 kWh-th. Full load hours: 200 full load hours here assumed, representing typical magnitude as given in [118].

The PhD project aims to yield a scientific contribution to answering the following general research question:

- *To which extent can heat pumps, heat storages, and electric vehicles contribute to integrating wind power?*

The results are intended as input to policy makers in prioritising efforts and incentives within the field of wind power integration. The potential users of the model developments in the thesis are researchers and other professionals using energy models.

The main focus is placed on wind power integration in the Danish energy system towards 2030. System effects of heat pumps, heat storages, and electric vehicles, will be evaluated in terms socio-economic costs, fuel consumption, and CO_2 emissions. Moreover, effects on energy system investments will be analysed, particularly to which extent the different technologies can facilitate larger socio-economically optimal wind power investments and reduced need for dispatchable power capacities. Considering the gaps in existing research within in the field, the main focus is put on individual heat pumps in the residential sector and complementing heat storage options.

The thesis is structure in the following way. First, the content of each of the paper is briefly described, including the connections between the papers. Next, an overview is given of relevant previous studies in the field. In this regard, the gaps identified in the existing literature are brought forward, thereby presenting the background for the focus of each paper. Chapter 2 describes the technologies analysed and expected demands for power balancing. The methods applied in the thesis are described in Chapter 3, covering the choice of models and the model developments performed. In Chapter 4, results of the energy systems analyses are presented and compared. Finally, a discussion and conclusion is given in Chapter 5. All full papers can be found in Appendix.

1.4 Contents of papers

The thesis includes six papers and a report chapter. An overview of the different publications is given in Table 1, also indicating how model development and energy systems analysis, performed by the author, is distributed among the publications.

Table 1. Overview of primary publications in the thesis.

Paper	Main focus	Model development	Energy systems analysis
Paper I	Wind power impacts and power balancing potentials of different flexibility measures		
Paper II + Report	Electric vehicles	+	X
Paper III	Individual heat pumps and heat storages	++	X
Paper IV	Individual heat pumps and heat storages	+++++	(X)
Paper V	Individual heat pumps and heat storages		X
Paper VI	District heating vs. individual heating	+	X

As shown, three of the papers focus on individual heat pumps and heat storages. One paper (and report chapter) focuses on electric vehicles, while the remaining two papers focus on other aspects related to wind power integration. Model development and/or energy systems analysis is performed in most of the papers; however, the main model development is undertaken in Paper IV and Paper III. The content of each paper is described further in the following. Throughout the thesis, references are made to the papers when relevant.

Paper I, "Wind power impacts and electricity storage – A time scale perspective", investigates wind power impacts and the expected demands for power balancing on different time scales for a future high wind system. The system of Western Denmark in 2025, with an expected wind power share of 57 %, is used as a case study. Furthermore, the paper categorises electric vehicles and a number of different electricity storage technologies, in terms of the time scales at which they are suited in providing power balancing. As a follow up, an addition has been made in the thesis, where heat pumps, electric boilers, and heat storages, are categorised in the same way.

In Paper II, "Effects of electric vehicles on power systems in Northern Europe", it is analysed how a large-scale penetration of battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) in Denmark, Finland, Norway, Sweden, and Germany towards 2030 would affect the energy systems. The paper investigates to which extent the electric vehicles can incorporate larger amounts of wind power into the system and reduce the need for dispatchable generation capacity, and how they will affect system costs and CO_2 emissions. Various energy systems analyses are performed using the Balmorel model and applying a socio-economic optimisation.

Paper III, "Wind power integration using individual heat pumps – Analysis of different heat storage options", focuses on the potentials of individual heat pumps and their different heat storage options, in terms of ensuring a fuel- and cost-efficient utilisation of wind power. The study covers model development and energy systems analysis, in EnergyPLAN, of the Danish energy system in 2020 with around 50 % wind power. The model development enables the representation of flexible heat pump operation utilising passive heat storage and heat accumulation tanks. A technical optimisation is applied that minimises total fuel consumption of the system and utilises as much wind power as possible.

Paper IV, "Energy system investment model incorporating heat pumps with thermal storage in buildings and buffer tanks", presents extensive model development in Balmorel. A model add-on is presented that facilitates optimising investments and operation of individual heat pumps and different heat storage options, in integration with the energy system. It is in Paper III found that intelligent heat storage in the building structure is the most fuel-efficient and cost-effective heat storage option among those analysed. Therefore, particular emphasis is put on this option in the further model development. The model developed in Paper IV thus improves the representation of the heat dynamics of buildings, compared to the modelling approach in Paper III. The model covers passive heat storage in the building structure via radiator heating systems, active heat storage in concrete floors via floor heating systems, and the use of thermal storage tanks. Through illustrative analyses and comparison with measured data, it is shown that the model is well qualified for analysing the possibilities and system benefits of operating individual heat pumps intelligently. This includes peak load shaving and prioritising heat pump operation for hours with low marginal electricity production costs.

In Paper V, "Influence of individual heat pumps on wind power integration – Energy system investments and operation", the Balmorel model add-on presented in Paper IV is applied in several energy systems analyses. Through socio-economic optimisations of the Danish energy system by 2030 with optimised wind penetrations of about 50-60 %, it is investigated how important individual heat pumps and their heat storage options are for the integration of wind power. Effects on wind power investments, the need for peak/reserve capacities, fuel consumption, CO_2, and system costs etc. are quantified. The analyses also reveal to which extent it will be socio-economically feasible to invest in different types of heat storages for the heat pumps.

The background for Paper VI, "District heating versus individual heating in a 100 % renewable energy system by 2050" is that district heating in the Danish energy system is determining for the future potential of installing individual heat pumps and large heat pumps and thermal storages in the CHP system. As such, the district heating grid sets boundaries for the possibilities of using these technologies for supporting wind power integration. Against this background, it is investigated whether there is a clear socio-economic advantage of building and operating a large-scale district heating system, in a long term perspective, i.e. in a 100 % renewable energy system by 2050. The analysis is most relevant for countries without existing district heating infrastructure.

1.5 Previous studies

In this section, a brief overview is given of existing studies within the research fields covered in the thesis. The main focus in the literature review is put on individual heat pumps, in line with the main focus of the thesis as a whole. More detailed literature reviews can be found in the introduction of the papers given in Appendix.

1.5.1 Individual heat pumps and heat storages

A number of studies have dealt with demand side management for increasing system flexibility in a more broad sense, e.g. [24-28]. However, the analysis of individual heat pumps in an energy system context is a relatively new research area. As such, very few studies within this area have been identified at the early stages of this PhD project. This forms an important part of the background for paying special attention to this research field in the project.

Recently, a significant amount of studies focusing on intelligent operation of individual heat pumps have emerged. A large group of these, apply a single building level perspective, e.g. [29-33] [34] and some apply a more large scale perspective, covering up to a few hundreds or thousands of buildings, e.g. [35-40]. However, only few studies analyse individual heat pumps in energy system models on national scale [8, 14, 41, 42].

All the studies identified apply models that cover only operation of the system, i.e. excluding investments. The reports by the Danish TSO [14] and the Danish Energy Association [8] make estimates on potential reductions in peak capacities, through flexible operation of the heat pumps. However, these estimates are made separately and not as part of the optimisation. Furthermore, the flexible operation is in these studies not modelled, but e.g. in [14] merely represented as a modified fixed demand profile, assuming that operation can be optimised within the day.

Individual heat pumps and complementing heat storages could have important effects on e.g. wind power investments and the required investment in peak and reserve capacities. Moreover, flexible operation of the heat pumps requires investment in control equipment and/or thermal storage tanks on consumer level. Such investments could suffer from low economies of scale, and will in some aspects compete with other flexibility measures in the system. These issues call for a model that can analyse individual heat pumps and heat storage options in integration with the energy system, when optimising both operation and investments. This forms the background for the model development presented in Paper IV.

Most of the existing studies in the field focus on presenting methods and control concepts for how individual heat pumps (or electric heating) can be operated flexibly, responding to the needs of the power system: i.e. contribute in load shifting, peak load shaving, delivering ancillary services, and in increasing wind power utilisation. Only few studies analyse how the heat pumps will affect the energy system [8, 14, 41, 42], and none of these apply an energy system model optimising both operation and investments. This is done in Paper V.

Several of the existing studies focus on using heat storage in the building structure for flexible heat pump operation, e.g. [36, 37, 41, 43, 44], while fewer focus on using thermal storage tanks, e.g. [35]. This indicates widespread acknowledgment of the potentials for utilising the thermal storage capacity of buildings in supporting flexible heat pump operation.

1.5.2 Electric vehicles

The modelling of electric vehicles in integration with the power system has been a research area for a longer period of time, comprising several studies, e.g. [2, 17, 45-53]. However, none of the existing studies investigate how transition towards increased electrification of the transport sector would affect power system investments and operation. This forms the background for Paper II, where this is analysed for the cases of Denmark, Norway, Sweden, Finland, and Germany.

1.5.3 Other fields

No previous studies have been identified that deal with future wind power impacts and expected demands for power balancing, by analysing the occurrence and length of low net load periods (high wind power and low electricity demand) and high net load periods (low wind power and high electricity demand). This is the point of departure for Paper I.

Previous studies analysing district heating versus individual heating in energy system models [11, 54] have used the existing district heating grid as a premise, and have analysed whether it is feasible to expand the district heating grid further. As supplement, it is relevant to analyse the socio-economic competitiveness of district heating versus individual heating, in a long term perspective, for a situation without existing district heating infrastructure as a premise. This perspective is however mainly relevant for countries without a district heating grid present. The above forms the background for Paper VI. Another new contribution of this paper, compared to the above mentioned studies [11, 54], is that possibilities to invest in heat savings in buildings are modelled endogenously, as an alternative to heat generation. Additionally, human health externalities related to local air pollution are internalised in the socio-economic cost optimisation. Heat savings and externalities are represented using the model developed in [55].

2 Technologies and power balancing

This chapter first summarises the results of Paper I, in terms of the expected demands for power balancing in a near term Danish high wind system. The term *power balancing* is here used in a broad sense, covering balancing responding to imbalances in supply and demand intra-hour and over longer periods, lasting up to several days or more. The future demands for power balancing intra-hour have however not been analysed.

Subsequently, the *flexibility measures* covered in the thesis are described: 1) Individual heat pumps and heat storages 2) Large heat pumps, electric boilers, and heat storages in the district heating system and 3) Electric vehicles. Main emphasis is here put on the technologies' technical potentials of providing power balancing, based on their storage possibilities and response times. At the end of the chapter, the power balancing potentials of the different technologies are compared and their magnitude illustrated.

2.1 Demands for power balancing

In Paper I, the case of Western Denmark in 2025 with an expected 57 % wind power penetration is used for analysing the expected demands for power balancing on different time scales. The system impacts of wind power have been analysed based on hourly data of net load (residual load), defined as gross load (electricity demand) minus wind power and minus an assumed minimum production at centralised power plants for grid stabilisation. The following two challenging operational situations are treated, namely:

- *Low net load periods* i.e. hours with low electricity demand and high wind power, representing hours with low electricity prices.
- *High net load periods*, i.e. hours with high electricity demand and low wind power, representing hours with high electricity prices.

By analysing the length of low and high net load periods, the expected demands for power system balancing at different time scales are investigated. Regarding the low net load periods, focus is placed on negative net load periods, representing situations with expected excess electricity production. The length of the low/high net load periods are analysed with the aim of investigating the demands for power balancing, in the following time scales:

- *Intra-day:* High/low net periods of one hour to around half a day (12 hours), corresponding to a time scale typically relevant for power balancing within the day, i.e. e.g. flexible electricity demand of one to several hours or e.g. shifting of demand from day to night.
- *Intra-week:* High/low net load periods approaching one day to several days, corresponding to a time scale relevant for balancing intra-week
- *Seasonal:* High/low net loads periods representing imbalances in supply and demand over months.

The results in Paper I indicate a demand for technologies capable of flexibly charging/activating demand and discharging/inactivating demand in periods of one hour to around half a day, providing intra-day balancing. Furthermore, the results indicates an expected demand for technologies flexibly charging/activating demand in periods approaching one day to several days, i.e. providing balancing intra-week, as well as a potential for power balancing on seasonal level.

The net load approach above is based on assuming perfect foresight on wind power and load. As such, this approach only captures the variability and not the imperfect predictability of wind power and load. In reality, forecast errors on wind power and load (as well operation problems at power plants and in transmission lines) create an additional need for power balancing. This is in the Danish system handled at the regulating power market and the reserve market (see Table 2).

Table 2. Current Danish electricity markets.

Market	Description
Elspot	Integrated part of the Nordic day-ahead spot market where power production, based on market bids and forecasted electricity demand and wind power, is planned for every hour of the next day, 12 to 36 hours before the actual operation hour.
Elbas	A continuous market operating after the end of the spot market where market actors expecting deviations between realised production and day-ahead production plans, have the possibility of trading with an official price towards balance up until 1 hour before the operating hour.
Regulating power market	Deviations between operation as planned after Elspot and Elbas and actual operation are balanced intra-hour by the TSO, using power installations with a response time of 15 minutes. The most important causes for imbalances are forecast errors on wind power and demand and operation problems at plants and in transmission lines, including outages.
Reserve market	The TSO buys system services, including primary and secondary reserves, which, in case of small imbalances of supply that have not been balanced by the regulating market, re-establish the balance and stabilise the frequency. • Primary reserves: frequency controlled, response time of a few to 30 seconds and deliver power of maximum 15 minutes (Western Denmark)[3]. • Secondary reserves: Response time of 15 minutes and rarely deliver power for longer than 15 minutes (Western Denmark)[2].

Sources: [56-58].

The models used in the energy systems analyses in the thesis, Balmorel and EnergyPLAN, have an hourly time resolution and are both deterministic, i.e. assuming perfect foresight of wind power and load [59, 60]. As such, the operation of the regulating power market and the reserve market is not integrated in the models. Nevertheless, the need for reserve capacities is incorporated via a capacity balance restriction, in the analyses in Balmorel (see Section 3.5 for the capacity balance restriction applied in the analyses of individual heat pumps). This ensures and adequate production capacity and reserve margin in each power region, taking into account the variable and only partly unpredictable nature of wind, and the risk of failure on transmission lines. The term *reserve capacity* is used in this broad sense, in the modelling in this thesis.

[3] In Eastern Denmark, Frequency controlled normal operation reserves and Frequency controlled operation disturbance reserves are instead used [56].

2.2 Individual heat pumps and heat storages

Heat pumps transfer heat from a low-temperature location, i.e. the heat source, to a warmer location, using energy input in the process. All individual heat pumps today are compression heat pumps, using electricity as input (in contrast to absorption heat pumps using steam, hot water or flue gas as input [61]). Individual heat pumps with a water-based central heating system, i.e. ground source heat pumps and air-to-water heat pumps, can store heat in thermal storage tanks, the building structure, and the central heating system. Thereby, they can provide a distributed flexible electricity demand. Individual heat pumps represent a *shiftable electricity demand*, since the heat pumps are restricted to satisfy the heat demand, while their operation can be shifted in time [62]. The energy efficiency of heat pumps can be characterised by the coefficient of performance (COP):

$$Heat\ output = Electricity\ consumption \cdot COP$$

For instance, a COP of 3 means that the heat pump converts 1 kWh electricity and 2 kWh of heat collected from the heat source (typically the ground or ambient air) into 3 kWh of heat output [63]. The COP in a given instance is closely related to the temperature lift, i.e. the difference between the temperature of the heat source and the output temperature of the heat pump. The higher the temperature lift required, the lower the COP [64, 65]. As such, the COP can vary from hour to hour; more for air-water heat pumps than for ground source heat pumps, considering that ambient air temperature variations are larger than ground temperature variations. It is however complex to model hourly COP variations and it can be difficult to handle in linear models. In energy systems analyses and technology assessments, an annual average COP is thus normally applied, as also done in this thesis.

Ground source heat pumps and air/water heat pumps are typically supplemented by an electric boiler to cover peak loads, in order to reduce heat pump investment costs. The heat pump is typically dimensioned to 72%-82 % of the total capacity [66]. Thereby, the heat pump can cover about 99 % of the annual heat demand[4]. The electric boiler has an efficiency of around 1, i.e. it converts 1 kWh electricity to 1 kWh heat. The influence of the electric boiler on the electricity consumption is illustrated in Figure 3. As shown, the electricity consumption increases significantly, when the heat demand exceeds the heat pump capacity, thereby forcing use of the less efficient electric boiler.

[4] For a full year simulation in a thermal building model, using ambient temperatures in [119].

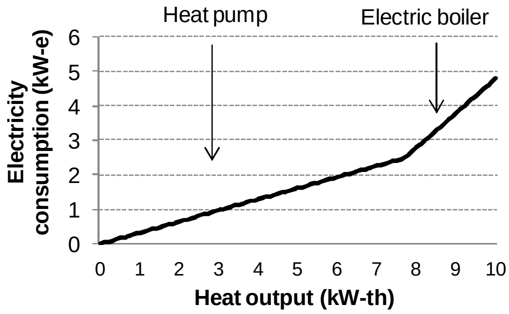


Figure 3. Illustration of how the supplemental electric boiler influences the electricity consumption of individual heat pumps. A total heat installation capacity of 10 kW-th, a heat pump capacity share of 77 %, and a COP of 3.1 is applied.

Heat pumps can be regulated between cold and full load instantly [67] and can thus deliver ancillary services intra-hour, i.e. up/down regulating power and secondary reserves through up/down regulation of demand [14, 36, 38, 39, 68, 69]. Heat pumps can be frequency controlled and thus also deliver primary reserves. [68].

It is hardly realistic to expect households to engage in individual trading on the electricity markets. As such, it is more likely that e.g. a balancing responsible agent controls a large group of heat pumps on aggregated level. This control concept is currently being demonstrated in a project initiated by Energinet.dk [14, 69]. In fact, a load of minimum 10 MW is currently required in order to be able to act on the regulating power market [56], which in itself necessitates the pooling of a large amount of individual heat pumps.

Individual heat pumps are generally available in two main types of regulation: *on/off regulation* and *capacity regulation*, continuously variable down to about 20 % of the maximum capacity. In on/off regulation, the compressor will work full load and stop at intervals adapted to the heat demand, while capacity regulation works through a variable-speed compressor where the amount of refrigerant flow through the refrigerant cycle is adapted to the demand. Most air-water heat pumps and all ground source heat pumps on the market today have on/off regulation [63].

The ability to shift demand from hour to hour depends on the available heat storage capacity. Ground heat pumps and air-to-water heat pumps for one-family houses are today typically installed in combination with a 150-200 litre tank for hot water (for showering, dish washing etc.), and a small buffer tank, typically around 40-80 litres. The buffer tank ensures that the number of heat pump start-ups can be minimised thereby enabling better operating conditions and improving the technical life-time. The buffer tank is nevertheless not large enough to enable flexible operation from hour to hour [18, 70]. Such flexibility can however be achieved if investing in a heat accumulation tank connected to the space heating circuit. Given space requirements, heat accumulation tanks of up to around 1000 litres can realistically be installed in a one-family house [18]. The small hot water tank can to some extent also shift demand from hour to hour; however, its storage capacity is limited, corresponding to less than one hour of full heat pump load [71].

As an alternative to using thermal storage tanks, heat can be stored passively in the building structure through radiation, thermal conductance, and convection, if allowing some variation in the indoor temperature. The term *passive* refers to the fact that the heat transfer occurs without the use of a heat transferring media going in and out of the storage [72]. Houses with a central concrete floor heating system can moreover store heat in the thermal mass of the concrete floor, via water tubes in the concrete, i.e. *actively* [72]. Concrete floor heating is the dominant type of floor heating installed in Danish houses today due to its low cost [73, 74] and is characterised by a large thermal capacity (in contrast to wooden floor heating systems, which have an insignificant thermal storage capacity [75]). In connection with utilising the storage capacity of buildings, an allowed indoor temperature interval of 20-23 °C during the day and 19-22 °C at night is considered realistic in satisfying thermal comfort needs. This is based on indoor temperature measurements in 28 Danish households [76] (see Appendix), as well as on indoor temperature preferences of a number of Danish households [32], and on [31].

The heat storage capacity of buildings can be increased with the use of phase change materials, thereby utilising latent heat storage. However, experiences show that the costs for such materials are unreasonably high, compared to the benefits they can provide (both for implementation in existing buildings and in new buildings) [75]. In the analyses of individual heat pumps in this thesis, focus is therefore placed on the other heat storage options described.

The magnitude of the different thermal storage potentials on house level is estimated in Figure 4a for a typical Danish one-family house. It should be noted that passive/active heat storage potentials will vary significantly from house to house, depending on the heat capacity of the building. The assumptions applied in the illustration are given in Table 3. Expected investment costs required for enabling the different thermal storage options are also illustrated in Figure 4b, given in annualised socio-economic costs.

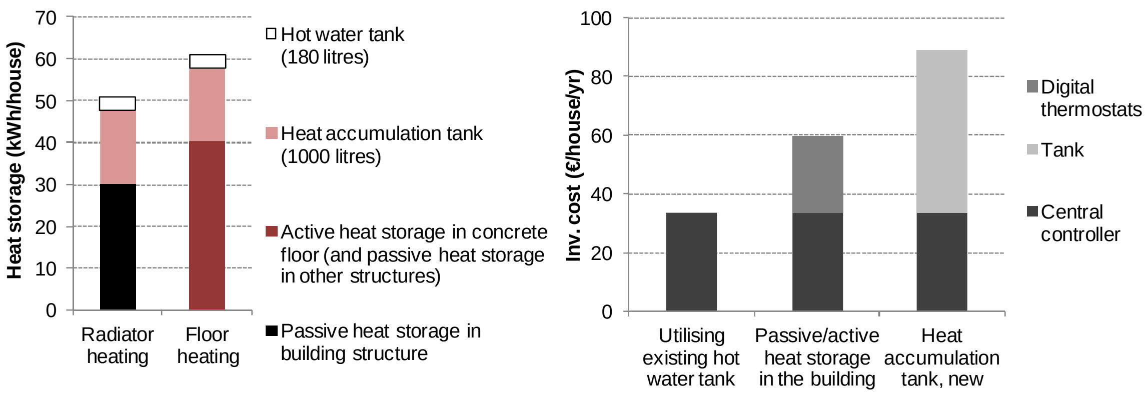


Figure 4. a) Magnitude of heat storage potentials for a typical Danish one-family house, depending on the central heating system. **b)** Investment costs for the different heat storage options are given in annualised socio-economic costs (source: [77, 78], discount rate of 3 % applied). Central controller cost represents expected cost, incl. installation [77].

Table 3. Assumptions applied in illustrating the magnitude of heat storage potentials for a typical Danish one-family house (151 m^2).

	Heat capacity	Temp. interval utilised in building, floor, or tank (°C)	Ref.
Passive heat storage in building structure	100 Wh/°C/m^2 floor area[a]	2[d]	[18]
Active heat storage in concrete floor	67 Wh/°C/m^2 floor area[b]	3[d]	[73, 74]
Heat accumulation tank (1000 litres)	17.4 Wh/litre	15[c]	[18, 70, 79]
Hot water tank (180 litres)	17.4 Wh/litre	15	[18, 71]

[a] Median of typical range for the *effective* heat capacity of Danish one-family houses 60-140 Wh°/C/m^2 floor area (the heat capacity of the building that can be utilised for passive heat storage diurnally) [79, 80]

[b] 10 cm concrete assumed, representing the typical application [35, 39].

[c] Up to 15 °C difference between forward and return temperature in the central heating system, representing a typical configuration of heat pumps in radiator heating, systems prioritising a reasonable COP [18, 70, 79].

[d] Simulations in a thermal building model have verified that this temperature difference can be utilised when allowing an indoor temperature variation of 20-23 °C at day and 19-22 °C at night and optimising heat pump operation diurnally.

Figure 4a shows that the heat storage potential offered by the hot water tank installed in connection with the heat pumps is relatively small, while heat storage in the building structure (passive/active heat storage) or in a large heat accumulation (1000 litres) can provide significantly larger storage capacities.

As shown, the total achievable heat storage capacity for a typical house is estimated to be in the magnitude of 50-60 kWh-th. When considering a typical heat pump capacity of around 6-8 kW-th (excl. supplemental electric boiler) [63, 81], the heat storage options can thus enable flexibility corresponding to several hours of full load heat pump operation. This illustrates that individual heat pumps through up/down regulation of demand can provide power balancing of several hours intra-day; if the required heat storage investments are made. Nevertheless, the storage potentials will typically not be sufficient to provide power balancing intra-week. This assessment is in agreement with the view in a recent report by Energinet.dk [82].

It can furthermore be noted that during the non-heating season, typically May 15 to September 15 in Denmark (33 % of the year), the heat storage potential of individual heat pumps will be limited to the small storage capacity of the hot water tank. Moreover, the capacity margin available for flexible operation is low in very cold periods, where the heat pump will be forced to operate at its capacity limit in several hours (illustrated in Section 4.2.2).

As shown in Figure 4b, flexible operation of individual heat pumps generally requires investment in control equipment communicating with the power system [77, 83]. In addition, intelligent heat storage in the building structure requires investment in digital thermostats, while the use of a heat accumulation tank requires investment in the tank [44, 83]. It can be seen that utilising the existing hot water tank is associated with the lowest investment costs; but on the other hand also offers limited storage potential. Among the two other heat storage options, intelligent heat storage in the building structure has lower investment costs than heat accumulation tanks. On the other hand, heat accumulation tanks have the advantage of not requiring any indoor temperature variation.

As indicated in Figure 4a, houses with concrete floor heating will typically have higher storage potential than houses with radiator heating. Furthermore, concrete floor heating systems deliver heat directly to the thermal storage in the concrete, which means that the heat pump can to some extent be operated flexibly, with only little indoor temperature variations, e.g. +/- 0.25 °C [30, 31]. In contrast, changes in the heat output from radiator heating systems will have a more direct influence on indoor temperatures. However, radiators have for a long period of time been the typical type of central heating system installed in connection with construction of new houses in Denmark. Furthermore, installation of floor heating in existing houses is expensive. As a result, radiator-based central heating is expected to comprise the bulk of the individual heat demand of Danish one-family houses by 2030 (see Figure 5). Therefore, when considering a large scale installation of individual heat pumps within this time frame, the storage possibilities offered by radiator heating systems are most important, while floor heating system are less influential.

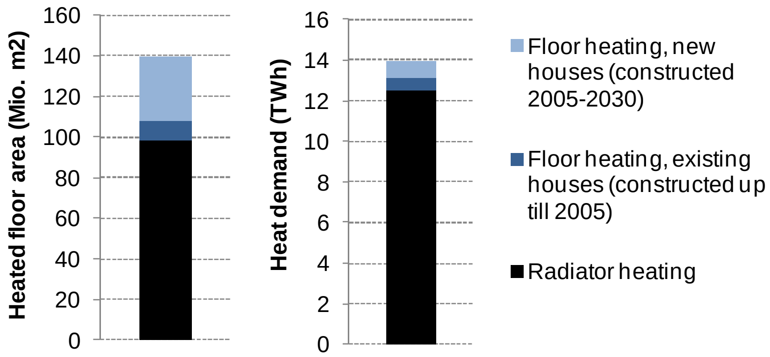


Figure 5. Individually heated one-family houses in Denmark by 2030 distributed on expected central heating system. Floor heating here represents central floor heating, i.e. not only in bathrooms/kitchen.
Sources: [74, 83-86].

Taking the distribution in Figure 5 into account, the total heat storage potential in individually heated one-family houses can be estimated to around 45 GWh-th. This corresponds to an electricity consumption for individual heat pumps of around 22 GWh-e, corresponding to some hours of high excess electricity production (negative net load)[5].

2.3 Large heat pumps, electric boilers, and heat storages in the district heating system

Large compression heat pumps and electric boilers can be connected to thermal storages in the district heating system and thereby represent a flexible electricity demand. Large heat pumps can moreover relieve CHP plants from heat bound power production and thereby increase system flexibility and support wind power integration. The thermal storages increase the flexibility of heat pumps and electric boilers and improve the integration of wind power into CHP systems: When wind power is high, possibilities for reducing power production from CHP plants are improved since heat demand can be satisfied from the heat storage, and when wind power is low,

[5] Assuming a COP of 3.1 and a heat pump capacity share of 77 % (the remaining covered by electric boilers).

feasibility of increasing power production at CHP plants is improved, since surplus heat production can be stored.

Large heat pumps and electric boilers represent a *convertible electricity demand,* when integrated in CHP plants, since the electricity demand can be converted to a fuel demand, using the fuel-based CHP units (or boilers) to satisfy the heat demand [62]. This creates good possibilities for turning off the heat pumps/electric boilers in longer periods with high electricity prices and in peak load hours, determining for the need for peak/reserve capacities. Large heat pumps can utilise various different heat sources to drive the process, i.e. waste-heat from industrial processes, heat in waste water, ambient air, ground, lakes or the sea [61]. Large heat pumps have a relatively high efficiency, but on the other hand also relatively high investment costs, compared to electric boilers (see Figure 6).

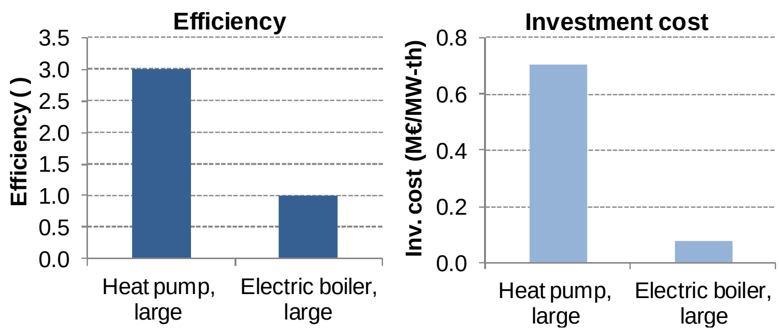


Figure 6. Efficiency and investment costs for large heat pumps (heat source: waste water) and electric boilers in the district heating system. Sources: [14, 87-89].

Therefore, investment in large heat pumps is only feasible to the extent that a relatively high number of full load hours can be ensured (4600-5200 full load hours identified for large heat pumps in Paper V). It will be economically attractive to operate large heat pumps in all hours where the ratio between the electricity price (in the given power region) and the district heating price (in the given area) is below the COP of the heat pump. For at heat pump with a reasonable COP, i.e. around 3, this can occur many hours of the year. In contrast, the low efficiency of electric boilers means that it is only economically attractive to operate them when the electricity price (incl. variable O&M cost) drops below the district heating price.

Large heat pumps and electric boilers can be regulated instantly and can thus deliver regulating power, and primary and secondary reserves [14, 67, 68, 90][6]. The possibility of using large heat pumps and electric boilers to flexibly activate demand in periods of several hours or days depends on the available thermal storage capacity. In Denmark, CHP plants typically have thermal storage tank capacity corresponding to two days to a full week of heat demand during the cold season [61, 91]. These heat storages can also be utilised for large heat pumps/electric boilers. Heat storage capacities can furthermore be increased in connection with installing heat pumps/electric boilers, and large scale thermal storage is relatively cheap, i.e. around 3 €/kWh-th (steel tank) [61] (and even lower for large seasonal storages) compared to 40-70 €/kWh-e for e.g. electricity storage in batteries [82]. Overall, large heat pumps and electric boilers are therefore

[6] However, among the electric boilers, only the type using electrical resistance have sufficiently low response time for delivering primary reserves [67].

suited for flexibly activating demand in periods of up to several days. As such, they can provide, provide intra-week balancing, in addition to intra-day and intra-hour balancing.

Due to storage capacity limitations and storage losses (typically corresponding to around 5 % of the stored content over a week [61]), conventional heat storages in the district heating system are not suited for storing heat across months [92]. However, the relative heat losses and investments costs per m^3 can be reduced significantly when up-scaling to very large heat storages and a few large seasonal thermal storage demonstration plants already exist in Denmark. The use of seasonal thermal storages have traditionally been focusing on improved utilisation of solar thermal, but can also be relevant for large heat pumps/electric boilers (or heat from waste and industrial waste heat) [92].

The economies of scale for thermal storages are illustrated in Figure 7, where also individual heat accumulation tanks are shown for comparison.

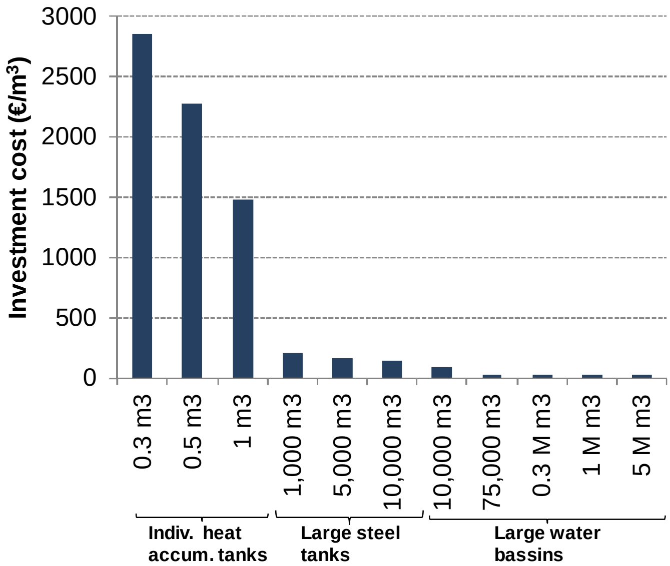


Figure 7. Investment costs per volume for different sizes of thermal storages. Large thermal storages: [92]. Individual heat accumulation tanks: [93].

It can be seen that the cost per storage volume is considerably lower for steel tanks in the district heating system compared to for individual heat accumulation tanks and even lower for seasonal thermal storages of large water basins. In addition, the relative heat losses are, as mentioned, lower the higher the heat storage (due to a reduced surface area in relation to storage volume) [92].

2.4 Electric vehicles

Plug-in electric vehicles can be divided in two overall categories:

- Battery electric vehicles (BEVs) driving on electricity only
- Plug-in hybrid electric vehicles (PHEVs) with a battery supporting short driving distances and a combustion engine, that can be used as a range extender, allowing for longer distance driving

With implementation of intelligent charging, electric vehicles can form a distributed flexible electricity demand. BEVs represent a *shiftable electricity demand*, as the demand can be shifted in time. The electricity demand of PHEVs can be characterised as a *convertible electricity demand,* since the combustion engine can be used as an alternative.

If intelligent vehicle-to-grid power capability is additionally implemented, the batteries can form a large-scale distributed electricity storage controlled by the needs of the electric system [50]. Electric vehicles can deliver high power to the grid within seconds and are well suited for delivering regulating power, and primary and secondary reserves [14, 15, 82]. Delivery of such ancillary services will very likely be the most beneficial are of the vehicle-to-grid capability [53].

Power flows between vehicle and grid can only take place when the vehicle is grid-connected. A typical weekday driving pattern can be assumed to express a cycle of driving for work in the morning and returning home in late afternoon. Electric vehicles will during this period only be grid connected to the extent that charging spots at employer lots and e.g. mass transit stations are set up and used. Moreover, with current battery technology, a typical battery electric vehicle has a driving range up to around 150 km per full charge [23] corresponding to a few hours of driving. Therefore, charging of BEVs on a daily basis will likely be pursued in most cases. If the expected larger driving ranges of BEVs, of up to 350 km towards 2030 [53], are achieved, daily charging would not necessarily be needed. However, even for a battery size supporting such a long driving range, 50 kWh-e [94], the electricity storage would not correspond to more than 7 hours of full load charging[7]. This indicates that the storage capacity of electric vehicles will, even in the longer term, mainly be suited for power balancing intra-day power and intra-hour (rather than intra-week balancing). This assessment is in agreement with the view in [82].

PHEVs have a shorter range in full electric mode, typically around 20-80 km per full charge [95]. Daily charging of PHEVs can be expected to be typical, due to the short battery range, and the fact that the lowest driving costs are achieved in electric mode [17, 53]. As such, also PHEVs can mainly be expected to provide power balancing intra-day.

A very ambitious large-scale implementation of electric vehicles corresponding to 53 % of the private passenger vehicle fleet, hereof 2/3 PHEVs and 1/3 BEVs (in total 1.7 million electric vehicles as assumed by 2030 in Paper II) corresponds to a total electric storage capacity of around 40 GWh-e. This corresponds to some hours of high excess electricity production. As such, even

[7] Assuming a grid-connection capacity of 6.9 kW, corresponding to a standard 230V connection with 3 phases 10 Amps each [15].

with a very large implementation, the electric vehicles cannot store several days of high excess electricity production.

If electric vehicles are not charged intelligently they will typically be charged at around 17:00-21:00 o'clock when people return from home, i.e. at the same time as the conventional electricity demand peaks. With intelligent charging, the battery can instead be charged over night when electricity prices are typically low and wind power high [14]. If utilising vehicle-to-grid capability, electric vehicles can deliver power back to the system, when conventional electricity consumption peaks and electricity prices are high, typically at around 9:00-13:00 o'clock and 16:00-20:00 [14], and/or when it is affordable to provide ancillary services.

2.5 Overview of the technologies' power balancing potentials

Figure 8 summarises the categorisation of the technologies, with respect to the time scales they will typically be suited for in supporting wind power integration.

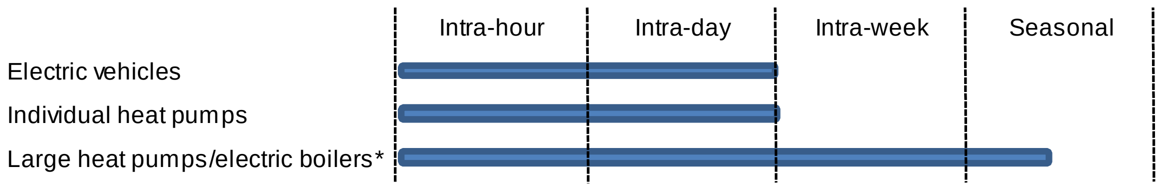


Figure 8. Categorisation of a number of flexibility measures in terms of the time scale, at which they will typically be suited for, in providing power balancing. *Seasonal balancing requires connection to seasonal thermal storages.

As shown, individual heat pumps and electric vehicles can provide power balancing intra-day and can also contribute in delivering ancillary services intra-hour. The connection to the large thermal storages in the district heating system makes large heat pumps and electric boilers capable of also providing intra-week balancing. In addition, they can contribute to seasonal power balancing, if combining them with seasonal thermal storages. Seasonal power balancing can however currently largely be handled through the electrical interconnections with Norway and Sweden, giving access to vast hydro power reservoirs [14]. As mentioned, the models used, Balmorel and EnergyPLAN, do not include operation of ancillary services intra-hour; however, the need for reserve capacities is included in the analyses in Balmorel (see Section 3.5).

In absolute terms (GWh-e), the power balancing potentials offered by individual heat pumps and electric vehicles will depend on the scale at which they are deployed in the system. However, the large scale implementations analysed in this thesis indicate that their balancing potential is in the same order of magnitude, i.e. 20-40 GWh-e, corresponding to some hours of high excess electricity production. According to data in the models, Balmorel, EnergyPLAN, and Ramses, the Danish district heating storages are in the same order of magnitude, i.e. 30-50 GWh-th. However, Energinet.dk roughly estimates the district heating storage to be around 300-500 GWh-th [82]. The magnitude of the different balancing potentials is illustrated in Figure 9. A district heating storage of 50 GWh-th, as used in Balmorel and EnergyPLAN, is here illustrated in parallel with the median of Energinet.dks high estimate, 400 GWh-th. As shown, the power balancing potential, represented by the district heating storages, depends on whether large heat pumps or electric boilers are used (due to differences in the electricity to heat conversion efficiency). The balancing potentials are purely technical, not economic, and are only used to illustrate magnitudes.

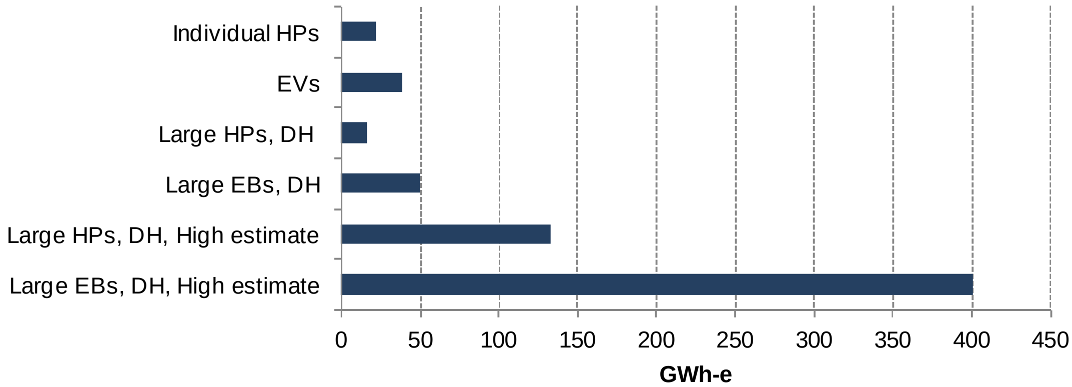


Figure 9. Magnitude of technical power balancing potentials (GWh-e) provided by individual heat pumps, electric vehicles, and the use of large heat pumps or electric boilers in Denmark. HP: heat pump. EV: electric vehicle. EB: electric boiler. DH: district heating.

Figure 9 shows that that in absolute terms, a large scale implementation of individual heat pumps and electric vehicles can provide power balancing in the same order of magnitude as the existing Danish district heating storages, according to the district heating data in the three energy system models. According to the higher estimates by Energinet.dk, the district heating system can however provide considerably larger balancing potentials, corresponding to up to several days of high excess electricity production. The Danish District Heating Association is currently investigating the size of the district heating storage potential [91].

In total, large heat pumps/electric boilers in connection with district heating storages, individual heat pumps and electric vehicles, can potentially provide a power balancing potential in the magnitude of 80-460 GWh-e, depending on the assumed district heating storage potential and whether large electric boilers or large heat pumps are used. In comparison, around 2000 GWh-e/year of excess electricity production have in a technical optimisation in the EnergyPLAN model been estimated, for the Danish energy system by 2020 with around 50 % wind power (in a situation without utilising these flexibility measures). Considering that the storages can be filled and emptied many times over the year, this indicates that heat pumps/electric boilers and electric vehicles can contribute significantly in increasing wind power utilisation and reducing excess electricity production, in the near term.

In a long term perspective, for a Danish system in 2050 independent on fossil fuels and with fluctuating renewable energy sources (mainly wind) comprising up to 80 % of annual electricity generation, Energiet.dk assess that heat pumps, heat storages, electric vehicles, and electrical interconnections, are not enough to handle the power fluctuations and to ensure security of supply [82, 96]. Moreover, the scarcity of biomass resources and the need for liquid/gaseous fuels for transport could create a need for converting electricity via electrolysis and hydrogen into various forms of renewable gases and liquids [13]. The vast gas storage capacities in salt caverns and underground formations could play an important role for storing such fuels [13, 82, 96]. The gas storages yield considerable storage potentials, around 11 TWh if stored as e.g. methane and 3-4 TWh if stored as hydrogen [82].

Overall, the technical power balancing potentials offered by heat pumps/electric boilers, heat storages, and electric vehicles, are of a magnitude facilitating a significant contribution to integrating wind power, in the near term. In the long term, towards a 100 % renewable energy system by 2050, additional energy conversion and storage technologies will likely become increasingly valuable.

3 Methods

Energy systems modelling and analyses forms the backbone of the methods applied in the thesis. As such, energy models are used in five of the six papers in the thesis. The Balmorel model is used in most of the studies, while EnergyPLAN is used in one of the papers. In this chapter, the background for selecting these two models is described. After short descriptions of the models, the model developments are then presented.

In the process of modelling and analysing individual heat pumps, several research institutions and producers of heat pumps have been contacted, in order to provide a solid ground for the work (see Acknowledgements). For model validation purposes, comparisons have been made with measured data for heat pump installations in Danish one-family houses [76].

3.1 Choice of models

The models used in the analyses have been chosen based on the following criteria. The models should:

- Have a sufficiently detailed representation of energy conversion and storage technologies (bottom-up models).
- Include hour-by-hour variations in wind power generation (and electricity and heat demand), in order to fully capture the influence of wind power variability.
- Represent the Danish CHP system, including back-pressure and extraction units, heat only boilers, large heat pumps, electric boilers, and thermal storages.
- Be able to cover individual heating (relevant for analyses focusing on individual heat pumps) and private passenger road transport (relevant for analyses focusing on electric vehicles)[8].
- Include a valid data set for the existing Danish heat & power plants and transmission and storage capacities.
- Be validated in scientific international journals.

Balmorel and EnergyPLAN both satisfy the criteria above and have therefore been selected. The reason for using EnergyPLAN in the first analysis of individual heat pumps is that such heat pumps have as a starting point been well represented in this model. Furthermore, EnergyPLAN includes the possibility of applying a technical regulation strategy. This facilitates analysing the potentials of individual heat pumps and heat storages, with respect to reducing excess electricity production and fuel consumption of the system, utilisation as much wind power as possible. Such technical potential cannot directly be revealed in economic optimisations.

The background for putting main emphasis on Balmorel in the PhD project is the following. First of all, Balmorel has the capability of optimising both investments and operation of all units in the energy system. This renders it possible to analyse the economic competitiveness of the different flexibility measures and to investigate whether they can facilitate increased wind power investments. Moreover, it allows for analysing to which extent flexible operation of e.g. individual heat pumps can reduce the need for investing in dispatchable power capacities. Finally,

[8] In Balmorel, only private passenger vehicles are currently represented via the transport add-on. EnergyPLAN also covers the other parts of the transport sector.

Balmorel provides direct access to model code, which is a necessity for allowing larger independent model developments.

3.2 EnergyPLAN

The EnergyPLAN model is developed and maintained at Aalborg University in Denmark. EnergyPLAN is a deterministic model, based on analytical programming and a selection of regulation strategies [97]. The model optimises the operation of an energy system over a full year with hourly time resolution. Inputs are demands and demand distributions, capacities of technologies included, distributions of fluctuating renewable energy sources, fuel potentials, fuel and CO_2 costs etc. The model outputs comprise energy balances, energy productions, fuel consumptions, CO_2 emissions, and costs etc. The model covers the whole energy system, i.e. individual heating and district heating, the electricity, transport, and industry sector [98]. EnergyPLAN is further described in [98, 99] and in [59], where previous applications and comparison with other models can also be found. The model allows the use of a technical regulation strategy, minimising fuel consumption of the system, or a market-economic regulation strategy, identifying the least-cost solution based on the business-economic costs of
the individual plant owners, assuming perfect competition. In EnergyPLAN, a full year simulation with hourly time resolution takes only a few seconds [98].

Individual heating is in EnergyPLAN represented as the total of space heating and hot water, using an aggregated heat demand profile. The electric boilers, which supplement individual heat pumps in covering peak loads, are included. The assumed capacity share of the heat pump is given as input by the user as a fraction (from 0 to 1). A heat storage capacity can be given as input (expressed in days of average heat demand).

3.3 Model development in EnergyPLAN

The model development performed in EnergyPLAN renders it possible to represent the following heat storage options:

- *Intelligent passive heat storage*: utilising the heat storage capacity of the building structure for flexible heat pump operation.
- *Heat accumulation tanks:* using a thermal storage tank operating on the space heating circuit for flexible heat pump operation.

The modelling of passive heat storage is focused on representing radiator heating, as this will be the dominating central heating system in Danish houses for many years to come (see Section 2.2). The modelling of heat accumulation tanks is generally applicable to both radiator heating and floor heating systems. The principle of the two different types of heat storage is illustrated in Figure 10.

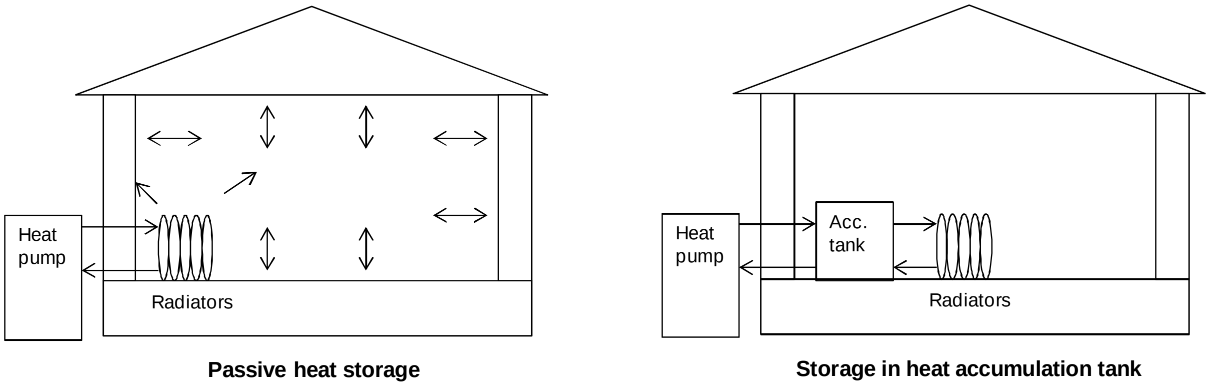


Figure 10. a) Passive heat storage in the building structure. **b)** Heat accumulation tank inserted on the space heating circuit (both illustrated for a radiator heating system, air-water heat pump).

As shown, in the passive heat storage concept, the radiators transfer heat to the indoor air (and to directly to the building structure through radiation) and heat is then exchanged between indoor air and building structure, via radiation, thermal conductivity, and convection [83]. The heat capacity of the building structure can thereby be utilised for flexible heat pump operation. The storage capacity of the building is mainly comprised by internal constructions in walls, ceiling, and floor, while windows, doors, and furniture have minor influence [80]. The term *intelligent* heat storage in this context refers to the fact that the storage capacity of the building is utilised for flexible heat pump operation, based on what is optimal for the energy system. As shown in Figure 10b, the heat accumulation tank interacts with the heat pump and the central heating system

The heat storage options have been integrated in the technical optimisation strategy in EnergyPLAN, minimising excess electricity production and fuel consumption of the energy system and utilising as much wind power as possible. The model development ensures that heat stored in the building structure or in heat accumulation tank can be used to satisfy space heating demand only. This is implemented by restricting the heat pump to satisfy the hot water demand in each hour, as a minimum (the hot water tank is not modelled).

Intelligent passive heat storage has been modelled based on considerations of heat capacities and temperature states of the relevant thermal masses. Due to the low heat capacity of air (0.8 Wh/°C/m^2 floor area [40]) and the fact that a radiator heating system is considered, it is assumed that a desired indoor air temperate can quickly be reached. Due to the large thermal mass of the building structure (60-140 Wh/°C/m^2 floor area, see Section 2.2), the temperature of this mass is assumed to vary from hour to hour, depending on the amount of heat stored in it. The possible loading/unloading to/from the passive heat storage in a given hour is assumed constrained by the temperature difference between indoor air and the building structure. As a result, the following loading/unloading restrictions have been implemented for the passive heat storage:

- When the passive heat storage is <u>empty</u>, the possible loading is highest, while the possible unloading is zero.
- When the passive heat storage is <u>full</u>, the possible unloading is highest, while the possible loading is zero.

- In the stages <u>between empty and full</u> passive heat storage, loading and unloading is constrained, based on assuming a linear relation between the situation at empty and full storage.

As a result, the development in the heat storage level during a full loading or unloading period is not linear. Rather, the possible marginal increase in the storage level is reduced during a loading period, and the possible marginal decrease in the storage level is reduced during an unloading period. This is illustrated in Figure 11 for a simulated loading and subsequent unloading period.

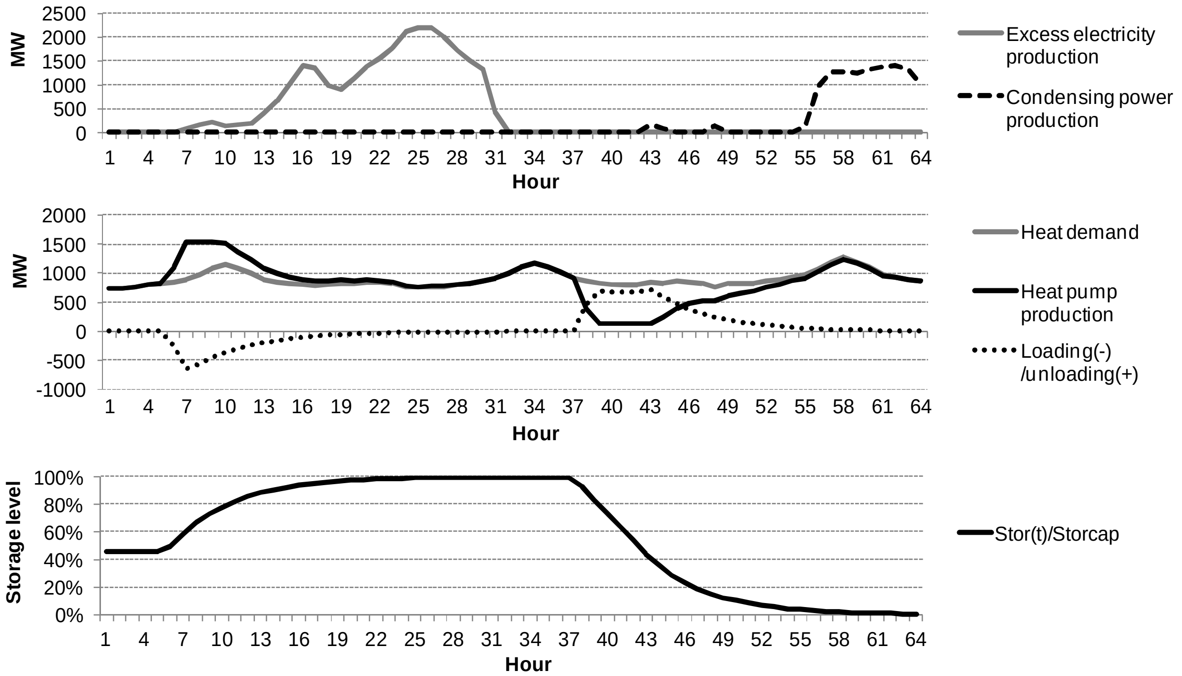


Figure 11. Optimisation of a large-scale installation of heat pumps using passive heat storage, modelled in integration with the energy system (allowing ∓ 1°C indoor air temp. var. and assuming a passive heat storage capacity of 120 W/m^2 floor area/K). A loading and subsequent unloading period is shown, together representing around 2-3 days in mid January with relatively mild weather. Excess electricity production and condensing power production is shown after the optimised heat pump operation minimising their occurrence [83].

In the model, loading of the passive heat storage corresponds to a situation where the heat transfer from indoor air to building structure is higher than the transmission loss from building structure to ambient air (outdoor environment). Correspondingly, unloading of the storage represents a situation where the heat transfer from indoor air to building structure is lower than the transmission loss from building structure to ambient air. The model is further described in Paper III, where the equations are also presented.

The model development makes it possible to analyse the potentials of individual heat pumps and the given heat storage options, in terms of supporting a fuel- and cost-efficient utilisation of wind power.

3.4 Balmorel

The Balmorel model was originally developed in a project financed mainly by the Danish Energy Agency and hosted by the former Danish TSO, ElkraftSystem and is today developed and distributed under open source ideals. Balmorel is currently used and developed at the Technical University of Denmark, at RAM-løse, at Ea Energy Analyses, and at the Danish Energy Association, among other institutions. Balmorel is an optimisation model and is deterministic, assuming perfect foresight. Furthermore, Balmorel assumes perfect competition, i.e. without monopolies or skewed market power and where all actors act economic rationally seeking to maximise their profit [2, 17, 60] [100]. A linear version of the Balmorel model is applied in this thesis.

The model optimises investments in power/heat production, storage, and transmission capacities, and the operation of the system. This is done minimising total costs in the energy system over a given year, covering annualised investment costs, operation and maintenance costs of existing and new units, and fuel and CO_2 quota costs. The optimisation is performed subject to a number of constraints, including satisfaction of demands for electricity and heat in each time period, fuel potentials, and technical unit restrictions on units in the system. The model covers the electricity and district heating sector, and additionally, individual heating, industry, and part of the road transport sector, depending on the use of model add-ons and data.

Inputs to the model comprise demands and demand distributions and capacities, technical lifetimes, and efficiencies of existing technologies as well as costs, technical lifetimes, and efficiencies of technologies available for investment, and distributions of fluctuating renewable energy sources, fuel potentials, and fuel and CO_2 costs etc. The model outputs comprise investments, electricity/heat generation, fuel consumptions, CO_2 emissions, and costs etc.

The assumed perfect foresight means that the model does not capture forecast errors on wind and electricity demand and the resulting need for operation of reserves. However, the need for reserve capacity can be represented in Balmorel, e.g. in the form of a capacity balance restriction, as used in this thesis (see Section 3.5). Furthermore, the linear version of Balmorel applied does not include start-up costs, minimum load requirements, or part load efficiencies.

Balmorel operates with three geographical entities: countries, regions, and areas. Countries are divided into regions connected with transmission lines and regions are further divided into areas. Electricity supply and demand is balanced on regional level, whereas heating is balanced on area level. The optimisation is performed with a yearly time horizon and the year is divided into seasons, which may be used to represent weeks, and into time periods, which may represent hours. Model runs can take minutes to days depending on the size of the problem.

Individual heating can be represented on aggregated level, typically with two areas representing Eastern Denmark and Western Denmark, respectively. Individual heating is represented as demand for space heating and hot water in total, using an aggregated demand profile. Within each individually heated area, different types of heating installations can be combined, e.g. heat pumps, fuel boilers, solar thermal, and electric boilers as well as thermal storage tanks. Electric boilers are not handled as an integrated part of the heat pump unit.

3.5 Model development in Balmorel

Intelligent heat storage in the building structure is in the analysis in EnergyPLAN (Paper III) identified as the most promising option, among those analysed. Therefore, particular emphasis is put on this heat storage option, in the further model development. In this regard, it is considered important to obtain a better representation of the thermal building dynamics. Furthermore, EnergyPLAN is not capable of optimising investments, and the technical optimisation applied does not account for electricity import/export. Finally, the modelling approach in Paper III does not facilitate analysing the use of thermal storage in concrete floor heating systems or in hot water tanks. Therefore, further model development is made in order to capture the above aspects.

A thermal building model add-on has thus been developed for the investment model Balmorel covering the following heat storage options:

- *Intelligent heat storage in the building structure:*
  - For houses with radiator heating: *Passive* heat storage in walls, ceiling, and floor[9]
  - For houses with (concrete) floor heating*: Active* heat storage in the floor (and passive heat storage in walls and ceiling).
- *Heat accumulation tanks* for space heating.
- *Hot water tanks* for domestic hot water (showering, dish washing etc.)

The scientific contribution of the model development is that it covers a wide range of different heat storage options for individual heat pumps and at the same time optimises both operation and investments in integration with the energy system. Such model capability not been observed in previous studies.

The basic principles of passive heat storage and heat accumulation tanks are here the same as previously illustrated in Figure 10. However, the thermal building dynamics are as mentioned better represented. In addition, heat losses from the thermal storage tanks are included as heat contributions to the indoor air. The hot water tank is modelled as a traditional thermal storage operating on the hot water circuit only.

Floor heating systems here represent floor heating systems used as the *central heating system* of the house, i.e. not only in bathrooms/kitchen. The modelling of floor heating is generally applicable to all floor heating systems. However, concrete floor heating systems are most relevant, due to their current market dominance and large thermal capacity. In concrete floor heating systems, heat is transferred to the concrete floor via water tubes, and then from the floor to the indoor air via thermal conductance, convection, and radiation [72] (see Figure 12).

[9] Windows, doors, and furniture have minor influence [80].

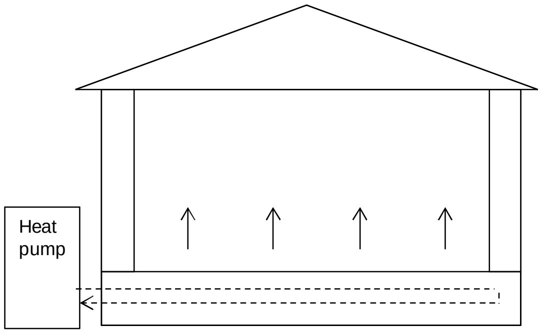


Figure 12. Active heat storage in concrete floor heating systems.

In connection with flexible heat pump operation, concrete floor heating systems can exploit that the heat supply (and thus the electricity consumption) can be changed rapidly, while the indoor temperature will change slowly [31]. This is due to the large heat capacity of the concrete floor, and that heat can be delivered directly to this thermal mass.

The thermal building model is based on physical definitions and relations of heat transfers and heat capacities and can be characterised as a linear state space model. The modelling of radiator heating systems and floor heating systems, respectively, is illustrated in Figure 13 and Figure 14. For simplicity, only the space heating circuit is here shown, i.e. excl. the hot water circuit.

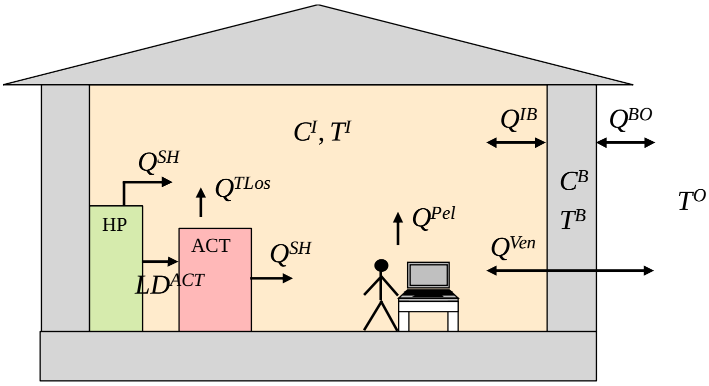


Figure 13. Thermal building model of houses with radiator heating (only the space heating circuit is illustrated). HP: Heat pump (or other heating installation). ACT: Heat accumulation tank. For further nomenclature, see the beginning of the thesis.

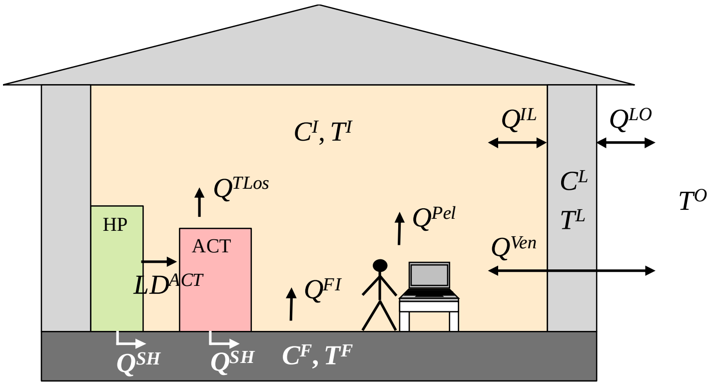


Figure 14. Thermal building model of houses with floor heating (only the space heating circuit is illustrated). HP: Heat pump (or other heating installation). ACT: Heat accumulation tank. For further nomenclature, see the beginning of the thesis.

As shown, the model includes the ambient temperature (T^O) and the heat capacity and temperature states of the indoor air (C^I, T^I) and building structure (C^B, T^B for houses with radiator heating, and C^L, T^L and C^F, T^F for houses with floor heating). In houses with radiator heating, the heating installation (e.g. a heat pump) delivers heat (Q^{SH}) directly to the indoor air, while in houses with floor heating, heat is delivered to the concrete floor. In a given hour, heat will be exchanged between the masses depending on the temperature difference between them, and the heat transfer coefficients applied (U values). The heat losses through the building envelope will create a need for space heating in order to ensure a given indoor temperature. Ventilation losses (Q^{Ven}) occur from indoor air to ambient air, through the small cracks in the building envelope etc. Transmission losses occur in two steps: 1) From indoor air to building structure (Q^{IB} and Q^{IL}, respectively) and 2) From building structure to ambient air (Q^{BO} and Q^{LO}, respectively). When allowing some indoor temperature variation, the heat storage capacity of the building can be utilised for shifting space heating in time. Alternatively or as a supplement, if investing in a heat accumulation tank, this can be used as buffer on the space heating circuit. The model is described in detail in Paper IV, where all equations are also presented.

Figure 15 shows in a very simplified manner how the thermal building model add-on is integrated into the energy system model Balmorel.

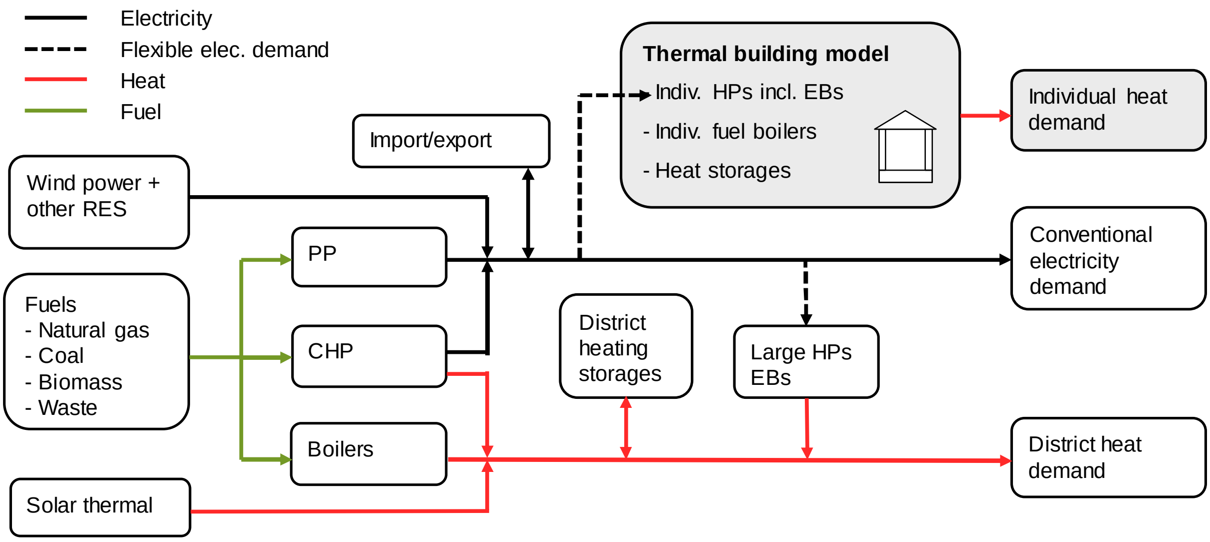


Figure 15. The integration of the thermal building model add-on into the energy system model Balmorel. The illustration is very simplified and does not reveal all technologies or functionalities covered in Balmorel.
PP: Power production, CHP: Combined heat and power production, HP: Heat pump, EB: Electric boiler. RES: Renewable energy sources.

As shown in Figure 15, the thermal building model represents the individual heating sector including, heat demands, heat supply technologies, and heat storages including the building structure. When combined with heat storages, the electricity consumption for the heat pumps becomes flexible. As illustrated, the electricity consumption for large heat pumps and electric boilers in the district heating system also becomes flexible, when connected to the district heating storages. The competition between these flexibility measures is captured in the model.

For validation purposes, the thermal building model has been compared against measured data for heat pump installations in Danish one-family houses. This comparison is illustrated in Figure 16. As indicated, the thermal building model gives a reasonable representation of actual space heating profiles.

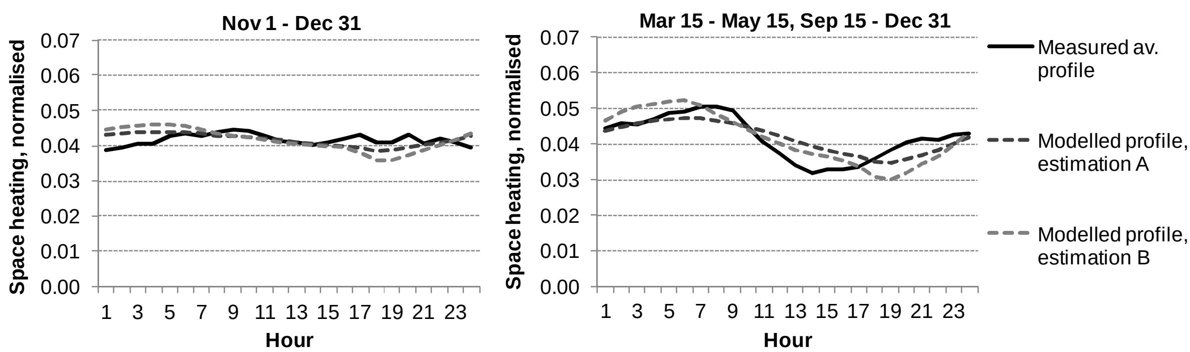


Figure 16. Model generated average diurnal space heating profile, compared to a corresponding measured average profile for heat pumps in Danish one-family houses [76]. Radiator heating systems are illustrated. Estimation A: U^{BO} for monitored houses estimated based on construction year. Estimation B: U^{BO} for monitored houses estimated based on measured space heating over the given period. **a)** Comparison covering November 1 to December 31 (data available for 24 houses). **b)** Comparison covering March 15 to May 1 and September 15 to December 31 (data available for 5 houses).

The situation without flexible heat pump operation is modelled by restricting the indoor temperature to a fixed level (in addition to deactivating the option of investing in thermal storage tanks). This reflects the typical constant temperature set-point applied in individual heat pump installations in Danish houses today [70, 76]. In this situation, the heat pump will be forced to supply the amount of heat needed to cover the net heat demand in the given hour, i.e. the transmission and ventilation minus the heat contribution from other sources (persons and electrical appliances[10]). As shown in Figure 17, the space heating supply will in this situation be high when the ambient temperature is low, and vice versa.

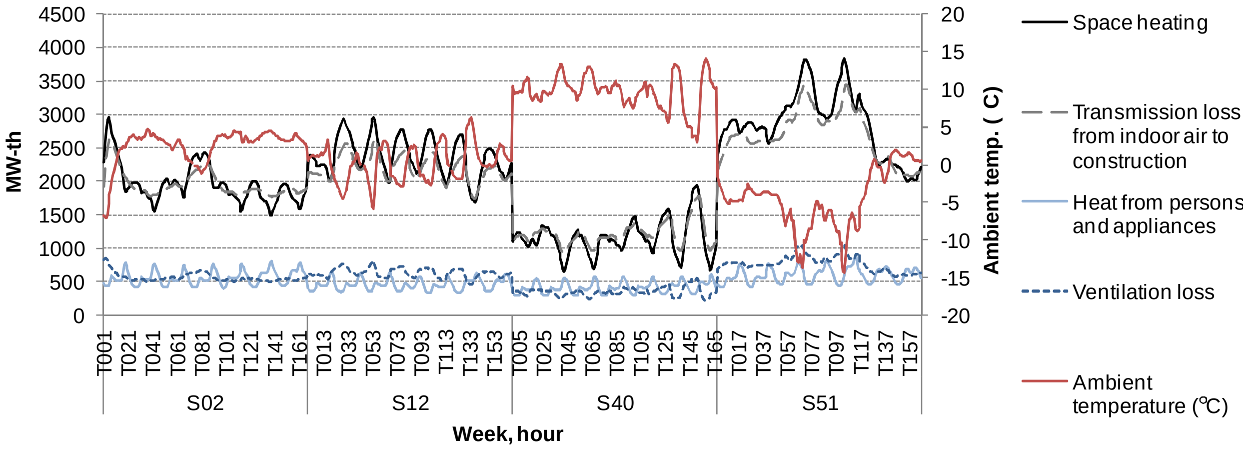


Figure 17. Space heating from individual heat pumps, other heat contributions, heat losses, and ambient temperatures, for a situation without heat storage investments, and with a fixed indoor temperature requirement of 21.5 °C (the simulated heating season is illustrated focusing on houses with radiator heating).

When allowing the indoor temperature to vary within a certain interval, the heat pumps can be operated flexibly, utilising intelligent heat storage in the building structure. In this situation, the heat pump operation will be prioritised for hours with low marginal electricity production costs, which can be interpreted as electricity prices. This is illustrated in Figure 18. Additionally, it enables using the heat pumps for peak load shaving, as described later in this section, and illustrated in Section 4.2.2.

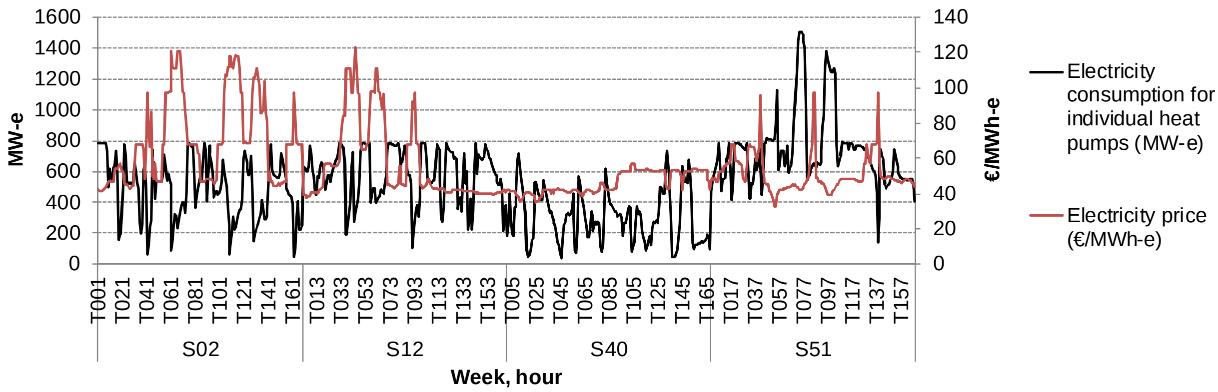


Figure 18. Modelled flexible operation of individual heat pumps in the heating season, shown for Western Denmark by 2030.

[10] Heat contribution from solar transmission has been excluded due to lack of data. Considerations on this issue are given in Paper IV.

Apart from incorporating thermal building dynamics, the model development generally improves the representation of individual heat pumps and other individual heating technologies. As such, the following investment constraints are implemented for individual heating installations:

1. It is ensured that each primary heating installation (heat pump or fuel-based boiler) complies with building regulations, in terms of being able to cover the dimensioning heat loss, at an ambient temperature of -12 °C and an indoor temperature of 20 °C, and satisfy the average hot water demand, at the same time [101, 102].
2. For individual heat pumps, the use of a supplemental electric boiler to cover peak loads is modelled. This is implemented by defining the capacity share covered by the heat pump (typically 72-82 % [66]).
3. In reality, residents in individually heated areas will invest in only one type of primary heating technology (in Denmark typically a fuel boiler or heat pump). Therefore, the use of one new primary heating installation (e.g. heat pump) for base load operation, supplemented by another new installation (e.g. natural gas or wood pellet boiler) for peak load operation, should be avoided in the model. This is taken into account, by restricting a minimum number of full load hours for new primary heating technologies in each area.
4. Based on space requirements, the possible investment in heat accumulation tanks is constrained to maximum 1000 litres per house [18].

The first of the above constraints ensures that the required capacity of individual heating installations cannot be reduced through flexible operation of these, as in reality. Furthhremore, the constraint ensures a more correct dimensioning of the individual heating installations by avoiding an underestimation of the required capacity. The reason is that the need for individual heating capacities would in Balmorel normally be based on aggregated heat demand profiles for several thousand of households. For such an aggregated heat demand, the peak demand would be relatively low due to levelling effects from the aggregation. In reality, each household must be able to cover their peak heat demand. This is reflected in the constraint implemented. Alternatively, the underestimation problem could to some extent be handled by setting a maximum number of full load hours in the model. However, the constraint described above is more accurate, as it is based on actual building regulations.

The inclusion of the electric boiler (constraint no. 2) is mainly important due to its high impact on the peaks in the electricity consumption of the total heat pump unit. This can be determining for the need for peak and reserve capacity investments. Moreover, the model will generally seek to minimise the use of the supplemental electric boiler, due to its low efficiency.

In Balmorel, sufficient dispatchable power capacity in each power region can to some extent be ensured by including the period of the year with highest net loads in the optimisation (residual loads, i.e. gross load minus wind power). This would however likely underestimate the need for peak and reserve capacity due to the assumed perfect foresight on wind power and load. Furthermore, electricity import would in the optimisation contribute in covering the high net loads, while in reality, risk of failures on transmission lines should be taken into account.

A capacity balance restriction has therefore been developed, inspired by [2] to ensure adequate production capacity and reserve margin in each power region (for full nomenclature, see beginning of the thesis):

$$\sum_{\mathrm{a} \in \mathrm{A(r)}} \sum_{\mathrm{g} \in G^{El}} \left(KE_{a,g} + KN_{a,g}\right) \cdot cc_g \geq D^{ElConv}_{r,w,h} + \sum_{\mathrm{a} \in \mathrm{A(r)}} \sum_{\mathrm{g} \in \mathrm{G}} D^{ElFlex}_{a,g,w,h}$$

$$\forall r \in R;\ w \in W; h \in H$$

The term *capacity credit* (*cc*) is here applied, which represents the share of total installed capacity that is available for electricity generation at a certain level of confidence. Based on [2], the capacity credit of conventional units is set to 0.99, while the capacity credit for wind power is set to 0.14. The capacity balance restriction takes into account that the need for new production capacity and reserves can be reduced through peak load shaving. As the constraint is applied for each hour and week, it allows for lowering the heat pump operation in peak load hours, taking the hourly pattern of conventional (D^{ElConv}) and flexible electricity demand (D^{ElFlex}) into account. This is new compared to the capacity balance restriction in [2] (also applied in Paper II), where the right hand side of the equation is a constant peak load set for each country. The peak load shaving capability is illustrated in Section 4.2.2.

The possibilities for exploiting intelligent heat storage in the building structure depend on the characteristics of the given house. This is taken into account in the modelling of the stock of one-family houses. As such, individually heated houses can in the model be divided into a number of different areas depending on: the type of central heating system, space heating demands (represented by heat transfer coefficients), heat capacity of the building, hot water demand, and house size. In the applications of the model, the individually heated (existing) Danish one-family houses have been divided into 10 different areas in Eastern and Western Denmark, respectively.

The use of an aggregated energy system model means that the heat storage capacity within each heating area can be shared among the heat pumps within the area. This implies best-case conditions for the heat storages, since the flexibility they offer can thus be distributed among the houses. Ideally, each of the many thousands of individually heated houses should be modelled separately (716,000 in this case). However, it would hardly be realistic to run such a model.

Due to the linearity of the model versions applied, the modelled heat pumps will be able to operate continuously between zero and full load. The observant reader might wonder how this fits with the fact that today's heat pumps are typically on/off regulated (as mentioned in see Section 2.2). However, with the hourly time resolution applied, the continuously variable operation corresponds to on/off regulation, where it merely varies how large a share of the given hour the heat pump is operating.

4 Energy systems analyses

In this chapter, an overview is first given of the energy systems analyses performed, in terms of preconditions and focus. Subsequently, the most important results are presented. Finally, the results are summarised and compared.

4.1 Overview of energy systems analyses

Table 4 gives an overview of the flexibility measures included in the different energy systems analyses. As shown, large heat pumps, electric boilers, and thermal storages in the district heating system are included in all the analyses. The reason is that these technologies compete with individual heat pumps and electric vehicles, in providing flexibility to the system. For instance, the large heat pumps/electric boilers will compete with individual heat pumps, in terms of prioritising operation for low electricity price periods. Furthermore, the system effects of the flexibility measures in the district heating system are in Paper II compared to the effects of electric vehicles. Possibilities to invest in transmission capacity expansions, further than planned, have moreover been included in Paper II and Paper V, representing other competing flexibility measures.

Table 4. Overview of flexibility measures included in the different energy systems analyses performed in the PhD project.

Sector	Flexibility measure	Paper II + Report	Paper III	Paper V[a]	Paper VI
District heating	Large heat pumps, electric boilers, thermal storages	X	X	X	X
Individual heating	Individual heat pumps		X	X	X
	Electric boiler supplementing in covering peak loads		X	X	(X)[b]
	Intelligent passive heat storage in the building structure via radiator heating		X	X	
	Intelligent active heat storage in concrete floors via floor heating			X	
	Heat accumulation tanks		X	X	(X)[c]
	Hot water tanks			X	(X)[c]
Transport	Battery electric vehicles and plug-in hybrid electric vehicles	X			

[a] The same applies to the analyses performed in Paper IV, illustrating model functionality.

[b] Electric boiler is included along with other individual heating installations but not as an integrated part of the heat pump unit.

[c] Individual thermal storage tanks included for total heating (space heating and hot water).

An overview of the energy systems analyses is given in Table 5, in terms of focus, preconditions, and type of model and optimisation applied. As shown, the analyses differ with regard to whether Danish policy goals concerning renewable energy and fossil fuels have been implemented as boundary conditions. This is due to fact that the Danish energy policy has changed during the course of the PhD project and due to differences in focus of the studies.

Paper II pays special attention to the development in the portfolio of power & heat plants over a period of years towards 2030, when assuming a gradually increasing penetration of electric vehicles. Therefore simulations are made with five year intervals, where optimal investments identified in previous years are included in the optimisations of subsequent years. In the remaining papers of the thesis, a single year is optimised.

The technical optimisation in EnergyPLAN (Paper III) is applied in order to investigate the potentials of individual heat pumps and heat storages in terms of increasing wind power utilisation and minimising fuel consumption of the system. In the analyses performed in Balmorel, the aim is to achieve the lowest cost solution for society incl. investment costs. Therefore, an optimisation minimising socio-economic investment and operation costs, i.e. excluding taxes, subsidies, and tariffs, has been applied.

Table 5. Overview of focus and preconditions for energy systems analyses performed during the PhD project.

	Paper II + Report	Paper III	Paper V	Paper VI
Year	2015, 2020, 2025, 2030	2020	2030	2050
Technology focus	Electric vehicles	Individual heat pumps	Individual heat pumps	District heating vs. individual heating
Model	Balmorel	EnergyPLAN	Balmorel	Balmorel
Optimisation	Min. socio-economic costs incl. investments and operation	Min. fuel consumption, operation only	Min. socio-economic costs incl. investments and operation	Min. socio-economic costs incl. investments and operation
Wind power in DK (pct. of annual elec. demand)	20-50 % (resulting from optimisation)	50% set (and 0-100 % in sensitivity analyses)	50-60% (resulting from optimisation)	75% (resulting from optimisation)
Danish energy policies implemented	Expected wind power capacities implemented in sensitivity analyses	50 % wind power by 2020	50 % wind power by 2020. Phase out of coal and individual oil boilers by 2030. Investment restrictions based on goal of 100 % renewable electricity & heat supply by 2035. The biomass agreement.	100 % renewable energy for electricity, heat and transport by 2050
Countries in focus	DK, NO, SE, FI, GE	DK (excl. electricity trade)	DK (incl. electricity trade)	DK (incl. electricity trade)
Countries modelled	DK, NO, SE, FI, GE	DK	DK, NO, SE, FI, GE	DK, NO, SE, FI, GE
Sectors modelled	Electricity, district heating, transport*	Electricity, district heating, individual heating, transport, industry,	Electricity, district heating, individual heating	Electricity, district heating, individual heating, industry

DK: Denmark. NO: Norway. SE: Sweden. FI: Finland. GE: Germany.
*Private passenger vehicles for road transport.

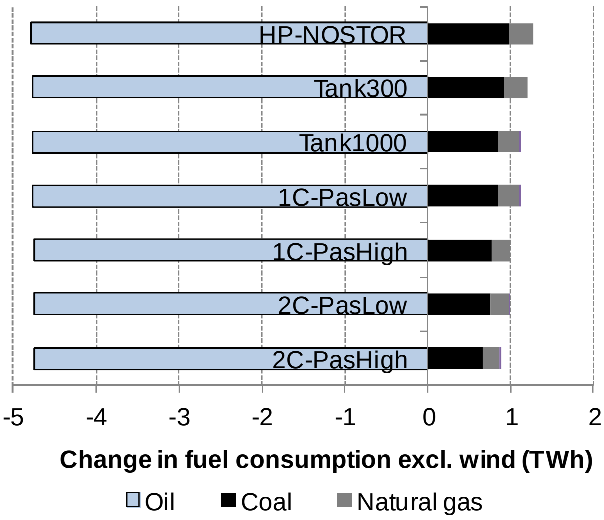
4.2 Results

4.2.1 System benefits of individual heat pumps and heat storages

The energy systems analyses in Paper III and Paper V both show that the installation of individual heat pumps can significantly support the integration of wind power, while complementing heat storages can contribute only moderately in this regard. This overall finding is illustrated in the following.

In Paper III, individual heat pumps and different heat storage options are investigated, in terms of their potentials in increasing wind power utilisation and reducing excess electricity production and fuel consumption of the system. This is facilitated by applying a technical optimisation in the EnergyPLAN model. The potentials are analysed in the context of a large-scale installation of individual heat pumps in the Danish energy system by 2020 with 50 % wind power. Individual heat pumps are assumed installed where they are considered particularly relevant in the short term, i.e. in houses presently heated with oil boilers and/or electric heating (detached houses are here considered). The resulting electricity consumption for individual heat pumps constitutes 1.9 TWh-e.

In Figure 19, the changes in fuel consumption of the system are shown, compared to a situation without individual heat pumps.



Scenario abbreviations	Description
NOHP	No heat pumps in the houses.
HP-NOSTOR	Heat pumps installed in detached houses with oil boilers and/or electric heating, but without investment in heat storages.
Tank300/500/1000	Inv. in 300/500/1000 litre heat accumulation tanks in all houses where heat pumps are installed.
PasLow/High	Inv. in passive heat storage in all houses with heat pumps, assuming low/high end passive heat storage cap. (60 Wh/K/m2 and 120 Wh/K/m2, respectively)
1C/2C	Allowing an indoor temp var. of ∓1°C/∓2°C when utilising passive heat storage

Figure 19. Changes in fuel consumption when installing individual heat pumps and when further adding heat storages to the heat pumps.

It can be seen that the installation of heat pumps results in large oil savings, resulting from the displacement of individual oil boilers (HP-NOSTOR scenario). Due to the high efficiency of the heat pumps[11] combined with the high efficiency of the Danish CHP system (and displacement of the less efficient electric heating), only moderate increases in coal and natural gas consumption for electricity generation are observed. In total, a significant net reduction in the fuel consumption of the system is achieved.

When equipping the heat pumps with heat storages (Tank300/1000, 1C/2C-PasLow/High scenarios), the flexible heat pump operation achieved means that more wind power production is utilised and more condensing power production displaced. This results in a lower net consumption of coal and natural gas. However, compared to the fuel savings achieved by installing the heat pumps, the fuel savings provided by the heat storages are moderate.

The explanation for this is that the efficiency advantage of the heat pumps has high impact on the fuel consumption, due to the many operating hours of the heat pumps throughout the year. In

[11] Average COP of 2.7 applied, representing heat pumps in radiator heating systems [11], hereof 75 % air-water heat pumps and 25 % ground source heat pumps [120].

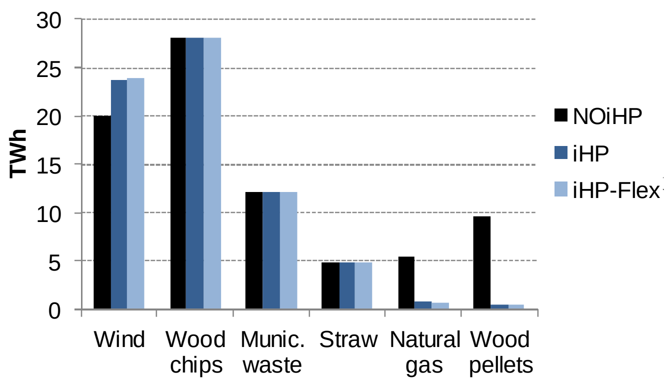
comparison, the potential for further reducing fuel consumption by increasing wind power utilisation is limited by the fact that excess electricity production only occurs in some periods of the year; in around 20 % of the year for the case of the Danish energy system by 2020. Overall, it is thus found that in terms of reducing fuel consumption of the system, the installation of individual heat pumps is the most important step, while the heat storages are less influential.

If applying a system boundary including not only Denmark but also neighbouring countries, the fuel savings provided by enabling flexible heat pump operation would be even smaller. The reason is that the excess electricity production, utilised with flexible heat pump operation, would otherwise have been exported, displacing fuels in other countries (to the extent that the excess electricity production it is within the transmission capacity). When taking this lost opportunity into account, the fuel savings provided by the heat storages would be reduced further.

In Paper V, the system benefits of individual heat pumps are analysed in Balmorel, taking into account effects on investments and applying a socio-economic cost optimisation. Moreover, the influence of electricity import/export is covered by including the energy systems of Sweden, Norway, Germany and Finland in the optimisation. The system in 2030 is analysed, including Danish energy policies of e.g. phasing out individual oil boilers and the use of coal for power/district heat generation. Individually heated one-family houses are modelled, representing the bulk (78 % [103]) of individual heating in Denmark. Existing houses are considered, which by 2030 will still comprise the large majority of the individual heat demand of Danish one-family houses (see Figure 5). In total, about 716,000 individually heated houses are covered.

When allowing investment in individual heat pumps, the optimisation yields heat pump investments in all the individually heated houses. This confirms the socio-economic competitiveness of the heat pumps found in previous studies [11, 54]. As a result, the individual heat pumps represent a significant electricity demand, i.e. 4.3 TWh. In comparison the expected conventional Danish electricity demand in the same year is 30.1 TWh [84].

The results of the analysis show that the installation of the heat pumps can bring significant benefits to the energy system, in terms of facilitating larger wind power investments and reducing fuel consumption. This is illustrated in Figure 20 (iHP scenario vs. NOiHP scenario).



Scenario	Description
NOiHP	No individual heat pumps.
iHP	Investment in individual heat pumps allowed
iHP-Flex	Investment in individual heat pumps allowed as well as in thermal storages enabling flexible operation of the heat pumps

Figure 20. Primary energy consumption in the Danish energy system in 2030 for different scenarios.

As shown, the consumption of wood pellets and natural gas is reduced significantly when installing individual heat pumps, displacing natural gas boilers and wood pellet boilers (23%). As a result, the CO_2 emissions of the Danish system are also reduced considerably (37 %). The percentagewise CO_2 reduction obtained is however relatively large, due to the implemented political goal of phasing out coal, resulting in generally low absolute CO_2 emissions. The large reduction in the wood pellet consumption shows, that the individual heat pumps can contribute significantly to reducing the pressure on the limited biomass resources. The national security of supply is in this case furthermore improved since wood pellets are in Denmark typically imported.

The increase in electricity demand resulting from the installation of individual heat pumps is largely met by wind power (97 %, the remaining amount is supplied by natural gas power plants). This is partly explained by the fact that wind power does not compete with coal power plants, due to the implemented political phase out of coal in the system. Moreover, the other low cost fuels, wood chips and municipal waste, are constrained by the available national resources, resulting in consumption up to this limit in all scenarios (the more costly wood pellets, which constitute an international trading good, are assumed unconstrained). Furthermore, even when individual heat pumps are operated without flexibility, their electricity demand is distributed over many hours in the day, and both heat demand and wind power is typically high in cold periods (see Figure 21). This creates good possibilities for utilising wind generation in covering the electricity demand for the heat pumps, while using dispatchable power generation to back it up. In contrast, e.g. dumb charging of electric vehicles would typically be concentrated in a few hours of the day, when people return from work, making it difficult to utilise wind power. The use of dispatchable power capacities as back up for wind power, in meeting the electricity demand increase, is illustrated in Figure 21.

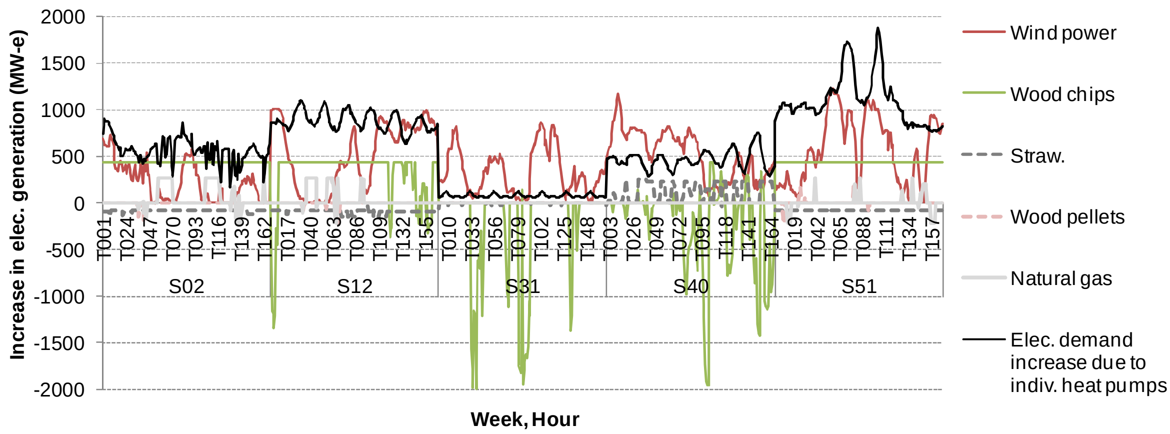


Figure 21. Increase in electricity demand due to installation of individual heat pumps, for a situation without flexible operation, shown together with the resulting increases/decreases in electricity generation.

As shown, the electricity generation on biomass and natural fired plants is increased, when needed to supplement the wind generation. Due to the limited national biomass resources, the electricity generation on the biomass fired plants is reduced accordingly in other periods. Electricity import/export is also changed on hourly level but is for simplicity not shown on the figure. The fluctuations in the increase in electricity demand in week S02 represent changes in the operation of large heat pumps in the system, resulting from the installation of the individual heat pumps.

When enabling flexible operation of the individual heat pumps, wind power generation is practically unchanged, as shown in Figure 20 (iHP-Flex vs. iHP scenario). Natural gas consumption is slightly decreased, due to an avoided use of open cycle gas turbines for peak load operation. As a result, only moderate reductions in fuel consumption and CO_2 emissions are achieved (0.3 % and 2 %, respectively).

The effects on system costs are illustrated in Figure 22.

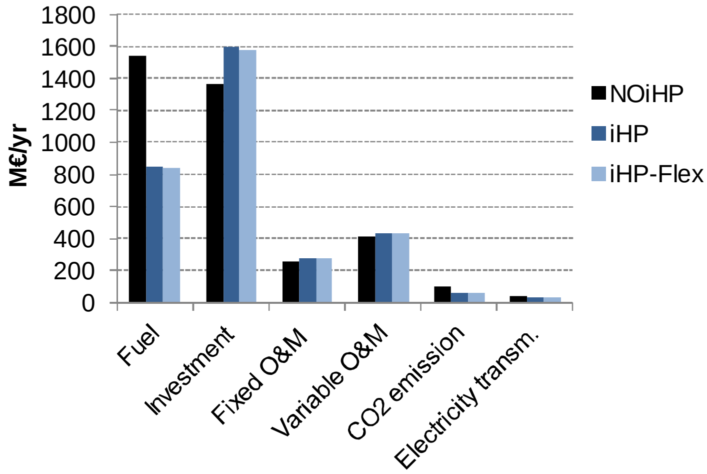


Figure 22. Annualised costs for the modelled Danish heat and power system in 2030 for different scenarios.

As shown, fuel costs are reduced considerably with the installation of individual heat pumps (iHP scenario). This is partly explained by the high efficiency of the heat pumps, and that the increase in electricity demand is largely covered by wind power. Furthermore, the displaced technologies, natural gas boilers and wood pellet boilers, have relatively high fuel costs. The increase in investment costs is caused by: 1) larger investment costs of individual heat pumps compared to individual gas boilers, and 2) the increased investments in wind power and dispatchable power capacities, needed to supply electricity for the heat pumps. The total system costs for the Danish heat and power system are reduced by 12 % with the installation of individual heat pumps. In comparison, system costs are reduced by only 0.9 %, when investing in heat storages for the heat pumps (iHP-Flex scenario).

Overall, the results show that the installation of individual heat pumps can provide significant system benefits, in terms of facilitating larger wind power investments and reducing fuel consumption, CO_2 emissions, and system costs. Flexible operation of the heat pumps, enabled by heat storages, can yield only moderate benefits in these regards. This result has been confirmed in various sensitivity analyses, covering e.g. variation in investment costs of control equipment required for the flexible heat pump operation, COP, investment costs, and capacity share of individual heat pumps, discount rate, as well as fuel and CO_2 prices. A full description of the sensitivity analyses can be found in Paper V.

4.2.2 Influence of individual heat pumps and heat storages on investments

This section focuses on how individual heat pumps and heat storages affect energy system investments. The section mainly draws upon the analysis in Paper V, applying the Balmorel model and covering socio-economic optimisations of investments and operation of the Danish energy system by 2030. Moreover, result figures in Paper IV are used to illustrate the peak load shaving ability of the heat pumps (the preconditions and input data applied in Paper IV correspond to those applied in the main scenarios in Paper V).

In Figure 23, the investments in electricity generation capacities in the Danish energy system are illustrated for the three scenarios analysed: the scenario without individual heat pumps (NOiHP), the scenario with individual heat pumps operated without flexibility (iHP), and the scenario with allowed investments in heat storages for the heat pumps (iHP-Flex). In the iHP-Flex scenario, investments in intelligent heat storage have been observed in 34 % of the houses with heat pump installations. The heat storage investments occur within all 20 defined categories of individually heated houses. However, the investments are highest in buildings with high heat capacities, typically corresponding to buildings with a high share of concrete, and in buildings with high heat demands (cf. Paper IV).

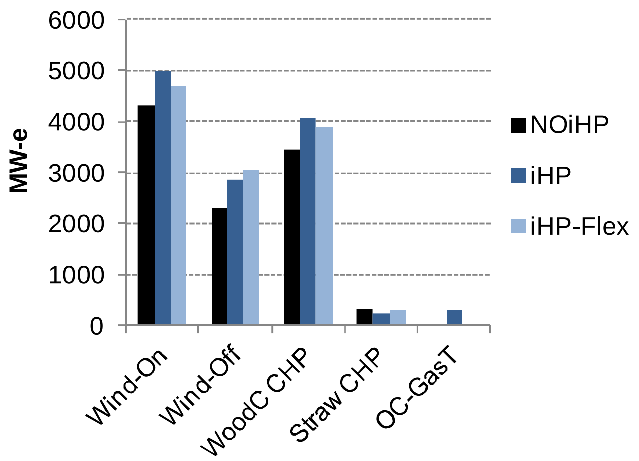


Figure 23. Investments in electricity generation capacities for different scenarios (NOiHP, iHP, and iHP-Flex). On: onshore, Off: offshore. WoodC: wood chips/waste, OC-GasT: open cycle gas turbines.

As shown, the installation of individual heat pumps facilitates significantly increased wind power investments (iHP vs. NOiHP scenario). This forms the background for the increased wind power generation, presented previously in Figure 20. Flexible operation of the heat pumps can be seen to facilitate reduced wind power investments onshore and increased investments offshore (iHP-Flex vs. iHP scenario). This is due to the fact that 1) flexibility added to a system generally improves the conditions for technologies with relatively high investment costs and low variable costs, and 2) that offshore wind power has higher investment costs, but on the other hand higher obtainable full load hours and a different variation profile. However, the total wind power generation is practically unchanged, as evident from Figure 20.

As shown in Figure 23, the installation of individual heat pumps leads to increased investments in wood chip CHP and open cycle gas turbines. This is caused by a need to supplement the fluctuating wind power, in covering the electricity demand for the individual heat pumps. In this regard, the wood chip and natural gas fired units also cover an increased need for peak and reserve capacity, imposed by the heat pumps.

The required investments in dispatchable power capacities are reduced, when operating the heat pumps flexibly, i.e. around 440 MW in the main scenario. The reason is that the flexible heat pump operation allows for shaving down the peaks in the total load of the system (via the implemented capacity balance restriction). This reduces the need for peak/reserve capacities. The peak load shaving in the Danish energy system is illustrated in Figure 24. The week with the highest peak loads of the year is illustrated, representing the week determining for the need for peak/reserve capacities in the optimisation.

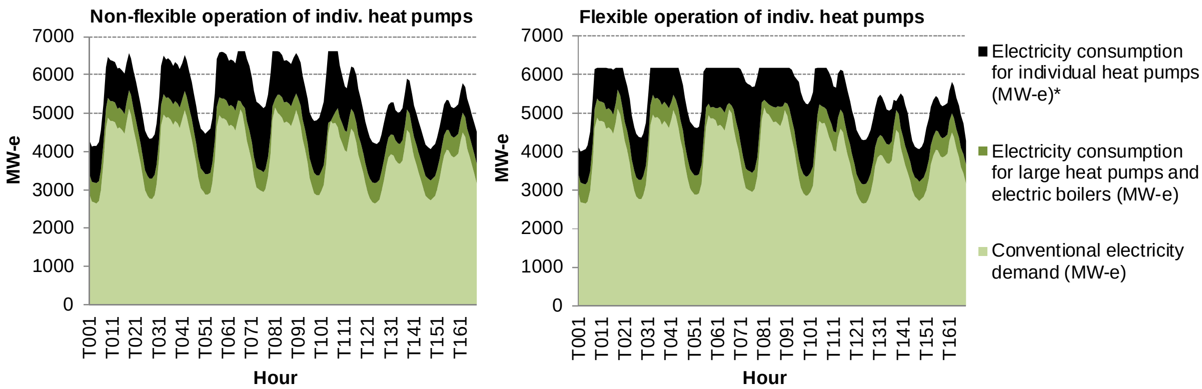


Figure 24. Peak load shaving achieved due to flexible operation of individual heat pumps. The week with the highest peak loads of the year is illustrated (week no. 51). *Incl. supplemental electric boilers.
a) HP scenario **b)** HP-Flex scenario.

The figure clearly shows that peaks in total load are shaved down, when the individual heat pumps are operated flexibly. This is facilitated by using the thermal storage capacity of the buildings for shifting the load of the individual heat pumps a few hours within the day: from the peak load hours in the morning and evening, to the load valleys in the afternoon, and to some extent also to the night.

Figure 24 illustrates that if peak loads were to be shaved down further, it would require lowering the individual heat pump load further, in longer consecutive periods lasting up to 15 hours (hour T056 to T070). This is difficult, since ambient temperatures are very low in this week (see Figure 25). The individual heat pumps are therefore forced to operate at their capacity limit in longer periods, and the electric boilers needed for covering peak loads. This leaves a limited capacity margin available for load shifting, regardless of the heat storage available.

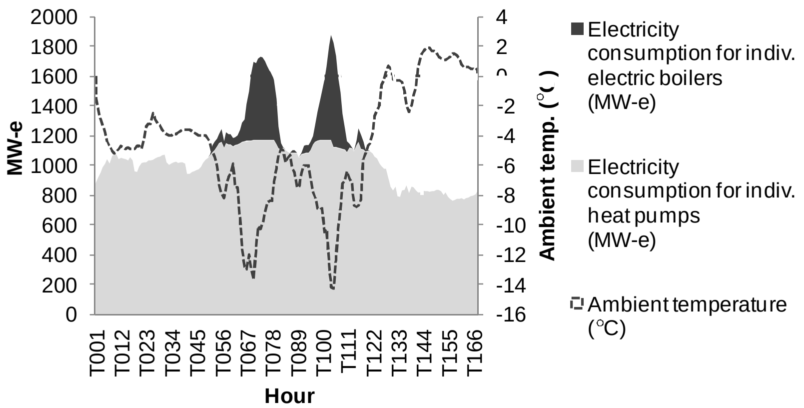


Figure 25. Electricity consumption for individual heat pumps and supplemental electric boilers, shown for the week with the highest peak loads of the year (week no. 51). The scenario without flexible heat pump operation is illustrated (HP scenario).

The above conditions explain why the need for peak/reserve capacity is not reduced further, when operating the heat pumps flexibly. Technically, further peak load shaving would be possible, to some extent, if investing in larger heat storage capacities. However, this is not economically feasible due to the challenges described above, and when accounting for the investment costs of the thermal storages.

It is found that the achievable reduction in peak/reserve capacity is sensitive to e.g. the dimensioning of the individual heat pumps and their efficiency. As such, with a heat pump capacity share in the low end (72 %), the impact of the electric boiler in peak load hours becomes more critical. This results in larger reduction in peak/reserve capacities (560 MW), when operating the heat pumps flexibly. Correspondingly, if applying a heat pump capacity share in the high end (82 %), the achieved reduction in peak/reserve capacity is lower (290 MW). A higher COP of the individual heat pumps results in a lower impact on peak loads and thus a lower reduction in peak/reserve capacities (320 MW). In all sensitivity analyses, the reduction in peak/reserve capacities is within the approximate interval 300-600 MW, corresponding to the size of a large power plant.

Investment in intelligent heat storage in the building structure generally brings a socio-economic cost reduction of around 21-38 M€ per year, corresponding to 0.6-1.1 % of system costs. When expressed in system benefit achieved per house investing in heat storage capability, a range of approximately 60-200 €/house/yr has been identified. The low end of this interval (60 €/house/year) is found when assuming low control equipment costs, yielding investment in heat storages in around 75 % of the houses, but resulting in lower benefit per house on average. The high end of the interval (200 €/house/year) represents a scenario with high control equipment costs, yielding investments in heat storages in only 20 % of the houses, but resulting in higher benefit per house on average. The feasibility of investing in intelligent heat storage in the building structure is thus sensitive to the control equipment costs.

The system benefit achieved with flexible heat pump operation mainly constitutes savings on energy system investment costs (mainly for peak/reserve capacities). This is illustrated in Figure 26 for the main scenario.

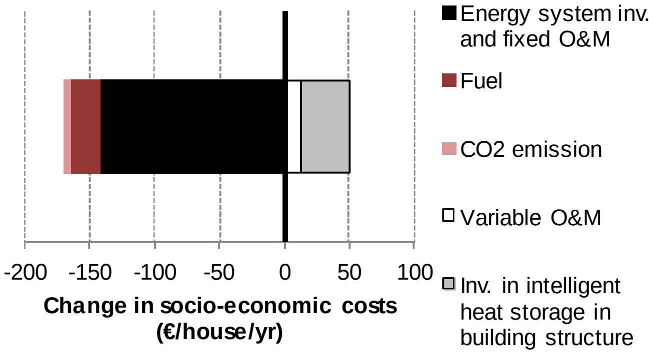


Figure 26. Change in annualised system costs due to flexible operation of individual heat pumps; given as average costs per house investing in intelligent heat storage in the building structure.

Figure 26 illustrates that the potential for reducing peak/reserve capacity investments is important for the feasibility of the thermal storages. This has been confirmed in various sensitivity scenarios. For instance, if forcing through investments in heat storages in all houses with heat pumps, instead of optimising the heat storage investments, practically the same reduction in peak/reserve capacity is achieved, while the average system benefit per house drops substantially (to 8 €/house/yr compared to 120 €/house/yr for the case with optimised heat storage investments). This illustrates that the optimised heat storage investments are largely made to the extent, that they can cost-effectively reduce the need for peak/reserve capacity in the system.

Overall, it has been found that when utilising the storage capacity of buildings, individual heat pumps can contribute to peak load shaving and thereby reduce the need for peak/reserve capacity; in Denmark with 300-600 MW, corresponding to the size of a large power plant. This is identified as the main system of equipping the heat pumps with heat storages, and is found to be crucial for the feasibility of the heat storage investments.

4.2.3 Comparison of heat storage options for individual heat pumps

In Paper III, two different heat storage options for individual heat pumps, namely heat accumulation tanks and passive heat storage in the building structure, have been compared with regard to their potentials in facilitating a fuel-efficient and cost-effectiveness integration of wind power. In Figure 27, it is shown how system costs are affected by the different heat storages.

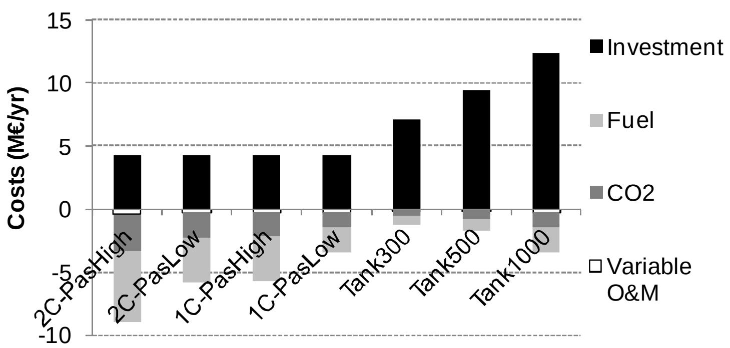


Figure 27. Changes in socio-economic system cost when enabling different heat storages for individual heat pumps (for scenario descriptions, see Figure 19).

As shown, passive heat storage (1C/2C-PasLow/High) has lower investment costs than heat accumulation tanks (Tank300/500/1000) and furthermore equivalent to higher benefits in terms of reduced costs for fuel and CO_2 (and variable O&M). This shows that passive heat storage is more cost-effective, as also confirmed in various sensitivity analyses. Furthermore, it is found that passive heat storage can bring equivalent to larger reductions in fuel consumption and excess electricity consumption compared to the heat accumulation tanks.

The socio-economic feasibility of different heat storage options has been analysed further in Paper V, optimising both investments and operation, and including electricity import/export. Furthermore, the representation of intelligent heat storage in the building structure is improved, and the possibility of utilising existing hot water tanks is also covered. As mentioned, this analysis focusing on the Danish energy system by 2030 reveals socio-economically feasibility of investing in intelligent heat storage in the building structure, in 20-75 % of the houses with heat pumps. In line with the analyses performed in Paper III, heat accumulation tanks have generally not been found competitive. This result has been confirmed by in various sensitivity analyses.

It is found that a reduction in peak/reserve capacity can also be obtained if merely utilising the existing hot water tank for flexible heat pump operation. This only requires investment in a central controller enabling communication with the power system. This option is identified as socio-economically feasible in about 20-70 % of the houses.

Tests have shown that forcing through investments in intelligent heat storage in the building structure in all houses, gives the same reduction in peak/reserve capacity, as forcing through investments in heat accumulation tanks of 1000 litres in all houses. The two types of thermal storages can thus provide equal flexibility in this regard. The reason why heat accumulation tanks are not competitive is their higher investment costs.

However, heat accumulation tanks have the advantage of not requiring any indoor temperature variations. In comparison, some indoor air temperature variation (here assumed 20-23 °C during the day and 19-22 °C at night) will particularly for houses with radiator heating, i.e. the bulk of one-family houses towards 2030, be required in order to utilise intelligent heat storage in the building structure. If excluding the option of investing in intelligent heat storage in the building structure, investments in heat accumulation tanks (1000 litres per house) are observed in around 4 % of the houses. However, when at the same time assuming intelligent use of the existing hot water tanks for flexible heat pump operation, investment in heat accumulation tanks becomes marginal, occurring in only 0.8 % of the houses[12]. This indicates that socio-economic feasibility of heat accumulation tanks is generally doubtful.

[12] In contrast, intelligent heat storage in the building structure has been found to be even more feasible when assuming that the hot water tank is already utilised intelligently. This is due to the fact that investment in the common control equipment has in this case already been made (see Section 2.2).

4.2.4 System effects of electric vehicles

In Paper II, it is analysed how a large-scale implementation of plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) towards 2030 would influence the energy systems of Denmark, Finland, Germany, Norway, and Sweden. Increasing shares of electric vehicles are assumed in all five countries; comprising 2.5 %, 15 %, 34 %, and 53 % of the private passenger vehicle fleet in 2015, 2020, 2025, and 2030, respectively (see Figure 28). The resulting electricity demand for electric vehicles in Denmark in 2025-2030 is 2.0-3.4 TWh-e (1.0-1.7 million electric vehicles). This represents a very ambitious penetration of electric vehicles compared to Energinet.dk's central projection of the electricity demand for electric vehicles in 2030 of 0.8 TWh [5].

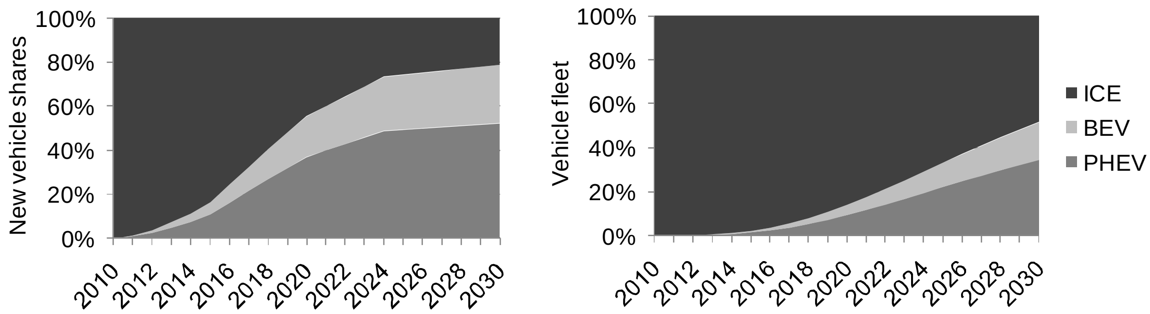


Figure 28. Assumed development in the fleet of private passenger vehicles distributed on internal combustion Engine vehicles (ICEs), battery electric vehicles (BEVs), and plug-in hybrid electric vehicles (PHEVs).

The Balmorel model is applied and road transport has been modelled, using the add-on presented by Juul and Meibom in [17]. However, further model development has been made, in order to handle the gradual implementation of different vehicle vintages in the vehicle fleet towards 2030. Intelligent charging/discharging is assumed in all electric vehicle scenarios. As in [17], plug-in patterns are based on a national investigation of transport habits, and intelligent charging/discharging is identified as part of the system optimisation. Socio-economic cost minimisation is applied.

The results show that the electric vehicles can facilitate significantly increased wind power investments in all of the countries analysed, particularly in the long term. As such, the study indicates that wind power will likely provide a large share of the electricity for electric vehicles in several of the countries (see Figure 29). However, a large part of the electricity generation increase, induced by the electric vehicles, is in several cases coal-based, particularly in the short term. This is thus is a likely outcome, if electric vehicles are not followed up by economic support for renewable energy technologies (other than CO_2 quotas[13]).

[13] In this study, in 2015-2030 assumed to be 20-39 €/tonne in main scenario [121] and 15-30 €/tonne and 26-60 €/tonne, respectively, in sensitivity analyses (given in €2008).

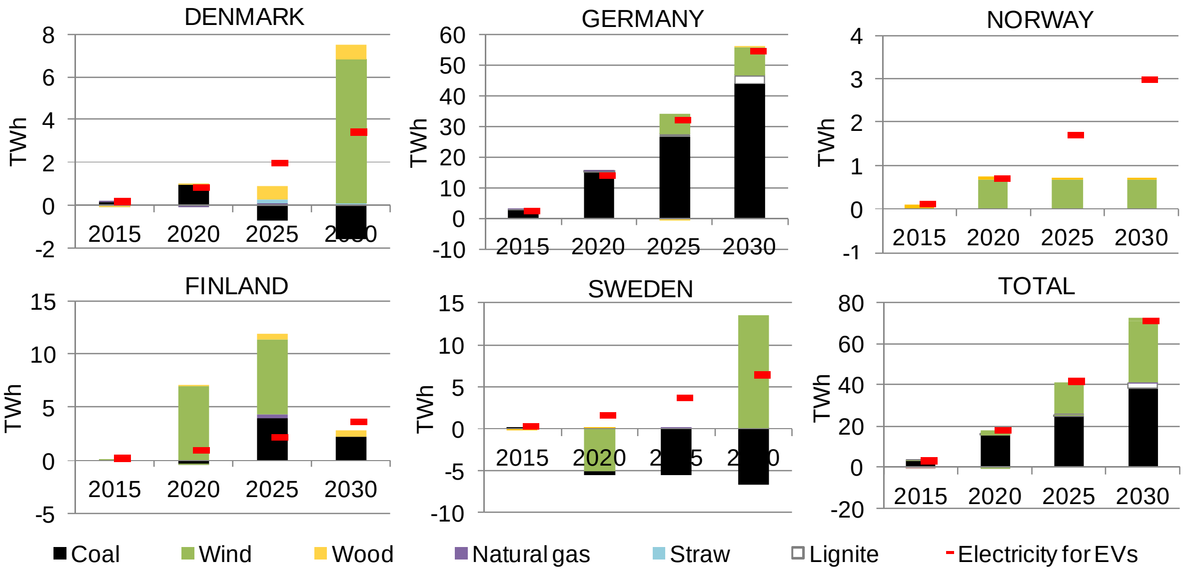


Figure 29. Changes in annual electricity generation due to implementation of electric vehicles. Generated power increases in each year will not necessarily correspond to the electricity demand for electric vehicles. This is mainly due to the influence of electricity import/export.

As illustrated, the effects of electric vehicles vary significantly from country to country. Moreover, the effects of electric vehicles on the system are found to be sensitive to e.g. fuel and CO_2 price variations. It is therefore difficult to draw more general conclusions regarding how electricity demand for electric vehicles would be met.

When charged/discharged intelligently, the electric vehicles can due to vehicle-to-grid capabilities contribute in covering peak loads and thereby reduce the need for new dispatchable power capacities in several of the countries, including Denmark. As such, the investment in coal/natural gas fired power capacities is in Denmark, in some cases, significantly reduced with the implementation of the intelligently charged/discharged electric vehicles (a reduction of 300-2200 MW by 2020-2030, mainly open cycle gas turbines and secondarily coal CHP). However, in some sensitivity scenarios, the introduction of electric vehicles results in net increases in the investment in dispatchable power capacities in Denmark (600-1700 MW).

For the five countries as a whole, the electric vehicles bring significant CO_2 reductions in the long term, 1-6 % in 2025 and 3-28 % in 2030; considering all sensitivity scenarios. Total system costs for the five countries are increased with around 0.8-3.9 %, depending on the year (see Figure 30). It is assessed that the cost increases are caused by the modelled forced implementation of BEVs, having relatively high investment costs; since PHEVs alone have previously been shown to provide system cost reductions [17, 53] and BEVs alone in system cost increases [53].

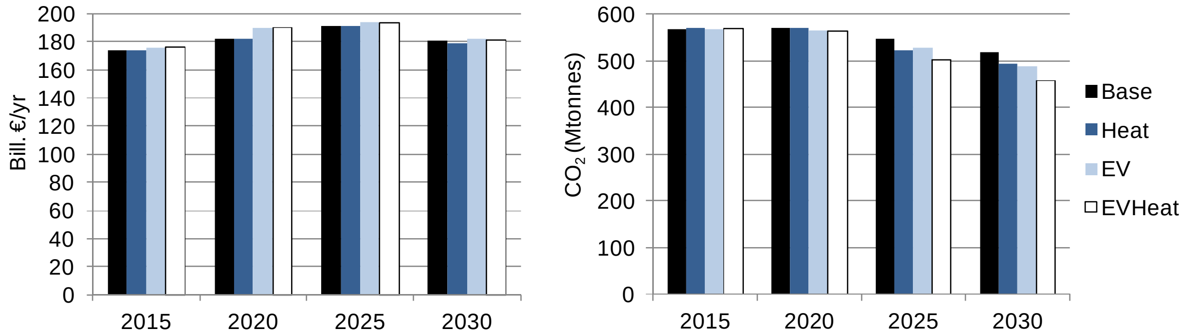


Figure 30. a) Total annualised system costs for the simulated countries, for scenarios with/without electric vehicles (EV) and with/without possibility to invest in large heat pumps, electric boiler, and thermal storages in the district heating system (Heat). **b)** Total CO_2 emissions for the simulated countries.

In relation to the cost effects, it can be noted that infrastructure costs, covering charging spots and potential local grid enhancements, are difficult to quantify and are in [104] assessed to be moderate compared to vehicle costs. Against this background, infrastructure costs are not included.

Average CO_2 reduction costs for the assumed implementation of electric vehicles are reduced considerably towards 2030; from very high levels of 7100 €/tonne in 2015 and 1500 €/tonne in 2020, to 140 €/tonne in 2025 and 80 €/tonne in 2030. This is firstly due to increased use of wind power to cover the electricity demand for electric vehicles over the period. This leads to higher CO_2 reductions, and hence reduced costs per ton CO_2 reduction achieved. Secondly, the technical and economic improvements of electric vehicles assumed towards 2030 also play a role.

4.2.5 District heating versus individual heating

The point of departure for Paper VI is that district heating forms as an important boundary condition for the market potentials of the different flexibility measures in the heating sector: large heat pumps, electric boilers, and thermal storages in the district heating system, and small heat pumps and heat storages for individual heating. The aim of this paper is to investigate whether there is a socio-economic advantage of having a large scale district heating system in a long term perspective, when not including existing district heating infrastructure as a premise, as is the case in many countries. Total system costs are compared for a 100 % renewable energy system by 2050, for the following two cases:

- A case where district heating infrastructure is built and operated (i.e. including all investment and operation costs).
- A case without district heating infrastructure, i.e. only individual heating.

The Danish energy system is applied as case study, and the Balmorel model is used to configure a socio-economic optimal energy system, for each of the two cases. The results reveal only small differences, 1.5-2.0 %, in total annualised system costs, between the case without district heating and the case with district heating (lowest cost for the system without district heating). As such, the results do not indicate a clear socio-economic advantage of building or not building a district heating system in the applied long term perspective.

However, there is a massive net import of electricity in the optimisation, corresponding to about 30-40 % of annual national electricity demand. This is due to the 100 % renewable energy condition implemented for Denmark, while no corresponding policies have been modelled for the neighbouring countries. This questions how realistic the optimised system configuration is from a self-sufficiency perspective. Furthermore, this dependency on net import of fossil fuel-based electricity from other countries would make it difficult to justify the system politically as being 100 % based on renewable energy.

For Denmark, and other countries already having a large scale district heating grid, the most relevant approach is to include the existing infrastructure as a premise, since this represents sunk costs. Studies applying this approach [11, 54] have found that it is socio-economically feasible to expand the Danish district heating grid further, and the Danish Energy Agency also projects a moderate increase in the district heating share towards 2030 [105].

4.3 Summary and comparison of results

4.3.1 Overview of results

The most important findings, concerning the flexibility measures' ability to support the integration of wind power, are summarised below:

Individual heat pumps and heat storages

- The installation of individual heat pumps can contribute significantly to facilitating larger wind power investments and reducing system costs, fuel consumption, and CO_2 emissions.
- Flexible operation of the heat pumps, enabled by heat storages, can contribute only moderately in these respects.
- The main benefit of adding heat storages to individual heat pumps is that the required investments in peak/reserve capacities can be reduced through peak load shaving (300-600 MW in Denmark).
- Investment in intelligent heat storage in the building structure is found socio-economically feasible in about 20-75 % of the houses.
- It is also found feasible to invest in control equipment, enabling the use of existing hot water tanks for flexible heat pump operation, in about 20-70 % of the houses.
- Investments in heat accumulation tanks for space heating are not competitive.

Electric vehicles

- Electric vehicles will, when charged/discharged intelligently, in the long term facilitate larger wind power investments, while they in the short term in many cases are likely to result in increased coal-based electricity generation.
- Electric vehicles can significantly contribute to reducing CO_2 emissions, while system costs are generally increased due to the modelled forced implementation of the costly BEVs.
- Average CO_2 reduction costs for electric vehicles are reduced considerably towards 2030 as a result of improved conditions for wind power and improved technical and economic properties of electric vehicles.

- The electric vehicles can through vehicle-to-grid capability reduce the need for dispatchable power capacity.

District heating vs. individual heating

- No clear socio-economic benefit is identified of building or not building a district heating system in a 100 % renewable energy system by 2050.

Table 6 summarises which flexibility measures have been found socio-economically feasible. The optimal investments identified are also given.

Table 6. Overview of which flexibility measures have been found socio-economically feasible.

Sector	Flexibility measure	Socio-economic feasibility	Optimal investments identified, Denmark by 2030	Papers including this technology
District heating	Large heat pumps	+	700-2300 MW-th	Paper II, III, IV, V, VI
	Large electric boilers	+	0-70 MW-th	Paper II, III, IV, V, VI
	Thermal storages	+	7-15 GWh-th	Paper II, III, IV, V, VI
Individual heating	Individual heat pumps	+	4700 MW-th	Paper III, IV, V, VI
	Intelligent passive heat storage in the building structure via radiator heating	+	20-75 % of houses[b]	Paper III, IV, V
	Intelligent active heat storage in concrete floors via floor heating	+	20-75 % of houses[b]	Paper IV, V
	Heat accumulation tanks	÷		Paper III, IV, V
	Intelligent utilisation of existing hot water tanks[a]	+	20-70 % of houses[b]	Paper V
Transport	Battery electric vehicles[a]	÷	Investments not optimised	Paper II
	Plug-in hybrid electric vehicles[a]	+	Investments not optimised	Paper II

[a] Based on supplementing the analysis in Paper II with results of other studies [17, 53].

[b] Percentages refer to shares of all modeled one-family houses, covering houses with radiator heating as well as houses with floor heating.

As shown, socio-economic feasibility has been identified for individual heat pumps and some heat storage options, PHEVs, and for large heat pumps, electric boilers, and thermal storages in the district heating system.

4.3.2 Comparison of system benefits

It is found that individual heat pumps, through peak load shaving, and electric vehicles, through vehicle-to-grid capability, can reduce the need for investing in dispatchable power capacity. Moreover, both individual heat pumps and electric vehicles can facilitate increased wind power investments and reductions in fuel consumption, and CO_2 emissions. The system benefits of individual heat pumps and electric vehicles cannot be compared further, based on the analyses performed. The reason is that the analyses vary significantly in the approach and boundary conditions applied (see Table 5).

In Paper II, it is shown that large heat pumps, electric boilers, and thermal storages in the district heating system can also facilitate increased wind power investments in several countries, including Denmark. It is found that in terms of increasing socio-economically optimal wind power investments, and reducing CO_2 emissions, these heat measures can together provide benefits in the same order of magnitude as a large-scale implementation of electric vehicles. However, while the heat measures reduce the total system costs of the five countries marginally (0.004%-0.9 %); the electric vehicles increase the system costs (0.8-3.9 %), due to the high investments costs of BEVs. The heat measures are in the following briefly compared to PHEVs alone, based on other studies.

Results in [53] indicate that PHEVs can bring larger cost reductions than the heat measures in the district heating system. On the other hand, large heat pumps in the district heating system can be seen to facilitate significantly larger increases in wind power generation, compared to PHEVs, for the Danish (and Finnish) energy system. This is in agreement with [2], which in analyses of the Finnish energy system, finds that heat measures in the district heating system can facilitate significantly larger increases in wind power investments. No clear indication can thus directly be extracted regarding the cost-effectiveness of PHEVs versus the heat measures, in terms of supporting wind power integration.

4.3.3 The importance of flexible operation for individual heat pumps and electric vehicles

The model developed to represent individual heat pumps, renders it possible to analyse scenarios with/without flexible operation. This allows for investigating the system effects of installing the heat pumps and of ensuring flexible operation, respectively. A corresponding approach is not possible with the transport add-on applied in the analyses of electric vehicles. As such, the transport add-on can only reveal the differences between not having electric vehicles in the system, and then having electric vehicles that are intelligently charged (intelligent discharging, i.e. vehicle-to-grid capability, can however be turned on/off in the model). The situation with/without flexible charging of the electric vehicles is assessed in the following.

As mentioned in Section 2.4, if electric vehicles are not charged intelligently they will typically be charged over the few hours, around 17:00-21:00 o'clock, when people return from home [14]. This is the time of the day when electricity demand is typically highest. As a result, natural gas and coal power plants will typically cover the electricity demand for the electric vehicles in this situation [106]. In contrast, the energy systems analyses indicate that for the case of individual heat pumps, wind power will by 2030 largely supply the electricity for the heat pumps, even when they are not operated flexibly. As mentioned, this is possible since the operation of the individual heat pumps is distributed over many hours of the day. This improves the possibilities for utilising wind power in satisfying the electricity demand of the heat pumps (while using dispatchable power plants as back up). Based on the above, it is assessed that in terms of facilitating larger wind power investments, flexible operation is more important for electric vehicles than for individual heat pumps.

Moreover, since dumb charging of electric vehicles would be concentrated in the peak load hours, this would likely have a relatively high impact on the needs for investing in peak/reserve capacity, and potentially also on enhancements in the distribution grids. In contrast, the electricity demand of individual heat pumps will be more distributed over the day, in the situation without flexible operation. This results in a lower impact on peak loads. As such, it is assessed that also in terms of reducing investment costs in the system, flexible operation is more important for electric vehicles than for individual heat pumps.

5 Discussion and Conclusion

This chapter begins with answering the general research question of the thesis. Subsequently, the most important results are compared with other studies and next, perspectives of the findings are presented. It is then described how the goals of the PhD have been fulfilled, including contributions to national decision making and model development. Finally, suggestions for further research are given.

5.1 Answer to research question

The thesis yields a scientific contribution to answering the following research question:

- *To which extent can heat pumps, heat storages, and electric vehicles contribute to integrating wind power?*

This question has been investigated in several energy systems analyses, mainly using the Danish energy system towards 2030, with up to around 60 % wind power, as a case. It is found that individual heat pumps can contribute significantly to the integration of wind power, even without flexible operation. As such, the heat pumps can contribute significantly to incorporating larger amounts of wind power into the system and to reducing total costs, fuel consumption, and CO_2 emissions. Furthermore, the heat pumps can reduce the pressure on the limited biomass resources by reducing the use of individual wood pellet boilers. The system benefits of the heat pumps are first explained by their high energy efficiency and socio-economic competitiveness, compared to the individual boilers they displace. Secondly, their load profile is distributed over many hours in the day, and heating demand is typically high in the same periods as when wind power is high. This creates good conditions for utilising wind power in covering the electricity demand for the heat pumps. In the case analysed, the political phase out of coal in Denmark by 2030 and the constrained biomass resource availability creates particularly good conditions for wind power.

When investing in heat storages complementing the heat pumps, the operation of the heat pumps can be shifted a few hours within the day. This renders it possible to prioritise the heat pump operation for hours with low electricity prices, and shave down the peaks in total electricity demand of the system. However, the flexible operation of the heat pumps can provide only moderate system benefits, in terms of facilitating larger wind power investments and reduce system costs, fuel consumption, and CO_2 emissions. The individual heat storages are thus less influential on the integration of wind power. The use of an aggregated energy system model means that the heat storage capacity in a given heating area is shared among the heat pumps within the area. Even under these conditions, only moderate system benefits have been identified for the heat storages.

The main system benefit of investing in heat storages for the heat pumps is that the need for peak/reserve capacities can be reduced; by about 300-600 MW-e, corresponding to the size of a large power plant, for the case of Denmark by 2030. This can be achieved with investments in socio-economically feasible heat storages complementing the heat pumps. This effect is crucial for the feasibility of the heat storages.

Investment in intelligent heat storage in the building structure is identified as socio-economically feasible in 20-75 % of the modelled houses with heat pumps by 2030, depending on particularly the investment cost of control equipment. This provides a socio-economic net benefit of around 60-200 € per year per house investing in this storage option. Hereof, savings on energy system investments generally constitute the largest share. In addition, it is found socio-economically feasible to invest in control equipment, facilitating use of existing hot water tanks for flexible heat pump operation, in about 20-70 % of the houses. In contrast, investments in heat accumulation tanks for space heating are not identified as competitive, due to their larger investment costs.

Energy systems analyses of electric vehicles show that when charged/discharged intelligently, they can in the longer term, 2025-2030, facilitate significantly increased wind power investments and reduced CO_2 emissions. Moreover, the electric vehicles can through vehicle-to-grid capability reduce the need for peak/reserve capacities. However, the results indicate that only PHEVs and not BEVs are socio-economically competitive towards 2030. Furthermore, electric vehicles are likely to be supplied by coal-based power in the short term.

Large heat pumps, electric boilers, and thermal storages in the district heating system can also contribute significantly to supporting wind power integration. As such, these heat measures can together provide system benefits in the same order of magnitude as a large-scale implementation of electric vehicles, in terms of facilitating larger wind power investments and reducing CO_2 emissions. The connection between the large heat pumps/electric boilers and the large district heating storages allows for storing electricity as heat during longer periods when needed. This is an advantage compared to individual heat pumps and electric vehicles, which will mainly be able to provide power balancing intra-day and intra-hour, due to smaller storage capacities.

In conclusion, individual heat pumps, flexibility measures in the district heating system, and PHEVs, can provide significant contributions to integrating wind power cost-effectively towards 2030. Heat storages for individual heat pumps can contribute only moderately in this regard.

5.2 Comparison with other studies

The identified potential for reducing investments in dispatchable power capacities (300-600 MW) is on level with the identified peak shaving potential in [49] for smart charging of electric vehicles in the Finnish system (540 MW). It is however lower than the peak shaving potential estimated by Energinet.dk, of 900 MW for flexible operation of individual heat pumps in Western Denmark alone [43]. Part of the reason is that the interaction between heat pump and thermal storages is in [43] not modelled but merely represented as a modified fixed demand profile, assuming that operation can be distributed freely within the day. Furthermore, the result in [43] represents a scenario where a biomass or gas boiler is assumed available to supplement the heat pump, instead of an electric boiler. This makes it possible to turn off the heat pump in longer periods. However, it will hardly be the typical situation that a household invests in a boiler in addition to a heat pump.

Flexible operation of the heat pumps is found to bring a system cost reduction of around 0.6-1.1 %, which is on level with the system cost reduction of 0.45-0.95 % found in [41], for flexible operation of a large scale installation of individual heat pumps in Germany. The identified system benefit of approximately 60-200 €/house/year, is not comparable with the system benefits per house estimated in [41] and [8, 14]. The reason is that in this thesis, investments in thermal storages have been optimised, in contrast to the other studies, where all heat pumps are assumed operated flexibly. Additionally, investment costs for control equipment have been included in this thesis, in contrast to at least [41][14]. If forcing through investments in intelligent heat storage in building structures and in 1000 litres heat accumulation tanks in all houses with heat pump installations, and excluding investment costs for the storages, an average system benefit of around 50 €/house/year is obtained. This is some-what higher than the system benefit of 25-40 €/house/year found in [41]. This fits well with the fact that only operation cost savings are included in [41], while the model applied in this thesis also includes savings on investment costs. The identified system benefit is however significantly lower than the benefit of 80-130 €/house/year estimated in [8, 14]. Part of the explanation for this is considered to be the identified lower reduction in dispatchable power capacity, compared to the estimate in [43]. Furthermore, [8, 14] include benefits in terms of reduced costs for delivering ancillary services, while the model in this thesis only covers impacts on reserve capacities. Finally, [8, 14] include expected cost reductions for enhancing distribution grids as well as an assumed socio-economic benefit of a smart grid, in terms of reduced costs for alternative fulfilment of energy savings obligations [8].

Regarding electric vehicles, the assessment of coal-based power being likely to deliver electricity for the electric vehicles in the short term is in line with findings of energy systems analyses in [106] for an electric vehicle implementation in the Nordic power system towards 2020. The assessment of wind power as being likely to supply the electricity for electric vehicles in the longer term, 2025-2030, is in agreement with results of energy systems analyses of electric vehicles [53], where it is found that electric vehicles drive on wind power in Denmark and Norway by 2030.

5.3 Perspectives

The energy systems analyses performed show that individual heat pumps are highly socio-economically competitive and can bring significant system benefits. However, whether the heat pumps will in fact be installed in the households, depends on whether they are attractive from a private economic perspective, i.e. considering existing taxes, tariffs, and subsidies. In [55], it is concluded that wood pellet boilers are in fact more attractive than individual heat pumps from a private economic perspective. This indicates that stronger economic incentives might be needed to ensure a large-scale implementation of individual heat pumps.

As shown, investments in heat storages complementing the heat pumps can through peak load shaving reduce the need for dispatchable power plants. This can be beneficial from a socio-economic perspective, in a time where the competitiveness of Danish thermal power plants is decreasing (among other things due to the increasing amounts of renewable energy in the Nordic system, pressing the electricity prices downwards) [107].

[14] It is not clear whether control equipment costs are included in the estimates in [8, 14].

However, whether investments in heat storages for individual heat pumps will in fact be realised, again depends on whether they are attractive from a private economic perspective. According to estimates by Energinet.dk, a household would today only be able to gain a benefit of around 40 € per/year, before investment in control equipment; even when gaining access to the regulating power market, in addition to the spot market. This is also expected to be valid in a longer time perspective, with larger price variations on the spot market and regulating power market [62]. As such, Energinet.dk does not assess investment in flexible operation of individual heat pumps to be attractive from a private economic perspective, under current regulation [62]. This assessment is further confirmed when taking into account that control equipment costs (in this thesis estimated to be around 11-37 €/house/year[15]) would further reduce the net benefit for the household.

The analyses performed nevertheless show that when including savings on energy system investments, the socio-economic benefit of enabling flexible heat pump operation is significantly higher, i.e. 60-200 €/house/yr (even when accounting for control equipment costs). The largest benefit of flexible heat pump operation, namely savings on investment costs in the system, will however not be visible on the electricity bill paid by the heat pump owner. It is therefore important to transfer some of this benefit to the consumers, if investments in flexible heat pump operation are to become attractive from a private economic perspective.

Currently, the electricity price faced by a household is typically set based on statistics concerning average electricity consumption patterns. As such, the households are not exposed to electricity price variations and do not have any economic incentive for operating heat pumps flexibly [69]. Such economic incentives require that access is increased for consumers to hourly accounted electricity consumption, possibly with the option of turning off electricity demand in peak load hours [14]. In practice, flexible operation of the heat pumps would e.g. be handled by a balancing responsible agent controlling a large group of heat pumps on an aggregated level. It is furthermore important that the consumers gain access to the regulating power market, since the price variations on this market are larger [62]. Moreover, a large share of the electricity price for Danish households is today comprised by fixed tariffs and taxes, while only a moderate share, around 20 % [108], follows the electricity price variations on the market [69, 109]. If making the taxes/tariffs dynamic, e.g. following electricity price fluctuations, it would increase the incentive for households to engage in flexible electricity demand options [108, 110].

Concerning electric vehicles, the results of this thesis and other studies [17, 53], indicate that PHEVs will be socio-economically attractive towards 2030, while BEVs will have difficulties in competing. In a private economic perspective, the current consumer price of BEVs compared to conventional vehicles is moreover significantly higher than for a conventional vehicle [111, 112]. Furthermore, the question is whether consumers will accept the limitations of BEVs, in terms of shorter driving range and longer charging time etc. compared to conventional vehicles. So far, the sale of BEVs in Denmark has been much slower than expected [113], which illustrates the difficulties of BEVs in competing on the market (only around 800 electric vehicles on the road in Denmark as of 2012). The PHEVs do not have the same disadvantages as the BEVs, due to their fuel flexibility, making them more competitive in this regard. As supplemental measures in relieving the transport sectors' dependency on oil, the use of other fuels such as compressed

[15] Applying a discount rate of 5 %, cf. Paper V, Table 7.

natural gas or biogas in combustion engines could also become relevant and is currently envisaged by the Danish Government [114].

5.4 Fulfilment of goals

Two overall goals of the PhD project have been outlined in the introduction. In the following, it is shortly evaluated how these goals have been fulfilled. The first goal is to:

1. *Contribute to the national decision-making with regard to using heat pumps, heat storages, and electric vehicles in supporting wind power integration*

In the course of this PhD project, several energy systems analyses have been performed, focusing on how and to which extent heat pumps, heat storages, and electric vehicles can support the integration of wind power. The results form basis for a number of policy recommendations. These are oulined below:

The results show that the system benefits of installing individual heat pumps are considerable, while the benefits of enabling flexible operation are moderate. When prioritising efforts and public funds for creating incentives within this field, first priority should therefore be given to ensure a large-scale deployment of the heat pumps. The enabling of flexible operation should be given second priority.

The main system benefit of operating individual heat pumps flexibly, namely the reduced peak/reserve capacity requirement, will not be visible on the electricity bills paid by the heat pump owners. It is therefore important to transfer some of this benefit to the heat pump owners, if investments in flexible operation are to become private economically attractive.

If electric vehicles are not operated intelligently, their charging will typically be concentrated in the hours, where conventional electricity demand peaks. In contrast, individual heat pumps will have a more distributed load profile in the situation with non-flexible operation. In terms of supporting wind power integration and avoiding significant impacts on the need for peak/reserve capacity investments (and potentially also distribution grid enhancements), it is therefore more important to ensure intelligent operation of electric vehicles than of individual heat pumps.

Expansion of renewable electricity generation technologies should be ensured along with deployment of individual heat pumps and electric vehicles. Otherwise, the resulting increase in electricity demand risks being met by coal based electricity generation in the short term.

The second goal of the PhD project is to:

2. *Improve the modelling of some of these wind integration technologies enabling a better representation and understanding of their potentials and limitations*

The energy system models, Balmorel and EnergyPLAN, have both been further developed, thereby improving the representation of individual heat pumps and the interaction with different types of heat storages. This renders it possible to analyse the possibilities and system effects of operating the heat pumps flexibly. The model development in Balmorel facilitates economic optimisation of investments and operation, covering the whole energy system, including individual heat pumps and various thermal storage options. This modelling functionality has not been found in previous studies. Furthermore, intelligent heat storage in the building structure is here represented by integrating a thermal building model into Balmorel, representing the hour by hour temperature states of the relevant thermal masses, and the heat exchange between them. Thereby, the thermal dynamics of buildings are best captured. The incorporation of the thermal behaviour of buildings in an energy system model has only been identified in one other study [41], which did not include energy system investments.

The model development in EnergyPLAN enables representing flexible operation of individual heat pumps, using heat storage in the building structure and in heat accumulation tanks, applying a technical optimisation. The technical optimisation facilitates analysing the potentials of individual heat pumps and complementing heat storages, in terms of minimising excess electricity production and fuel consumption of the system, and utilising as much wind power as possible. This is a new functionality compared to existing models in the field. The technical optimisation can be a valuable supplement to economic optimisations, since these cannot directly reveal the technical potentials described above. The model development made in EnergyPLAN has the advantage of being compatible with heat demand profiles often used in energy system models. It is therefore easier to integrate into the typical structure of energy system models and requires less input data and calibration.

Overall, the two model developments thus provide an important methodological contribution in the representation of individual heat pumps and heat storages and supplement each other well. Finally, both model developments have the advantage of facilitating analyses of scenarios with/without flexible operation of the heat pumps.

The thermal building model developed has been used for analysing the potentials of individual heat pumps in supporting wind power integration. However, the model is also qualified for other applications, e.g. analysing possibilities for involving individual heat pumps in the integration of other fluctuating renewable energy sources or in the optimisation of thermal/nuclear power dominated systems (peak load shaving, optimised power plant portfolio and operation etc.).

In warmer climates, there would typically be a demand for cooling of buildings rather than space heating. Such cooling demand would in many cases be covered by an air-condition unit or a heat pump, i.e. also an electricity driven unit. The thermal building model could with only minor modifications also be used for analysing the system benefits of operating such cooling units flexibly, by utilising the thermal capacity of the building. Finally, the stand-alone version of the thermal building model[16] could be used for private-economic analyses on household level; investigating e.g. required incentives, comparing heating installations, or identifying optimal heat pump/electric boiler capacity shares.

5.5 Further research

Both energy system models used, Balmorel (linear version) and EnergyPLAN are linear and do not include start-up costs, minimum load requirements, or part load efficiencies. Moreover, the models assume perfect foresight and hence do not include power balancing responding to errors

[16] The model version not integrated in Balmorel but using electricity price profiles as input.

in forecasts of wind power and load; only effects on required reserve capacities are modelled in Balmorel. Start-up costs and minimum load requirements for thermal power plants can have a significantly influence on the operation cost savings obtained, when operating individual heat pumps flexibly, as illustrated in [41]. As a result, the savings on operation costs are conservatively represented in the models applied. It would therefore be interesting to integrate the thermal building model into a stochastic unit commitment model, such as Wilmar [115]. This would yield improved estimates of the operation costs savings, including provision of ancillary services. However, effects on energy system investments would not be captured in such a model, and these effects have been identified as crucial. The ideal approach would therefore be a two step approach, where 1) effects on energy system investments are first revealed in e.g. the Balmorel model, and 2) where the optimised energy system configuration is then used as input in e.g. the Wilmar model, for analysing the effects on system operation, including ancillary services. Such an approach has previously been applied for the case of electric vehicles in [49].

The models applied in analysing the system effects of individual heat pumps (and electric vehicles) do not cover potential needs for distribution grid enhancements. A significant expansion with individual heat pumps might require enhancing the distribution grid in certain areas [14]. In [14], it is roughly estimated that savings from distribution grid enhancements are of the same magnitude as savings on the spot market and the regulating power market, respectively [69]. On the other hand, overloading of the distribution grids could be amplified, if synchronising the heat pumps to react to the same price signals [116]. It would therefore be interesting to include the aspect of distribution grid enhancements in further modelling work. Inclusion of hourly COP variations and the heat contribution from solar transmission also constitute relevant subjects for further research.

The feasibility of individual heat pumps and electric vehicles are mutually influential as they both represent an electricity demand. Furthermore, intelligent solutions for individual heat pumps will in some aspects compete with those for electric vehicles. For instance, it is found that the need for peak/reserve capacities can be reduced if either investing in heat storages for the heat pumps, or if utilising vehicle-to-grid capability for the electric vehicles. Competition can also arise in terms of placing operation in hours with low electricity prices. It would be interesting to analyse this competition in further analyses.

In economic optimisations, it is generally assumed that all agents behave economically rational. However, this assumption does not always hold; perhaps particularly not for individual consumers, where other factors such as comfort, convenience, safety, ease of use, social identity, and habits also play a role [117]. Therefore, it would be relevant to supplement the economic optimisations with social behaviour studies, emphasising the influence of such matters. It would be interesting to perform socio-economic valuation and internalisation of relevant factors, and include them in the optimisation. In this regard, it would be relevant to include a valuation of the thermal comfort, as influenced by the indoor temperature variations experienced, when utilising intelligent heat storage in the building structure.

Nevertheless, the model development performed in this PhD project is considered a big step forward, in providing the methodology needed for analysing individual heat pumps and heat storages in an energy system context.

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Appendix

Paper I: Wind power impacts and electricity storage – A time scale perspective

Paper II: Effects of electric vehicles on power systems in Northern Europe

Paper III: Wind power integration using individual heat pumps – Analysis of different heat storage options

Paper IV: Energy system investment model incorporating heat pumps with thermal storage in buildings and buffer tanks

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Paper VI: District heating versus individual heating in a 100 % renewable energy system by 2050

Report chapter: Balmorel model results – EVs and power system investments.

Supplemental data and model illustrations

Paper I

Wind power impacts and electricity storage – A time scale perspective

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Wind power impacts and electricity storage – A time scale perspective

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ABSTRACT

Integrating large amounts of wind power in energy systems poses balancing challenges due to the variable and only partly predictable nature of wind. The challenges cover different time scales from intra-hour, intra-day/day-ahead to several days and seasonal level. Along with flexible electricity demand options, various electricity storage technologies are being discussed as candidates for contributing to large-scale wind power integration and these also differ in terms of the time scales at which they can operate. In this paper, using the case of Western Denmark in 2025 with an expected 57% wind power penetration, wind power impacts on different time scales are analysed. Results show consecutive negative and high net load period lengths indicating a significant potential for flexibility measures capable of charging/activating demand and discharging/inactivating demand in periods of 1 h to one day. The analysis suggests a lower but also significant potential for flexibility measures charging/activating demand in periods of several days. In addition, the results indicate a physical potential for seasonal electricity storage. In the study, a number of large-scale electricity storage technologies – batteries, flow batteries, compressed air energy storage, electrolysis combined with fuel cells, and electric vehicles – are moreover categorised with respect to the time scales at which they are suited to support wind power integration. While all of these technologies are assessed suitable for intra-hour and intra-day/day-ahead power balancing only some are found suited for responding to several days with high/low net loads and even fewer for seasonal balancing.

1. Introduction

Several countries expect large wind power penetrations in the future and this will pose system balancing challenges due to the variable and only partly predictable nature of wind. The Danish energy system forms an interesting case for analysing these challenges. This is firstly due to a high amount of wind power, corresponding to almost 20% of annual electricity consumption. Secondly, around 50% of the power production is based on combined heat and power (CHP), resulting in a large amount of heat bound power production [1]. As a result, in periods with high wind power production, high heat demand and low electricity demand, forced electricity export occurs. Furthermore, in order to ensure stable system operation and meeting electricity demand over the year, there is a significant need for regulating power and ancillary services. The target of 50% wind power in Denmark in 2025 points to significantly increasing challenges of wind power integration in the near future [2]. Moreover, considering the long term goal of the Danish Government of phasing out the use of fossil fuels an efficient utilisation of the wind power is important.

In addition to enhancing and expanding the existing power grid and interconnections with neighbouring countries and to activate flexible electricity demand options such as heat pumps or electric boilers, a broad range of electricity storage technologies can become relevant, e.g. batteries, flow batteries, compressed air energy storage (CAES), electrolysis combined with fuel cells, and electric vehicles used as a distributed energy storage.

The challenges of balancing power production and demand cover different time scales from e.g. intra-hour, intra-day to seasonal level. Due to differences in properties such as response time, storage efficiency, power related costs and storage related costs, storage technologies differ with regard to the time scales at which they are suited to support wind power integration. The above calls for a time scale perspective on the system impacts of wind power and the potentials of different electricity storage technologies.

A number of studies, e.g. [3–5] analyse wind variations and their impacts on the Nordic electricity system and Jónsson et al. [6] analyse how day-ahead wind forecasts affect electricity spot

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prices at the day-ahead spot market. Another study [7] evaluates the current occurrence of low and high wind power shares (as pct. of electricity demand) in Western Denmark on an overall level as well as the impact on electricity prices. In this paper, using the case of Western Denmark in 2025 with an expected 57% wind power penetration, wind power impacts on different time scales are analysed. The power system of Western Denmark is in focus as this will continue to comprise the majority of the Danish wind power production, 75% in 2025 (the remaining in Eastern Denmark forming the second part of the power system).

The system impacts of wind power are analysed based on hourly data on net load, defined as gross load (electricity demand) minus wind power[1] (see Section 2). Net loads provide a better indication of wind power impacts than do wind power shares. The reason is that net loads capture variations in wind power as well as in electricity demand expressing what have to be covered by other units in the power system. Overall, there are two possible challenging operational situations, namely high net load and low net load, and these are both treated in this study. By analysing the length of high and low net load periods, the expected demand for power system balancing at different time scales is investigated. This approach has not been found in previous studies and brings interesting perspectives to discussing wind power integration.

Regarding electricity storage technologies, a group of studies, e.g. [8–10] focus on technical and economic properties of different technologies while other studies, e.g. [11–14] analyse different wind power integration measures based on energy system analyses. In this study, based on existing knowledge on technology characteristics, a number of electricity storage technologies are categorised with respect to the time scales at which they are suited to support wind power integration (see Section 3). This intends to provide a qualitative foundation for dealing with electricity storage in the context of wind power integration.

2. System impacts of wind power

2.1. The system today and in 2025

A certain minimum power production is needed to maintain voltage and frequency stability of the grid, today normally supplied from the large power plants. In Western Denmark, this minimum power production is currently considered to be in the neighbourhood of 400 MW [15]. This constraints the system's ability to respond to wind power variations and is therefore taken into consideration. Thus, the net loads used in this study are defined as gross load minus wind power and minus the minimum power production provided by the centralised thermal power plants.

In 2006–2008, in Western Denmark, wind power and minimum power production together exceeded electricity demand, resulting in negative net load; in relatively few hours corresponding to around 2% of the year on average and the negative net loads were well within the export capacity of 3840 MW (see Fig. 1). Furthermore, as shown there is currently plenty of dispatchable thermal power capacity and import capacity to backup periods with high net loads, i.e. low wind power and high electricity demand.

Based on data from the Danish TSO regarding expected wind power production, electricity demand and thermal power capacities, a corresponding figure has been set up for 2025 (see Fig. 2). The estimated wind power production for Western Denmark in 2025 is based on expected on-shore and off-shore wind power capacities at different locations and wind power production variations based on wind speed measurements at different locations. In total, 2800 MW wind power on-shore and 1760 MW off-shore is assumed in 2025 covering 57% of the electricity demand on annual basis. The estimates are made to represent a normal wind year.

An interconnection between the power system of Western and Eastern Denmark established in 2010 (600 MW) reduces the need for minimum power production at thermal plants in Western Denmark. Moreover, in a future energy system with wind power penetration as high as 50% or more, wind turbines may be able to contribute to grid stabilising system services [18]. Overall, somewhat less, around 300 MW of minimum centralised power capacity for grid stabilisation is therefore assumed in Western Denmark in 2025. As shown in Fig. 2, the number of hours with surplus wind power, i.e. negative net load, can be expected to be considerable in 2025; corresponding to around 22% of the year.

In addition, the dispatchable centralised thermal power capacity will be lower; around 2000 MW in 2025 compared to around 3000 MW currently. As a result, compared to the present situation less abundant thermal capacity will be available to cover electricity demand in high net load periods. Part of the high/negative net load periods in Western Denmark can be balanced through the interconnection with Eastern Denmark. When also including interconnections with neighboring countries, sufficient import and export capacity, 3300–6000 MW and 3800–6000 MW, respectively, is expected to be available in 2025 for handling high and negative net load periods [19]. However, considerable wind power expansions

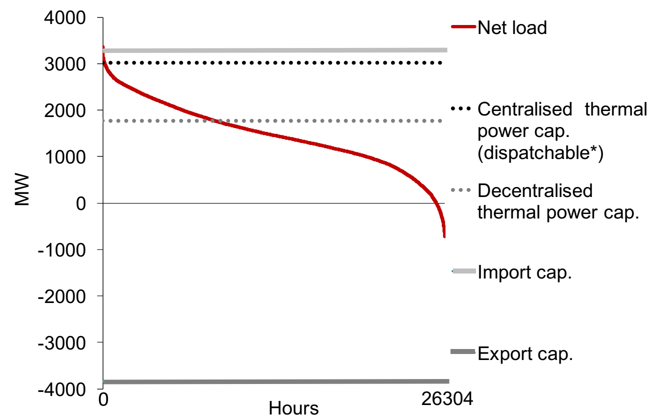

Fig. 1. Net load duration curve for 2006–2008 vs. thermal power capacities and import/export capacities in 2009 for Western Denmark (Net load [16], Capacities [17]).

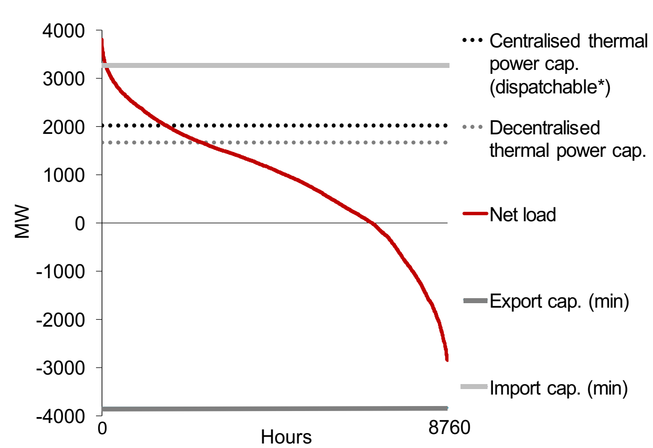

Fig. 2. Estimated net load duration curve and expected thermal power capacities and minimum import/export capacities in 2025 for Western Denmark (Capacities [19]).

[1] Danish power generation from other variable renewable energy sources such as photo voltaic and wave power is negligible.

are expected in the neighbouring areas, and wind power variations in these areas typically show patterns similar to the wind variations in Denmark. As a consequence, future electricity prices in neighbouring areas can often be expected to be low when domestic electricity prices are low leading to low value of exported wind power [20]. Correspondingly, electricity import in high net load periods could be costly. The higher the ability to obtain balance in the energy system without having to rely on electricity import/export, the better possibilities will be for using external electricity trade only when it is profitable. Against this background, electricity storage and flexible electricity demand options can therefore become relevant.

Setting a general threshold level for what should be considered high net loads in Western Denmark in 2025 is very difficult as the power production activated to cover the net load is based on an economic market optimisation and as the situation will vary from hour to hour. Acknowledging the difficulties in setting such a threshold limit, high net loads above 2000 MW, 2500 MW and 3000 MW, respectively, are investigated. Correspondingly, different degrees of negative net loads are analysed, i.e. net loads below 0 MW, −500 MW, −1000 MW, −1500 MW and −2000 MW, respectively.

2.2. Categorisation of system impacts

Apart from the financial market, the Danish power market includes four market places: Elspot, Elbas, the regulating power market and the reserve market. *Elspot* is an integrated part of the Nordic day-ahead spot market where power production based on market bids and forecasted electricity demand and wind power is planned for every hour of the next day (24 h), 12–36 h before the actual operation hour. *Elbas* is a continuous market operating after the end of the spot market where market actors expecting deviations between realised production and day-ahead production plans have the possibility of trading with an official price towards balance closer to the operating hour. On the regulating market, deviations between operation as planned after *Elspot* and *Elbas* and actual operation are balanced intra-hour by the Transmission System Operator (TSO) using power installations with a response time of 15 min [21]. The most important causes for imbalances are consumption and wind forecast errors and operation problems at plants and in transmission lines, including outages [5]. Finally, at the reserve market, the TSO buys system services, including primary and secondary reserves, which in case of small imbalances of supply that have not been balanced by the regulating market re-establish the balance and stabilise the frequency. Primary reserves have an activation time of a few to 30 s and deliver power of maximum 15 min, while secondary reserves have a response time of 15 min and rarely deliver power for longer than 15 min [22]. On an aggregated regional level, i.e. for Western Denmark in the present case, the system impacts of wind power can be categorised into the following types:

- *Intra-hour impacts*: Impacts due to the imperfect predictability of wind power requiring intra-hour balancing at the regulating market and at the reserve market. A subdivision can be made into impacts requiring activation of primary reserves with an activation time of a few to 30 s and impacts requiring regulating power and activation of secondary reserves within 15 min.
- *Intra-day/day-ahead impacts:* Impacts due to the hourly and daily variability and imperfect predictability of wind power creating negative or high net load periods of 1 to 24 h affecting unit commitment and economic dispatch of units at Elspot day-ahead and at Elbas intra-day.

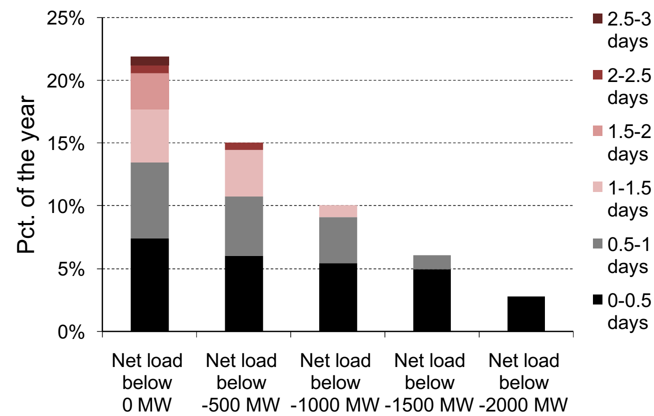

Fig. 3. Consecutive negative net load periods expected for Western Denmark in 2025.

- *Several days' impacts:* Impacts resulting in several days with negative or high net loads
- *Seasonal impacts:* Impacts due to seasonal wind variations creating net load variations across months

Data for Danish wind power production and electricity demand on second or minute level have not been available and hence, *intra-hour* impacts cannot be evaluated. However, wind power variations on second to a few minutes basis are smoothened by different gusts for the individual turbines, inertia of the large rotors as wells as the variable speed turbines absorbing the variations and there is no correlation between the variations of geographically dispersed wind farms. As a result, wind power variations within seconds or few minutes, in the order of the activation notice of primary reserves, have very small effects on system operation even at considerable penetration [3,4]. For regulating power and secondary reserves with an activation time of maximum 15 min, the impact of wind power forecast errors is significant but nevertheless lower than the impact of hourly wind power variations [23].

The remaining wind power impacts are in the following analysed using projected hourly net load variations for Western Denmark in 2025. The length of negative and high net load periods[2] is investigated based on two different approaches:

1) Length of consecutive negative/high net periods and
2) Rolling averages indicating periods with negative/high net loads on average.

It can be noted that the net load approach captures the variability and not the imperfect predictability of wind power and load.

2.3. Negative and high net load periods

The results show that consecutive negative net load periods in 2025 will have a length of maximum three days (see Fig. 3). Hereof, the majority will cover periods with a length of up to one day, i.e. 61%, 71%, 91%, 100% and 100%, of the periods with net loads below 0 MW, −500 MW, −1000 MW, −1500 MW and −2000 MW, respectively. Periods of one to two days will comprise a lower but also significant part; 32%, 25% and 9%, of the periods with net loads below 0 MW, −500 MW and −1000 MW, respectively. As illustrated in Fig. 4, consecutive high net load periods will all have a length below one day.

[2] After subtracting of 300 MW minimum power production on large plants.

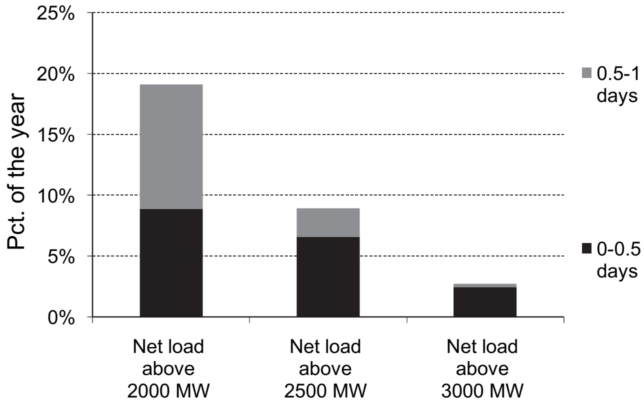

Fig. 4. Consecutive high net load periods expected for Western Denmark in 2025.

The use of rolling averages indicates that periods where net loads are on average negative will have a length of up to several days (see Fig. 5). As such, e.g. periods with net loads below 0 MW on average, when seen over 2–7 days, have a frequency of around 9–20%. However, the frequency of periods with more critical degrees of excess electricity, e.g. net loads below −500 MW on average, is more modest. Periods with high net loads on average when seen over 2–3 days have a moderate frequency (5–9%) while average high net load periods lasting 4 days or more are rare (frequency below 2%) (see Fig. 6).

The estimated length of consecutive negative and high net load periods in Western Denmark 2025 indicate a significant physical potential for electricity storage or flexible electricity demand being able to charge/activate demand and discharge/inactivate demand in periods from 1 h up to one day, i.e. responding to *intra-day/day-ahead impacts* of wind power. The occurrence of consecutive negative net load periods with lengths of one to three days and of average negative net load periods with lengths of several days indicate a lower but also significant potential for flexibility measures capable of charging/activating demand in periods of several days.

2.4. Seasonal variations

Wind power production in Western Denmark expresses significant seasonal variations with typically highest wind power production in the cold months of the year (October to February) and lowest production in the warmer months (April to August).

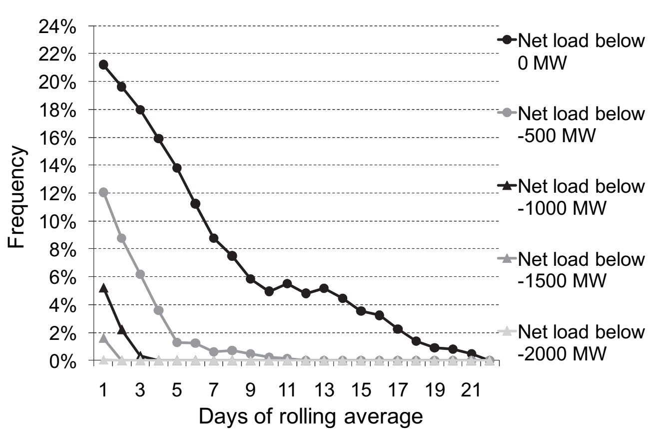

Fig. 5. Periods in Western Denmark 2025 with average negative net load indicated by rolling averages.

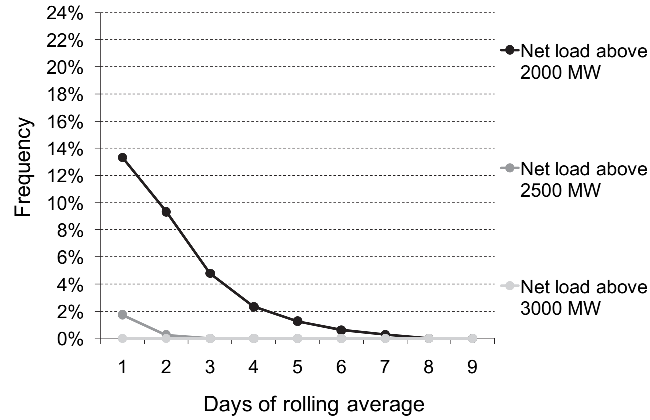

Fig. 6. Periods in Western Denmark 2025 with average high net loads indicated by rolling averages.

Electricity demand in the region also expresses variations across months; presumably due to the influence of electricity based heating and seasonal holidays (see Fig. 7). As shown, the projected net load variations for 2025 also show significant seasonal variations.

Fig. 8 illustrates that the amount of surplus wind power (net loads below 0 MW) exceeds the amount of high net loads (above 2000 MW) in some months, while in other months; the amount of high net loads exceeds surplus wind power. This indicates a physical potential for electricity storage from month to month.

It should be stressed that the analysis in this study only reveals physical balancing potentials while economic potentials of electricity storage and other flexibility measures will be determined by electricity price variations and market conditions.

3. Electricity storage technologies in a time scale perspective

The following subsections cover different technologies that could be relevant for large-scale electricity storage putting emphasis on the time scales, at which the technologies are suited for power system balancing. Electricity storage technologies such as flywheels, superconducting magnets and super capacitors are not included, as these are mainly suited for special applications and are not likely to play a substantial role in the future energy system [24]. Due to the dependence on revenue potentials at the market and energy system in question, economic feasibility of a storage

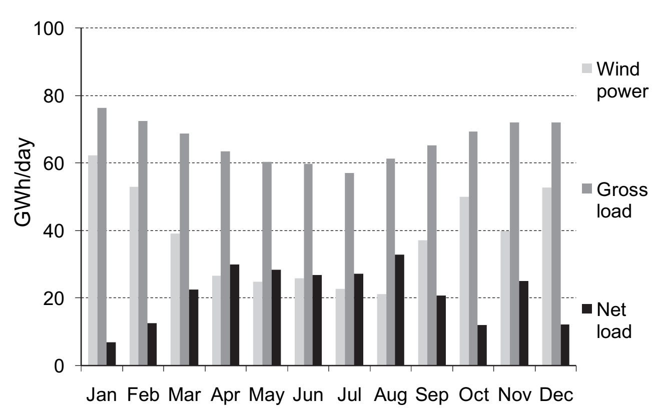

Fig. 7. Average wind power production, gross load and net load per day in each month estimated for Western Denmark in 2025.

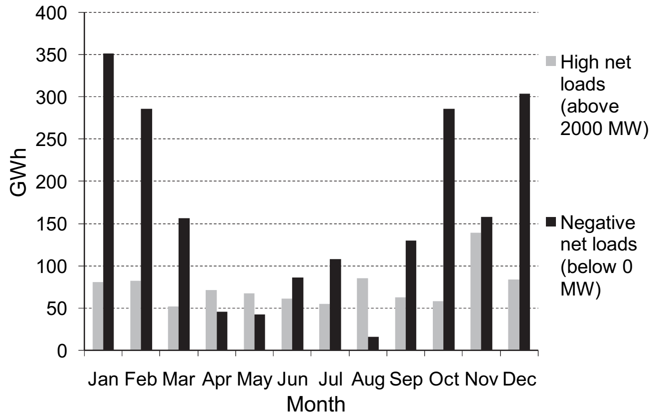

Fig. 8. Monthly distribution of expected negative net loads and high net loads (above 2500 MW) in Western Denmark in 2025.

technology in different time scales should ideally be evaluated case by case. However, based on technology properties such as response time, storage losses, power related costs ($/kWe) and storage related costs ($/kWh), electricity storage technologies can be categorised according to the time scales they will typically be suited for. The term *power related costs* refers to costs related to the power production capacity, e.g. the water turbine for pumped hydro, while *storage related costs* cover cost for the storage facilities, e.g. costs of pumping and storing water in reservoirs for pumped hydro. *Storage losses* are defined as losses from the storage depending on the duration while *loading/unloading losses* refer to losses from loading and unloading in total.

3.1. Batteries

Many different battery types exist whereof the lead–acid and the sodium–sulphur batteries are the most common for large-scale installations. Batteries can be regarded as a mature technology with many commercial MW-scale installations worldwide [25]. Batteries can react instantly to system disturbances and can thus deliver primary reserve capability. Currently, battery applications covering durations of less than one second to around 5 h seem to be commercially feasible [26]. Batteries have low power related costs and high storage related costs compared to many of the other electricity storage technologies, which supports the assessment of batteries being mainly suitable for electricity storage of shorter durations. In addition, depending on the battery type, storage losses can be high (see Table 1).

3.2. Flow batteries

Flow batteries are an emerging technology but only few MW systems have been installed so far [25]. Flow batteries do not have any self-discharge, i.e. loss of energy over time of storage, as the electrolytes cannot react when they are stored separately. This makes them more suitable than conventional batteries for applications that require long duration storages [26]. The size of the electrolyte reservoirs used in the flow batteries determines the storage capacity while the power capacity depends on the rates of the electrode reactions occurring at the anode and cathode. In effect, the power capacity can be designed independently from the energy storage volume, which is an advantage compared to conventional batteries. This should reduce costs and could allow flow batteries to provide power for many hours or even days [24]. For economic reasons, the storage volume is however currently typically limited to maximum one day [27] and storage related costs for flow batteries are also relatively high (see Table 1), indicating a limited suitability for storing large amounts of energy. Very fast response times make flow batteries suitable for providing primary reserves [24].

3.3. Electric vehicles

With implementation of intelligent charging, electric vehicles can form a flexible electricity demand supporting integration of wind power. If in addition, intelligent vehicle-to-grid power capability is implemented, the batteries can form large-scale distributed electricity storage controlled by the needs of the electric system [1]. Thus, charging when electricity prices are low and discharging when electricity prices are high can be prioritised. In addition, since electric vehicles can deliver high power within seconds for short duration of time they are ideally suited for delivering primary reserves [28].

However, power flow between vehicle and grid can only take place when the vehicle is grid-connected, i.e. when not driving. A typical weekday driving pattern can be assumed to express a diurnal cycle of driving in the morning when going for work and in late afternoon when returning from work. Depending on the diffusion of charge spots at employer lots and e.g. mass transit stations, part of the electric vehicles could be grid-connected in periods of the day when not driving. However, the system flexibility

Table 1
Characteristics for a number of large-scale electricity storage technologies

	Power related cost ($/kWe)	Storage related cost ($/kWh)	Response time	Loading/unloading loss	Storage loss	Ref. cost	Ref. response	Ref. loss
Batteries	270–530	330–660	<1 s	30–40%	0–20%/month[c]	[25]	[26]	[25]
Flow batteries	1100–4500[a]	110–320[a]	<1 s	30–40%	0%	[25]	[26]	[25]
Electric vehicles	1750	n/a	Few sec.	20–30%	1–20%/month[f]	[11]	[26]	[29]
CAES	400–500	1-40	9–12 min	30%[d]	Very low	[25]	[10]	[9,30]
Pumped hydro	600–1000	1–20	Few sec.	15–30% in total	[25]	[10,24]	[9,10,24]	
Underground pumped hydro	1100–1300	33–60	Few sec.	15–30% in total	[25]			
Electrolysis, SOFC, hydrogen storage in caverns	Electrolysis: 290–2000 SOFC: 1170[b]	<1	Few sec–hours	55–65%[e]	<0.1%/year	[31–33]	[27,32]	[32, 38]

[a] Low numbers are future prices assuming large-scale production.
[b] Medium term goal for costs.
[c] 0 % for sodium-sulphur batteries, 2–5%/month for lead-acid batteries and 5–20% for nickel–cadmium batteries [26].
[d] In addition to the power consumption for compression, around 1.2 kWh natural gas per 1 kW power output is typically needed [30].
[e] Electrolysers with 60–73% electricity to fuel efficiency are commercially available and SOFCs have a potential electric efficiency of around 60%. The process heat from the fuel cell can be utilised for district heating yielding CHP production [32].
[f] The batteries used in electric vehicles will be largely lithium ion, (loss of 1%/month), or nickelmetal hydride (loss of 5–20%/month for nickel–cadmium) [26].

Table 2
Categorisation of selected large-scale electricity storage technologies with respect to the time scales at which they can support wind power integration.

Batteries	X	X	X		
Flow batteries	X	X	X	(X)	
Electric vehicles	X	X	X		
CAES		X	X	X	X
Pumped hydro	X	X	X	X	X
Electrolysis, SOFC hydrogen storage in caverns	(X)*	(X)*	X	X	X
	Few to 30 s response (primary reserves)	15 min response (regulating power, secondary reserves)	Intra-day/Day-ahead	Several days	Seasonal
	Intra-hour				

"X" and "(X)" indicate suitable and potentially suitable applications, respectively. *Possible only if the plant is already in operation.

provided by electric vehicles can generally be expected to be highest at evening/night and more limited during the day. Moreover, with current battery technology, a typical electric vehicle has a driving range up to around 150 km per full charge [23] corresponding to a few hours of driving. As a result, charging (and discharging) on a daily basis will likely be pursued in most cases. Overall, at least with the current battery technology, electric vehicles can mainly be expected to provide balancing intra-hour and intra-day/day-ahead. The main vehicle-to-grid function is likely to be fast reserves within a limited period [27].

3.4. CAES

CAES have been studied for many years but only two systems have been constructed in the world so far, both dominated by combustion of natural gas. CAES relies on the possibilities of using a cavern or other underground geological formation enabling a large storage volume since the technology becomes prohibitively expensive in the lack of such storage facilities [27].

A CAES plant has a start-up time of around 9 min for an emergency start and around 12 min under normal conditions. Thus, a CAES system is slower in its response than batteries, flow batteries and vehicle-to-grid applications but approximately the same as conventional combustion turbine peak plants [10]. As such, CAES is suitable for providing regulating power and secondary reserves intra-hour [2] and for levelling out daily power imbalances [34] while its ability to deliver primary reserves requires that the plant is already in operation. Relatively low costs of storage capacity ($/kWh) further makes CAES suited for storing large amounts of energy [25] and very low energy losses makes it possible to store energy for more than one year [10]. CAES is suitable to level out daily load fluctuations [34] and according to Cavallo [35], seasonal energy storage with CAES/wind systems can be economically feasible.

3.5. Pumped hydro

Pumped hydro has been at commercial level for a long time in many countries where the topography is suitable. However, new techniques of utilising underground caverns or subsurface reservoirs [36,37] are opening up possibilities of using pumped hydro in areas without mountains, such as Denmark. Like other hydroelectric plants, pumped hydro can respond to load changes within seconds and can thus provide primary reserve capability [10]. Moreover, like CAES, pumped hydro has relatively low storage related costs ($/kWh) [25] and storage losses and pumped hydro is currently the most cost-effective means of storing large amounts of electrical energy. Pumped hydro is also suitable to level out daily power imbalances [34]. However, capital costs and the presence of suitable geography are critical factors for the feasibility of pumped hydro installations [10].

3.6. Electrolysis combined with fuel cells

Use of hydrogen as a storage of electrical energy requires the conversion from electrical to chemical energy through electrolysis. Among different hydrogen storage options, pressurised hydrogen storage in underground caverns is expected to have the lowest costs [33]. Several types of fuel cells exist whereof Solid Oxide Fuel Cells (SOFC) have a potential for replacing existing technologies in distributed central or local CHP/power plants. Compared to other fuel cells, SOFCs have the strength of potentially higher efficiencies, rather long life-times at constant operation and are rather fuel-flexible. The costs of electrolysers and fuel cells are still high, SOFCs are still in the developmental stage and none of the hydrogen storage options are easily applied in practice [24,32].

Electrolysis plants in operation can be up and down regulated within few seconds and are therefore well suited for providing regulating power and primary and secondary reserves. From cold, an electrolysis plant however needs hours to start-up [27]. Due to a high operating temperature (500–1000 °C) and the temperature gradients, SOFCs have start-up time of several hours. Hydrogen storage in underground caverns offers potentially low storage related costs and could therefore be suited for storing large amounts of energy. In addition, preliminary experiences show negligible storage losses [38]. As such, hydrogen storage in underground caverns is suited for storage of several days' production as well as for seasonal storage.

3.7. Technology overview

Table 2 summarises the categorisation of the different electricity storage technologies with respect to the time scales they are suited for in supporting wind power integration.

It can be seen that while all the storage technologies are suitable for intra-hour and intra-day/day-ahead balancing, only some are suitable for responding to several days with high or low net load and even fewer for seasonal electricity storage.

4. Conclusion

In this study, system impacts of wind power are analysed from a time scale perspective for an energy system with 57% wind penetration, using Western Denmark in 2025 as case. The system impacts of wind power are categorised into *intra-hour impacts, intra-day/day-ahead impacts, several days' impacts* and *seasonal impacts.* Based on hourly net load variations, the physical potential for power balancing on different time scales is investigated. Expected lengths of consecutive negative and high net load periods indicate a significant potential for electricity storage or flexible electricity demand being able to charge/activate demand and discharge/inactivate demand in periods of 1 h to one day, i.e. responding to *intra-day/day-ahead* impacts of wind power. The results suggest a lower but also significant potential for flexibility measures capable of charging/activating demand in periods of *several days*. Finally, the estimates indicate a physical potential for *seasonal* electricity storage. *Intra-hour* impacts could not be evaluated since only hourly data where available.

Based on technology properties, number of large-scale electricity storage technologies are moreover categorised with respect to the time scales at which they are suited to support wind power integration. All technologies covered, i.e. batteries, flow batteries, electric vehicles, CAES, pumped hydro and electrolysis combined with fuel cells (SOFC, underground hydrogen storage) are found suitable for *intra-hour* and *intra-day/day-ahead* balancing. Only CAES, pumped hydro, electrolysis/fuel cells and potentially flow batteries are considered suitable for balancing responding to *several days* with high or low net load. Merely CAES, pumped hydro and electrolysis/fuel cells combined with underground hydrogen storage are assessed suitable for *seasonal* balancing.

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Paper II

Effects of electric vehicles on power systems in Northern Europe

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Effects of electric vehicles on power systems in Northern Europe

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ABSTRACT

In this study, it is analysed how a large-scale implementation of plug-in hybrid electric vehicles and battery electric vehicles towards 2030 would influence the power systems of five Northern European countries, Denmark, Finland, Germany, Norway, and Sweden. Increasing shares of electric vehicles (EVs) are assumed; comprising 2.5%, 15%, 34%, and 53% of the private passenger vehicle fleet in 2015, 2020, 2025, and 2030, respectively. Results show that when charged/discharged intelligently, EVs can facilitate significantly increased wind power investments already at low vehicle fleet shares. Moreover, due to vehicle-to-grid capability, EVs can reduce the need for new coal/natural gas power capacities. Wind power can be expected to provide a large share of the electricity for EVs in several of the countries. However, if EVs are not followed up by economic support for renewable energy technologies, coal based power will in several cases, particularly in the short term, likely provide a large part of this electricity. The effects of EVs vary significantly from country to country and are sensitive to fuel and CO_2 price variations. The EVs bring CO_2 reductions of 1–6% in 2025 and 3–28% in 2030 while total costs are generally increased.

1. Introduction

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

Modelling of the integrated power and transport system has only been the focus of few studies so far. McCarthy, Yang, and Ogden [5] have developed a simplified dispatch model for California's energy market to investigate the impacts of integrating EVs into the energy system. In [6], a unit commitment model of the Texas power system is used to simulate system operations with fleets of plug-in hybrid electric vehicles (PHEVs), estimating the value of vehicle-to-grid (V2G) services. Soares et al. [7] evaluate the possibility of using a fleet of PHEVs to regularise possible energy imbalances for a north-eastern Brazilian case. In [8], it is investigated how it affects the power system when EV charging is dispatched optimally. Kiviluoma and Meibom [9] analyse the influence of PHEVs, heat pumps, electric boilers, and heat storages on power system investments in Finnish high wind power scenarios. In [10], the same authors analyse the value of smart charging of EVs compared to charging immediately when being connected to the grid. Lund and Kempton [11] have developed a rule based model of an integrated power and transport system, focussing on the value of including V2G in different wind penetration scenarios. In [12], Kristoffersen et al. calculate the optimal charging patterns of EVs when buying and selling electricity on the Nordic day-ahead power market. Model generated investments in different vehicle types have been introduced in [13–15].

The transition path towards large-scale deployment of PHEVs and battery electric vehicles (BEVs), has e.g. in [16,17] been studied with focus on how to ensure a smooth transition. However, none of the existing studies identified investigate how transition towards increased electrification of the transport sector would affect the power system. This is the subject of this paper.

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Barriers are to be overcome before a large-scale deployment of EVs can be realised. One of the obstacles is the current significant price difference between EVs and conventional vehicles faced by the consumers [18]. In [19], it is found that battery costs must drop significantly before EVs will find a mass market without subsidies. With respect to gaining consumer's acceptance, BEVs furthermore have disadvantages in the form of a relatively short driving range and a long charging time. Electricity consumption for air conditioning or cabin heating can also shorten the driving range in hot/cold weather [20]. Thus, further technology development and likely also economic incentives, as established by several national and local governments [21], are required before widespread use of EVs can be realised. Finally, large-scale implementation of EVs requires a set up of sufficient infrastructure in terms of charging spots etc. The focus of this study is not on how to realise a large-scale use of EVs but on how such a large-scale implementation would affect the power system.

A large-scale implementation of electric vehicles would not only affect power system operation but also investments. As power system investments are realised continuously, these effects are best investigated by analysing a period of several years. In this study, it is analysed how a gradual large-scale implementation of PHEVs and BEVs in the Northern European countries, Denmark, Finland, Germany, Norway, and Sweden, would influence power system investments and operation towards 2030. Inspired by scenarios set up the Electric Power Research Institute (EPRI) and the International Energy Agency (IEA), increasing shares of electric vehicles are assumed; comprising 2.5%, 15%, 34%, and 53% of the private passenger vehicle fleet in 2015, 2020, 2025, and 2030, respectively. The analyses performed are based on the model of the integrated power, district heat, and transport system described in [14,22]. Simulations are made with five year intervals where optimal investments identified in previous years are included in the optimisations of subsequent years. Plug-in patterns based on a national investigation of transport habits are implemented as in [14] and intelligent charging/discharging is identified as part of the energy system optimisation. A socio-economic optimisation is applied in order to investigate how EVs would affect the power systems in the absence of taxes, tariffs and subsidies. Under these conditions, the results reveal which power generation technologies are likely to meet the large electricity demand induced by EVs over the period. In a sustainability perspective, the relevant question is to which extent renewable energy sources would cover this electricity demand. Additionally, effects of EVs on CO_2 emissions and costs are evaluated. Putting the impacts of EVs into perspective, these are compared to the effects of investing in heat storages, and flexible electricity demand options in the form of heat pumps, and electric boilers in the district heating system, forming alternative ways of increasing system flexibility.

Section 2 in the article presents the model, Balmorel, and the transport add-on used for the analyses. In Section 3, the application of the model is described including scenarios and input data. Section 4 covers presentation and discussion of results. Finally, a conclusion is given in Section 5.

2. Model

The integrated power and road transport system is modelled in Balmorel, which is a deterministic partial equilibrium model assuming perfect competition [9,14,22] .The model optimises investments in power/heat production, storage, and transmission capacities. This is done minimising total costs in the energy system, covering annualised investment costs, operation and maintenance costs of existing and new units, as well as fuel and CO_2 quota costs. The optimisation is performed subject to a number of constraints including satisfaction of demands for electricity, heat, and transport in each time period, renewable energy potentials, vehicle restrictions, and technical restrictions on units in the power system.

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

2.1. Transport add-on

Road transport is modelled using the add-on presented by Juul and Meibom in [14]. Further model development has been made in order to handle the gradual implementation of different vehicle vintages in the vehicle fleet towards 2030. The transport model includes demand for transport services, vehicle investments and operational costs, and electricity balancing in the integrated road transport and power system. As such, the model makes it possible to analyse interactions between the two systems and to identify benefits and optimal investments, and operation. In this study, vehicle investments are fixed to an assumed development path, while investments in the power system are generated endogenously. Among the vehicle technologies available in the model, the following are included in the analysis:

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

In the model, all EVs are assumed to leave the grid with a fully charged battery, restricting the charging to meet this load factor. The plug-in hybrids are assumed to use the electric storage (the usable part of the battery) until depletion before using the engine. This assumption is considered reasonable due to the high efficiency of the electric motor compared to that of the combustion engine and due to the low price of electricity (average prices in the neighbourhood of €50/MWh in the simulations) compared to the price of diesel (64–80 €/MWh in 2015–2030, cf. Table 8). Moreover, the batteries have no loss of power before almost depleted, leaving the motor able to perform as demanded until down to the minimum state of charge.

Integrating the power and transport systems and introducing intelligent charging and discharging requires a number of additions to the existing system. E.g. communication between vehicles and the power system, vehicle aggregators communicating with power markets, and agreement upon connection standards is needed. In the model, all such changes are assumed to be in place. Infrastructure costs covering charging spots and potential local grid enhancements are difficult to quantify and are in [23] assessed to be moderate compared to vehicle costs. Against this background, infrastructure costs are not included. The model works with a capacity credit restriction ensuring enough production capacity to meet peak power demand as presented in [9]. Due to V2G capabilities of BEVs and PHEVs, they are able to contribute in meeting peak power demand. The modelling of this contribution is taken from the PhD thesis by Nina Juul [24].

3. Application

The model includes the power sector, the district heating sector, and the part of the road transport sector comprising private passenger vehicles. With the intent to obtain reasonable computation times, Norway, Sweden, and Finland are each treated as one power region. Thus, internal transmission bottlenecks in these countries are not modelled. Germany is aggregated into two regions, representing the transmission bottlenecks between Northern Germany with its large share of wind power and the large consumption centres in Central & Southern Germany. Denmark is divided into two regions: Western Denmark being synchronous with the UCTE power system and Eastern Denmark being synchronous with the Nordel power system. Also based on computation time limitations, Norway, Sweden, and Finland, are each modelled as one district heating area, Germany as two, and Denmark as four district heating areas.

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

The assumed implementation of EVs is based on scenarios set up by EPRI [25] and IEA [26]. In the Medium scenario in [25], a development in PHEVs new vehicle shares as outlined in Fig. 1a is assumed. Based on the relative development in sales of PHEVs and BEVs towards 2030 in the Blue Map scenario in [26], additional BEV market shares corresponding to half of the PHEV new vehicle shares have been assumed. Applying an average vehicle lifetime of 16 years, the resulting development in the vehicle fleet shares towards 2030 is illustrated in Fig. 1b. Consequently, EVs are assumed to comprise around 2.5%, 15%, 34%, and 53% of the vehicle fleet in 2015, 2020, 2025, and 2030, respectively. This represents an ambitious scenario for implementation of EVs and should not be interpreted as a forecast. Rather, the scenario is used for analysing how such a large-scale implementation would affect the power system. The assumed BEV implementation, comprising 1/3 of the EV fleet shares, can be interpreted to represent use as second/third cars of the households. This is reasonable since statistics show that a large share of all trips, 25% for the case of Denmark, are driven with second/third cars [15].

3.1. Scenarios

In order to investigate the effect of EVs, scenarios are set up with/without the gradual large-scale EV implementation given in Fig. 1b. When evaluating the effects of EVs, possible investments in heat storages, heat pumps, and electric boilers in the district heating system should be taken into account. This is relevant as these represent competing measures of increasing system flexibility. Furthermore, it is intended to compare the effects of EVs with the effects of heat measures. Based on these considerations, four main scenarios are created with/without EVs and with/without the possibility to invest in heat measures in the district heating system (see Table 1).

When assessing the effects of EVs, the Heat and EVHeat scenario are compared. When comparing the effects of EVs with the effects of heat measures, differences between the Base scenario and the EV and Heat scenario, respectively, are used as basis.

In addition, a number of sensitivity scenarios are made, covering e.g. low/high fuel and CO_2 price developments. The sensitivity scenarios are described and analysed in Section 4.5. Keeping main focus on the effects of EVs when competing with heat measures, the sensitivity scenarios comprise variants of the Heat and EVHeat scenario.

3.2. Input data

Electricity, district heating and transport demands as well as annual driving per vehicle are all given as data inputs to the model (see Tables 2 and 3).

The expected development of vehicle technologies in terms of costs, efficiencies, electric storage capacities, and battery ranges is taken into account. The data applied for the different vehicle technologies and vintages are given in Table 4. As in the study in general, all costs are given in €2008.

As in [14], plug-in patterns for BEVs and PHEVs have been derived from driving patterns obtained from the investigation of transport habits in Denmark [33]. In this regard, it has been assumed that the EVs are plugged-in at all times when parked. Furthermore, it is assumed that driving habits are the same for all the countries in the simulation. An iterative process has been required in order to make the total transport demands fit with the number of each type of vehicle, the annual driving distances for ICEs/PHEVs and BEVs, and the driving patterns. Total transport demands have thus been adjusted and are still close to the demands in the sources used. It is assumed that BEVs of vintage 2015 and 2020 can cover trips lasting up to 2 h (corresponding to 115 km) yielding an annual driving of 10,230 km/yr and that BEVs of vintage 2025 and 2030 can cover trips of up to 3 h (corresponding to 205 km) yielding 12,671 km/yr. This is considered reasonable based on the distances supported by the BEV battery capacities in Table 4; assuming that people will be reluctant to drive close to emptying the battery and that spare battery capacity will in some cases be required for a second trip in the day.

The model includes comprehensive data on capacities, efficiencies, operation costs, technical lifetimes etc. for existing units

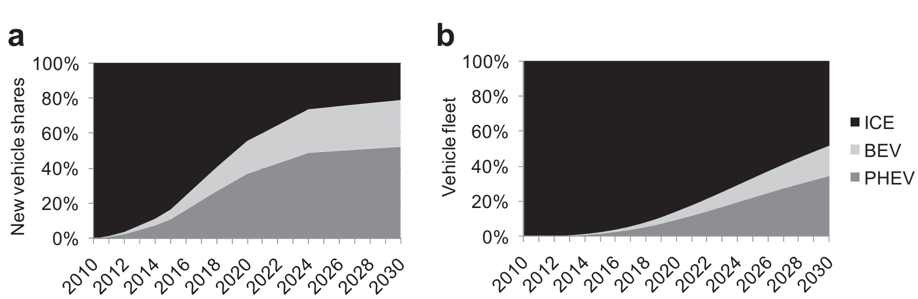

Fig. 1. a) Development in plug-in hybrid electric vehicle (PHEV) new vehicle shares in the Medium scenario in [22] and illustration of the assumed relation between battery electric vehicle (BEV) and PHEV new vehicle shares based on the Blue Map Scenario in [23]. b) Assumed gradual penetration of PHEVs and BEVs in the vehicle fleet.

Table 1
Main scenarios in the analysis.

	Base	EV	Heat	EVHeat
Gradual implementation of PHEVs and BEVs towards 2030		+		+
Inv. in heat storages, heat pumps, and electric boilers allowed			+	+

for power/heat production, storage, and transmission. As such, gradual decommissioning of existing power/heat production capacities towards 2030 is included. The current electricity production distributed on sources for each of the five countries is illustrated in Fig. 2 (as generated by the model).

Based on national policies, nuclear power investments are assumed allowed only in Finland and Sweden. The Swedish government has decided that investments in new nuclear power plants can only be made if replacing existing plants [34]. Hence, the maximum allowed installed Swedish nuclear power capacity is set to the current capacity (around 10,200 MW). For Finland, the new Olkiluoto reactor 3 (1600 MW) being under construction and planned for operation from 2013 is included in the model. The maximum allowed installed nuclear power capacity in Finland towards 2030 is set to 7260 MW, representing current capacity plus the capacity of Olkiluoto 3 and of two additional nuclear power units considered for construction towards 2030 (Olkiluoto 4 and Pyhäjoki, around 1500 MW each) [35]. Based on experiences concerning time scales for construction of nuclear power plants, investment in Finnish nuclear power plants is only allowed from year 2020 and only up to 1500 MW per five years, corresponding to the implementation of one unit. In response to the Fukushima incident, the current German government has decided to phase out nuclear power. Acknowledging this but also considering possible delays in the phase out and shifts in the political opinion, German nuclear power capacities are assumed decommissioned based on technical lifetimes.

As coal based power plants are not considered among the feasible options for future energy supply in the hydro power dominated Norwegian energy system, investment in this technology is in this case excluded. The power system units assumed available for investment are given in Table 5. In addition, investment in transmission capacities between regions is allowed.

Wind power investments are in reality not alone based on economic rationales but are also influenced by national energy and climate policies. However, if restricting wind power investments in the model, e.g. to meet national wind targets for each year as a minimum, the effects of EVs on wind power investments and generation would not be fully reflected. Therefore, such restrictions have not been included. Accumulated onshore wind power capacities have, however, been constrained by onshore wind potentials as given in Table 6. In addition, capacity growth limits on wind power have been applied to ensure reasonable capacity increases per year.

Hydro power is characterised by costs and implementation barriers that are site specific to a higher degree than many other sources of electricity generation [43]. Against this background, investments in new hydro power capacity are not identified as part of the energy system optimisation. Instead, expected increases in hydro power production are included as fixed generation levels (see Table 7).

Historically, Finland has had a significant net import from countries outside the system boundary of this analysis; mainly from Russia; in 2010 around 13.4 TWh corresponding to 15% of domestic electricity demand. Therefore, based on hourly data for 2010 [44], this net import is included as a fixed electricity exchange.

Table 2
Electricity demand (TWh/yr)/District heating demand (TWh/yr)/Transport demand (10^9 person km/yr) given in rounded numbers.

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

Sweden, Finland, and Germany: [27], Norway: based on current relation between Norwegian and Swedish demands/number of cars. Denmark, electricity and district heating: [28], transport: based on [27,29].

Table 3
Annual driving for each vehicle type.

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

Table 4
Vehicle technology data.

Veh. type	Vintage	Inv. cost (€/yr)[a] [26,30]	O&M cost (€/yr) [30]	Elec. stor. cap[b] (kWh) [26]	Eff. (km/kWh) [14] [c]	Bat. range (km)[d] [14,31]
ICE	2015	1058	1168	–	1.8	–
	2020	1058	1168	–	1.9	–
	2025	1058	1168	–	1.9	–
	2030	1058	1168	–	2.0	–
BEV	2015	3035	1101	40	5.5	220
	2020	2509	1101	43	6.0	260
	2025	1962	1101	47	6.5	303
	2030	1745	1101	50	7.0	350
PHEV	2015	2122	1168	12	5.5	65
	2020	1784	1168	11	6.0	65
	2025	1521	1168	10	6.5	65
	2030	1387	1168	9	7.0	65

[a] A discount rate of 5% is applied in fixed prices based on [32].
[b] The usable storage capacity of the battery.
[c] 5 km/kWh for BEV/PHEV vintage 2010 and 7 km/kWh for vintage 2030 [14].
[d] Battery range of 150 km for BEV vintage 2010 [31] and 350 km for vintage 2030 [14].

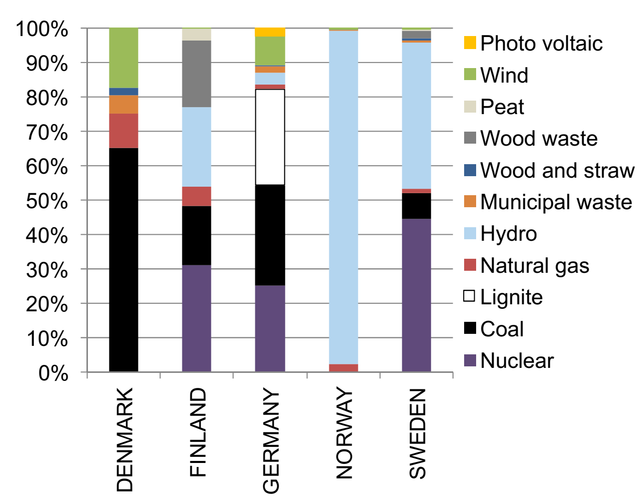

Fig. 2. Electricity generation in the present power systems of the five Northern European countries distributed on sources. The distribution is generated by the model for the Base scenario for 2010 when not allowing investments in new capacities.

Table 5
Technologies available for investment in the optimisation.

Technology	Fuel	Period available	Inv. cost[a] (M€/MW)	Variable O&M cost (€/MWh)	Fixed O&M cost (k€/MW/yr)	Lifetime (years)	Eff[b]	CB	CV	Ref.
Onshore wind turbine	–	2011–2020	1.33	12.50	–	20	1.00	–	–	[36]
	–	2021–2030	1.24	11.75	–	25	1.00	–	–	[36]
Offshore wind turbine	–	2011–2020	2.50	17.00	–	20	1.00	–	–	[36]
	–	2021–2030	2.25	15.50	–	25	1.00	–	–	[36]
Steam turbine, extraction, CHP	Coal	2011–2020	1.43	7.00	–	40	0.46	0.75	0.15	[36]
		2021–2030	1.40	7.00	–	40	0.50	0.93	0.15	[36]
Open cycle gas turbine, condensing	Natural gas	2011–2030	0.32	2.40	16	20	0.37	–	–	[37]
Combined cycle gas turbine, extraction, CHP	Natural gas	2011–2020	0.52	3.20	20	25	0.59	1.55	0.13	[36,37]
		2021–2030	0.47	3.20	20	25	0.62	1.75	0.13	[36,37]
Nuclear, condensing[c]	Uranium	2011–2030	2.81	7.7	56	40	0.37	–	–	[37]
Steam turbine, extraction, CHP	Wood	2011–2020	1.68	3.20	23	30	0.46	0.53	0.15	[36]
		2021–2030	1.60	3.20	23	30	0.48	0.58	0.15	[36]
Steam turbine, back pressure, CHP	Wood	2011–2020	4.40	–	154	20	0.25	0.30	–	[36]
		2021–2030	3.95	–	138	20	0.25	0.30	–	[36]
Steam turbine, back pressure, CHP	Straw	2011–2020	4.35	–	174	20	0.30	0.49	–	[36]
		2021–2030	3.90	–	156	20	0.30	0.49	–	[36]
Heat boiler	Wood	2011–2030	0.50	–	24	20	1.08	–	–	[36]
Heat boiler	Natural gas	2011–2030	0.09	–	3.2	20	1.01	–	–	[36]
Heat pump[d]	Electricity	2011–2020	0.65	–	6.9	20	2.8	–	–	[36,38]
		2021–2030	0.65	–	6.9	20	3.0	–	–	[36,38]
Electric boiler	Electricity	2011–2030	0.06	0.5	1	20	0.99	–	–	[36]
Heat storage	–	2011–2030	0.00185	–	–	20	0.99	–	–	[39]

[a] Based on [32], investment costs are in the model annualised with a discount rate of 5% given in fixed prices. Investment costs for heat storage are given in M€/MWh storage.
[b] For heat boilers, heat efficiency, for heat pumps, coefficient of performance, and for other units, electric efficiency.
[c] Allowed in Finland and Sweden only.
[d] Investment costs for heat pumps given in M€/MW-thermal.

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

	Medium wind target [40]	High wind target [40]	Onshore wind potential assumed
Denmark	7291	8020	4500 (East: 1000 MW, West: 3500) [41,42]
Finland	3200	6000	12,000[b]
Germany	54,244	63,587	63,600[a]
Norway	5980	11,970	12,000[a]
Sweden	10,000	17,000	17,000[a]

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

However, part of the background behind installing new nuclear power capacities in Finland is supposedly to reduce its dependency on electricity import from Russia [45]. In addition to the new nuclear power 1600 MW installed in 2013, model optimisations suggest an additional capacity of 1500 MW to be installed in 2020. This leads to a total increase in nuclear power generation of around 23 TWh/yr (assuming a capacity factor of 0.85 [35]), thus, exceeding current Finnish net import from Russia. Based on this, the Finnish net import from countries outside the system boundary is assumed diminished from year 2020.

For Denmark, the system boundary covers all countries with which electricity is exchanged. For Sweden and Norway, electricity exchange with countries outside the system boundary is of very low magnitude[1] and has therefore been excluded. For Germany, annual import/export in 2008–2010 from/to countries outside the system boundary corresponded to 5–7%/9–11% of domestic electricity demand yielding a net export corresponding to 2–6% of the demand [46]. As such, for the case of Germany, this exchange is moderate but not insignificant in magnitude. However, as German electricity exchange with countries outside the system boundary is distributed over many countries[2] the exchange is complex. Hence, a satisfactory inclusion of this electricity exchange would require expanding the model to include all relevant countries with which Germany trades electricity. This would require comprehensive data collection and increase model calculation times to a level challenging completion of model runs and the analysis. This has been without scope of this study. Due to its large volumes, the German energy system is highly influential on total CO_2 emissions and costs for the five Northern European countries as a whole. Thus, when interpreting the results for Germany and for the five countries as a whole it should be keep in mind that not all German electricity exchange options have been modelled.

Based on [47], CO_2 prices are assumed to increase from 20 €/tonne in 2015 to 39 €/tonne in 2030, and the assumed fuel prices correspond to an oil price of \$88/barrel in 2015 and \$117/barrel in 2030 (see Table 8).

Table 7
Hydro power generation assumed.

TWh/yr	2010	2015	2020	2025	2030	Ref.
Germany	19.7	20.8	20.9	21.4	22.0	[27]
Finland	13.8	13.9	14.0	14.2	14.4	[27]
Norway	126.8	131.8	136.8	141.8	146.8	[43]
Sweden	66.4	66.7	67.0	67.0	67.0	[27,34][a]

[a] Swedish hydro power production in 2010 set to the average production for the last five years based on [34] and relative increase based on [27].

[1] In 2008–2010, Swedish import/export to/from countries outside the system boundary corresponded to 0.1–0.3%/0.5–1.5% of domestic electricity demand and corresponding numbers for Norway were 0.3–2.1%/1.1–2.7% [46].

[2] Austria, Switzerland, Czech Republic, France, Lithuania, The Netherlands and Poland [46].

Table 8
Fuel and CO_2 quota prices assumed (€/GJ) [47].

	Fuel oil	Diesel	Natural gas	Coal	Lignite	Uranium [48]	Wood	Straw	Wood waste [9], municip. waste[a]	CO_2 (€/tonne)
2010	6.7	14.8	6.0	2.9	1.5	0.7	6.0	5.1	0	14
2015	8.3	17.7	8.2	2.9	1.4	0.7	6.6	5.8	0	20
2020	9.4	19.7	9.2	3.2	1.6	0.7	6.9	5.9	0	25
2025	10.2	21.0	10.0	3.4	1.7	0.7	7.2	6.1	0	32
2030	10.9	22.4	10.7	3.4	1.7	0.7	7.5	6.2	0	39

Fuel costs include distribution costs.
[a] Municipal waste is assumed to have zero cost applying a socio-economic perspective.

4. Results

Results of the main scenarios are presented in Sections 4.1–4.4 and results of sensitivity scenarios in Section 4.5.

4.1. Effects on power system investments

Socio-economic optimal investments in new power production capacities generated in the Base, EV, Heat, and EVHeat scenario are illustrated in Fig. 3. As shown, the increases in production capacity mainly comprise coal CHP and wind power. Nuclear power investments are also realised for the case of Finland and Sweden, where this option is allowed. In addition, moderate investments in wood CHP extraction plants and open cycle gas turbines are observed; the latter used for ensuring sufficient capacity to meet peak power demands.

Due to increasing fuel and CO_2 prices, the economic conditions for wind power generally improve over the period. This is clearly illustrated for the cases of Denmark, Germany, and Sweden where wind power investments mainly occur in the last part of the period towards 2030. Moreover, existing wind power capacities in Denmark and Germany are significantly decommissioned from 2020 to 2025 (from around 3200 MW to 0 MW in Denmark and from around 23,000 MW to 11,000 MW in Germany), which is also part of the explanation for the large wind power investments in these countries in 2025. In Norway, Sweden, and Finland, where onshore wind power resources are relatively high in terms of obtainable full load hours,[3] wind power investments occur earlier than for the cases of Denmark and Germany. The accumulated wind power capacities in 2030 for the EVHeat scenario can be identified to 5100 MW for Denmark, 12,000 MW for Finland, 56,600 MW for Germany, 10,700 MW for Norway, and 12,000 MW for Sweden. Comparing these with the national medium wind targets for 2030 in Table 6, it can be seen that the target is met or exceeded for Finland, Germany, Norway, and Sweden and not far from being met for the case of Denmark. This indicates that the accumulated wind power investments generated in the optimisation are reasonable.

Comparing the EVHeat scenario and the Heat scenario, the implementation of EVs can be seen to facilitate increased wind power investments in all five countries. In Finland and Norway, this effect is observed already in 2020, where EVs comprise 15% of the vehicle fleet. The effect is most significant in Finland where wind power investments in 2020 are doubled from approximately 2700 MW to 5400 MW. At higher EV fleet shares of 34% in 2025, EVs make wind power investments more attractive in Germany and particularly in Sweden where wind power investments are increased from around 4100 MW to 6000 MW. In 2030, where EVs comprise 53% of the vehicle fleet, increased wind power investments are observed in Denmark and Germany, and particularly in Sweden where wind power investments are increased manifold from around 800 MW to 6000 MW. In Finland, the assumed onshore wind potential of 12,000 MW is reached in 2030 in both the Heat and EVHeat scenario. Hence, in this case the EVs push forward the investments in wind power. The reason for the increased investments in wind power when implementing EVs is that their flexible charging/discharging facilitates integration of the variable production from wind power into the power systems.

As a result of the large-scale EV implementation and the resulting increase in electricity demand, one might expect significantly increased investments in dispatchable power production capacity in terms of e.g. coal or natural gas power plants. However, the results in Fig. 3 show that when EVs are charged/discharged intelligently, increased investments in thermal power production capacity are only observed in very few cases. As such, the only significant increases are observed in Germany in 2020–2030 where investments in coal CHP are increased with around 1100–1500 MW in the EVHeat scenario compared to the Heat scenario. In fact, rather than increasing investments in thermal production capacity, for the case of Denmark, Finland, and Sweden, EVs result in reduced need for new thermal power capacities. Thus, investments in open cycle gas turbines and/or coal CHP capacities are reduced significantly in these countries in 2025–2030 with the implementing of EVs. This is explained by the V2G capability of EVs which contributes in covering peak loads resulting in a reduced need for dispatchable production capacity.

Like EVs, heat pumps, electric boilers, and heat storages in the district heating system can also be seen to support wind power investments in several of the countries. While the optimisation generates heat measure investments in all five countries, the effect on wind power investments is most significant in Finland and Sweden, where e.g. wind power investments in 2025 are significantly higher in the EVHeat scenario compared to in the EV scenario (and in the Heat scenario compared to in the Base scenario). This is due to the combination of relatively large onshore wind potentials and obtainable full load hours in Finland and Sweden (as opposed to in Germany and Denmark) combined with a significant district heating volume (as opposed to Norway, cf. Table 2).

The Finnish and Swedish investments in heat measures cover heat storages and heat pumps.[4] Heat pumps (and electric boilers) are able to support wind power investments as they represent a flexible electricity demand that can be activated when electricity prices are low, corresponding to periods with large amounts of wind power and low electricity demand. Additionally, the activation of heat pumps can contribute in relieving CHP plants from heat bound power production. This also enhances system flexibility and

[3] Assumed full load hours for onshore wind power: Norway: 3000 [43,50], Finland, Sweden: 2600 [43,51], Denmark, West: 2440, Denmark, East: 1960 [42], Germany: 1750 (based on [52,53]).

[4] E.g. for the Heat scenario, Finland: 1.2–6.2 GWh/yr heat storage capacity, 600–4600 MW-thermal/yr heat pump capacity, Sweden: 9.6–47 GWh heat storage capacity, 60–950 MW-thermal/yr heat pump capacity.

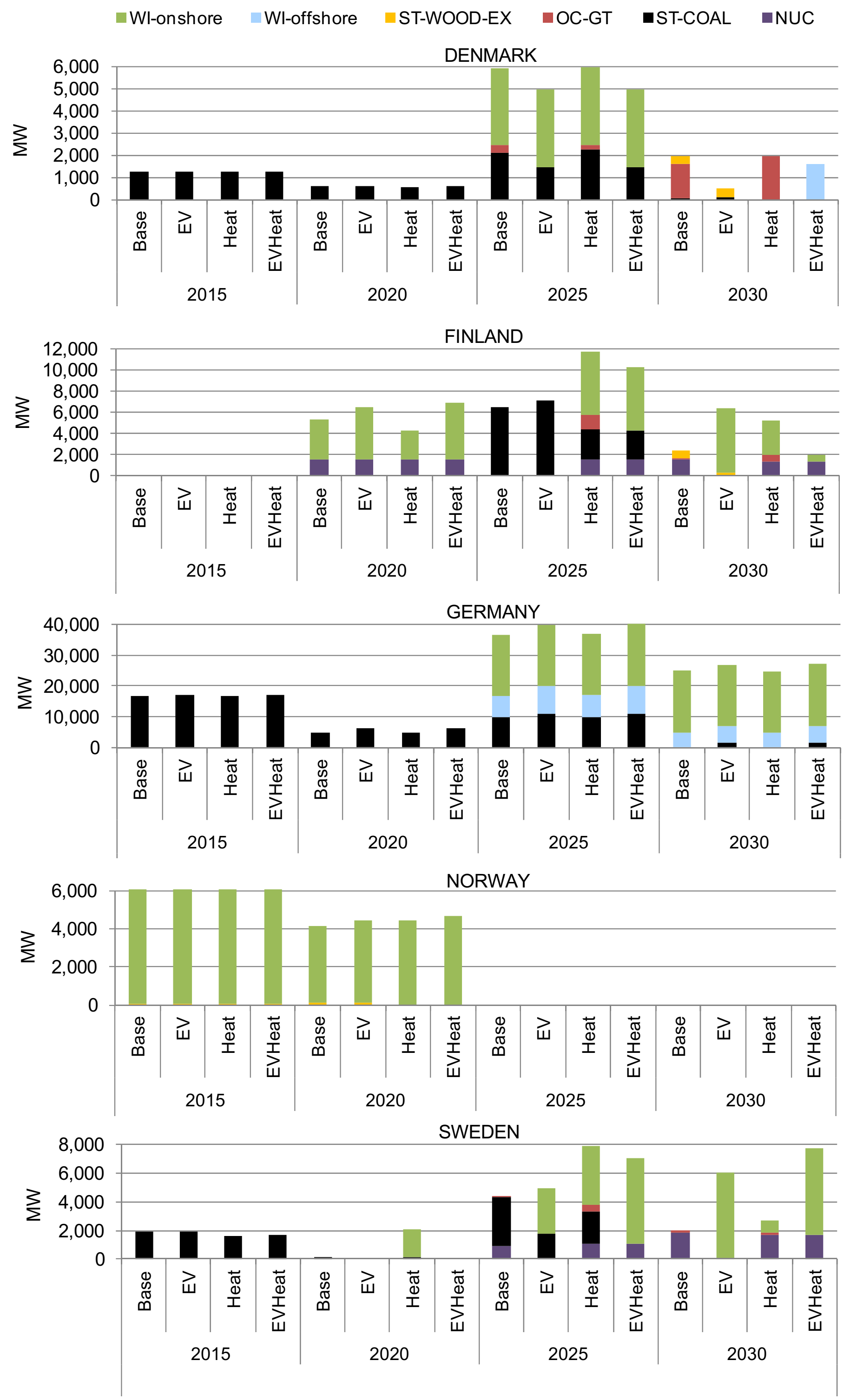

Fig. 3. Investments in power production capacities in the Base, EV, Heat, and EVHeat scenario, representing accumulated investments over each five year period. E.g. investments in 2020 represent accumulated investments from 2016 through 2020. WI: Wind power; ST-COAL: Steam turbine, extraction, coal; ST-WOOD-EX: Steam turbine, extraction, wood; OC-GT: Open cycle gas turbine; NUC: Nuclear power.

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

Fig. 3 shows that in terms of increasing socio-economically optimal wind power investments, heat measures can have effects of the same magnitude as EVs. As such, the accumulated wind power capacities by 2030 in the EV and Heat scenario, respectively,

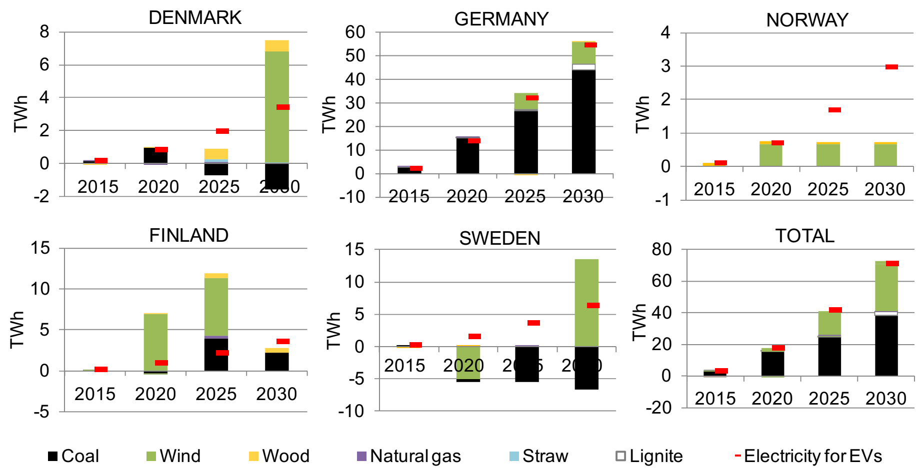

Fig. 4. Changes in annual electricity generation due to implementation of electric vehicles (EVHeat scenario vs. Heat scenario). Due to import/export and possible changes in electricity consumption for heat pumps/electric boilers, generated power increases in each year will not necessarily correspond to the electricity demand for electric vehicles.

are identical or close to being identical for the case of Germany, Norway, and Denmark; and while EVs in Sweden generate larger accumulated wind power investments than heat measures (9200 MW in the EV scenario vs. 6900 MW in the Heat scenario) the opposite is the case for Finland (10,900 MW in the EV scenario vs. 12,000 MW in the Heat scenario). Apart from influencing wind power investments, heat measures can also be seen to affect investments in thermal production capacities. For instance in Finland and Sweden in 2025, where wind power investments are increased significantly in the Heat scenario compared to in the Base scenario, this displaces a significant amount of new coal CHP capacity. To compensate for this loss in dispatchable capacity, an increased investment in open cycle gas turbines is observed for covering peak loads.

The results do not show any clear indications of EVs having lower impact on wind power investments when competing with heat measures. This is reflected in similar wind power investment increases when comparing the Base and EV scenario, and the Heat and EVHeat scenario, respectively. Rather, an example of a synergy effect from combining EVs and heat measures is evident for the case of Denmark in 2030, where wind power investments are observed in the EVHeat scenario but not in the EV, Heat or Base scenario.

4.2. Effects on electricity generation

By observing electricity generation in the EVHeat scenario compared to in the Heat scenario, it can be revealed how electricity for EVs is produced in the optimisation (see Fig. 4).

Fig. 4 shows that the EVs generate significantly increased wind power production in all five Northern European countries. This is a direct consequence of the increased wind power investments identified in Fig. 3. In some countries (Denmark, Finland, and Sweden), the increases in wind power generation caused by EVs are even considerably larger than domestic electricity demand for EVs in the given year. Consequently, a significant amount of the increase in wind power generation is exported or is displacing coal based power production in the domestic energy system (Denmark and Sweden in 2030).

However, for several of the countries, i.e. Denmark, Germany, and Sweden, wind power is not included in the electricity mix for EVs until the last part of the period. As a result, coal based power production provides a large share of the electricity for EVs in Denmark and Germany in the first part of the period. An opposite trend can be observed for Finland, where EVs generate increased wind power production until the assumed onshore wind potential is reached.[5] After that point, EVs in Finland are mainly driven on coal based electricity. However, if the Finnish onshore wind potential was set higher, increased wind power generation would most likely also have been observed for 2030.

In some cases, e.g. in Denmark and Finland in the last part of the period, increased production on existing biomass power plants also provides a share of the electricity for EVs. This is a consequence of the increasing CO_2 prices and the relatively large increase in fossil fuel prices compared to biomass prices over the period (cf. Table 8).

Norway is a large net exporter and the most optimal response to the implementation of EVs is therefore largely to reduce the export. This explains the gaps between generated electricity production and the electricity demand for EVs in 2025 and 2030. Also in Sweden, electricity for EVs is in 2020–2025 mainly supplied by cutting down export. The reduction in Swedish wind power production in 2020 is due to the lower wind power investments in the EVHeat scenario compared to the Heat scenario for this year (cf. Fig. 3). This is explained by the high Finnish wind power investments in the EVHeat scenario in 2020, which significantly reduce the economic potential for Swedish electricity export to Finland. As a consequence, Swedish wind power investments in 2020 are made less attractive. In 2025, the difference in Swedish wind power generation in the two scenarios is diminished and coal based power production further displaced.

Focussing on the five Northern European countries in total, the average EV is driven on a mix of mainly coal and wind power. Coal dominates in the first part of the period while wind power comprises increasing shares towards 2030.

4.3. CO_2 emissions

For the five countries as a whole, CO_2 emissions from the power, heat, and transport sector modelled are only slightly reduced in 2015–2020, 0.1–0.8%, while significant reductions are obtained in 2025–2030, 4–7% (EVHeat scenario vs. Heat scenario, see Fig. 5a).

[5] In addition, in 2025 a wind power capacity increase limitation of 6000 MW per five years results in identical wind power investments in the Heat and EVHeat scenario, respectively.

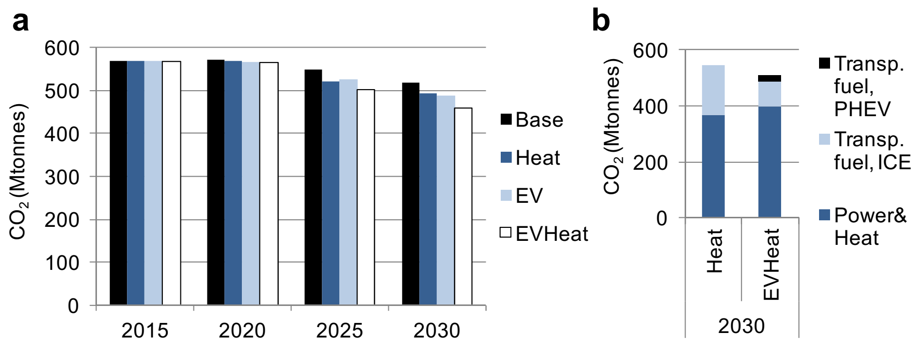

Fig. 5. a) Total CO_2 emissions for the modelled power, heat, and transport system in the Base, Heat, EV and EVHeat scenario b) Distribution of total CO_2 emissions in 2030, divided on sources for the Heat and EVHeat scenario.

The most important factors behind the improvement in the CO_2 balance over the period are 1) the increasing shares of wind power in the electricity mix for EVs, 2) the gradual improvement in the efficiency of EVs (cf. Table 4), and 3) the increasing shares of EVs in the fleet. As illustrated for year 2030 (Fig. 5b), while EVs generate increased CO_2 emissions from power & heat production and fuel combustion in PHEVs, a larger CO_2 reduction is obtained by displacing fuel combustion in ICEs. Comparing the EV scenario with the Heat scenario, heat measures and EVs can be seen to provide CO_2 reductions of the same magnitude.

As shown in Fig. 6, also on national level the EVs bring significant CO_2 emission reductions in 2025–2030 and in some countries already from 2020. The only exception is the case of Finland in 2025 where EVs generate coal power production significantly larger than the electricity demand for EVs, leading to a CO_2 emission increase. The Norwegian and Swedish CO_2 emission reductions in 2025–2030 and Danish emission reductions in 2030 are high; reaching 17–40%. This is partly explained by the fact that electricity for EVs in these cases is covered purely by renewable energy sources or export reductions. In some cases (Denmark and Sweden), further displacement of coal based power production also occurs (cf. Fig. 4). Moreover, due to large shares of hydro power and/or nuclear in the electricity supply (cf. Fig. 2), CO_2 emissions from the Swedish and Norwegian power sector are low. As a result, CO_2 emission reductions obtained in the transport sector lead to relatively large reductions for the three sectors as a whole.

4.4. System costs

The analysis shows that the assumed large-scale implementation of EVs results in an increase in total system costs for the Northern European countries as a whole; around 1.5–7.1 € bill./yr depending on the year, corresponding to increases of 0.8–3.9% (for EVHeat vs. Heat scenario, see Fig. 7).

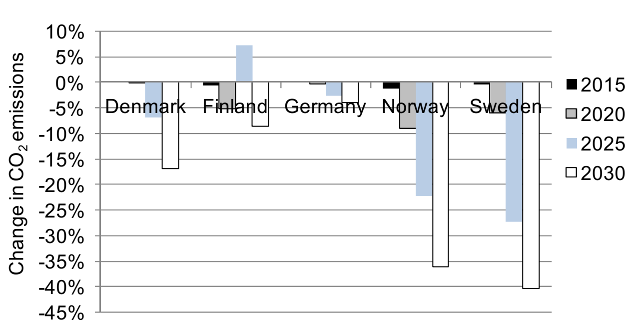

Fig. 6. Change in national CO_2 emissions from the power, heat and transport sector modelled when implementing electric vehicles (EVHeat compared to Heat scenario).

The cost increase is partly caused by larger investment costs per vehicle for BEVs and PHEVs compared to ICEs. Furthermore, due to the lower annual driving of BEVs compared to ICEs, a larger amount of BEVs is required to provide a given transport demand. This increases total investment and O&M costs for the transport sector and the cost reduction from displacing fuel use in ICEs is not enough to compensate for this. Fig. 7b illustrates this for year 2025. The cost effects of EVs are, however, based on an assumed implementation of PHEVs as well as BEVs while PHEVs alone have in [14,15] been shown to provide system cost reductions. The cost increase is thus likely due to the forced implementation of BEVs. This is confirmed by the fact that BEVs have also in [15] been shown to result in cost increases. It should also be noted that the possibility for using EVs for providing regulating power and power reserves is not included. Likewise, a socio-economic valuation of reduced local air and noise pollution has not been performed. As shown, the cost increase is highest in 2020 (3.9%) and then lower in 2025 (1.2%) and 2030 (0.8%); reflecting the influence of expected technical and economic improvements of EVs over the period (cf. Table 4).

Relating the cost increases (excluding CO_2 quota costs) to the CO_2 emission reductions, the average CO_2 reduction costs for EVs can be estimated. This reveals that CO_2 reduction costs are reduced manifold over the period, from very high levels of around 7100 €/tonne in 2015 and 1500 €/tonne in 2020, to 140 €/tonne in 2025 and 80 €/tonne in 2030. However, even in 2030, the CO_2 reductions costs for EVs are high compared to the expected CO_2 price level of around 39 €/ton [47]. Comparing the EV scenario with the Heat scenario, it can be seen that while EVs result in cost increases (0.8–3.9%) heat measures reduce total costs (0.004–0.9%).

4.5. Sensitivity analysis

Variants of the Heat and EVHeat scenarios are set up assuming low/high fuel prices and low/high CO_2 prices, respectively. Comparing the two scenarios makes it possible to analyse the effects of EVs under different price conditions:

- Fuel prices: set to low at $80/barrel in 2015 (corresponding to 2010 level) increasing linearly to $90/barrel in 2030 and at high increasing linearly from $80/barrel in 2010 to $95/barrel in 2015 and $140/barrel in 2030. Ratios between prices on different fuels are kept constant and are based on [47].
- CO_2 prices: set to low at 15 €/tonne in 2015 increasing linearly to 20 €/tonne in 2030 and at high increasing linearly from 14 €/tonne in 2010 to 26 €/tonne in 2015 and 60 €/tonne in 2030.

These analyses show that also at low/high fuel and low/high CO_2 prices, EVs facilitate increased wind power investments and

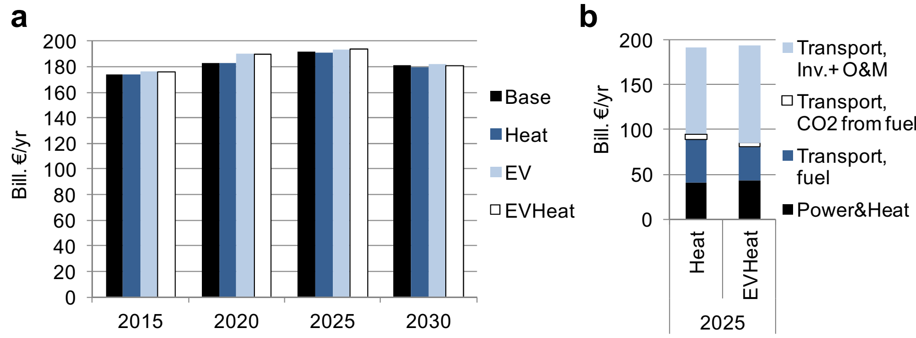

Fig. 7. a) Total annualised costs for the power, heat and transport systems modelled, for the Base, Heat, EV, and EVHeat scenario. b) Distribution of total costs in 2025 divided on sources for the Heat and EVHeat scenario.

reduced need for new coal/natural gas production capacities in several countries. However, the changes in power system investments and electricity generation caused by EVs are found to be sensitive to the development in fuel and CO_2 prices. This is illustrated in Fig. 8 using the Danish case as an example.

Under the low fuel price conditions, in Denmark, wind power is not included in the electricity mix for EVs and in Germany not before 2030. In Finland, Sweden, and Norway, where wind power investments are generally more attractive, lower fuel prices have the effect of increasing the relative importance of EVs in facilitating wind power investments. As an example, EVs facilitate increased wind power investments in Norway already at the low vehicle fleet shares of 2.5% in 2015, i.e. five years earlier than at the fuel prices in the main scenario.

At the low CO_2 price conditions, electricity demand for EVs is in Germany met by increased coal based power production. In Denmark, the lower CO_2 prices have the effect of reducing onshore wind power investments in the Heat scenario below the onshore potential for Western Denmark (3500 MW). This facilitates an increase in onshore wind power investments in 2025 when adding EVs to the system. In Finland and Sweden, EVs do not generate large increases in wind power investments before year 2030. As a result, electricity demand for EVs in Finland and Sweden is to a large extent met by coal based power production. In Norway, the lower CO_2 prices have the effect of increasing the impact of EVs on wind power investments, leading to increased wind power generation from 2015.

Under the high fuel price conditions, EVs generate considerable increases in Danish wind power generation from year 2025, i.e. five years earlier than at the fuel prices in the main scenario. In Finland, the higher fuel prices lead to EVs facilitating increased wind power investments from year 2015, i.e. also earlier than originally. For Germany, the electricity demand induced by EVs is still largely comprised by coal power and only moderate increases in wind power generation are observed in the last part of the period.

At the high CO_2 price conditions, EVs facilitate considerably increased Danish wind power investments in 2025 and 2030 and increased Finnish wind power investments from 2015. In addition, the higher CO_2 prices make investment in wood CHP extraction plants attractive in several countries. Thus, wind power largely competes with wood based power production rather than coal based power production. For the Danish case, this is reflected in increased wind power generation in 2025 displacing wood based power production (cf. Fig. 8). In Germany, the increase in electricity production for EVs is in 2025 partly and in 2030 solely based on renewable energy sources; mainly wood and secondarily wind. However, coal based power still provides a large share of the electricity for EVs in Germany and Denmark, particularly in the first part of the period.

Further sensitivity analyses have been set up investigating the influence of other boundary conditions. As shown in Table 7, a significant expansion of Norwegian hydro power generation from 2010 to 2030 is included in the model (20 TWh). A sensitivity scenario has been set up, assuming that only 50% of this increase is realised. In this scenario, due to reduced electricity export from Norway to Denmark, EVs facilitate increased Danish wind power investments from year 2025, i.e. five years earlier than in the main scenario. Moreover, Danish wind power investments generated by

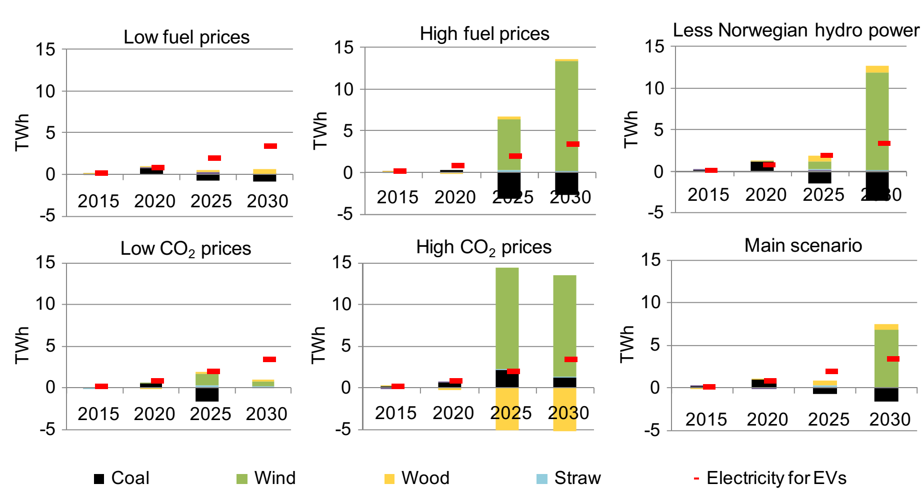

Fig. 8. Changes in Danish electricity generation due to implementation of electric vehicles, illustrated for different scenarios.

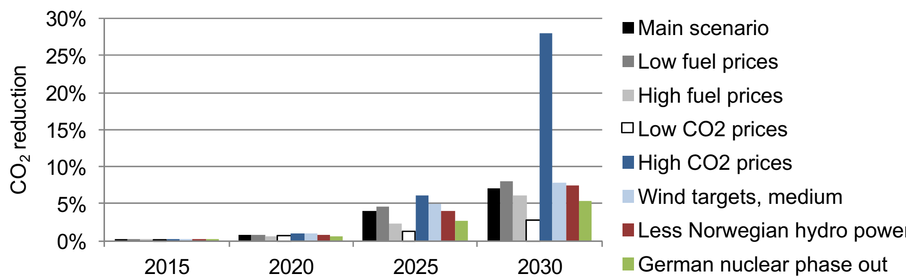

Fig. 9. CO_2 emission reductions in the five countries as a whole due to implementation of electric vehicles, illustrated for different scenarios.

EVs in 2030 are increased significantly (from around 1600 MW to 2600 MW). For Norway, the impact of EVs on wind power investments is reduced in the short term and increased in the long term.

Another sensitivity analysis has been set up assuming a phase out of nuclear power in Germany according to [49] leading to a reduction from 17.2 GW in 2010, to 10.7 GW in 2015, 8.1 GW in 2020, and 0 MW in 2022. The main effect of this is that German coal and wind power investments are increased over the period. However, wind power investments in Germany are still not observed before 2025. Furthermore, German wind power investments become highly attractive in the last part of the period even without the implementation of EVs, leading to only small increases in wind power investments when adding EVs to the system. A phase out of German nuclear power represents a reduction in nuclear power generation of 40, 63, and 129 TWh/yr in 2015, 2020, and 2025–2030, respectively, i.e. a considerable change in the German power system. Nevertheless, it shows to have no significant influence on the effect of EVs in the four other countries. This indicates that the fact that not all German electricity exchange options are modelled; is also likely to have little influence on the results for the other countries.

Finally, a sensitivity analysis has been made where future wind power capacities in 2015, 2020, 2025, and 2030 are restricted to meet national wind targets in [40] as a minimum level. As a consequence of this restriction, effects of EVs facilitating additional wind power investments are not observed in Denmark and significant increases in Finnish wind power investments due to EVs are not apparent until 2030. This illustrates that when forcing in future wind power capacities based on political targets it becomes difficult to analyse how EVs can influence the investments. Nevertheless, this sensitivity scenario might give a more realistic picture on the development in wind power capacities over the period and thus, how EVs can influence operation costs of future power systems. However, this sensitivity analysis shows increases in total costs of 0.7–3.9% depending on the year, i.e. very close to the cost increases identified when wind power investments are identified without wind target restrictions (0.8–3.9%). The explanation is that total costs of the power and district heating systems in the five countries only comprise a moderate part compared to the investment, O&M and fuel costs of the transport system (cf. Fig. 7b).

Among all sensitivity scenarios, CO_2 emission reductions provided by EVs for the five countries as a whole in 2025 and 2030 are lowest for the low CO_2 price scenario, 1% and 3% respectively, and highest for the high CO_2 price scenario, namely 6% and 28%, respectively (see Fig. 9). As such, CO_2 reductions provided by EVs are particularly sensitive to CO_2 price variations.

The cost balance for EVs is worst in the low fuel price scenario with increases of 2.4% and 3.1% in 2025 and 2030, respectively. The high fuel price scenario represents the best cost balance for EVs with a cost increase of 0.5% in 2025 and a cost reduction of 0.9% in 2030. That high fuel prices are beneficial for the cost effects for EVs is explained by the fact that high fuel prices result in larger cost benefits from fuel savings caused by the high efficiency of EVs.

In all sensitivity scenarios, average CO_2 reduction costs for EVs are reduced manifold towards 2030. However, the average CO_2 reductions cost in a given year varies significantly among the sensitivity scenarios. Overall, average CO_2 reduction costs develop from high levels of around 1600–11,900 €/tonne in 2015, to 1400–2300 €/tonne in 2020, 115–359 €/tonne in 2025 and (−)16 to 168 €/tonne in 2030 (negative number for high fuel price scenario due to cost reduction).

5. Conclusion

In this study, it is analysed how a gradual large-scale implementation of PHEVs and BEVs towards 2030 would affect the power systems of five Northern European countries; Denmark, Finland, Germany, Norway, and Sweden. This is done using a model optimising power system investments and operation and applying socio-economic costs, i.e. excluding taxes, subsidies, and tariffs.

The results reveal that if charged/discharged intelligently EVs can due to vehicle-to-grid capability contribute in meeting peak power demand and thus, reduce the need for new coal/natural gas power production capacities in several of the countries. Furthermore, EVs facilitate significantly increased wind power investments in all of the countries analysed. For the fuel and CO_2 price developments assumed in main scenarios, increases in wind power investments are first seen in 2020 (in Norway and Finland) when EVs are assumed to comprise 15% of the private passenger vehicle fleet. In sensitivity scenarios with low/high fuel prices or low CO_2 prices, respectively, EVs facilitate increased wind power investments even at the low vehicle fleet shares of 2.5% assumed in 2015 (in Norway and Finland). As such, depending on the country and fuel/CO_2 prices, EVs can in a transition period even at early stages support the integration of wind power into power systems.

The study shows that wind power would likely provide a large share of the electricity for EVs towards 2030 in several of the countries analysed. However, in the optimisation, for several countries (Denmark, Germany, and Sweden), wind power does not contribute in providing electricity for EVs before 2025/2030 and in some sensitivity scenarios not at all. As a result, electricity demand for EVs is in many cases largely met by an increase in coal based power production; particularly for the case of Denmark and Germany in the first part of the period. As such, this would likely be the outcome if an introduction of EVs is not followed up by economic support for renewable energy technologies (other than CO_2 quotas).

The effects of EVs on the power system vary significantly from country to country and are found to be sensitive to variations in fuel and CO_2 prices. In addition, the extent with which Norwegian hydro power expansions and a phase out of German nuclear power is realised have an influence on the results for some countries. It is therefore difficult to draw more general conclusions regarding how electricity for EVs would be produced over the period.

The sensitivity towards CO_2 price variations is expressed in CO_2 emission reductions for the five countries as a whole varying from 1% to 6% in 2025 and from 3% to 28% in 2030, depending on whether low or high CO_2 price levels are assumed. Changes in total costs due to the EV implementation vary from 0.5% to 2.4% in 2025 and from (−)0.9% to 3.1% in 2030, depending on whether low or high fuel price development is assumed. Average CO_2 reduction costs for the assumed implementation of PHEVs and BEVs are reduced manifold towards 2030. Nevertheless, the CO_2 reduction costs are in most scenarios high compared to expected CO_2 price levels. As such, the CO_2 reductions achieved with the assumed large-scale implementation of PHEVs and BEVs are rather costly, particularly in the short term. However, an implementation of only PHEVs might have shown better cost effectiveness since PHEVs previously have been found to bring cost reductions (for 2030) [15]. It should also be mentioned that EVs have the benefit of increasing security of supply by reducing the transport sector's dependency on oil.

The effects of EVs have been compared with the effects of allowing investment in heat measures, i.e. heat pumps, electric boilers, and heat storages, in the district heating system, representing alternative ways of increasing system flexibility. The comparison shows that in terms of increasing socio-economically optimal wind power investments, and reducing CO_2 emissions, heat measures can have effects of the same magnitude as EVs. However, while the assumed implementation of EVs result in costs increases heat measures reduce total costs. The results do not show any clear indications of EVs having lower impact on wind power investments when competing with heat measures.

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Paper III

Wind power integration using individual heat pumps – Analysis of different heat storage options

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Wind power integration using individual heat pumps – Analysis of different heat storage options

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Significant installations of individual heat pumps are expected in future energy systems due to their economic competitiveness. This case study of the Danish energy system in 2020 with 50% wind power shows that individual heat pumps and heat storages can contribute to the integration of wind power. Heat accumulation tanks and passive heat storage in the construction are investigated as two alternative storage options in terms of their ability to increase wind power utilisation and to provide cost-effective fuel savings. Results show that passive heat storage can enable equivalent to larger reductions in excess electricity production and fuel consumption than heat accumulation tanks. Moreover, passive heat storage is found to be significantly more cost-effective than heat accumulation tanks. In terms of reducing fuel consumption of the energy system, the installation of heat pumps is the most important step. Adding heat storages only moderately reduces the fuel consumption. Model development has been made to facilitate a technical optimisation of individual heat pumps and heat storages in integration with the energy system.

1. Introduction

Wind power is considered as a key renewable energy technology in future energy systems. However, wind power is highly variable, which challenges a fuel-efficient and cost-effective integration of large amounts of wind power. In systems with high wind penetration, forced electricity export can thus occur when wind power is high and electricity demand low. In the near future significant expansion of wind power is planned in many European countries [1]. The Danish energy system is characterised by a large share of wind power, around 20% on annual basis [2], and this share is expected to increase to 50% in 2020. The Danish case thus forms an interesting case for analysing challenges of integrating wind power that may be faced by other countries in the coming years.

Studies suggest that flexible technologies such as large heat pumps, electric boilers, and heat storages in (combined heat and power) CHP systems, and electric vehicles can play a significant role in facilitating the integration of wind power [3–6]. Demand side management can also contribute to the flexible operation of power systems with high wind power penetrations [7–9]. In this regard, small (electric) compression heat pumps in households (in this study referred to as individual heat pumps) could also contribute. As such, ground heat pumps and air/water heat pumps can be operated flexibly by storing heat in the central heating system and in the construction. Energy system analyses show that in relation to costs, fuel consumption, and CO_2 emissions, individual heat pumps together with district heating form the best heat supply solutions [10]. This is found to be valid for present systems that are mainly based on fossil fuels, and for potential future systems that are fully based on renewable energy sources. The cost-competitiveness of heat pumps is confirmed in Ref. [11], where individual heat pumps, in socio-economic cost optimisations outcompete all other individual heating technologies. This is found for an energy system in 2025 with 30% renewable energy and for a system in 2050 with 90% CO_2 emission reduction. In the future, individual heat pumps will thus likely represent a significant electricity demand that could be made flexible. Investments in heat storage and/or control system units are however required in order to enable significant flexibility and different heat storage options exist. From a socio-economic perspective, it is therefore relevant to investigate the possible benefits that different heat storages for individual heat pumps can bring to the energy system.

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Nomenclature

A_{floor}	heated floor area (m^2)[1]
c	active heat capacity depending on the type of building (Wh/m^2 floor area/K)
CF	heat pump capacity factor, representing heat pump capacity relative to maximum heat demand
COP	coefficient of performance
EB(t)	heat production from electric boiler in h t (Wh)
HD(t)	heat demand in h t (Wh)
HD_{max}	highest hourly heat demand over the year (Wh)
$HP_{el}(t)$	electricity consumption for heat pump operation in h t (Wh)
$HP_{heat}(t)$	heat production from heat pump in h t (Wh)
HWD	hot water demand (Wh)
Load(t)	loading of heat storage in h t (Wh)
Unload(t)	unloading of heat storage in h t (Wh)
Stor(t)	heat storage level in h t (Wh)
$Stor_{cap}$	heat storage capacity (Wh)
ΔT_{in}	temperature change of the indoor air allowed when utilising passive heat storage (°C, K)
ΔT_{pas}	temperature change of the construction utilised for passive heat storage (°C, K)
U	heat transfer coefficient between construction and indoor air (W/m^2 floor area/K)

Among existing studies, Ref. [12] discusses the possibilities and challenges of individual heat pumps and thermal storage options in terms of increasing system flexibility. A group of studies analyse possibilities for flexible heat pump operation on a single building level, e.g. [13–16]. A more large-scale perspective is applied in Ref. [17], where a simulation of a 2 week period is performed of a high wind power system with 3000 households, of which 1500 are supplied with heat pumps using buffers for space heating and hot water. Only a few studies deal with individual heat pumps in energy system models on national scale, e.g. [10,11,18,19]. However, the studies do not analyse the possibilities and effects of flexible operation of individual heat pumps. Ref. [20] presents a methodology for assessing the potential flexibility that a building stock equipped with heat pumps can offer to power systems with significant penetration of wind power. This methodology is applied to a case study of the German energy system in 2020 and 2030 with high renewable energy penetration levels, however, without presenting quantitative results. Ref. [21] touches upon the effect of individual heat pumps in an energy system perspective and also includes scenarios with and without assumed flexibility. However, flexible heat pump operation is not modelled but merely represented as a modified fixed demand profile based on assuming that heat pump operation can be distributed within the day.

No existing studies have been found, which model and analyse the energy system effects of individual heat pumps and different heat storage options. This is therefore the subject of this paper. Using a case of the Danish energy system in 2020 with a wind power share of around 50%, the potential of individual heat pumps and heat storages is investigated in terms of their ability to increase wind power utilisation and provide cost-effective fuel savings. In this regard, the potentials of heat accumulation tanks and passive heat storage in the construction are compared as two alternative heat storage options. Several energy system analyses are made in the energy system analyses tool EnergyPLAN, applying an hourly time resolution and covering a full year. Analyses are made for the aggregated building stock, for different representative building categories, and for a range of different reference systems, covering realisation of heat savings, different amounts of wind power, and installation of other flexible technologies. Further development of the model has been made to make it possible to represent flexible heat pump operation using the construction as thermal storage. In the process of reviewing state-of the-art heat pump systems, experts and producers of small heat pumps have been contacted to provide a solid ground for the analyses. The study is aimed at decision makers and researchers dealing with heat pumps in an energy system context.

The article is structure in the following way. Section 2 includes the methodology applied, while Section 3 presents the modelling of heat pumps and storage options. Section 4 covers the results including sensitivity analyses. Finally, a conclusion is given in Section 5 and suggestions for future work in Section 6.

2. Methodology

The potentials of individual heat pumps and different heat storage options are analysed in the context of a large-scale installation in the system. Heat pumps are assumed installed where they are considered particularly relevant in a near term perspective, i.e. in houses presently heated with oil boilers and/or electric heating. Only existing buildings are considered as these will for many years comprise the majority of all buildings, i.e. 85–90% in 2030 for the Danish case [10]. The analyses focus on detached houses as these comprise by far the largest heat demand of houses in non-district heating areas in Denmark (close to 90%[2]) [22].

Only heat pumps capable of storing heat in the central heating system and in the construction are considered, i.e. ground heat pumps and air/water heat pumps. For the large majority of existing houses with central heating, the heating system will mainly be based on radiators. Installation of floor heating in existing houses is associated with high costs and is therefore typically only carried out in connection with large renovation projects. Against this background, only radiator systems are considered. In some houses, radiator substitution and/or renovation of the building envelope would be required prior to heat pump installation. This aspect is however not important for the focus of this study.

Ground heat pumps and air/water heat pumps are today typically installed in combination with a hot water tank (typically around 150–200 L) and a small buffer tank (typically around 40–80 L) connected to the central heating system. The hot water tank ensures that sufficient hot water is available during the day and is loaded continuously. The buffer tank ensures that the number of heat pump start-ups can be minimised, thereby enabling better operating conditions and improving COP and the technical life-time [23,24]. The buffer tank is not large enough to enable shifting operation from one hour to the other. However, such flexibility can be obtained through different options, e.g. by investing in a heat accumulation tank connected to the central heating circuit [24]. Given space requirements, it is realistically to insert an accumulation of up to around 1000 L in each house [23]. Alternatively, if allowing a given indoor air temperature variation, heat can be stored passively in the construction. The analyses cover different levels of passive heat storage and different sizes of heat accumulation tanks (300, 500, and 1000 L). Based on a need to limit the analyses and considering that space heating normally comprises

[1] All floor areas in the study refer to heated floor areas.

[2] When including farm houses.

Table 1
Characteristics of the buildings stock in which heat pumps are assumed installed.

Existing detached houses	Unit	Weighted average or total	Construction period				Ref.
			1850–1960[d]	1961–1972	1973–1978	1979–1998	
Heat demand per floor area	kWh/m^2 yr	172	210	143	117	90	[25]
Hot water share of annual heat demand	pct.	16%	15%	15%	18%	27%	[26]
Economically feasible space heat savings potential (pct. of space heating)	pct.	34%	39%	20%	27%	28%	[26]
Passive heat storage cap.[a]	kWh/house	18–72	18–72	18–72	18–72	18–72	
Accum. tank storage cap., 300–1000 L[b]	kWh/house	5–17	5–17	5–17	5–17	5–17	
COP[c]	–	2.7	2.8	2.8	2.7	2.5	
Heat demand converted to heat pumps	TWh/yr	5.0	3.5	0.78	0.44	0.28	[2,22,31]

[a] Assuming passive heat storage capacity of 60–120 Wh/K/m^2 [27,28], an allowed indoor air temperature variation of ∓1–2 °C [30] and an average house size of 151 m^2 [22].
[b] Assuming 15 °C temperature difference in the radiator system corresponding to a typical configuration of heat pump radiator systems [23,24,28] prioritising a reasonable COP.
[c] COP (coefficient of performance) estimated based on Refs. [10,25] depending on hot water share. Based on Ref. [22], ground heat pumps are assumed to cover 25% of the heat demand converted to heat pumps, and air/water heat pumps the remaining 75%. The COPs apply for use of heat pumps in the Danish climate, which is temperate with outdoor air temperatures typically ranging from around −5 °C to 15 °C in the heating season [32].
[d] Due to close resemblances, the categories of houses built in year 1850–1930, 1931–1950, and 1951–1960 have been aggregated into one category (1850–1960).

the dominating part of the heat demand,[3] possibilities for using hot water tanks for flexible heat pump operation have not been investigated.

2.1. Modelling of the building stock

The existing building stock of detached houses is modelled based on data in Refs. [25,26] for different representative building categories. The buildings are categorised depending on the year of construction, reflecting historical changes in insulation standards and heat demands (see Table 1). The heat demands in Table 1 have been calibrated with energy statistics of the Danish Energy Agency.

Passive heat storage capacities are estimated in Table 1 assuming utilisation of the thermal storage capacity facing the rooms inside the insulation, which can be utilised actively during a diurnal temperature variation. The capacity is mainly comprised by internal constructions in walls, ceiling, and floor while windows, doors, and furniture have minor influence. The storage capacities are estimated as $c \cdot \Delta T_{in}$ where c is the active heat capacity (Wh/K/m^2) and ΔT_{in} is the temperature change of the indoor air allowed in connection with utilising passive heat storage.

Based on current data and knowledge, typical existing buildings in Denmark are expected to have c values of around 60–120 Wh/K/m^2 floor area, the low end representing buildings of extra-light to medium-light materials and the high end representing buildings of medium–heavy materials [27,28]. The analyses have been made assuming active heat capacities in the low end and high end, respectively. Typically, Danish households keep an indoor temperature of around 22 °C [29] but if variations around the traditional level are accepted heat pumps can be operated flexibly utilising passive heat storage. Based on recommendations in Ref. [30] for an acceptable comfort level in residential buildings, an allowed indoor temperature variation of ∓2 °C from the initial level can reasonably be assumed ($\Delta T_{in} = 4$ °C). Considering that thermal comfort preferences are likely to vary among residents, the effect of a lower indoor temperature variation, namely ∓1 °C, is also investigated ($\Delta T_{in} = 2$ °C).

[3] On average 84% for existing detached houses in Denmark [26].

2.2. Heat demand variations

Heat demand variations in the model are based on hourly heat demand profiles on an aggregated level for a large number of Danish households [33]. As part of the study, model development has been made to ensure that heat stored in the construction or in the heat accumulation tank can only be used to satisfy space heating demand. This is implemented by ensuring that the heat pump as a minimum has to satisfy the hot water demand in each hour. In the model, the hot water demand is identified as the minimum heat demand over the year. Therefore, the heat demand profiles are modified in the sense that a constant hot water demand profile is applied to represent the average hot water demand (see Fig. 1). Additionally, separate heat demand profiles have been created depending on the hot water share for the given building category.

2.3. The EnergyPLAN model

EnergyPLAN is a deterministic input/output model that optimises the operation of an energy system over a full year, by performing hour-by-hour analyses. Inputs are demands and demand distributions, capacities of technologies included, distributions of fluctuating (renewable energy sources) RES, fuel and CO_2 costs etc. The model outputs comprise energy balances, energy productions, fuel consumptions, electricity imports/exports, CO_2 emissions, and costs. The model covers the whole energy system, i.e. individual heating and district heating, the electricity, transport, and industry sector [34]. EnergyPLAN is further described in Refs. [34,35] and in Ref. [36] where previous applications and comparison with other models can also be found. The model makes it possible to use different regulation strategies depending on the purpose of the analysis.

2.4. Reference energy system

Apart from increased wind power capacities, the Danish energy system in 2020 is assumed identical to the current system based on Ref. [37]. The effects of individual heat pumps and heat storage options are then analysed in the context of increased wind power production. Expected wind power capacities in 2020 [38] have been applied, yielding a wind power production of

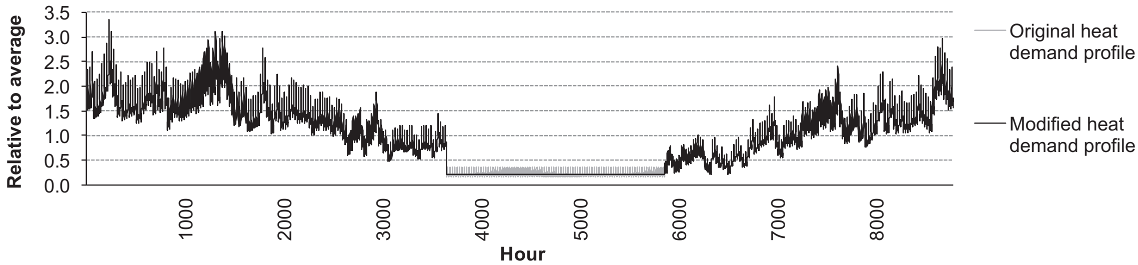

Fig. 1. Hourly heat demand profile applied for the aggregated building stock of existing detached houses.

16.5 TWh and corresponding to around 50% of annual electricity demand.[4] Supplemental analyses have been made for wind power production varying from 0 TWh to 34 TWh, corresponding to 0% to 100% of annual electricity demand. Compared to other countries, the Danish energy system is characterised by a large share of wind power and district heating (46% [10]), and high total energy efficiency with a large share of CHP (55% of thermal power production and 80% of district heating [2]). Fuel prices corresponding to \$100/barrel are applied and a CO_2 price of 25 €/tonne assumed for 2020 based on the Danish Energy Agency and the International Energy Agency [39].

2.5. Methodology for the energy system analyses

The potential of heat pumps and different heat storage options in supporting wind power integration is investigated in terms of their ability to increase wind power utilisation, reducing (excess electricity production) EEP and fuel consumption[5] of the system. The cost-effectiveness of the different heat storage options is identified as the annualised average socio-economic costs per fuel saved (referred to as fuel saving costs).

A technical optimisation of a closed system is applied, where the electricity and heat supply/demand are balanced in a way that minimises the overall fuel consumption and that utilises as much wind power as possible. In the optimisation, the electricity production from CHP plants and from RES is prioritised hour-by-hour. The remaining electricity demands are met by condensing power production, and the remaining district heating demands are met by boilers. By utilising heat storages and extra capacity at the CHP plants, the production at the condensation plants is minimised. To the extent that it can help reduce EEP, CHP generation is replaced with boiler operation in the district heating system. As a result, the presence of CHP does not contribute to generating EEP in the optimisation. The remaining EEP is thus mainly due to wind power fluctuations and required minimum power supply from central power plants for ensuring grid stability (450 MW). This makes the results relevant also for countries without large-scale CHP.

Heat storages added to individual heat pumps allow the heat pumps to prioritise their operation for hours with EEP, while intending to avoid operation in hours with condensing power production. In this way, the heat storages contribute to reduce EEP and fuel consumption of the system. In situations where the measures introduced to ensure balance between electricity demand and supply from CHP and RES are insufficient, EEP will occur. For an open system, the EEP will represent forced electricity export.

2.6. Scenarios

Naming conventions used in the main scenarios are presented in Table 2. Heat demand distributions before and after the installation of heat pumps are given in Table 3.

It can be noted that for countries without large-scale district heating, the market potential for individual heat pumps would be significantly larger than for the Danish case considered here (all other things equal).

2.7. Heat storage and control system costs

For the passive heat storage concept, the heat pump and central heating system is assumed controlled through an automatic variation of the indoor temperature set point, depending on when it is optimal to load/unload the storage. In order to facilitate this and still ensure satisfactory regulation of the indoor air temperature, electronic thermostats (wireless) for the radiators are assumed required.[6] In a low cost sensitivity scenario (LCOST), it is alternatively assumed that a satisfactory temperature regulation can be handled through a single electronic indoor air thermostat placed at a suitable reference point in the house (wireless, programmable, 67 €/house [40]). With this type of control system, the automatic regulation of the individual heat supply from each radiator would have to be shut off. As such, a less accurate regulation of the temperature in each room would be expected in the LCOST scenario [24,28].

When using either passive heat storage or a heat accumulation tank for intelligent heat pump operation based on signals/prices from the energy system, a central controller would be required. Such a device does not yet exist on the market and future prices are therefore difficult to predict. In the main scenarios, no additional costs for a central controller are included, assuming that it will be integrated in intelligent heat pumps in the future. In a high cost sensitivity scenario (HCOST), the current price of a related type of controller recently introduced on the market is added[7] (348 €/house [40]). Experience shows that new innovative electronic products normally drop significantly in price over a period of years. Thus, the control system cost included in the HCOST scenario represents a high estimate of the future cost for a controller including installation. Installation costs are expected to be low considering that the control system can be installed in connection with the heat pump and that a wireless system is considered. Assumed heat storage and control system costs in the main scenarios are given in Table 4.

[4] Excl. electric heating and electricity for individual heat pumps, which vary across the scenarios (1.4–2.1 TWh for main scenarios).

[5] Excl. fluctuating RES, i.e. wind power for the Danish case.

[6] An electronic air temperature sensor is also required but this device is normally delivered together with the heat pump [24].

[7] Used for digital intelligent control of a central heating system (wireless).

Table 2
Naming conventions used in main scenarios.

Scenario	Description
NOHP	No heat pumps in households.
HP-NOSTOR	Heat pumps installed in detached houses with oil boilers and/or electric heating without investment in heat accum. tanks or passive heat storage.
Tank300/500/1000	Inv. in 300/500/1000 litre heat accum. tanks in all houses where heat pumps are installed.[a]
PasLow	Inv. in passive heat storage assuming low end passive heat storage cap. (60 $Wh/K/m^2$)[a]
PasHigh	Inv. in passive heat storage assuming high end passive heat storage cap. (120 $Wh/K/m^2$)[a]
1C	Allowing an indoor air temp var. of ∓ 1 °C when utilising passive heat storage
2C	Allowing an indoor air temp var. of ∓ 2 °C when utilising passive heat storage

[a] Heat pump installation as in HP-NOSTOR.

3. Modelling of heat pumps and heat storages

The most important equations and rules, representing the model of the individual heat pumps, are presented in this section. Eq. (1) is the heat balance equation and Eq. (2) defines the relation between electricity input and heat output for the heat pump. Eqs. (3) and (4) represent heat storage balance and heat storage capacity restrictions and Eq. (5) the heat pump capacity constraint. Eq. (6) has been introduced as part of this study, restricting the heat pump to meet hot water demand in all hours. In this way, it is ensured that the heat storages considered can only enable flexible heat pump operation in satisfying space heating demand.

$$\mathrm{HD}(t) = \mathrm{HP_{heat}}(t) + \mathrm{EB}(t) + \mathrm{Unload}(t) - \mathrm{Load}(t) \quad \forall t \tag{1}$$

$$\mathrm{HP_{heat}}(t) = \mathrm{HP_{el}}(t) \cdot \mathrm{COP} \quad \forall t \tag{2}$$

$$\mathrm{Stor}(t) = \mathrm{Stor}(t-1) + \mathrm{Load}(t) - \mathrm{Unload}(t) \quad \forall t \tag{3}$$

$$\mathrm{Stor}(t) \le \mathrm{Stor_{cap}} \quad \forall t \tag{4}$$

$$\mathrm{HP_{heat}}(t) \le \mathrm{CF} \cdot \mathrm{HD_{max}} \quad \forall t \tag{5}$$

$$\mathrm{HWD} \le \mathrm{HP_{heat}}(t) \quad \forall t \tag{6}$$

Ground heat pumps and air/water heat pumps are typically supplemented by an electric boiler to cover peak loads, in order to limit heat pump investment costs. As shown in Eq. (1), this is also represented in the model. A heat pump (capacity factor) CF of 0.80 is assumed, corresponding to the typical dimensioning of these types of heat pumps [28,42]. As a result, the heat pump covers more than 99% of annual heat demand in the model. Due to the low efficiency of the electric boiler, it is only operated in hours where

Table 3
Net heat demand distribution in the scenario without heat pumps (NOHP) and in scenarios with heat pumps.

TWh/yr	Heat pumps	Oil boilers	Elec. heating	Biomass boilers/stoves	Natural gas boilers	District heating (excl. grid loss)
NOHP[a]	0	4.8	1.4	8.6	7.0	28.4
HP scenarios[b]	5.0	0.9	0.3	8.6	7.0	28.4

[a] Current heat demands as given in Danish energy statistics [2]. Individual heat demands represent households. The existing amount of heat pumps is low and has been neglected for simplicity.
[b] Heat pumps installed in detached houses with oil boilers and/or electric heating.

Table 4
Storage and control system costs applied in main scenarios.

Storage concept		Inv. cost			Technical life-time (yr)	Ref.
		€/house	€/100 L	€/house/yr[a]		
Heat accum. tank	300 L	856	285	37	40	[41]
	500 L	1138	228	49	40	[41]
	1000 L	1485	149	64	40	[41]
Passive heat storage	Electronic thermostats	265	–	22	15	[40]

[a] A discount rate of 3% in fixed prices is applied.

heat demand exceeds the heat pump capacity and when sufficient heat storage is not available to cover demand either. In hours with EEP, the heat storage is loaded, thereby maximising heat pump operation and utilisation of wind power in the system. In hours with condensing power production, the heat storage is unloaded, intending to minimise heat pump operation. Unloading of the heat storage is thus prioritised for reducing condensing power production in the system and thereby obtaining highest possible fuel displacement.

Further model development has been made to implement the following restrictions on use of the passive heat storage:

$$\mathrm{Load}(t) \le U \cdot \Delta T_{\mathrm{pas}} \cdot \left(1 - \frac{\mathrm{Stor}(t-1)}{\mathrm{Stor_{cap}}}\right) \cdot A_{\mathrm{floor}} \quad \forall t \tag{7}$$

$$\mathrm{Unload}(t) \le U \cdot \Delta T_{\mathrm{pas}} \cdot \frac{\mathrm{Stor}(t-1)}{\mathrm{Stor_{cap}}} \cdot A_{\mathrm{floor}} \quad \forall t \tag{8}$$

Due to the low heat capacity of air (0.8 $Wh/m^2/K$ [9]) and the fact that a radiator system is considered, it is assumed that a desired indoor air temperate can quickly be reached. The temperature of the construction is assumed to vary from hour to hour, depending on the amount of heat stored in it (Stor(t)). This reflects the large thermal mass of the construction. When loading and unloading of the passive heat storage occurs over periods of sufficient length, ΔT_{pas} will be equal to ΔT_{in}. Thus, the product $U \cdot \Delta T_{\mathrm{pas}}$ represents the highest obtainable loading/unloading of the passive heat storage. This corresponds to loading at empty storage and unloading at full storage. The loading/unloading capacity in a given hour depends on the passive heat storage level (Stor(t)) as expressed in Eqs. (7) and (8).

The temperature variation of the construction will be parallel-shifted downwards compared to the temperature variation of the indoor air (typically with around 1 °C for existing buildings). This is due to the fact that transmission losses from the construction to the outdoor environment will occur continuously during the heating season. In the model, loading of the passive heat storage corresponds to a situation where the heat transfer from indoor air to construction is higher than the transmission loss from construction to outdoor environment. Correspondingly, unloading of the storage represents a situation where the heat transfer from indoor air to construction is lower than the transmission loss from construction to outdoor environment. U is estimated to 22 W/m^2 floor area/K based on [43,44]. The principle of the passive heat storage model is illustrated in Fig. 2 for a loading and subsequent unloading period.

Fig. 2 shows that the heat pump is operated at maximum capacity in the first part of the loading period. In the end of the loading period, limitations on loading (Eq. (7)) imply that the heat pump production must be lowered accordingly. In the start of the unloading period, the heat pump production is lowered to the minimum level, thereby satisfying only hot water demand. Due to limitations on unloading (Eq. (8)) and the increase in heat demand, the heat pump production

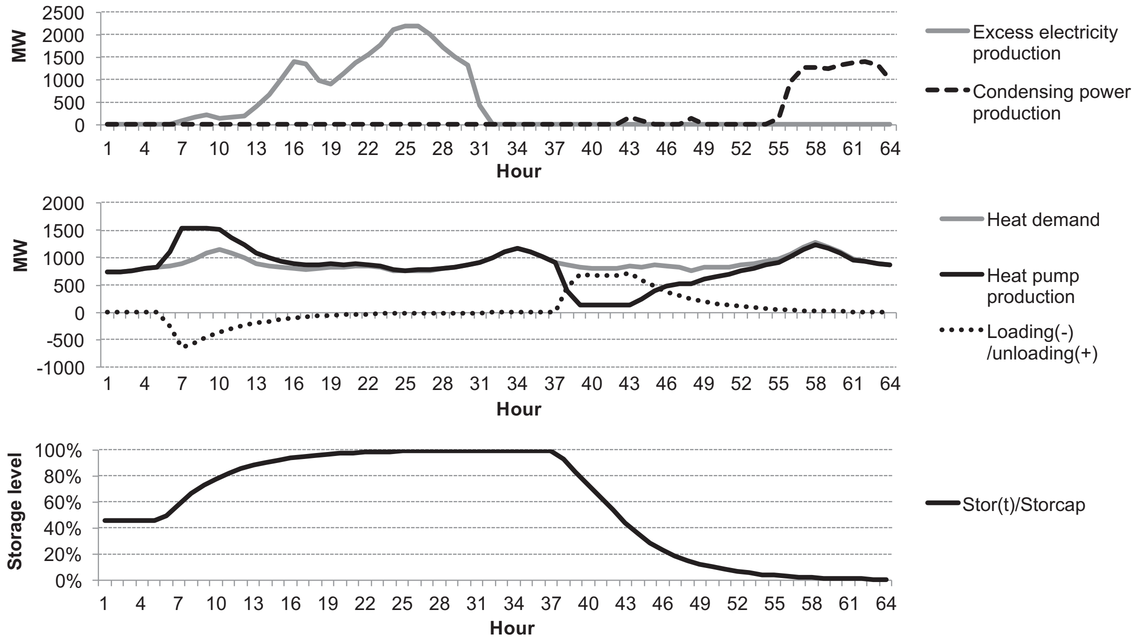

Fig. 2. Optimisation of a large-scale installation of heat pumps using passive heat storage, modelled in integration with the energy system (allowing ∓1 °C indoor air temp. var. and assuming a passive heat storage cap. of 120 W/m^2 floor area/K). A loading and subsequent unloading period is shown, together representing around 2–3 days in mid January. Excess electricity production and condensing power production is shown after the optimised heat pump operation minimising their occurrence.

is then increased towards the end of the unloading period. Due to the influence of Eq. (7), the marginal increase in the storage level, $Stor(t)/Stor_{cap}$ is reduced during the loading period. Correspondingly, Eq. (8) implies that the marginal decrease in the storage level is reduced during the unloading period.

In the model of the passive heat storage, full/empty storage corresponds to a situation where the temperature of the construction is 1 °C or 2 °C above/below the traditional level. Depending on the passive heat storage level, increased transmission losses to the outdoor environment will thus occur in some periods while reduced transmission losses will occur in other periods. Overall, transmission losses are therefore assumed unchanged. Correspondingly, overall ventilation losses are assumed unchanged. Heat losses from heat accumulation tanks are moderate [45] and have not been modelled.

The modelling methodology developed for representing heat accumulation tanks and passive heat storage is compatible with the use of aggregated heat demand profiles, which are commonly used in energy system models. The methodology thereby has the advantage of being easy to integrate in the typical structure of energy system models. The focus of this paper is not to address the model and controllers for the operation of individual heat pumps in detail.

4. Results

Main results and sensitivity analyses are presented in the following sections for the assumed large-scale installation of heat pumps and heat storages.

4.1. *Excess electricity production*

As illustrated in Fig. 3, heat pumps even without the flexibility provided by heat storages (HP-NOSTOR scenario), can contribute to increase wind power utilisation and thus reduce excess electricity production (EEP). As such, EEP is reduced with around 0.12 TWh (from 1.58 TWh to 1.46 TWh, i.e. 8%) for the system in 2020 with 16.5 TWh wind power. This is alone due to the increased electricity demand resulting from the heat pump installations. It can be noted that the assumed heat pump installations partly displace an amount of electric heating in households, which due to its low efficiency represents a relatively large electricity demand. This lowers the overall increase in electricity demand resulting from the heat pump installations.

When heat pumps are equipped with heat storages they are able to place a larger amount of their operation in hours with EEP. This results in larger EEP reductions. If investing in heat accumulation tanks, an EEP reduction of 0.15–0.19 TWh (9–12%) is thus obtained. If enabling passive heat storage (1C/2C-PasLow/High), equivalent to larger EEP reductions can be achieved, 0.19–0.30 TWh (12–19%). The patterns illustrated in Fig. 3 have also been identified at lower/higher wind penetrations.

Fig. 4 illustrates the reduction in EEP over the year for the scenario with heat pumps and a high level of passive heat storage (2C-PasHigh).

As shown, a large part of the EEP exceeds the total capacity of heat pumps and thus their ability to absorb EEP. In addition, the heat pumps ability to reduce EEP is very limited in the summer period (around 3700–6000 h) where they only operate to satisfy hot water demand (46 MW-e).

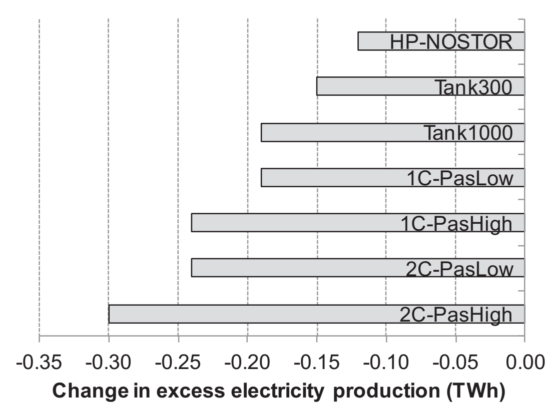

Fig. 3. Change in excess electricity production depending on type and size of heat storage available for individual heat pumps, compared to a system without heat pumps.

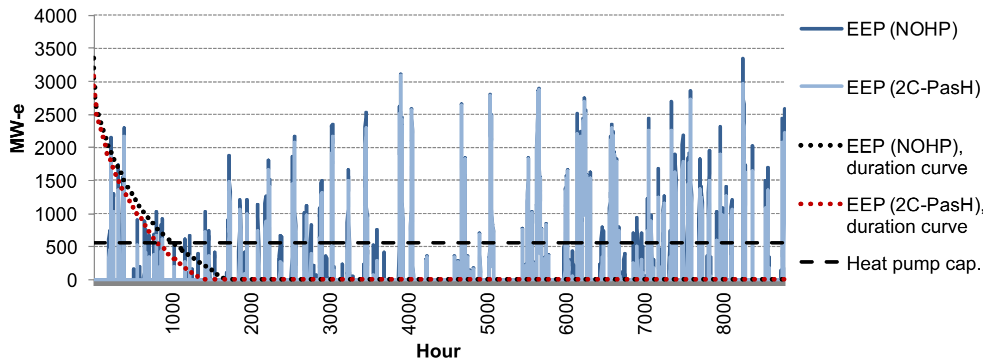

Fig. 4. Excess electricity production (EEP) for a scenario without individual heat pumps (NOHP) and for a scenario with large-scale installation of heat pumps, displacing oil boilers and electric heating, assuming utilisation of passive heat storage (2C-PasHigh).

4.2. Fuel consumption

Changes in the systems fuel consumption due to the installation of heat pumps and heat storages are illustrated in Fig. 5 at the wind power level expected for 2020.

As shown, the installation of heat pumps (HP-NOSTOR scenario) alone results in a large reduction in oil consumption due to the displacement of oil boilers. Due to the higher efficiency of heat pumps compared to the displaced heating technologies (oil boilers and electric heating) only moderate increases in coal and natural gas consumption for electricity production are observed. As a result, significant net fuel savings are obtained, around 3.5 TWh (2%[8]). When adding heat storages to the heat pumps, a larger share of the wind power production is utilised and condensing power production reduced. This results in a lower consumption of coal and natural gas. In line with the observed effects on EEP, passive heat storage provides equivalent to larger fuel savings compared to heat accumulation tanks, 3.7–3.9 TWh vs. 3.6–3.7 TWh (2%). However, compared to the fuel savings provided by heat pumps alone (HP-NOSTOR scenario), the additional fuel savings provided by heat storages (Tank300...2C-PasHigh) are moderate. The high efficiency of heat pumps compared to the displaced heating technologies is of course part of the explanation for this. Moreover, the occurrence of EEP is moderate (occurring around 20% of the year in the NOHP scenario), compared to the many operating hours needed for the heat pumps to satisfy heat demand throughout the year. The heat pumps limited ability to absorb EEP also plays a role (see Section 4.1). The above patterns have also been identified at lower/higher wind penetrations.

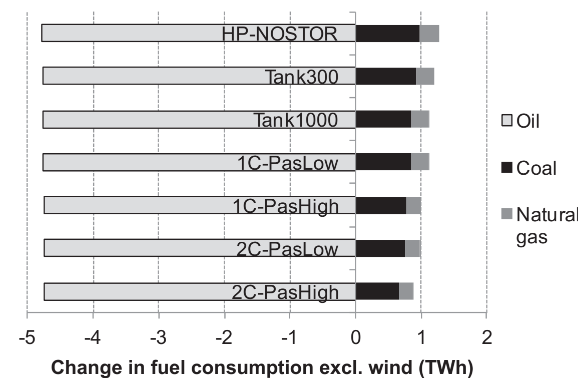

Fig. 5. Changes in fuel consumption excl. wind when installing individual heat pumps and heat storages compared to a system without heat pumps (NOHP).

4.3. Costs

In Fig. 6, changes in socio-economic costs from adding heat storages to the heat pumps are presented for the system in 2020. As a measure of cost-effectiveness, average costs per fuel saved (€/MWh) are presented in Fig. 7; where costs represent annualised investment costs and variable O&M costs.

Fig. 6 shows that for the passive heat storage scenarios, the savings on fuel, CO_2, and variable O&M costs are around the same level or larger than the annualised investment costs required for enabling the storage. Thus, passive heat storage provides an approximate break-even or a net reduction in costs depending on the scenario. This is also reflected in fuel saving costs of 10–29 €/MWh, i.e. below or close to the expected price levels in 2020 of the fuels displaced, i.e. 20 €/MWh for coal, and 33 €/MWh for natural gas (when including CO_2 costs and fuel handling costs).

For the case of heat accumulation tanks, the economic benefits are far from being sufficient to cover the investment costs. As such, the annualised investment costs are around 4 times higher than the cost savings for the 1000 L tank and around 6 times higher for the 300 L tank. As a result, fuel saving costs are very high, around 86–140 €/MWh. The results in Fig. 7 indicate that heat accumulation tanks are far from cost-effective as a measure of increasing wind power utilisation for fuel displacement in the system. In contrast, passive heat storage provides significantly lower fuel saving costs and demonstrates a reasonable cost-effectiveness. The robustness of this assessment is tested in a number of sensitivity analyses in the following section. Among the three tank sizes analysed, fuel saving costs can be seen to be lowest for 1000 L tanks. Therefore, sensitivity analyses of the tanks are limited to cover this size only.

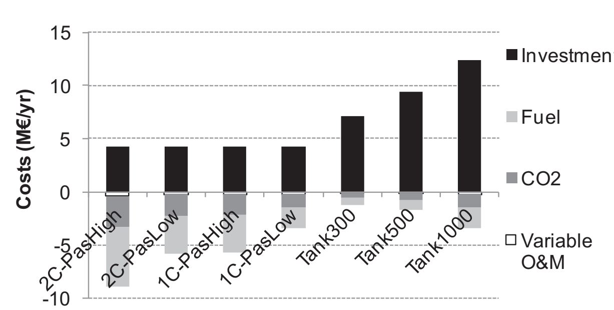

Fig. 6. Changes in socio-economic cost when enabling different types/sizes of heat storages for individual heat pumps.

[8] Relative to fuel consumption of the whole energy system covering individual heating, district heating, the electricity, transport, and industry sector.

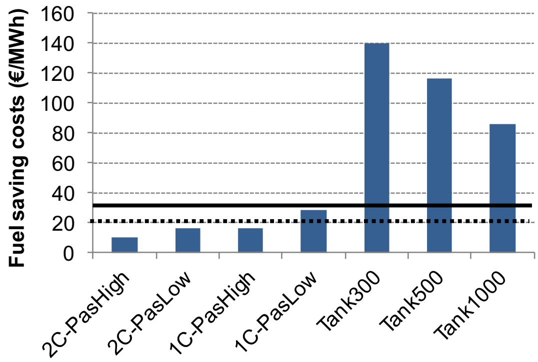

Fig. 7. Average annualised costs per fuel saved for different heat pump storage options. For comparison, the expected coal price, 20 €/MWh (dashed line) and natural gas price, 33 €/MWh (black line) in 2020, including CO_2 costs and fuel and handling costs, is indicated.

Table 5
Naming conventions used in sensitivity analyses of the system in 2020.

Name	Description
HS	Economically feasible heat savings (cf. Table 1) assumed realised prior to heat pump and heat storage installation.
LCOST	Low control system costs for passive heat storage assuming that a single electronic indoor air thermostat is sufficient to ensure satisfactory regulation of the indoor air temperature (cf. Section 2.7).
HCOST	Inclusion of a high cost estimate of a central controller applying current price of a related product recently introduced on the market (cf. Section 2.7).
EBHP	Electric boilers and large heat pumps assumed installed in the district heating system (250 MW-e electric boilers [38] and 400 MW-e heat pumps based on Ref. [21]).
EV	Electric vehicles assumed implemented corresponding to 10% of the vehicle fleet in 2020.
25DT	Operation with 25 °C temp. difference in the radiator system on average, yielding larger utilisation of the heat accum. tank but reducing COP of the heat pump [24], corresponding to 40% reduction when loading the tank.[a]
R5%	Discount rate of 5% applied in fixed prices.

[a] COP reduction occurs due to a needed increase in the forward temperature from typically around 40 °C on average to 55 °C and the fact that COP is typically reduced with 2–3% per degree increase in forward temperature [46].

4.4. Sensitivity analyses

Sensitivity analyses on fuel saving costs for the heat storage options have been made considering installation in each of the four different building categories in Table 1. Deviations of −15% to +33% from the results in the main scenario have been found for the case of passive heat storage. Correspondingly, deviations of −9% to +4% have been identified for the case of 1000 L heat accumulation tanks. Regardless of the building category, passive heat storage has been found to be significantly more cost-effective than heat accumulation tanks.

Naming conventions used in further sensitivity scenarios are given Table 5. Fuel saving costs for the different sensitivity scenarios are presented in Fig. 8.

Fig. 8 shows that for the aggregated building stock, heat savings have very low impacts on the results (HS scenarios). Costs of control system components are however highly influential. As such, in the LCOST scenarios for passive heat storage, fuel saving costs are very low. Whether the control system in the main scenarios or the control system in the LCOST scenarios is most likely to be installed in practice depends on how the individual household weighs costs vs. comfort. When including costs of a central controller (HCOST scenarios) based on the current price of a related product newly introduced on the market, fuel saving costs are increased considerably. However, the results of the HCOST scenarios represent a worst-case-end as the price of new innovative electronic products, will normally be reduced considerably over a period of years. If operating with 25 °C temperature difference in the radiator system (25DT scenario) fuel saving costs for heat accumulation tanks are reduced moderately. When assuming installation of electric boilers and large heat pumps in the district heating system (EBHP scenarios), fuel saving costs for the heat storages in households are increased. This shows that competition with other flexible technologies can have a significant influence on the cost-effectiveness of adding further flexibility to the system. If also assuming large-scale implementation of electric vehicles (EBHPEV scenarios) further increases in fuel savings costs are observed. The use of a discount rate of 5% (R5% scenarios) on heat storage and control system investments, results in significantly increased fuel saving costs for the heat accumulation tank scenario. For the passive heat storage scenarios, the discount rate has minor influence due the lower investment cost and technical life-time for the type of devices in question (cf. Table 4). Overall, the sensitivity analyses confirm that heat accumulation tanks are far from being cost-effective while passive heat storage can provide significantly lower fuel saving costs, potentially at a reasonable level.

It can be mentioned that in the 25DT scenario, the EEP reduction obtained with a heat accumulation tank of 1000 L is found to be 0.24 TWh, i.e. on level with the EEP reduction for the 1C-PasHigh

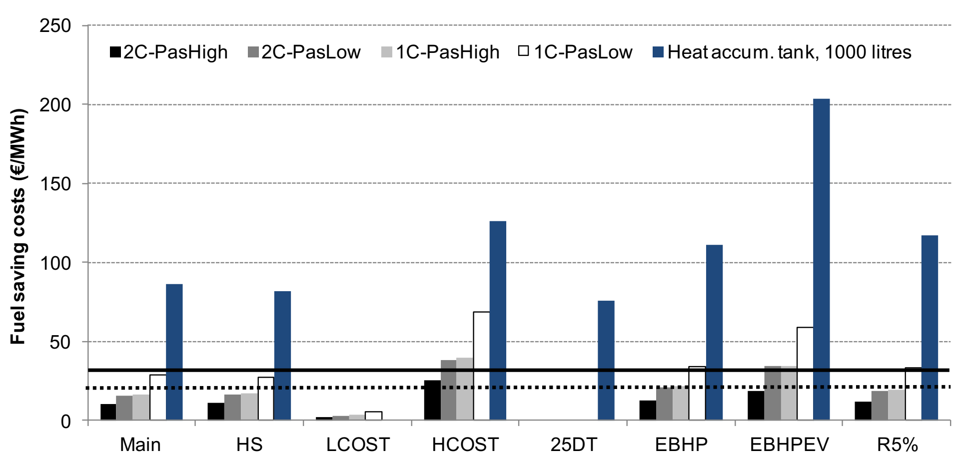

Fig. 8. Average annualised costs per fuel saved for sensitivity scenarios of different heat pump storage options. For comparison, the expected coal price, 20 €/MWh (dashed line) and natural gas price, 33 €/MWh (black line) in 2020, including CO_2 costs and fuel and handling costs, is indicated.

scenario, some-what larger than for the 1C-PasLow scenario, but still lower than for the 2C-PasHigh scenario. Due to the COP reduction in the 25DT scenario, the fuel saving obtained is nevertheless still below or at level with the fuel savings obtained in all passive heat storage scenarios.

5. Conclusion

Compression heat pumps in households (individual heat pumps), using heat accumulation tanks or passive heat storage in the construction, have been analysed in terms of their potentials in increasing wind power utilisation and providing cost-effective fuel savings. The Danish energy system in 2020 has been used as case, representing a system with a large share of wind power (around 50%), district heating, and CHP. Installation of heat pumps in existing detached houses is assumed, displacing individual oil boilers and electric heating. For the analyses, a modelling methodology has been developed to enable representation of flexible heat pump operation using the heat storages in question. The methodology has the advantage of being compatible with the typical representation of heat demands in energy system models.

Results show that by displacing less efficient heating technologies and increasing electricity demand, the installation of heat pumps alone can contribute to the integration of wind power, providing significant reductions in excess electricity production and fuel consumption. If additionally investing in heat accumulation tanks, moderately increased reductions are obtained. However, if instead investing in passive heat storage, equivalent to larger reductions can be achieved. Moreover, heat accumulation tanks are found to be far from cost-effective while passive heat storage proves to have a significantly higher, potentially reasonable, cost-effectiveness.

Overall, in terms of enabling flexible operation of individual heat pumps for a fuel-efficient and cost-effective integration of wind power, promising potentials have been identified for passive heat storage but not for heat accumulation tanks. Nevertheless, in terms of reducing fuel consumption of the system, the installation of heat pumps is the most important step. The additional fuel savings provided by adding heat storages are moderate in comparison.

6. Future work

It would be interesting to analyse the effect of the heat storages in a model that minimises total system costs, including operation costs and annualised investment costs, also taking external electricity trade into account. In this regard, it would be relevant to investigate to which extent investment in passive heat storage is likely to be economically attractive, considering possibilities to invest in competing flexible technologies. As in many other energy system models, the heat pumps were represented by a yearly average COP in this study. It could be interesting to analyse the effect of heat storages when taking hourly COP variations (caused by variations in outdoor and ground temperatures etc.) into account. An inclusion of hourly COP variations is however not expected to change the overall conclusion on the comparison of heat pumps and the different heat storages.

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Paper IV

Energy system investment model incorporating heat pumps with thermal storage in buildings and buffer tanks

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Energy system investment model incorporating heat pumps with thermal storage in buildings and buffer tanks

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ABSTRACT

Individual electric heat pumps constitute a potentially valuable resource in supporting wind power integration due to their economic competitiveness and possibilities for flexible operation. When analysing the system benefits of flexible heat pump operation, effects on energy system investments should be taken into account. In this study, we present a model that facilitates analysing individual heat pumps and complementing heat storages in integration with the energy system, when optimising both investments and operation. The model incorporates thermal building dynamics and covers various heat storage options: passive heat storage in the building structure via radiator heating, active heat storage in concrete floors via floor heating, and use of thermal storage tanks for space heating and hot water. It is shown that the model is well qualified for analysing possibilities and system benefits of operating individual heat pumps flexibly. This includes prioritising heat pump operation for hours with low marginal electricity production costs, and peak load shaving resulting in a reduced need for peak and reserve capacity investments.

Key words: Residential heat pumps, Flexible electricity demand, Peak load shaving, Wind power integration, Thermal building model, Demand side management.

1. Introduction

Wind power is considered a key technology in transforming our energy systems towards sustainability. However, the variable and partly unpredictable nature of wind challenges an effective integration of large amounts of wind power and requires dispatchable power capacities to back it up. Flexible technologies such as large heat pumps and heat storages in combined heat and power (CHP) systems and electric vehicles can play a significant role in facilitating the integration of wind power [1-6]. Demand side management (DSM) is also expected to play a central role in increasing system flexibility for incorporating larger shares of wind power [7-9]. Small electric compression heat pumps on consumer level (individual heat pumps) can develop into an important DSM resource. Analyses show that individual heat pumps together with district heating form the best heat supply solutions in present and future energy systems [10, 11], and the use of heat pumps for individual heating in Denmark is expected to grow considerably [12]. Individual heat pumps will thus represent a significant electricity demand in future energy systems. This electricity demand becomes flexible if e.g. investments are made in control equipment, enabling intelligent heat storage in the building structure and/or intelligent use of existing hot water tanks, and/or if investing in heat accumulation tanks for space heating.

A group of recent studies present methods and control concepts for how individual heat pumps (or electric heating) can be operated flexibly responding to the needs of the power system. Many of these studies operate on building level, e.g. [13-15]. A larger scale perspective is applied in [16], which models the operation of a high wind system with 3000 households, of which 1500 are supplied with heat pumps using buffers for space heating and hot water. Parkinson *et al.* [17] introduce a demand response control strategy aimed at thermostatically controlled electric heating and cooling of buildings. The study simulates management of the aggregated heat pump load of 1000-2000 buildings in regulating power fluctuations of two wind turbines. In [18], a method is presented to model and control a population of thermostatically controlled loads applying a simulation, where the loads follow the output of 138 wind turbines. A distribution system platform is presented in [19] for simulating control of load flow fluctuations in the distribution grid via self-regulating heat pump cycling. Wang *et al.* [20] present a strategy for optimal demand response control based on managing comfort-constrained individual heat pumps to provide regulation and spinning reserves. A new market approach is presented in [21] for integrating large distributed populations of heat pumps, electric vehicles, and electrolysers as demand-side virtual power plants providing spinning reserves. In [22], a thermal building model is presented for investigating the use of price-responsive electric space heating.

Only few studies integrate flexible operation of individual heat pumps in energy system models on national scale. Papaefthymiou *et al.* [23] present a methodology for coupling a model of buildings thermal behaviour with an electricity market model using the German energy system as a case study. In [24], model development is presented that facilitates technical optimisation of individual heat pumps and thermal storages in integration with the energy system minimising fuel consumption of the system and utilising as much wind power as possible. Finally, [25] presents a simulation approach for covering day-ahead and intra-day operation of the power system in analysing a broad range of demand response options including cooling and electric heating in the residential sector.

The above mentioned models mainly focus on operational aspects, i.e. how individual heat pumps can contribute to peak load shaving, load shifting, provision of ancillary services, and increasing wind power utilisation. However, investments in heat storage options, required to enable flexible operation of the heat pumps, could suffer from low economies of scale and will in some aspects compete with other flexible energy technologies in the system. Moreover, the heat pumps could have important effects on energy system investments, e.g. on the need for peak and reserve capacities. The objective of this study has therefore been to develop a model that integrates individual heat pumps and their flexibility options in an energy system model that optimises both operation and investments of the whole system. Such model capability has not been identified in previous studies. The model is made as an add-on to the energy system investment model Balmorel. The add-on covers the following heat storage options: 1) intelligent passive[1] heat storage in the building structure for houses with radiator

[1] I.e. heat transfer through radiation, thermal conductance, and convection without the use of a heat transferring media going in and out of the storage [53].

heating (or floor heating), 2) intelligent active heat storage in concrete floor heating systems, and 3) thermal storage tanks for space heating and hot water, respectively. The model is illustrated using a case study of a possible future Danish energy system in 2030 with around 60% wind power.

The article first describes the Balmorel model and the add-on. Subsequently, the model functionality is illustrated by using the case study described and by comparing with measured data. In the end, a discussion and conclusion is given including suggestions for future work. Nomenclature can be found in Appendix at the end of the paper.

2. Balmorel

Balmorel is a deterministic partial equilibrium model assuming perfect competition [3, 26]. It is formulated as a linear optimisation problem[2] in GAMS, a high-level modelling system for mathematical programming and optimisation. The model optimises investments in power/heat production, storage, and transmission capacities, and the operation of the system. This is done by minimising total costs in the energy system over a given year covering annualised investment costs, operation and maintenance costs of existing and new units, and fuel and CO_2 quota costs. The optimisation is performed subject to a number of constraints including satisfaction of demands for electricity and heat in each time period, renewable energy potentials, and technical restrictions on units in the system. The CPLEX solver[3] is normally used to find the optimal solution.

Balmorel operates with three geographical entities: countries, regions, and areas. Countries are divided into regions connected with transmission lines and regions are further divided into areas. Electricity supply and demand is balanced on regional level, whereas heating is balanced on area level. In this study, the existing model structure in Balmorel is used for representing the integrated power and district heating system, while individual heating of houses is modelled using the new add-on. In Balmorel, the optimisation is performed with a yearly time horizon where the year is divided into seasons, that are often used to represent weeks, and into time periods that are often used to represent hours.

3. Thermal building model add-on

The thermal building model renders it possible to represent houses with radiator heating as well as houses with floor heating as the central heating system. This division is relevant since it influences the possibilities for utilising the heat storage capacity of the building. Houses with radiator heating can store heat passively in the building structure, while houses with concrete floor heating can foremost store heat actively in the large thermal mass of the concrete floor (in addition heat can be stored passively in the remaining building structures). The model also includes thermal storage tanks for space heating and hot water, respectively, representing other options of enabling flexible heat pump operation.

[2] A mixed integer model version is also available.
[3] CPLEX is a high-performance solver for linear, mixed integer, and quadratic programming.

Fig. 1 and Fig. 2 illustrate how the two different central heating systems are modelled. For simplicity, only the space heating circuit is shown, i.e. excluding the hot water circuit.

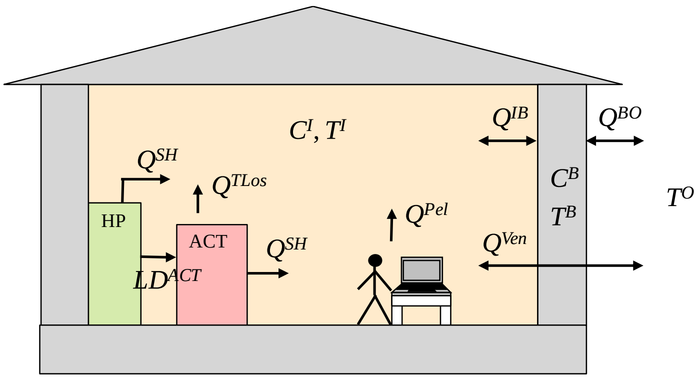

Fig. 1. Thermal building model of houses with radiator heating (only the space heating circuit is illustrated). HP: Heat pump (or other heating installation). ACT: Heat accumulation tank. $Q^{SH} = Q^{SHe} + Q^{SHn}$.

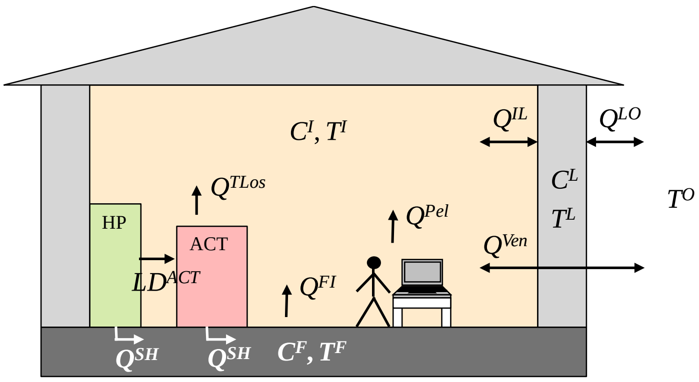

Fig. 2. Thermal building model of houses with floor heating (only the space heating circuit is illustrated). HP: Heat pump (or other heating installation). ACT: Heat accumulation tank. $Q^{SH} = Q^{SHe} + Q^{SHn}$**.**

For houses with radiator heating, the indoor air and the building structure are modelled as two separate thermal masses. The model of floor heating systems covers three thermal masses, namely the indoor air, floor, and walls/ceiling. The modelling of both types of central heating systems thus comprises at least two dominating heat accumulating masses as required in order to sufficiently capture the heat dynamics of buildings [27]. The model is based on physical definitions and relations of heat transfers and heat capacities and can be characterised as a linear state space model. It is inspired by the modelling approach in [22].

Through integration of the add-on into Balmorel, existing constraints on e.g. fuel consumption, electricity balance, and relation between heat output and electricity input for heat pumps are utilised4. In the following Sections 3.1-3.6, the new equations introduced in the model add-on are presented. Cost elements added to the objective function are presented in Section 3.1 and the heat balance

[4] Heat output = COP · electricity input, where COP is the coefficient of performance.

equations in Sections 3.2-3.4. Section 3.5 covers investment restrictions set up for individual heating installations, while Section 3.6 deals with methodology implemented to represent peak load shaving through flexible heat pump operation. The Sections 3.7-3.8 touch upon the influence of solar transmission and cooling. Finally, model output is compared with measured data in Section 3.9.

3.1 Costs

The use of heat storage in the building structure for flexible heat pump operation can be facilitated by investing in digital thermostats, enabling intelligent control of the central heating system, and in a central controller enabling communication with the power system. In addition, frequent measurements of indoor and ambient temperatures are required (using electronic thermometers, which are typically included in modern individual heat pumps). The temperature of the building structure can be estimated based on the calculated heat transfers to/from the building, as given by the temperature levels measured. The central controller then optimises the operation of the heat pump, based on various data, such as temperature measurements/estimations, weather forecasts, and various measurements on the central heating and hot water circuit [24, 28].

The use of thermal storage tanks (in addition to the small hot water tank of 150-200 litres, typically installed in combination with individual heat pumps [29, 30]) requires investment in the tank in addition to a central controller [24, 31]. The cost components described above have been added to the objective function in Balmorel, which covers total system costs. The added costs are shown in Eq. (1).

$$\sum_{a \in A^{Ind}} \sum_{g \in G^{ACT}} KN_{a,g} \cdot co_{a,g}^{Inv} + \sum_{a \in A^{Ind}} \sum_{g \in G^{HWT}} KN_{a,g} \cdot co_{a,g}^{Inv} + \sum_{a \in A^{Ind}} HS^{Inv} \cdot co_{a,'BSTO'}^{Inv} \quad (1)$$

The investment cost for thermal storage tanks is a function of the cost per storage capacity ($co_{a,g}^{Inv}$) and the invested new capacity (*KN*). The cost of intelligent heat storage in the building structure is determined by the investment cost per house ($co_{a,'BSTO'}^{Inv}$) and the number of houses investing in this option (HS^{Inv}). The following Eqs. (2)-(27) all represent constraints on the cost minimisation performed in the optimisation.

3.2 Hot water demand

Eq. (2) balances the hot water supply (from existing, Q^{HWe}, and new heating installations, Q^{HWn}) and demand (D^{HW}) in each hour, also taking loading of hot water tanks (LD^{HWT}) into account.

$$\sum_{g \in G^H} \left(Q_{a,g,w,h}^{HWe} + Q_{a,g,w,h}^{HWn} \right) - LD_{a,w,h}^{HWT} = D_{a,w,h}^{HW} \qquad \forall a \in A^{Ind}; w \in W; h \in H \quad (2)$$

3.3 Space heating

General conditions

Space heating is assumed only in the heating season, in Denmark defined as September 15 to May 15 (W^{HSea}) [32]. The need for space heating is modelled by restricting the indoor temperature (T^I) to be within a certain defined minimum (T^{IMin}) and maximum level (T^{IMax}), as shown in Eqs. (3)-(4). When fixing the indoor air temperature in each hour ($T^{IMin} = T^{IMax} = T^{IRef}$), the heating installation is forced to supply exactly the amount of space heating needed to cover the net heat demand in each hour, i.e. total heat loss of the building minus heat contributions. This does not allow for intelligent heat storage in the building structure, and is referred to as the *reference situation.* If allowing a given indoor temperature span, i.e. $T^{IMax} > T^{IRef}$ and $T^{IMin} < T^{IRef}$, the heating installation can be operated flexibly by utilising intelligent passive/active heat storage in the building structure. In Eqs. (3)-(4) it is implemented that the larger the share of houses that invest in this option (HS^{Inv}/HS^{Tot}), the larger the possibilities for flexible heat pump operation.

$$T^{I}_{a,w,h} \geq T^{IRef}_{w,h} + \left(T^{IMin}_{w,h} - T^{IRef}_{w,h}\right) \cdot \frac{HS^{Inv}_{a}}{HS^{Tot}_{a}} \qquad \forall a \in A^{Ind}; w \in W^{HSea}; h \in H \tag{3}$$

$$T^{I}_{a,w,h} \leq T^{IRef}_{w,h} + \left(T^{IMax}_{w,h} - T^{IRef}_{w,h}\right) \cdot \frac{HS^{Inv}_{a}}{HS^{Tot}_{a}} \qquad \forall a \in A^{Ind}; w \in W^{HSea}; h \in H \tag{4}$$

Eq. (5) ensures that the number of houses investing in this heat storage option (HS^{Inv}) can maximum be equal to the number of houses in the given area (HS^{Tot}).

$$HS^{Inv}_{a} \leq HS^{Tot}_{a} \qquad \forall a \in A^{Ind} \tag{5}$$

Eq. (6) ensures same average indoor temperature in the reference case and in the case with an allowed indoor temperature span. This results in the same demand for space heating in the two cases, which makes them comparable. The difference between the two cases thereby reflects the effect of operating the pumps flexibly, as intended. If leaving out Eq. (6), the difference between the cases would mainly show the effect of accepting a generally lower indoor temperature level, i.e. lower thermal comfort, implying a reduced space heating demand.

$$\frac{\sum_{h \in H} T^{I}_{a,w,h}}{\sum_{h \in H} 1} \geq T^{IRef}_{w,h} \qquad \forall a \in A^{Ind}; w \in W^{HSea} \tag{6}$$

Heat transfers occur each hour between the thermal masses in the model depending on the heat transfer coefficients and the temperature difference between the masses. The ventilation loss through the building envelope (Q^{Ven}) depends on the heat transfer coefficient U^{Ven} and the temperature difference between the indoor air (T^I) and the ambient air (T^O) (see Eq. (7)).

$$Q^{Ven}_{a,w,h} = U^{Ven}_{a} \cdot \left(T^{I}_{a,w,h} - T^{O}_{w,h}\right) \cdot AR_{a} \cdot 10^{-6} \qquad \forall a \in A^{Ind}; w \in W^{HSea}; h \in H \tag{7}$$

The remaining heat transfer equations represent heat transfer by transmission. These equations vary depending on whether houses with radiator heating or floor heating are considered.

Radiator heating systems

For houses with radiator heating, heat transfer between indoor air and building structure (Q^{IB}) is covered by Eq. (8), and heat transfer between building structure and ambient air (Q^{BO}) by Eq. (9).

$$Q^{IB}_{a,w,h} = U^{IB} \cdot \left(T^{I}_{a,w,h} - T^{B}_{a,w,h}\right) \cdot AR_a \cdot 10^{-6} \qquad \forall a \in A^{Rad}; w \in W^{HSea}; h \in H \quad (8)$$

$$Q^{BO}_{a,w,h} = U^{BO}_{a} \cdot \left(T^{B}_{a,w,h} - T^{O}_{w,h}\right) \cdot AR_a \cdot 10^{-6} \qquad \forall a \in A^{Rad}; w \in W^{HSea}; h \in H \quad (9)$$

The temperature of a thermal mass will increase if the total amount of heat transferred to the mass exceeds the amount leaving it; and vice versa. This is expressed in Eq. (10) for the case of the indoor air. The heat transferred to the indoor air covers heat supply from the heating installations (existing, Q^{SHe}, and new Q^{SHn}), heat contribution from persons and electrical appliances (Q^{Pel}), and the heat loss from thermal storage tanks contributing to space heating (Q^{TLos}). The heat flows leaving the indoor air cover heat losses through the building envelope (Q^{Ven}, Q^{IB}) and to little extent possible cooling (Q^{Cool},see Section 3.8). Loading of heat accumulation tanks is also accounted for (LD^{ACT}). The lower the heat capacity of the thermal mass (C^{I} in this case), the faster will the temperature change in response to a net heat transfer to/from it.

$$T^{I}_{a,w,h++1} = T^{I}_{a,w,h} + \frac{\sum_{g \in G^H}\left(Q^{SHe}_{a,g,w,h} + Q^{SHn}_{a,g,w,h}\right) + Q^{Pel}_{a,w,h} + Q^{TLos}_{a,w,h} - Q^{Ven}_{a,w,h} - Q^{IB}_{a,w,h} - LD^{ACT}_{a,w,h} - Q^{Cool}_{a,w,h}}{\mathrm{C^{I}} \cdot \mathrm{AR_a} \cdot 10^{-6}} \quad (10)$$

$$\forall a \in A^{Rad}; w \in W^{HSea}; h \in H$$

$$\text{where } Q^{TLos}_{a,w,h} = SL^{ACT} \cdot SC^{ACT} \cdot S^{ACT}_{a,w,h} + SL^{HWT} \cdot SC^{HWT} \cdot S^{HWT}_{a,w,h}$$

Eq. (11) correspondingly represents the development in the temperature of the building structure (T^{B}).

$$T^{B}_{a,w,h++1} = T^{B}_{a,w,h} + \frac{Q^{IB}_{a,w,h} - Q^{BO}_{a,w,h}}{C^{B}_{a} \cdot AR_a \cdot 10^{-6}} \qquad \forall a \in A^{Rad}; w \in W^{HSea}; h \in H \quad (11)$$

$$\text{where } C^{B}_{a} = C^{Pas}_{a} - C^{Fur}$$

Floor heating systems

For floor heating systems, the heat transfer between floor and indoor air (Q^{FI}) is covered by Eq. (12), heat transfer between indoor air and walls/ceiling (Q^{IL}) by Eq. (13), and heat transfer between walls/ceiling and ambient air (Q^{LO}) by Eq. (14).

$$Q^{FI}_{a,w,h} = U^{FI} \cdot \left(T^{F}_{a,w,h} - T^{I}_{a,w,h}\right) \cdot AR_a \cdot 10^{-6} \qquad \forall a \in A^{Flo}; w \in W^{HSea}; h \in H \quad (12)$$

$$Q^{IL}_{a,w,h} = U^{IL} \cdot \left(T^{I}_{a,w,h} - T^{L}_{a,w,h}\right) \cdot AR_a \cdot 10^{-6} \qquad \forall a \in A^{Flo}; w \in W^{HSea}; h \in H \quad (13)$$

$$Q^{LO}_{a,w,h} = U^{LO}_{a} \cdot \left(T^{L}_{a,w,h} - T^{O}_{a,w,h}\right) \cdot AR_a \cdot 10^{-6} \qquad \forall a \in A^{Flo}; w \in W^{HSea}; h \in H \quad (14)$$

The temperature development of the floor (T^{F}), indoor air (T^{I}), and walls/ceiling (T^{L}) is represented by Eqs. (15), (16), and (17), respectively.

$$T^{F}_{a,w,h++1} = T^{F}_{a,w,h} + \frac{\sum_{g\in G^{H}}\left(Q^{SHe}_{a,g,w,h}+Q^{SHn}_{a,g,w,h}\right)-LD^{ACT}_{a,w,h}-Q^{FI}_{a,w,h}}{\mathrm{C^{F}}\cdot\mathrm{AR_{a}}\cdot 10^{-6}} \quad \forall a\in A^{Flo}; w\in W^{HSea}; h\in H \quad (15)$$

$$T^{I}_{a,w,h++1} = T^{I}_{a,w,h} + \frac{Q^{FI}_{a,w,h}+Q^{Pel}_{a,w,h}+Q^{TLos}_{a,w,h}-Q^{Ven}_{a,w,h}-Q^{IL}_{a,w,h}-Q^{Cool}_{a,w,h}}{\mathrm{C^{I}}\cdot\mathrm{AR_{a}}\cdot 10^{-6}} \quad \forall a\in A^{Flo}; w\in W^{HSea}; h\in H \quad (16)$$

$$T^{L}_{a,w,h++1} = T^{L}_{a,w,h} + \frac{Q^{IL}_{a,w,h}-Q^{LO}_{a,w,h}}{\left(C^{Pas}_{a}-C^{Fur}-C^{F}\right)\cdot AR_{a}\cdot 10^{-6}} \quad \forall a\in A^{Flo}; w\in W^{HSea}; h\in H \quad (17)$$

3.4 Thermal storage tanks

The equations for heat accumulation tanks, which operate on the space heating circuit only [30], are shown in this section. Eq. (18) determines the development in the heat storage level (S^{ACT}) over time depending on the loading (LD^{ACT}), unloading (Q^{SHe}, Q^{SHn}), and the fractional storage loss (SL^{ACT}).

$$S^{ACT}_{a,w,h++1} = S^{ACT}_{a,w,h}\cdot\left(1-SL^{ACT}\right) + LD^{ACT}_{a,w,h} - \sum_{g\in G^{ACT}}\left(Q^{SHe}_{a,g,w,h} + Q^{SHn}_{a,g,w,h}\right) \quad (18)$$

$$\forall a\in A^{Ind}; w\in W^{HSea}; h\in H$$

Eq. (19) ensures that the storage level is kept within the available storage capacity.

$$S^{ACT}_{a,w,h} \le \sum_{\mathrm{g}\in\mathrm{G^{ACT}}}\left(KE_{a,g} + KN_{a,g}\right) \quad \forall a\in A^{Ind}; w\in W^{HSea}; h\in H \quad (19)$$

Eqs. (20)-(22) represent storage loading/unloading constraints.

$$Q^{SHe}_{a,g,w,h} \le KE_{a,g} \quad \forall a\in A^{Ind}; g\in G^{ACT}; w\in W^{HSea}; h\in H \quad (20)$$

$$Q^{SHn}_{a,g,w,h} \le KN_{a,g} \quad \forall a\in A^{Ind}; g\in G^{ACT}; w\in W^{HSea}; h\in H \quad (21)$$

$$LD^{ACT}_{a,w,h} \le \sum_{\mathrm{g}\in\mathrm{G^{ACT}}}\left(KE_{a,g} + KN_{a,g}\right) \quad \forall a\in A^{Ind}; w\in W^{HSea}; h\in H \quad (22)$$

Corresponding constraints have been implemented for hot water tanks. In this case, the constraints apply for the full year, since hot water is not only needed in the heating season.

3.5 Investment constraints for individual heating installations

Eq. (23) ensures that the total heat generation capacity is dimensioned to comply with Danish building regulations in terms of being able to cover the dimensional heat loss at an ambient temperature of -12 °C (T^{ODim}) and an indoor temperature of 20 °C (T^{IDim}); and satisfy the average hot water demand at the same time (D^{HWAv}) [33, 34].

$$\sum_{g\in G^{PH\ or\ EBi}}\left(KN_{a,g} + KE_{a,g}\right) \ge \left(U^{IO}_{a} + U^{Ven}_{a}\right)\cdot\left(T^{IDim} - T^{ODim}\right)\cdot AR_{a}\cdot 10^{-6} + D^{HWAv} \quad (23)$$

$$\forall a\in A^{Ind}$$

Due to Eq. (23), the required capacity of individual heating installations cannot be reduced through flexible operation of these, as in reality. The heat transfer coefficient between indoor air and ambient air (U^{IO}) is identified by using principles of series and parallel connections of thermal resistances:

$$U_a^{IO} = \frac{U^{IB} \cdot U_a^{BO}}{U^{IB} + U_a^{BO}} \;\; \forall a \in A^{Rad}, \qquad U_a^{IO} = \frac{U^{IL} \cdot U_a^{LO}}{U^{IL} + U_a^{LO}} \;\; \forall a \in A^{Flo}$$

Ground source heat pumps and air/water heat pumps are typically supplemented by an electric boiler to cover peak loads in order to reduce heat pump investment costs. In the model, this is reflected in Eq. (24), which ensures that the heat pump is dimensioned to constitute a given share (*CS*) of the total capacity, while an electric boiler covers the rest. Heat pumps are typically dimensioned to cover 72%-82 % of the dimensional heat loss defined in Eq. (23) [35]. This corresponds to that the heat pump covers around 99 % of the annual heat demand[5].

$$\sum_{g \in G^{HPi}} KN_{a,g} = \frac{CS}{1-CS} \cdot \sum_{g \in G^{EBi}} KN_{a,g} \qquad \forall a \in A^{Ind} \tag{24}$$

Residents in individually heated areas will normally invest in only one type of primary heating technology (in Denmark typically a fuel boiler or heat pump). In order to reflect this in the model, it is therefore avoided that different types of invested primary heating technologies are used to supplement each other within a given area; e.g. using one technology for base load operation and another for peak load operation. Eq. (25) ensures this by setting a minimum number of full load hours (FLH^{Min}) for new primary individual heating technologies.

$$\sum_{w \in W} \sum_{h \in H} \left(Q_{a,g,w,h}^{HWn} + Q_{a,g,w,h}^{SHn}\right) \cdot hL_{w,h} \geq KN_{a,g} \cdot FLH_a^{Min} \qquad \forall a \in A^{Ind}; g \in G^{PH} \tag{25}$$

Given space requirements, it is realistic to insert a heat accumulation tank of up to around 1000 litres in each house (V^{MaxACT}) [29]. This is taken into account in Eq. (26).

$$\sum_{g \in G^{ACT}} \left(KN_{a,g} + KE_{a,g}\right) \leq HS_a^{Tot} \cdot V^{MaxACT} \cdot SV^{ACT} \qquad \forall a \in A^{Ind} \tag{26}$$

3.6 Capacity balance restriction

In Balmorel, a reasonable amount of dispatchable power capacity in each power region can to some extent be ensured by including the period of the year with highest net load, i.e. gross load minus power from wind (and other fluctuating renewable energy sources), in the optimisation. However, this will likely underestimate the need for peak and reserve capacity; firstly due to the assumed perfect foresight on wind power and load. Secondly, electricity import can in the optimisation contribute to cover high net loads, while in reality risk of failures on transmission cables should be taken into account.

Inspired by [3], a capacity balance restriction is therefore added to ensure adequate production capacity and reserve margin in each power region (Eq. (27)). The term *capacity credit* (*cc*) is here applied, which determines the share of total installed capacity that is available for electricity generation at a

[5] For a full year simulation in the thermal building model using ambient temperatures in [51].

certain level of confidence. Based on [3], the capacity credit of conventional units is set to 0.99, while the capacity credit for wind power is set to 0.14. Eq. (27) states that sufficient electricity generation capacity must be available in each power region to cover the peak load; covering both conventional electricity demand (D^{ElConv}) and flexible electricity demand of heat pumps/electric boilers (and electricity storages) (D^{ElFlex}).

$$\sum_{\mathrm{a}\in\mathrm{A(r)}}\sum_{\mathrm{g}\in G^{El}}\left(KE_{a,g}+KN_{a,g}\right)\cdot cc_g \geq D^{ElConv}_{r,w,h}+\sum_{\mathrm{a}\in\mathrm{A(r)}}\sum_{\mathrm{g}\in\mathrm{G}} D^{ElFlex}_{a,g,w,h} \qquad \forall r\in R;\ w\in W;h\in H \tag{27}$$

The equation reflects that the need for production capacity and reserves can be reduced through peak load shaving (by reducing D^{ElFlex}). As the constraint is applied for each hour and week it allows for lowering the heat pump operation in peak load hours taking the hourly pattern of conventional and flexible electricity demand into account. This is a new development compared to the capacity balance restriction in [3], where the right hand side of the equation is a constant peak load set for each country.

3.7 Solar transmission

Heat contribution from solar transmission through windows has been excluded due to lack of data. This delimitation can also be found in other thermal building model simulations, e.g. [15, 22, 36]. The heat contribution from solar transmission will vary greatly from house to house depending on in particular the total window area, the orientation of the windows, the shading effects from surroundings, and transmittance of the window type (depending on glazing an number of glass panes) [37, 38]. According to estimates in [39], the largest share of the total free heat contribution[6] over the heating season in existing one-family houses however stem from electrical appliances and persons i.e. around 2/3, which is included in this model. The relative influence of solar transmission will generally be highest in the most well insulated houses. New houses constructed towards 2030, having very low heat demands (10 kWh space heating annually per m^2), have therefore not been included in this study. This delimitation is reasonable since new houses only constitute about 6 % of the individual heat demand expected by 2030.

3.8 Cooling

The possibility of cooling has been introduced to ensure that the indoor temperature can be kept below T^{IMax} in all periods of the year. In the optimisation, the possibility of cooling is only used in houses with (concrete) floor heating and mainly when requiring a fixed indoor temperature. Since the floor heated houses constitute only 5 % of the modelled individual heat demand the cooling has no importance for the model illustration.

[6] I.e. contribution from other sources than the heat installation.

3.9 Comparison with measured data

Measurements of 28 Danish heat pump installations in one-family houses indicate that a constant indoor temperature setting over the day/night is typical in the reference situation (21.5 °C on average) [40]. Model generated diurnal space heating profiles for this indoor temperature setting (21.5 °C) have been compared with corresponding measured profiles for Danish heat pump installations (see Fig. 3).

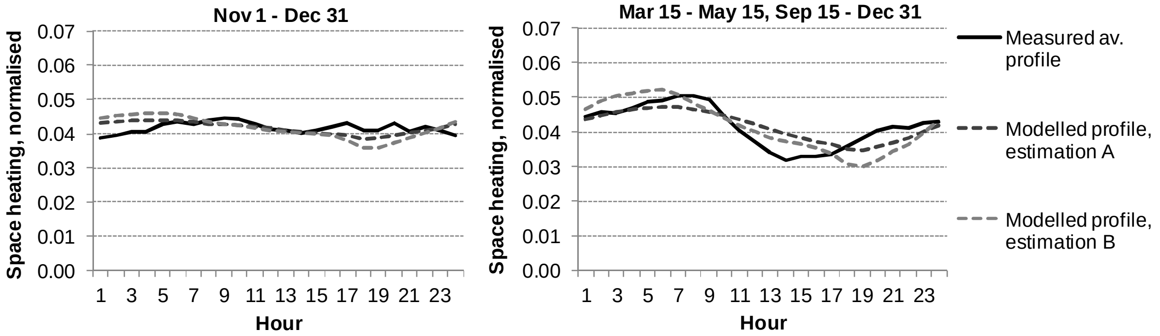

Fig. 3. Model generated average diurnal space heating profile compared to a corresponding measured average profile for heat pumps in Danish one-family houses [40]. Radiator heating systems are illustrated. Estimation A: U^{BO} for monitored houses estimated based on construction year. Estimation B: U^{BO} for monitored houses estimated based on measured space heating over the given period. **a)** Comparison covering November 1 to December 31 (data available for 24 houses). **b)** Comparison covering March 15 to May 15 and September 15 to December 31 (data available for 5 houses).

Fig. 3 indicates that the thermal building model gives a reasonable representation of actual space heating profiles. Furthermore, it confirms that the assumption of constant indoor temperature setting in the reference situation is realistic. The larger diurnal variation observed in the right part of Fig. 3 is mainly explained by the fact that this period also covers autumn/spring periods, where there is a larger relative influence of diurnal ambient temperature variations and heat contributions from solar transmission, persons, and appliances.

The measured space heating profile has a valley around mid-day, when solar transmission is highest. The valley of the model generated space heating profile occurs a few hours later, due to the exclusion of solar transmission (see Section 3.7), and since the heat contribution from electrical appliances (and persons) is highest in the early evening. Fig. 3 shows that the modelled space heating profile is in some situations potentially[7] a bit lower than the measured profile, in the hours where conventional electricity demand typically peaks, i.e. around 8.00-9.00 and 18.00 o’clock (in Denmark). This means that the model could slightly underestimate the peak load shaving achieved when operating the heat pumps flexibly. However, the deviation between the profiles is acceptable as it is believed to be within the general uncertainties related to analyses of individual heat pumps on energy system level: the uncertainty of representing a large-scale building stock on aggregated level (covering around 716 000

[7] If assuming that the estimation procedure B is the best approximation of the building stock data (see Fig. 3).

houses for the Danish case) and the uncertainties on other input data (fuel and CO_2 prices, investment costs for technologies etc.).

4. Application

For the illustrative case study of the Danish energy system by 2030, the most important preconditions are outlined in the following. Energy demands and fuel potentials are based on the Future scenario in the report of The Danish Commission on Climate Change Policy [41]. Technology data are mainly based on technology catalogues developed by the Danish Energy Agency [42, 43] and secondarily on [10, 44]. Electricity trade with neighbouring countries is taken into account by including Germany, Norway, Sweden, and Finland in the optimisation.

The thermal building model add-on is applied for the stock of existing individually heated one-family houses in 2030. Houses with radiator heating are assumed to constitute 95 % of this heat demand. This is based on the tradition for installing radiator-based central heating systems in new houses until the 1990'ies [45, 46] and the high costs of installing floor heating in existing houses [24, 47]. The one-family houses are divided into 3 different categories, depending on the year of construction, reflecting changes in insulation standards. The heat capacity of the building that can be utilised for passive heat storage diurnally (effective heat capacity) is based on typical values for Danish buildings as given in [48] and on the following general distribution 60 Wh/°C/m^2 floor area: 25 % of the houses, 100 Wh/°C/m^2 floor area: 50 % of the houses, and 140 Wh/°C/m^2 floor area: 25 % of the houses [49]. The effective heat capacity of the building is mainly comprised by internal construction in walls, ceiling, and floor, while windows, doors, and furniture have minor influence [24]. For houses with floor heating, a typical concrete layer of 10 cm [46, 50] has been assumed representing a thermal mass of 67 Wh/°C/m^2 floor area.

Overall, the stock of individually heated one-family houses is aggregated into 10 different areas both in Eastern and Western Denmark (20 areas in total). Based on a need to limit computation time, five weeks are simulated to represent a full year; hereof four weeks in the heating season and one summer week. Weighting factors are applied to account for the period length that each of the simulated weeks represent. The heat transfer coefficients for the houses, U^{BO} and U^{LO}, have then been calibrated to give the annual space heating demand for each building category. The calibrated heat transfer coefficients deviate less than 2 % from the heat transfer coefficients corresponding to a full year simulation. This shows that the simulated weeks give a very good approximation of the space heating demand over a full year.

Typical diurnal and seasonal variations in ambient temperatures (T^O) are represented using hourly average temperature data for the Danish design reference year [51]. The hourly hot water demand variation is based on a demand profile on aggregated level for a large number of Danish households [52]. The average heat contribution from persons and electrical appliances is set to 5 W/m^2 floor area; hereof 1.5 W/m^2 from persons and 3.5 W/m^2 from electrical appliances [48]. The variation in the heat contribution from electrical appliances is based on the aggregated electricity demand variation for Danish households.

5. Results illustrating model functionality

Fig. 4 shows the development in space heating from the heat pumps in a situation without allowing heat storage investments, and where the required indoor temperature is fixed to 21.5 °C. In this situation, the heat pumps are restricted to provide the space heating needed to cover the net heat demand in each hour, i.e. transmission and ventilation loss minus heat contribution from other sources (persons and electrical appliances in this case). It can be seen that when the ambient temperature is low, space heating is high due to high heat losses.

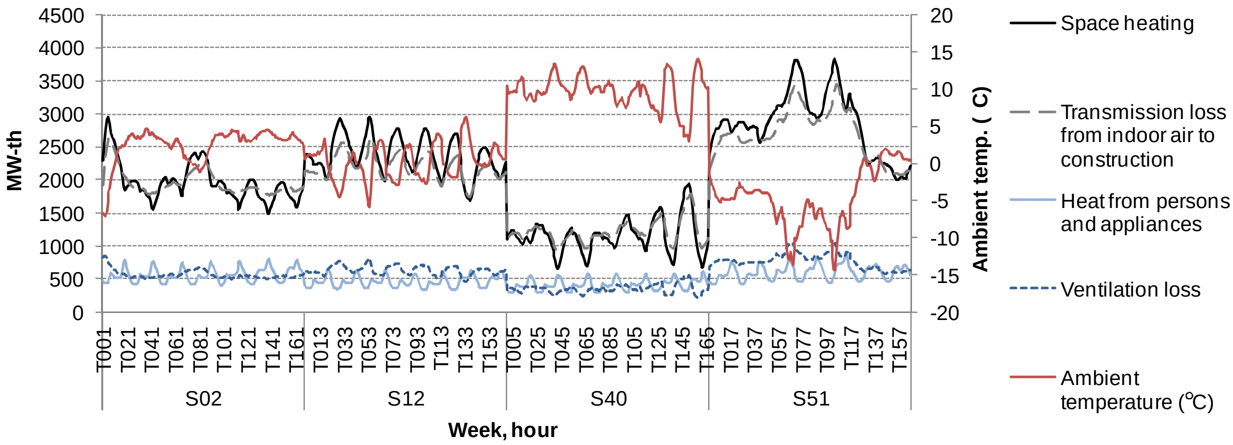

Fig. 4. Space heating from individual heat pumps, other heat contributions, heat losses, and ambient temperatures for situation without heat storage investments and with a fixed indoor temperature requirement of 21.5 °C (the simulated heating season is illustrated focusing on houses with radiator heating).

When allowing investments in thermal storages complementing the heat pumps, investments in intelligent heat storage in the building structure are observed. In houses investing in this option, the indoor temperature is allowed to vary within an interval of 20-23 °C during the day and 19-22 °C at night, ensuring thermal comfort [14, 15, 40]. The optimisation suggests that it is socio-economically feasible to invest in this heat storage option in around 34 % of heat pump installations in one-family houses. The optimisation reveals no feasible investments in heat accumulation tanks (or hot water tanks). The feasibility of investing in control equipment, enabling intelligent use of the existing small hot water tanks, has not been tested in this model illustration. The investments in intelligent heat storage in the building structure are observed across all the defined categories of insulation levels, central heating systems, and heat capacities of the building structure (see Fig. 5).

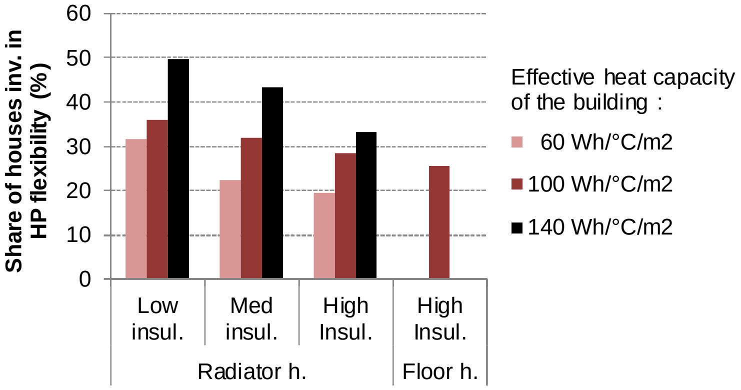

Fig. 5. Shares of existing individually heated one-family houses investing in intelligent heat storage in the building structure for flexible heat pump operation. Houses with (concrete) floor heating will foremost utilise the thermal mass of the concrete floor of 67 Wh/°C/m^2 floor area.

However, the investments in intelligent heat storage in the building structure are generally larger the larger the heat capacity of the building. This is expected, since the possibilities for flexible heat pump operation utilising heat storage in the building structure will be higher the larger the heat capacity of the building. Fig. 5 furthermore indicates a higher feasibility of investing in intelligent heat storage in the building structure in houses with lower insulation level. This might seem counterintuitive since low insulation level results in higher heat losses in the process of storing heat in the building structure. The explanation is that a low insulation level corresponds to a higher space heating demand per house. This means higher electricity consumption for heat pump operation and thus a higher potential benefit of enabling the storage in absolute terms.

Fig. 6 illustrates the modelled flexible operation of the heat pumps. The electricity price on the figure represents the marginal cost of generating electricity in energy system optimisation. It can be seen that the electricity consumption of the heat pumps is low, when the electricity price is high and vice versa. This shows that the model works as it should, i.e. that investments in heat storage capability render it possible to optimise the heat pump operation in integration with the energy system.

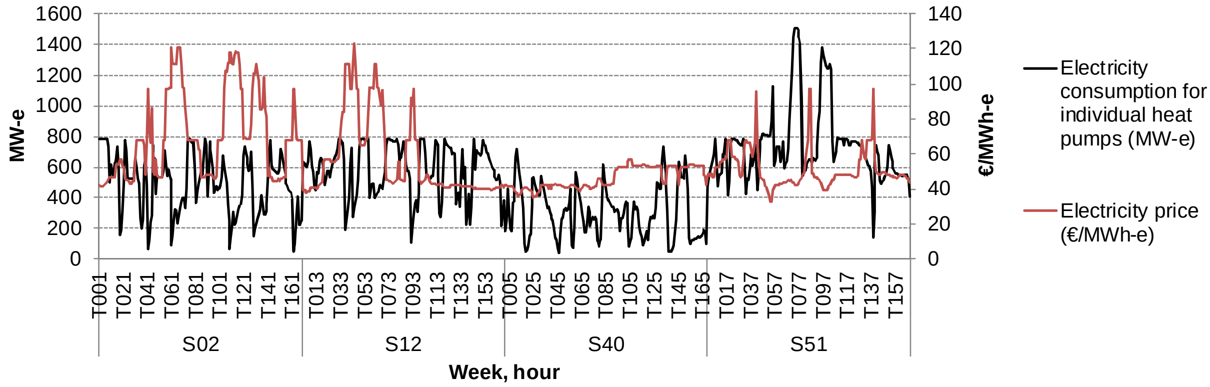

Fig. 6. Modelled flexible operation of individual heat pumps over the heating season shown for Western Denmark by 2030.

The use of an aggregated system model means that a heat storage capacity in a given area can be shared among all heat pumps within the area. This is evident from Fig. 6, where the heat storage investments realised in 34 % of the houses render it possible to operate a larger share of the heat pumps flexibly to some extent. The flexibility offered by heat storages can thus be distributed among the houses, which implies best-case conditions. Ideally, each of the many thousands of individually heated houses should be modelled separately (716,000 in this case). However, it would hardly be realistic to run such a model.

As illustrated in Fig. 7, the flexible heat pump operation contributes to peak load shaving due to the capacity balance restriction implemented in Eq. (27). The week with the highest peak loads of the year is illustrated representing the week determining for the need for peak and reserve capacities in the optimisation.

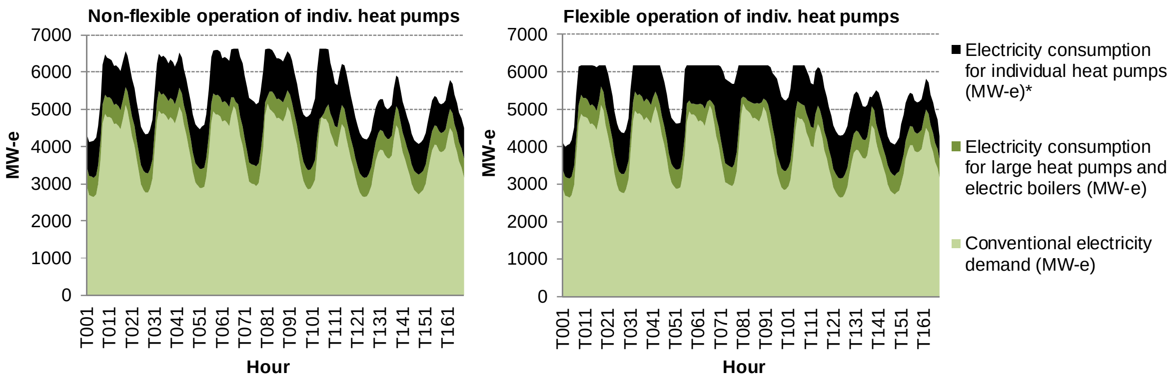

Fig. 7. Peak load shaving achieved due to flexible operation of individual heat pumps. The week with the highest peak loads of the year is illustrated (week no. 51). *Incl. supplemental electric boilers.

The peak load shaving is facilitated by using the heat storage capacity of the building for shifting the load of the individual heat pumps a few hours within the day: from the peak load hours in the morning and evening to the load valleys in the afternoon; and to some extent also to the night. As a result, the investment in peak/reserve capacity is in the optimisation reduced by 440 MW corresponding to the size of a large power plant.

Fig. 7 illustrates that if peak loads were to be shaved down further it would require lowering the individual heat pump load further in longer consecutive periods lasting up to 15 hours (hour T056 to T070). This is difficult since ambient temperatures are very low in this week (see Fig. 8). As a result, the individual heat pumps are forced to operate at their capacity limit in longer periods, and the electric boilers needed for covering peak loads. This means that the capacity margin available for load shifting is limited regardless of the heat storage possibilities.

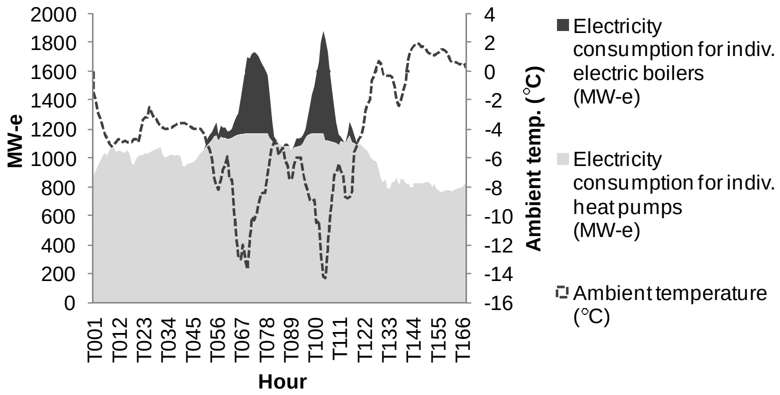

Fig. 8. Electricity consumption for individual heat pumps and supplemental electric boilers shown for the week with the highest peak loads of the year (week no. 51). The situation without flexible heat pump operation is illustrated.

The two cases exhibit different computational times. The case without flexible heat pump operation, i.e. fixed indoor temperature (and no allowed investments in thermal storage tanks), takes only about 3 hours to complete. The case with flexible operation of the heat pumps is more complex and takes around 16 hours. These computational times are considered reasonable and acceptable given the size of the problem.

Overall, the results presented illustrate that the model is well qualified for analysing the possibilities and system effects of flexible heat pump operation.

6. Discussion and Conclusion

We have presented a model that renders it possible to analyse individual heat pumps and complementing heat storages in integration with the energy system when optimising both investments and operation. The model covers various heat storage options: i.e. passive heat storage in the building structure via radiator heating, active heat storage in concrete floors via floor heating, and use of thermal storage tanks for space heating and hot water, respectively. Through comparison with measured data, it is indicated that the model gives a reasonable representation of actual space heating profiles.

The capability of the model is illustrated in a case study of the Danish energy system by 2030 with optimised wind penetrations of around 60 %. The case study shows that the model is well qualified for analysing the possibilities and system benefits of operating individual heat pumps intelligently. This includes prioritising heat pump operation for hours with low marginal electricity production costs and reducing required investments in peak and reserve capacity through peak load shaving.
As the model is linear, it does not include start-up costs, minimum load requirements, or part load efficiencies. Moreover, the model assumes perfect foresight and therefore does not include power balancing responding to errors in forecasts of wind and load; only requirements for reserve capacities are included. As illustrated in [23], start-up costs and minimum load requirements for thermal power plants can have a significant influence on the operation cost savings obtained when using individual heat pumps for demand side management. This means that potentials for reducing operation costs

through flexible heat pump operation are conservatively represented in the model. However, we incorporate effects on energy system investments in contrast to previous models focusing on individual heat pumps.

As in many other energy system models, the heat pumps in this study were represented by a yearly average COP. It could be interesting to include hourly COP variations in the model caused by variations in the heat source temperature and in the output temperature of the heat pump. Another subject for further research would be to model how flexible operation of the heat pumps influences required enhancements in the distribution grids. The inclusion of heat contribution from solar transmission in the model also forms a relevant subject for future work.
Nevertheless, the model development is considered a big step forward, in providing the methodology needed for analysing individual heat pumps and heat storages in an energy system context. It would be interesting to use the model for analysing the impact that heat pumps can have in terms of integrating wind power at a national level, including impacts on investments, system costs, fuel consumption, and CO_2 emissions.

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APPENDIX

Nomenclature

Indices

a, A	heating area, set of heating areas
A^{Ind}	set of individually heated areas
A^{Rad} , A^{Flo}	set of individually heated areas with radiator heating and floor heating, respectively
g, G	generation technology/storage, set of generation technologies/storages
G^{ACT}, G^{HWT}	set of individual heat accumulation tanks and hot water tanks, respectively
G^{H}	set of individual heating technologies (heat pumps, boilers, solar thermal and heat storages)
G^{El}	set of electricity generation technologies
G^{PH}	set of primary individual heating technologies (heat pumps, fuel boilers)
G^{HPi}, G^{EBi}	set of individual heat pumps and electric boilers, respectively
h, H, hL	time period (hour), set of time periods simulated, length of time period (hours)
$h{+}{+}1$	Gams notation ensuring circular connection, i.e. that the value in the last hour of the week is linked to the value in the first hour of the week
r, R	region, set of regions
w, W, W^{Hsea}	week, set of weeks simulated, set of weeks in the heating season

Variables

D^{ElFlex}	electricity consumption for heat pumps/electric boilers and loading of electricity storages (MW)
LD^{ACT}, LD^{HWT}	loading of hot water tank/heat accumulation tank (MW)
HS^{Inv}	number of houses investing in intelligent heat storage in the building structure (houses)

KN	capacity of new generation technologies (MW) and storages (MWh)
S^{HWT} , S^{ACT}	storage level in hot water tank, storage level in heat accumulation tank (MWh)
T^{B}	temperature of building structure (°C)
T^{F}	temperature of floor (°C)
T^{I}	temperature of indoor air (°C)
T^{L}	temperature of walls/ceiling (°C)
Q^{Cool}	cooling (MW)
Q^{HWe} , Q^{HWn}	hot water generation from existing and new technologies, respectively (MW)
Q^{SHe} , Q^{SHn}	space heating from existing and new technologies, respectively (MW)
Q^{Ven}	ventilation loss through building envelope (MW)
Q^{IB}	heat transfer from indoor air to building structure (MW)
Q^{BO}	heat transfer from building structure to ambient air (MW)
Q^{FI}	heat transfer from floor to indoor air (MW)
Q^{IL}	heat transfer from indoor air to walls/ceiling (MW)
Q^{LO}	heat transfer from walls/ceiling to ambient air (MW)
Q^{TLos}	heat loss from thermal storage tanks contributing to space heating (MW)
Parameters	
AR	heated floor area (m^2)
C^{B}	effective heat capacity of building structure (Wh/°C/m^2 floor area)
C^{I}	heat capacity of indoor air, furniture and for radiator heating systems, also water in radiators (Wh/°C/m^2 floor area)
C^{Fur}	heat capacity of furniture (Wh/°C/m^2 floor area)
C^{F}	heat capacity of concrete floor heating system incl. concrete and water in tubes (Wh/°C/m^2 floor area)
C^{Pas}	effective heat capacity of building incl. furniture (Wh/°C/m^2 floor area)
C^{L}	effective heat capacity of walls/ceiling (Wh/°C/m^2 floor area)
CS	heat pump capacity share ( )
cc	capacity credit of electricity generation unit ( )
co^{Inv}	annualised investment costs for given heat storage option (€/MWh/yr or €/house/yr)
D^{ElConv}	conventional electricity demand, i.e. excl. heat pumps, electric boilers, and electricity storage (MW)
D^{HW}	hot water demand (MW)
D^{HWAv}	average hot water demand (MW)
FLH^{min}	minimum full load hours required (hours)
HS^{Tot}	total number of houses (houses)
KE	capacity of existing generation technologies (MW) and storages (MWh)
Q^{Pel}	heat contribution from persons and electrical appliances (MW)
SL^{HWT}, SL^{ACT}	stationary heat loss from hot water tank/heat accumulation tank in share of heat stored per hour ( )
SC^{HWT}, SC^{ACT}	share of heat loss from hot water tank/heat accumulation tank contributing to space heating ( )
SV^{ACT}	heat content per volume for heat accumulation tank (MWh/litre)
T^{O}	ambient (outdoor) air temperature (°C)
T^{IDim}	dimensioning indoor temperature (°C)
T^{ODim}	dimensioning ambient temperature (°C)
T^{IMin}	minimum indoor temperature required (°C)
T^{IMax}	maximum indoor temperature required (°C)
T^{IRef}	indoor temperature setting in reference situation without flexible heat pump operation (°C)
U^{BO}	heat transfer coefficient between building structure and ambient air (W/m^2 floor area/°C)
U^{IB}	heat transfer coefficient between indoor air and building structure (W/m^2 floor area/°C)
U^{IL}	heat transfer coefficient between indoor air and walls/ceiling (W/m^2 floor area/°C)

U^{LO}	heat transfer coefficient between walls/ceiling and ambient air (W/m^2 floor area/°C)
U^{Vent}	heat transfer coefficient for ventilation loss through building envelope (W/m^2 floor area/°C)
U^{IO}	total heat transfer coefficient for transmission loss through building envelope (W/m^2 floor area/°C)
V^{MaxAct}	maximum heat accumulation tank size per house due to space requirements (litre/house)

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Paper V

Influence of individual heat pumps on wind power integration – Energy system investments and operation

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Influence of individual heat pumps on wind power integration – Energy system investments and operation

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Individual heat pumps are expected to constitute a significant electricity demand in future energy systems. This demand becomes flexible if investing in complementing heat storage capabilities. In this study, we analyse how the heat pumps can influence the integration of wind power by applying an energy system model that optimises both investments and operation, and covers various heat storage options. The Danish energy system by 2030 with around 50–60% wind power is used as a case study. Results show that the heat pumps, even without flexible operation, can contribute significantly to facilitating larger wind power investments and reducing system costs, fuel consumption, and CO_2 emissions. Investments in heat storages can provide only moderate system benefits in these respects. The main benefit of the flexible heat pump operation is a reduced need for peak/reserve capacity, which is also crucial for the feasibility of the heat storages. Socio-economic feasibility is identified for control equipment enabling intelligent heat storage in the building structure and in existing hot water tanks. In contrast, investments in new heat accumulation tanks are not found competitive.

1. Introduction

Wind power has great potential in mitigating CO_2 emissions and improving security of supply through displacing use of fossil fuels in the energy system. The share of wind power is high in the Danish energy system, around 30% of annual electricity demand [1], and the Government plans to increase this share to by 2020 [2]. This makes the Danish case interesting for analysing challenges of integrating wind power that may be faced by other countries in the future.

Previous studies have shown that large heat pumps, electric boilers, and heat storages in combined heat and power (CHP) systems, as well as electric vehicles, can play a significant role in facilitating the integration of wind power [3–8]. Similarly, demand side management can contribute significantly to increasing system flexibility [9–13], and individual heat pumps in the residential sector could also contribute in this regard. Analyses show that individual heat pumps together with district heating form the best heat supply solutions in present and future energy systems [14,15]. Furthermore, the use of individual heat pumps is expected to grow considerably in Denmark [16], thereby developing into a significant part of the total electricity demand. The electricity demand of the heat pumps becomes flexible if e.g. investing in control equipment, enabling intelligent heat storage in the building structure and/or in existing hot water tanks, and/or if investing in heat accumulation tanks for space heating. This can potentially provide system benefits in terms of e.g. rendering wind power investments more attractive and reducing the need for peak and reserve capacities. However, investments in heat storages in the households could suffer from low economies of scale and will in some aspects compete with other flexible energy technologies in the system. This makes it relevant to analyse individual heat pumps and supplementing heat storages in integration with the energy system, optimising both investments and operation.

Only few studies evaluate the effects that flexible operation of individual heat pumps can have on the system by applying a large-scale energy system model. Papaefthymiou et al. [17] assess the system benefits of operating a large amount of individual heat pumps flexibly, using the building stock as thermal storage. Applying a case study of the German power system in 2030 with a renewable electricity share of 50–70% (hereof, two thirds wind power), it is found that flexible operation of the heat pumps can reduce system operation costs with 0.45–0.95% corresponding to 25–40 €/house/year [17]. Hedegaard et al. [18] compare the potentials of individual heat pumps and different heat storage options in terms of facilitating a fuel-efficient and cost-effective integration of wind power. In a case study of the Danish energy system in 2020 with 50% wind power, it is shown that the installation of heat pumps significantly reduces fuel consumption, while flexible operation provides only moderate fuel savings. Klobasa [19] analyses a broad range of demand response potentials and costs, including

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cooling and electric heating in the residential sector, and compares them to costs of conventional balancing technologies.

The above mentioned studies mainly focus on operational aspects without investigating how flexible heat pump operation can influence energy system investments. In reports by the Danish TSO and the Danish Energy Association [20,21] it is estimated that flexible heat pump operation can significantly reduce investments in peak capacity and reduce system costs by 80–130 €/house/year on average (socio-economic costs) [22]. However, the applied model covers only operation of the system, while investments are estimated separately. Moreover, flexible operation is not modelled but e.g. in [20] merely represented as a modified fixed demand profile, assuming that operation can be optimised within the day.

No existing studies have been identified, which analyse the system effects of individual heat pumps, applying a national scale energy system model that optimises both operation and investments. This is therefore the subject of this study. In a case study of the Danish energy system in 2030 with optimised wind power shares of around 50–60%, we analyse how individual heat pumps and complementing heat storages affect investments in the energy system; particularly to which extent they can facilitate increased wind power investments and reduce the need for peak and reserve capacity. Moreover, we investigate to which extent investments in individual heat storages are socio-economically attractive. In this regard, we include competition with other flexibility measures in the system – here represented as large heat pumps, electric boilers, and heat storages in the CHP system. Effects on system costs, fuel consumption, and CO_2 emissions are also quantified. The results are intended as input to policy makers in prioritising efforts and incentives within the field of individual heat pumps and wind power integration. The main research question investigated is: to which extent can individual heat pumps and complementing heat storages support an effective wind power integration?

We apply an add-on recently developed for the investment model Balmorel (see Section 2), which incorporates thermal building dynamics and various heat storage options for individual heat pumps. The model has been described in detail in [23]. Socio-economic cost minimisation is applied in order to identify what is optimal for the system as a whole. The article is structure in the following way; Section 2 describes the Balmorel model and the add-on developed. Section 3 presents how the model has been applied, covering scenarios and input data. In Section 4, results of the energy system analysis are presented, and a discussion and conclusion is given in Sections 5 and 6. Finally, Section 7 outlines suggestions for future work.

2. Model: Balmorel with thermal building model add-on

Balmorel is a partial equilibrium model assuming perfect competition [3,24]. The Balmorel model has in previous studies been used for analysing e.g. wind power development, security of supply, the role of district heating, development of international electricity markets, the role of demand response, compressed air energy storage, unit commitment, international markets for green certificates and emission trading as well as evaluation of environmental policies cf. e.g. [15,25].

The model minimises total costs of the system, covering annualised investment costs, operation and maintenance costs of existing and new units, and fuel and CO_2 quota costs. In this process, the model optimises investments in power/heat production, storage, and transmission capacities, and the operation of the system. The optimisation is done subject to a number of constraints including satisfaction of demands for electricity and heat in each time period, renewable energy potentials, and technical restrictions on units in the system. The model is deterministic assuming perfect foresight and the linear version applied does not include start-up costs, minimum load requirements, or part load efficiencies [3,24].

The model operates with three geographical entities, namely countries, regions, and areas. Countries are divided into regions connected with transmission lines, while regions are further divided into areas. Electricity supply and demand is balanced on regional level, and heating is balanced on area level. In this study, the existing model structure in Balmorel is used for handling the integrated power and district heating system. Individually heated one-family houses are represented using the new thermal building model add-on. In Balmorel, the optimisation is performed with a yearly time horizon, where the year is divided into seasons, which are further divided into time periods. When applying an hourly time resolution, seasons represent weeks, while time periods represent hours. A full description of the Balmorel model can be found in [24,26].

Heat pumps (compression heat pumps) are in Balmorel represented as commonly in energy system models, where the relation between heat output (Q_t) and electricity input in a given time period (P_t) is expressed as $Q_t = COP \cdot P_t$, where COP is the average annual coefficient of performance for the heat pump. In the thermal building model add-on, the individual heat pumps (ground source heat pumps and air/water heat pumps) are supplemented by an electric boiler to cover peak loads in order to reduce heat pump investment costs, as in reality. The capacity shares of heat pump and electric boiler, respectively, are defined in the input data. When the heat pumps are connected to heat storage, they can be operated flexibly. The large heat pumps are in Balmorel connected to the district heating storages, while the individual heat pumps can utilise the different heat storage options covered in the thermal building model add-on, if the required investments are made.

The thermal building model applied represents houses with radiator heating as well as houses with floor heating, as the central heating system. In the model, houses with radiator heating can utilise the option of storing heat passively in the building structure through radiation, thermal conductance, and convection. The term *passively* refers to the fact that heat is stored without the use of a heat transferring media going in and out of the storage. The storage concept mainly utilises the heat capacity of internal constructions in walls, ceiling, and floor, while windows, doors, and furniture have minor influence [18]. Houses with (concrete) floor heating can via the water tubes in the floor foremost store heat *actively* in the large thermal mass of the concrete floor (in addition, heat can be stored passively in the rest of the building structure). Thermal storage tanks for space heating and hot water are also covered, representing other options of enabling flexible heat pump operation. The add-on is a linear state-space model and is based on physical definitions and relations of heat transfers and heat capacities. A full description of the model add-on is given in [23].

3. Application

3.1. Scenarios

Three main scenarios are compared in the analysis: NOiHP, iHP, and iHP-Flex (see Table 1). By comparing the scenarios NOiHP and iHP, it is analysed how the individual heat pumps affect the energy system, when not operated flexibly. The difference between the scenarios iHP and iHP-Flex reveals the effect of investing in heat storages complementing the heat pumps, thereby facilitating flexible operation. Investment in heat storages will only occur to the extent that it is socio-economically attractive, in the optimisation. Focusing on the largest storage potentials, the following heat storage options are optimised in the main scenarios:

Table 1
Main scenarios analysed in the optimisation.

	NOiHP	iHP	iHP-Flex
Investment in individual heat pumps allowed		+	+
Investment in intelligent passive/active heat storage in the building structure allowed[a]			+
Investment in heat accumulation tanks allowed			+

[a] Indoor temperature variation allowed in this regard: day: 20–23 °C, night: 19–22 °C.

- *Intelligent heat storage in the building structure*: investment in digital thermostats[1], enabling intelligent control of the central heating system, and in a central controller communication with the power system [18,27]. For houses with radiator heating, this renders it possible to utilise passive heat storage in the building structure, while for houses with (concrete) floor heating, it also facilitates using active heat storage in the concrete floor.
- *Heat accumulation tanks*: investment in a heat accumulation tank for the space heating circuit of a size up to 1000 l per house and in a central controller communicating with the power system [18].

A small hot water tank of around 180 l [28] is typically installed in connection with individual heat pump installations. The hot water tank can to some extent also support flexible heat pump operation if investing in control equipment (a central controller). The feasibility of investing in this option is analysed in a supplementary analysis (see Section 4.4). In a sensitivity analysis, the feasibility of the space heating storages listed above is moreover investigated in a situation where the investment in intelligent use of the hot water tank has already been made (see Section 4.4). This analysis approach is applied in order to avoid double counting the cost of the common control equipment (the central controller) and to ensure a reasonable computation time.

The system model covers the power and district heating sectors of not only Denmark, but also Norway, Sweden, Finland, and Germany, in order to cover the influence of electricity import/export. For Denmark, individually heated one-family houses are additionally modelled, representing the bulk, app. 80% [29], of individual heating. Existing individual heating installations are assumed decommissioned by 2030 based on a typical lifetime of around 15–20 years [14,30].

Denmark is divided into a Western power region, being synchronous with the former UCTE power system, and an Eastern power region being synchronous with the former Nordel power system (both power systems are today represented by ENTSO-E). In order to limit computation time, the Danish district heating system is aggregated into 4 areas. This aggregation has no real influence on the results since (1) A linear model is applied, i.e. investments can be made in continuous capacity sizes. (2) The total district heating demand for each actual heating area covers several thousands of consumers and is thus already very smoothened from aggregation. (3) The district heating expansion is in the analysis fixed based on [31]. (4) A large share of existing district heat generation capacities are decommissioned towards 2030. Due to the focus on individual heating, 20 different individual heating areas with different characteristics are modelled (see Section 3.4).

[1] On each radiator for radiator heating and in each room for floor heating.

3.2. Period simulated

Based on a need to limit computation time, five weeks are simulated to represent a full year, hereof four weeks in the heating season and one summer week. In order to ensure good representation of variations in wind power, electricity, and heat demands, an hourly time resolution within each week is applied. When scaling up to a full year, weighting factors are applied to account for the period length that each of the simulated weeks represent. The weeks have been carefully selected based on the following criteria:

(a) The weeks give a good representation of the varying heat demands over the seasons.
(b) The highest net load (electricity demand minus wind power) over the year for Denmark is covered. This captures the need for peak capacity for periods, where electricity demand is high and wind power low.
(c) The highest total load (conventional plus flexible electricity demand) over the year for Denmark is covered. This captures the need for adequate production and reserve capacity, via a capacity balance restriction applied.
(d) Peaks in individual heat demand over the year are covered. This ensures good representation of the electric boiler, which supplements the heat pump in covering peak loads [32]. Due to its low efficiency (around 1 compared to an applied COP of 3.1–3.8 for the heat pump), the electric boiler is highly influential on peaks in electricity consumption for the total heat pump unit.
(e) The weeks cover significant wind power variations.

The heat transfer coefficients for the houses have been calibrated to give the annual space heating demand for each building category (cf. Table 3). The calibrated heat transfer coefficients deviate less than 2% from values corresponding to a full year simulation. This shows that the simulated weeks give a very good approximation of the space heating demand over a full year. Based on this and the selection criteria a-e, the modelled period is thus representative for a full year.

3.3. Energy demands applied

Electricity and heat demands in 2030 are based on the Future scenario set up by The Danish Commission on Climate Change Policy [31] (see Table 2). In this scenario, the district heating share for heating of buildings is increased from 46% in 2008 to 55% in 2030 [33].

The stock of existing individually heated one-family houses in Denmark (app. 716,000 houses) is modelled, representing the large majority of the individually heated one-family houses by 2030 (94 % of the heat demand).

3.4. Modelling of individually heated one-family houses

The development in the Danish building stock and in the heat demands towards 2030 is based on the Future scenario in [31]. As a result, the heat demand for existing individually heated one-family houses is assumed reduced by about 25% towards 2030, mainly due to heat savings and secondarily due to demolition of old buildings. The houses are divided into 3 different categories, depending on the year of construction; reflecting changes in insulation standards (see Table 3). The assumed heat savings have been distributed on the different construction periods based on heat saving potentials given in [34].

Radiator systems have for a long period of time been the typical type of central heating system installed in connection with construction of new houses in Denmark. Use of floor heating as central

Table 2
Electricity and heat demands modelled in 2030 (TWh).

	Denmark[a]	Finland	Germany	Norway	Sweden
Electricity	30.1	98.1	569.6	145.3	160.5
District heating[b]	32.5	34.1	86.8	1.9	46.4
Indiv. heating, one-family houses	13.1	–	–	–	–

[a] Demands of the future scenario in [31] are used.
[b] Incl. district heating to industry.

Table 3
Modelled stock of existing individually heated one-family houses in Denmark by 2030.

	Unit[c]	Average or total	Construction period			
			1850–1960	1961–1978	1979–2005	Ref.
Av. net heat demand[a]	kWh /m^2	122	157	111	68	[31,34–36]
Net heat demand	TWh	13.1	7.4	4.1	1.6	[31,34–36]
Heated floor area	10^6 m^2	108	47	37	24	[31,34–36]
House size, av.	m^2/house	151	142	151	171	[37]
Floor heating share	%	5%/9%[b]	0%	0%	40%	[38,39]
Hot water share	pct.	17%	13%	16%	28%	[37]

[a] After heat savings based on [31] and [34], representing improvement of the building envelope. Net heat demand: demand for heating from installation considering heat losses and heat contributions.
[b] 5% of net heat demand and 9% of heated floor area.
[c] All areas given in m^2 refer to heated floor areas.

heating system (i.e. not only in the bathroom) was introduced during the 1990s and has from around 1995–2000 been the common type of central heating system installed in new houses [38,39]. Against this background, houses constructed from 1995 are assumed to have a central floor heating system and houses constructed before 1995, a radiator-based central heating system. This results in radiator heating covering 95% of the individual heat demand of existing one-family houses in 2030. Installation of floor heating as central heating system in existing buildings is much more expensive than when installed in the construction phase [40]. Therefore, installation of floor heating in existing houses is typically only carried out in connection with full renovation of the floor [18]. Floor renovations are expensive, as also reflected by the fact that this is not included among the feasible heat saving measures in [31]. Installation of floor heating in existing houses has therefore been neglected.

Houses with a radiator-based central heating system have been divided into three groups depending on the heat capacity of the building structure that can be utilised for passive heat storage diurnally. This heat capacity is based on typical values for Danish buildings as given in [41] and on the following general distribution: 60 Wh/°C/m^2 floor area: 25% of the houses, 100 Wh/°C/m^2 floor area: 50% of the houses, and 140 Wh/°C/m^2 floor area: 25% of the houses [42]. Overall, the stock of individually heated one-family houses is represented as 10 different heating areas in Eastern and Western Denmark, respectively. The 10 areas in each region constitute 1 floor heated area and 9 areas with radiator heating, expressing combinations of insulation standards and heat capacities of the building structure. Concrete floor heating systems have been applied as this is the dominant type of water-based floor heating system installed in houses in Denmark, due to its low costs [39,43]. A typical concrete layer of 10 cm has been assumed (67 Wh/°C/m^2 floor area) [39,43].

Reflecting the average diurnal indoor temperature profile for 28 Danish households with heat pump installations [44], a constant indoor temperature requirement of 21.5 °C is applied in the iHP scenario. [45] confirms that a constant indoor temperature setting is typical for current heat pump installations in one-family houses. This setting has moreover been found to give the best correlation with diurnal space heating profiles for the measured houses. Based on typical indoor temperature levels for the households [44] (measured in living room/kitchen), an interval of 20–23 °C is assumed allowed in the iHP-Flex scenario during the day. The allowed temperature interval at night is set to 19–22 °C based on [46,47]. Allowing the indoor temperature to vary within such moderate intervals facilitates utilising the heat storage capacity of the building structure for flexible heat pump operation. Typical diurnal and seasonal variations in ambient air temperatures are represented using hourly data for the Danish design reference year [48].

Individual heat pumps can mainly be operated flexibly within the day, given the heat storage options presented [49]. In comparison, large heat pumps can be connected to the larger district heating storages, which give a higher level of flexibility. As such, large heat pumps can be activated flexibly in periods of up to several days, e.g. responding to longer periods with high wind power and low electricity prices. Furthermore, the large heat pumps can be supplemented by a fuel based unit (CHP unit or a fuel boiler). This means that large heat pumps can be turned off in longer periods when wind power is low and electricity prices are high [49].

3.5. Fuel and CO_2 prices

The fuel and CO_2 prices used in the main scenarios are based on [31], which is based on IEAs Reference scenario [50] (see Table 4). In a sensitivity analysis, fuel and CO_2 prices corresponding to a very ambitious international climate mitigation are applied [31,50]. Fossil fuel prices in this scenario are lower, mainly due to lower demand resulting from CO_2 reduction requirements, while CO_2 prices are significantly higher.

3.6. Energy policies implemented in model

The following Danish energy policies towards 2030 have been implemented in the model:

- Wind power must in Denmark by 2020 correspond to at least 50% of the national electricity consumption [2].
- The use of coal at Danish heat and power plants is phased out by 2030 [2]
- Individual oil boilers are phased out by 2030.
- 1.2 Mtonnes straw and 0.2 Mtonnes wood chips must be incinerated at Danish heat and power plants annually [52].

Table 4
Fuel and CO_2 prices assumed for 2030 (€/GJ).

€/GJ	Main scenario [31]	Sensitivity analysis [31]	Transport cost [51]	
			Power plant	Individual consumer
Crude oil ($/barrel)	120	94	–	–
Coal	3.1	1.8	0	–
Natural gas	9.3	7.4	0.4	3.3
Straw	5.3	5.3	1.8	–
Wood pellets	11.5	11.6	0	3.4
Wood chips	6.4	6.4	1.6	–
Biogas	14.1	14.1	0	–
Munic. waste	−3	−3	–	–
CO_2 (€/tonne)	38	77	–	–

The Danish energy policy also includes a target of electricity and heat generation to be 100% based on renewable energy by 2035 [53]. The policy does not specify whether this applies to district heating only or all heating including individual heating. In the light of this uncertainty, it is chosen to include the possibility to invest in individual natural gas boilers in the model by 2030. Historically, the Danish natural gas grid expansion for supplying heat to one-family houses has declined since 1999 [29]. The use of individual natural boilers is therefore constrained to the amount supported by the current natural gas grid, and further reduced due to the heat savings assumed towards 2030. This corresponds to allowing new natural gas boilers only in the form of reinvestments.

Binding EU energy targets apply for the member states in 2020, ensuring a renewable energy share of 20% for EU as a whole for the gross final energy consumption for electricity, heating, cooling, and transport [54]. Each of the EU member states have set up national renewable energy action plans that will ensure compliance with these targets. Planned renewable energy capacities, as given in these plans, have been implemented in the model for the other EU countries modelled (Germany, Sweden, and Finland). Where relevant, planned renewable electricity generation levels have furthermore been implemented as minimum generation levels. Other energy policies implemented in the model include planned nuclear and hydro power capacities and the German policy of phasing out nuclear power towards 2022 [55].

The Danish energy policy, targeting a 100% renewable heat and power sector by 2035, is more ambitious than the actions needed in the other countries to comply with EUs renewable energy targets for 2020. Particularly the phasing out of the coal in Denmark by 2030 could lead to significant net import of electricity from other countries. A large permanent net import of electricity cannot be considered reasonable from a security of supply perspective, as neighbouring countries will face similar challenges of converting their energy systems towards sustainability [31]. Therefore, as done in [31], Danish electricity generation is constrained to be minimum equal to the electricity demand on annual level.

3.7. Biomass and waste potentials

Use of straw, wood chips/wood waste, firewood, biogas, and municipal waste is in the analysis limited to the national resources. Wood pellets import is allowed since wood pellets are to a large extent traded internationally. The Danish biomass and waste potentials applied are presented in Table 5.

Table 5
Danish biomass and waste potentials in 2030 [31].

Fuel	Potential (PJ)
Straw	40
Wood chips/wood waste[a]	101
Biogas	32
Munic. waste	43

[a] Wood residues and energy crop potential available for heat and power generation.

3.8. Investment options modelled

In the optimisation, it is in all five modelled countries made possible to invest in the technologies presented in Table 6, for satisfying the electricity and district heating demand. Investments in open cycle gas turbines and natural gas boilers are allowed also in the Danish system, since these are suited in scale and technology for a later shift to using renewable fuels (biogas or gasified biomass) [31]. Based on [56], investment costs are in the model annualised with a discount rate of 3% given in fixed prices. All costs in the study are socio-economic and are given in €-2011.

In individually heated areas, the model includes possibilities to invest in the technologies presented in Table 7. Individual heat pumps are in the analysis dimensioned to 77% of the total heat output capacity, reflecting the typical situation in Danish heat pump installations (72–82% [32]). Thereby, the heat pumps cover around 99% of the annual heat demand, while the supplemental electric boilers cover the rest.

Planned expansions of electrical transmission capacities towards 2030 have been included. The possibility to invest in further transmission capacities has however been excluded in the main scenarios. This is most reasonable considering that most of the Northern European countries other than Denmark are here modelled without representation of internal bottlenecks in the power system. Nevertheless, the influence of allowing further transmission capacity investments is covered in a sensitivity analysis.

4. Results

When not allowing investments in individual heat pumps (NOi-HP scenario), the investments in individual heating installations constitute natural gas boilers, to the extent supported by the natural gas grid (37% of total individual heat demand), and then wood pellet boilers to cover the rest of the heat demand. When investments in individual heat pumps are allowed (iHP and iHP-Flex scenario), air–water heat pumps are installed in all individually heated areas. This represents a significant electricity demand of 4.3 TWh-e.

In the iHP scenario, the heat pumps are restricted to cover the net heat demand in each hour, i.e. heat transmission and ventilation losses minus heat contributions. As shown in Fig. 1, space heating will in this situation (non-flexible operation) be highest, when ambient temperatures are lowest.

Table 6
Power and district heating technologies assumed available for investment in 2030.

Technology	Fuel	Inv. cost (M€/MW)[a]	Var O&M (€/MWh)	Fix O&M (k€/MW/yr)	Lifetime (years)	Eff.[b]	CB	CV	Ref.
Open cycle gas turbine, condensing	Natural gas	0.34	2.5	16.8	25	0.46	–	–	[57,58]
Combined cycle gas turbine, extraction, CHP[c]	Natural gas	0.58	3.4	21.0	25	0.61	1.75	0.13	[57,58]
Steam turbine, extraction, CHP[c]	Coal	1.47	7.3	–	40	0.52	1.01	0.15	[58]
Steam turbine, extraction, CHP	Wood pellets	1.47	7.3	–	40	0.52	1.01	0.15	[58]
Steam turbine, extraction, CHP	Wood chips	1.68	3.4	24.1	30	0.49	0.61	0.15	[58]
Steam turbine, back pressure, CHP	Straw	2.31	6.4	39.8	25	1.02	0.4	–	[58]
Centralised biogas plant, back pressure, CHP	Biogas	5.45	34.6	–	20	0.92	1.07	–	[58]
Steam turbine, back pressure, CHP	Munic. waste	8.91	23.1	162.4	20	0.97	0.37	–	[58]
Offshore wind turbine	–	2.31	15.7	–	25	1.00	–	–	[58]
Onshore wind turbine	–	1.28	12.0	–	25	1.00	–	–	[58]
Photo voltaic	Sun	1.83	18.9	–	30	1.00	–	–	[58]
Heat pump, waste-water	Electricity	0.70	–	7.0	20	3.0	–	–	[20,59,60]
Electric boiler	Electricity	0.08	0.5	1.0	20	0.99	–	–	[58]
Heat boiler	Wood chips	0.09	–	3.3	20	1.01	–	–	[58]
Heat boiler	Natural gas	0.52	–	24.6	20	1.08	–	–	[58]
Heat boiler	Munic.waste	1.15	5.6	52.4	20	0.98	–	–	[58]
Solar thermal	Sun	0.22	0.5	–	20	1.00	–	–	[58]
Thermal storage tanks	–	0.0030	–	–	40	0.99	–	–	[61]

[a] Investment costs for thermal storage tanks are given in M€/ MWh storage and for heat pumps in M€/MW-thermal.
[b] For heat boilers, heat efficiency, for heat pumps, coefficient of performance, and for other units, electric efficiency (for CHP extraction plants, electric efficiency in condensing operation).
[c] Excluded for investment in Denmark in the light of the Danish political phase out of coal by 2030, and the goal of 100% renewable energy use for electricity and heat generation by 2035.

Table 7
Individual heating technologies assumed available for investment in 2030.

Technology	Fuel	Inv. cost (M€/MW)	Inv. cost (€/house)	Fix O&M (k€/MW/yr)	Var O&M (€/MWh)	Lifetime (years)	Eff.[c]	Ref.
Heat pump, air/water[b]	Electricity	0.78	–	5.1	–	15	3.1	[14,30]
Heat pump, ground[b]	Electricity	1.56	–	5.1	–	15/40	3.8	[14,30]
Natural gas boiler	Natural gas	0.50	–	4.0	7.2	22	1.02	[30]
Biomass boiler, automatic stoking	Wood pellets	0.98	–	3.0	–	20	0.91	[14,30]
Solar thermal	Sun	1.10	–	14.8	0	30	1.00	[30]
Heat accum. tank, space heating (1000 l)[a]	–	0.073	1275	–	–	40	0.99	[62]
Digital thermostats (wireless)	–	–	312	–	–	15		[63]
Central controller	–	–	134	–	–	15	–	[62]

[a] Investment costs for heat storages are given as M€/ MWh storage capacity.
[b] Data in [14] for today's heat pumps in radiator systems (after heat savings) are projected to 2030 based on [30]. Costs include an electric boiler supplementing in covering peak loads. For ground source heat pumps, a life time of 15 years for the heat pump unit and 40 years for pipes in the ground [14].
[c] For heat boilers, heat efficiency, for heat pumps, annual COP including electric boiler, and for heat storages, accounting for 1% heat loss per hour. For simplicity and due to the low share of floor heating, same COP for floor heating as for radiator heating is applied.

When allowing investments in heat storages for the heat pumps (iHP-Flex scenario), investment in intelligent heat storage in the building structure is observed in 34% of the houses. The heat storage investments occur within all 20 defined categories of individually heated houses; however the investments are highest in buildings with high heat capacities (typically corresponding to buildings with a high share of concrete) and in buildings with high heat demand (low insulation level) (cf. [23]). No investments in heat accumulation tanks are observed, due to their higher investment costs. As shown in Fig. 1, the heat storage capability of the buildings renders it possible to prioritise the operation of the heat pumps for hours with low electricity prices. The electricity prices in the model represent the marginal electricity generation cost in the given power region and time period. Fig. 1 thus illustrates that when connected to heat storage, the heat pump operation is optimised in integration with the energy system.

The interaction between heat pumps and heat storages in individually heated areas is modelled on aggregated level. This means that a heat storage capacity in a given area is shared among all heat pumps within the area. This is evident from Fig. 1, where the heat storage investments occurring in 34% of the houses render it possible to operate a larger share of the heat pumps flexibly to some extent, e.g. reflected by the significant load reductions in hour T109 and T163. As such, the model implies best case conditions for the heat storages, since the flexibility can be distributed among the houses in this way. Ideally, each of the many thousands of individually heated houses should be modelled separately (716,000 in this case); however it would hardly be possible to run such a model.

4.1. Energy system investments

In all three scenarios for 2030, the bulk of the annual Danish electricity generation is based on wind power (57–61%) and wood chips (28–31%), while straw (4%), municipal waste (6–7%), wood pellets (1%), and natural gas (1%) contribute with smaller shares.

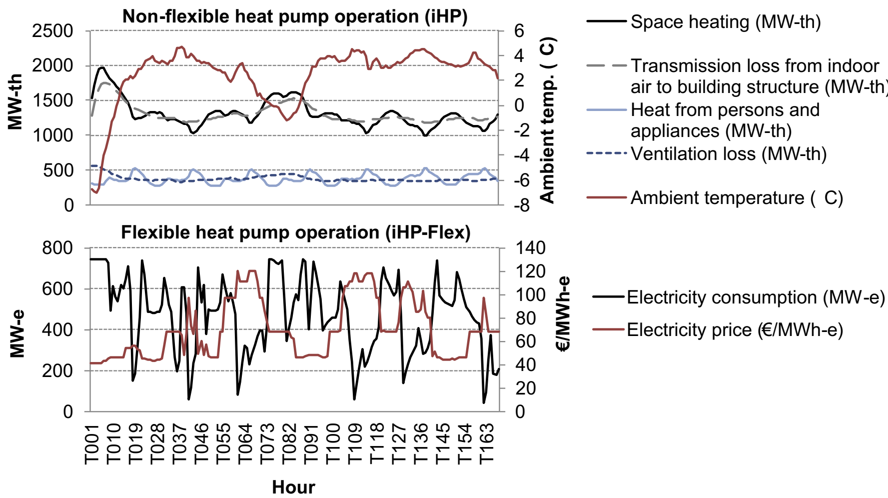

Fig. 1. Non-flexible heat pump operation (iHP scenario) and flexible heat pump operation (iHP-Flex scenario) illustrated for a week in the heating season. Total heat output and electricity consumption is shown for heat pump installations in houses with radiator heating in Western Denmark.

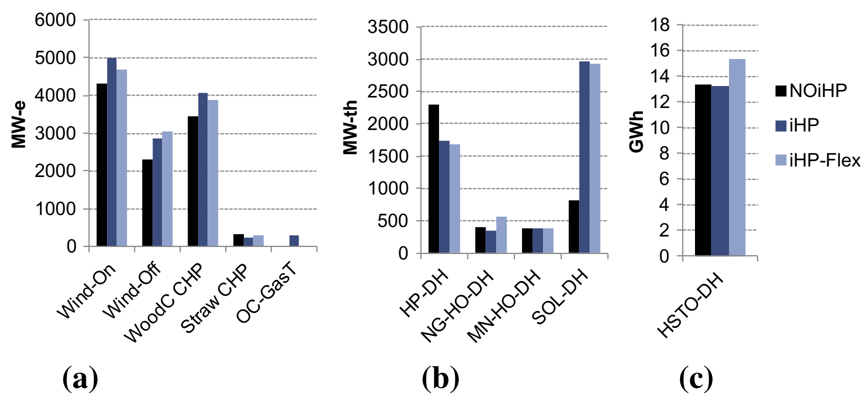

Fig. 2. Investments in the Danish system by 2030 for different scenarios (a) investments in electricity generation capacities, (b) investments in district heat generation capacities and (c) Investment in thermal storages in the district heating system. On: onshore, Off: offshore. WoodC: wood chips/waste, OC-GasT: open cycle gas turbines, DH: district heating, HO: heat only, MN: municipal waste. SOL: solar thermal.

The diminishing share of fossil-based electricity generation is mainly explained by the implemented political goal of phasing out coal at Danish power plants.

The investments in new electricity and heat generation capacities in Denmark for the three different scenarios are illustrated in Fig. 2. As shown, the new electricity generation capacities cover onshore and offshore wind power, biomass CHP steam turbines, and open cycle gas turbines. The wood chip and straw CHP plants are mainly used for intermediate load operation, supplementing the large amounts of wind power. Open cycle gas turbines are used as peak/reserve capacities (cf. Fig. 3).

Fig. 2a shows that the installation of individual heat pumps facilitates increased investments in wind power, wood chip CHP, and open cycle gas turbines (iHP vs. NOiHP scenario). The increase in wind power capacities occurs in order to meet the increase in electricity demand from the installation of the heat pumps. As such, wind power covers 97% of the increase in annual electricity demand, while natural gas peak power plants cover the rest. Part of the explanation for this is that the competitor coal is politically phased out by 2030 in the Danish system and that the other low cost fuels, wood chips and municipal waste, are constrained by the available national resources. This leaves good conditions for wind power. Moreover, the electricity consumption of the heat pumps is distributed over many hours in the day, even without flexible operation (see Fig. 1) and both heat demand and wind power is typically high in cold periods. This creates good possibilities for utilising wind power in covering the electricity demand for the heat pumps while using dispatchable power capacities to back it up. In contrast, e.g. dumb charging of electric vehicles would typically be concentrated in a few hours of the day when people return from work, making wind power utilisation difficult in this case.

The increased investments in wood chip CHP and open cycle gas turbines are driven by a need to supplement the fluctuating wind power. In this regard, these dispatchable technologies also cover an increased need for peak/reserve capacities imposed by the heat pumps. The annual wood chips-based electricity generation is however identical in all scenarios since the wood chips consumption is limited by the national biomass resources.

As shown in Fig. 2a, the investments in open cycle gas turbine and wood chip CHP capacities are reduced with 440 MW when the heat pumps are operated flexibly (iHP-Flex scenario compared to iHP scenario). The reason is the heat pumps contribute in peak load shaving, when operated flexibly, which reduces the need for peak/reserve capacity. The flexible heat pump operation moreover facilitates reduced wind power investments onshore and increased

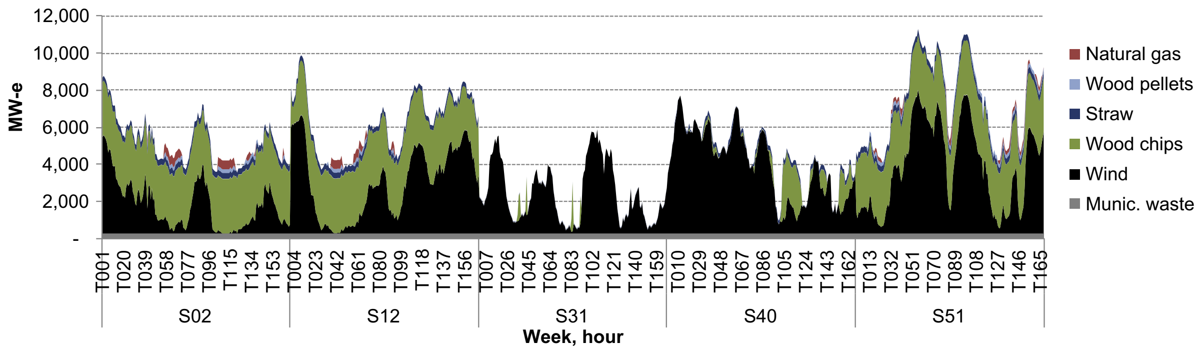

Fig. 3. Modelled hourly electricity generation in the Danish energy system by 2030 (iHP scenario).

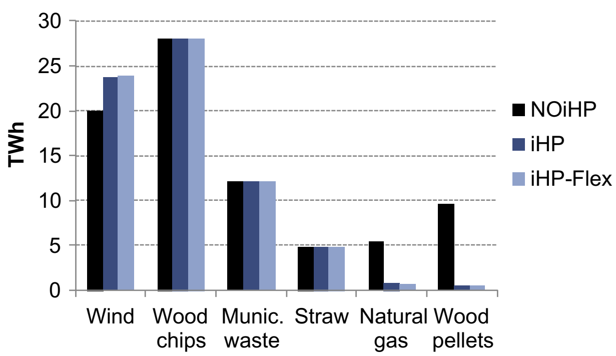

Fig. 4. Primary energy consumption in the Danish energy system by 2030 for different scenarios.

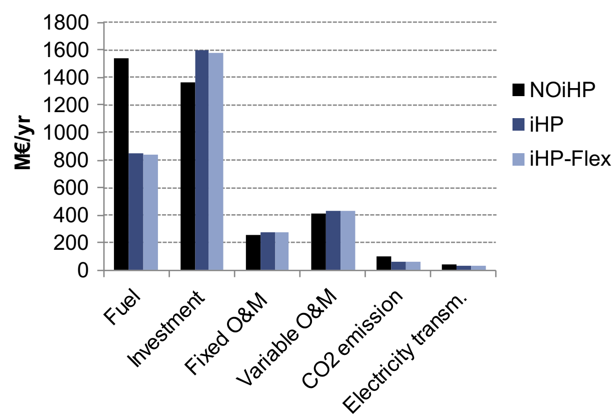

Fig. 5. Annualised system costs for the modelled Danish heat and power system by 2030 for different scenarios.

investments offshore. This is due to the fact that flexibility added to a system generally improves the conditions for technologies with relatively high investment costs and low variable costs. In this regard, offshore wind power has higher investment costs, but on the other hand higher obtainable full load hours (and a different variation profile) compared to onshore wind power.

The investments in large heat pumps in the district heating system are clearly reduced with the installation of individual heat pumps (see Fig. 2b). This is explained by the increase in electricity demand resulting in generally increased electricity prices, making large heat pumps less attractive. The lower investment in large heat pumps is the explanation for the increase in solar thermal in the iHP scenario.

When adding flexibility to the individual heat pumps (iHP-Flex scenario), the investment in large heat pumps is reduced further. The reason is that the individual heat pumps compete with the large heat pumps in placing operation in low electricity price periods. The reduced investments in large heat pumps result in increased investments in natural gas heat only boilers or solar thermal and in thermal storages in the district heating system. It can be noted that the solar thermal capacities are relatively large due to their low number of full load hours (app. 730).

4.2. Fuel consumption and CO_2 emissions

The primary energy consumption of the Danish heat and power system in the three scenarios is shown in Fig. 4. It can be seen that the installation of individual heat pumps facilitates a significant increase in wind power generation (iHP vs. NOiHP scenario). This is due to the increased wind power investments presented in Section 4.1. The consumption of wood chips and municipal wastes is the same in all scenarios due to the resource constraints. The use of straw for heat and power generation only occurs to the extent enforced by the Danish biomass agreement and is therefore unchanged across scenarios. The individual heat pumps displace a significant amount of wood pellets and natural gas used in individual boilers. This reduces the pressure on biomass resources and also increases national security of supply in this case since wood pellets are in Denmark typically imported.

Flexible operation of the individual heat pumps merely results in a slight increase in wind power generation and a slight decrease in natural gas consumption, due to an avoided use of open cycle gas turbines for peak load operation (iHP-Flex vs. iHP scenario).

The total fuel consumption excl. wind is reduced significantly as a result of the individual heat pump installations (23%). This is explained by the higher efficiency of the heat pumps, and that the increase in electricity demand imposed by the heat pumps is largely met by wind power. When activating flexible operation of the heat pumps, an additional minor fuel saving is achieved (0.3%). The CO_2 emissions in 2030 are reduced considerably with the installation of individual heat pumps (37%) (iHP scenario) and further reduced by only 2% with flexible operation of the heat pumps (iHP-Flex scenario). It can be noted that the percentagewise CO_2 reductions are enlarged by the Danish no coal policy, which yields generally low absolute CO_2 emissions.

4.3. System costs

The annualised socio-economic system costs for the three scenarios are presented in Fig. 5. As shown, fuel costs are reduced considerably with the installation of individual heat pumps. This is explained by the high efficiency of the individual heat pumps, and that the increase in electricity demand is largely covered by wind generation. Furthermore, the displaced technologies, natural gas boilers and wood pellet boilers, have relatively high fuel costs. Investment costs and fixed O&M costs are on the other hand increased, due to the larger investment costs (annualised) of individual heat pumps compared to individual gas boilers, and the increased investments in wind power and dispatchable power capacities needed along with the heat pump installations. In total, system costs for the Danish heat and power system are reduced significantly with the installation of individual heat pumps (12%). The cost reduction achieved when operating the heat pumps flexibly is moderate (0.9%).

The flexible operation of the heat pumps provides a socio-economic cost reduction of around 120 € per year per house investing in intelligent heat storage in the building structure. This cost reduction is mainly caused by savings on energy system investments (incl. fixed O&M, mainly peak/reserve capacities), as illustrated in Fig. 6.

Due to the self sufficiency constraint implemented, electricity import equals export on annual level. However, significant electricity trade is utilised hour-by-hour as expected. For the other countries modelled, energy system investment and operation is practically unchanged by the installation of individual heat pumps and heat storages in Denmark.

Overall, the results indicate that individual heat pumps can contribute significantly to facilitating larger wind power investments and reducing fuel consumption, CO_2 emissions, and system costs. Heat storages for the heat pumps, enabling flexible operation, have shown to provide only moderate system benefits in these respects. Investment in intelligent heat storage in the building structure is identified as socio-economically feasible in a given share of the houses, while heat accumulation tanks are not identified as socio-economically competitive.

4.4. Sensitivity analyses

The general results stated above have been confirmed in all sensitivity analyses presented in this section. However, the share of houses in which intelligent heat storage in the building structure is feasible, the achieved reduction in peak/reserve capacity, and the average system benefit per house, is found sensitive to certain factors. These sensitivities are presented in the following, focusing on the most important deviations from the main scenario. Other exploratory sensitivity analyses are also presented.

As a first test, investment in intelligent heat storage in the building structure is forced through in all houses with heat pump installations, instead of optimising the heat storage investments as in the main scenario. This provides practically the same reduction in peak/reserve capacity, while the average system benefit per house decreases substantially (to 8 €/house/yr compared to 120 €/house/yr in the main scenario). This illustrates that the optimised heat storage investments in the main scenario have largely been made to the extent that peak/reserve capacities can be cost-effectively reduced.

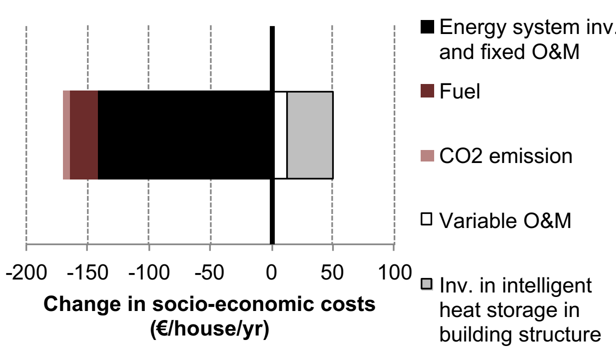

Fig. 6. Change in annualised system costs due to flexible operation of individual heat pumps; given as average costs per house investing in intelligent heat storage in the building structure.

If forcing through investments in both 1000 l heat accumulation tanks and in the enabling of intelligent heat storage in the building structure in all houses, only moderate increases in wind power generation (0.1 TWh) and reductions in fuel consumption (0.5%) are still observed; while system costs are increased moderately (1%). Peak/reserve capacity investments are reduced only slightly more than when optimising the heat storage investments (460 MW compared to 440 MW).

When assuming a heat pump capacity share in the low end, 72%, the impact of the electric boiler in peak load hours becomes more critical in the situation without flexible operation. As a result, a larger reduction in peak/reserve capacity is achieved when operating the heat pumps flexibly (560 MW, with optimised heat storage investments). Correspondingly, if assuming a heat pump capacity share in the high end, 82%, a lower reduction in peak/reserve capacity is achieved (290 MW). When assuming higher investment costs and COP (3.7–4.0) for the heat pumps as given in [30], the heat pumps still outcompete all other individual heating installations. However, the higher COP results in lower impact on peak/reserve capacities, which are therefore reduced by only 320 MW with the flexible heat pump operation.

If assuming 50% higher/lower investment cost for control equipment (digital thermostats and central controller), investment in intelligent heat storage in the building structure occurs in 20% and 75% of the houses, respectively. Peak/reserve capacities are reduced by 426–430 MW and the average system benefit per house is 190 €/house/yr and 60 €/house/yr, respectively. If allowing an indoor temperature of 20–23 °C at night, only moderate changes are observed since the peak loads occur in the day time. When applying a discount rate of 5%, generally lower wind penetration and higher investments in thermal power plants is observed. The reduction in peak/reserve capacity obtained with flexible heat pump operation is higher (640 MW).

When assuming an ambitious international climate mitigation (high CO_2 prices, lower fossil fuel prices, cf. Table 4), the reduced investment in peak/reserve capacity mainly comprises wood pellet CHP, and the system benefit is increased to 180 €/house/yr. If assuming 50% higher biomass prices, wind power investments are increased significantly, wood-based CHP investments reduced considerably, and open cycle gas turbine investments increased considerably. However, the overall outcome of the analysis is not changed. If not restricting balance in electricity import and export on annual level, the net electricity import is increased from 0 to 2–3 TWh/yr without altering the overall outcome of the analysis. The overall picture is not changed either, if allowing investment in transmission capacities further than planned.

In another sensitivity analysis, we have assumed intelligent utilisation of the existing hot water tanks (180 l [28]) by forcing through investment in a central controller in all houses. This leads to a reduction of the required investments in peak/reserve capacity by about 310 MW. In this situation, the possibility for achieving further reductions in peak/reserve capacity, by investing in intelligent heat storage in the building structure, is limited to 120 MW. However, since investment in the central controller in this case has already been made, the additional investment cost of enabling intelligent heat storage in the building structure is reduced (to cover only the digital thermostats). As a result, investment in further flexibility still occurs in a significant share of the houses (48%). When optimising the investments in the intelligent use of existing hot water tanks, investments occur in about 20–70% of the houses, depending on the cost of the controller (applying ± 50% of the cost given in Table 7).

5. Discussion

The results confirm the findings of previous studies [14,15] in identifying individual heat pumps as highly socio-economically competitive in non-district heating areas. Our results indicate that in terms of making wind power investments more attractive and reducing system costs, fuel consumption, and CO_2 emissions, the installation of the heat pumps is the most important step, while the system benefits of adding flexibility to the heat pumps are moderate. This is in line with the findings in [18], which identified a similar pattern concerning effects of heat pumps and heat storages on fuel consumption of the system. We find that utilising the heat storage capacity of the building is socio-economically feasible, while heat accumulation tanks are not competitive. This is also in line with the findings in [18].

The possibility for reducing investment in peak/reserve capacity is identified as crucial for the feasibility of heat storages for the heat pumps. This is illustrated by the fact that savings on energy system investment generally constitute the largest part of the cost reduction achieved with flexible heat pump operation. The substantial decrease in the system benefit per house, with an increasing number of houses with heat storage capability, is another illustration of this. This result is in agreement with patterns previously identified for the case of EVs in [3], which found that system benefits per smart vehicle decrease substantially with an increasing number of EVs.

The achievable reduction in peak/reserve capacity identified, 300–600 MW, is on level with the identified peak load shaving potential in [64] for smart charging of EVs in the Finnish system (540 MW). Furthermore, the identified system costs reduction, due to flexible operation of the heat pumps, generally around 0.6–1.1%, is on level with the system cost reduction of 0.45–0.95% found in [17]. If forcing through investment in intelligent heat storage in the building structure and in 1000 l heat accumulation tanks in all houses with heat pump installations, and excluding investment costs for the storages, the system benefits become comparable to the results in [20,21,17]. For this case, a system benefit of about 50 €/house/year is identified, i.e. close to the result in [17] (25–40 €/house/year) and significantly lower than the estimate in [20,21] (80–130 €/house/year).

As the applied model is deterministic and does not include start-up costs, minimum load requirements, or part load efficiencies, the potentials for reducing operation costs through flexible heat pump operation are conservatively represented. However, we include effects on investments, in contrast to previous studies modelling the impacts of individual heat pumps and supplementing heat storages on the energy system. Our use of an aggregated energy system model means that heat storages are represented optimistically in the sense that the flexibility provided by an optimised heat storage capacity can be distributed among the heat pumps within the given area. Even under these conditions, only moderate system benefits have been identified for the heat storages.

6. Conclusion

The influence of individual heat pumps on wind power integration has been analysed using a model that optimises both investments and operation of the energy system. The Danish energy system by 2030 with an optimised wind power share of around 50–60% is used as case. The optimisations result in a large scale installation of heat pumps in individually heated one-family houses (716,000 houses, 4.3 TWh-e).

We find that individual heat pumps can contribute significantly in facilitating larger wind power investments and in reducing system costs, fuel consumption, and CO_2 emissions. In addition, the heat pumps can reduce the pressure on the limited biomass resources, due to displacement of individual wood pellet boilers. The system benefits of the heat pumps are first explained by their high efficiency and socio-economic competitiveness. Moreover, the aggregated electricity demand profile of the heat pumps is well suited for integrating wind power, even without flexible operation of the heat pumps. As a result, the increase in electricity demand imposed by the heat pumps can largely be covered by increased wind generation, while supplementing with dispatchable power generation. In the case analysed, the political phase out of coal in Denmark by 2030 and the constrained biomass resource availability creates particularly good conditions for wind power.

When investing in individual heat storages, the heat pumps contribute in peak load shaving, and their operation is prioritised for hours with low electricity prices. However, the flexible operation provides only moderate system benefits. Hereof, the main benefit is a reduced need for peak/reserve capacity investments of about 300–600 MW for the case analysed, corresponding to the size of a large power plant. The possibility for reducing peak/reserve capacity investments is identified as crucial for the feasibility of the heat storages.

It is found that investments in intelligent heat storage in the building structure can be feasible to some extent, i.e. in around 20–75% of the houses with heat pump installations, depending on the cost of control equipment in particular. The flexible operation of the heat pumps provides a socio-economic cost reduction of about 60–200 € per year per house investing in this storage option. The result intervals have been identified through various sensitivity analyses covering e.g. variation in investment cost of control equipment, COP, investment costs, and capacity share of the heat pumps, discount rate, as well as fuel and CO_2 prices. A reduction in the peak/reserve capacity requirement can also be obtained if investing in control equipment that enables intelligent use of the hot water tank typically installed in combination with heat pumps. Investment in this option is found feasible in around 20–70% of the houses. In contrast, investments in heat accumulation tanks are not found competitive due to their larger investment costs.

The main benefit of the flexible heat pump operation, namely the reduced peak/reserve capacity requirement, will not be visible on the electricity bills paid by the individual heat pump owners. Some of this benefit should therefore be transferred to the heat pump owners when developing incentives for them to invest in heat storage capability. The relevance of this is reflected by the fact that under current regulation it is, according to the Danish TSO, not attractive for heat pump owners to invest in flexible operation, even if gaining access to both the spot market and the regulating power market [22].

Overall, large-scale installation of individual heat pumps is identified as an important step in supporting the integration of wind power. Heat storages, facilitating flexible operation of the heat pumps, can contribute only moderately in this regard. When policy makers prioritise efforts and public funds for creating incentives within this field, first priority should thus be given to ensure a large-scale deployment of the heat pumps. The enabling of flexible operation should be given second priority.

7. Future work

After having assessed the socio-economically feasibility of investments in individual heat pumps and heat storage options, the next relevant step would be to analyse the feasibility of the technologies seen from a private economic perspective. Whether individual heat pumps and supplemental control equipment and heat storages will in fact be installed, depends heavily on the regulation and incentives. It would therefore be interesting to analyse to which extent the existing regulation and incentives promote the socio-economically optimal solutions and whether further incentives are needed. Furthermore, it would be relevant to analyse how flexible operation of the heat pumps affect investments in distribution grid enhancements. Supplementary analyses, where investments in individual natural gas boilers are excluded, could also be relevant in the light of the long term goal of moving towards a renewable energy society. Finally, it would be interesting to include additional competing flexible demand technologies, such as electric vehicles, in analysing the impacts on wind power integration.

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Paper VI

District heating versus individual heating in a 100 % renewable energy system by 2050

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District heating versus individual heating in a 100% renewable energy system by 2050

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ABSTRACT

In a future 100% renewable based energy system is district heating (DH) then socio-economically attractive? Analyses of 100% renewable energy systems are often made either without or with existing DH infrastructure as a premise, as most of the energy system models do not have the possibility to invest in DH grids endogenously. In this paper, we compare total socio-economic costs for achieving a future renewable energy system for the two following cases: 1) A case where DH infrastructure is built and operated and 2) A case with no DH infrastructure, i.e. only individual heating. Denmark is used as "test area", and the linear optimisation model Balmorel is used to configure a socio-economic optimal energy system in 2050 for each of the two cases. The model has a higher level of detail for Denmark and includes the possibility to invest in heat savings in buildings, as an alternative to heat generation. Additionally, human health externalities related to local air pollution are internalised in the socio-economic cost optimisation. The results do not show a clear socio-economic benefit of building or not building a DH system in a future 100% renewable energy system.

INTRODUCTION

What should be the role of district heating (DH) in a future 100 % renewable energy system?
The presence of DH in an energy system can have an impact on the balancing of the power system via large heat pumps and electric boilers combined with thermal storages. This possibility is more limited if all heating is based on individual installations. Furthermore, individual boilers based on biomass have higher negative health impacts compared to biomass in large central combined heat and power plants. On the other hand, a future building stock with significant heat savings and a power system with large amounts of electricity generation without surplus heat, i.e. wind, sun and wave energy, could make DH less favourable. So considering these aspects, is large scale DH then socio-economically attractive? This question forms the background for this study.

We use Denmark as a test area in trying to come up with an answer to this question, applying a long term perspective and focusing on a 100 % renewable energy system. To do this we need to include all costs related to the energy system, also the full cost of a district heating network.

The analysis is carried out using the energy system model Balmorel. Balmorel is a linear optimisation model of heat and power supply in Denmark and power and district heating supply in Norway, Finland, Sweden and Germany [1]. The model has a higher level of detail for Denmark and here includes a possibility to invest in heat saving measures in buildings as an alternative to heat generation technologies. Additionally, local air pollution related to human health externalities are internalised in Balmorel, in order to design a renewable heat and power system with the least negative impact on human health. The valuation of effects and cost of impact on human health from air pollution is based on the work in the Centre for Energy, Environment and Health (www.ceeh.dk).

The analysis is based on running the model for the year 2050 with no existing power and heat production capacity, leaving it up to the model to create an energy system. This is done for a case where a district heating network is present and for a case with no district heating network. Then two different fuel price scenarios are applied adding up to the four scenarios presented in the paper.

The paper is built up in sections describing inputs to the model, outputs and conclusions. Section 2 describes projections of future energy prices and demand for electricity and heat in the model area. Section 3 describes technology data and assumptions implemented in the model database. Section 4 is about new model developments needed for making the analysis and the paper is concluded in section 5.

ENERGY DEMAND IN 2050

For all the surrounding countries the total electricity demand is projected from an energy service growth rate and an efficiency improvement rate. Subtracting the efficiency improvement rate from the energy service growth rate gives the growth rate for the energy demand. For Denmark the electricity demand consists of an exogenously projected part which relates to increase in energy service level and an endogenously derived part comprising electricity demand from heat pumps, electrolysers etc.

Table 1. Energy demand growth and improved efficiency.

Country	Growth rate energy demand 2008-2020 (% p.a.)		Growth rate energy demand 2020-2050 (% p.a.)	
	Service	Efficiency	Service	Efficiency
Norway	2.4	1.5	1.9	1.5
Sweden	2.3	1.5	1.6	1.5
Finland	1.9	1.5	1.4	1.5
Germany	1.7	1.5	1.0	1.5
Denmark	2.0	2.2	2.0	2.2

Using the assumptions in Table 1 leads to the energy demands for Norway, Sweden, Finland, and Germany shown in Table 2.

Table 2. Electricity and district heating demand in Norway, Sweden, Finland and Germany.

TWh/year	2008	2050
Norway electricity	131.7	165.3
Norway district heat	1.7	2.2
Sweden electricity	151.7	171.9
Sweden district heat	43.9	49.7
Finland electricity	99.2	100.8
Finland district heat	34.4	35.0
Germany electricity	614.2	541.1
Germany district heat	93.6	82.5

Table 3 below shows the assumed demand for heat and electricity used as exogenous inputs to Balmorel in the two modelled cases (with and without DH). The countries around Denmark are assumed to have the same demands in both cases, while in Denmark the demand for heat in district heating areas is transferred to individual heating in the case without district heating. Process energy is higher in the case without DH, because a part of the DH demand is used for process in the other case.

Table 3. Demand for heat and electricity in Denmark in 2050 in the two cases.

TWh/year	2008	Case incl. DH 2050	Case without DH 2050
Electrical appliances	26.1	58.6	58.6
Electricity for transport	0.3	29.2	29.2
DH demand	28.6	51.1	0
Indiv. room heat excl. DH	32.8	29.4	62.5
Process energy	30.2	33.3	42.8

TECHNOLOGY DATA AND RESOURCES

When looking at year 2050, there is great uncertainty on the costs and efficiencies of energy technologies. Some technologies being expensive today are expected to improve through the period, and a technology as photovoltaic is expected to be competitive by then. The technology assumptions are based on the Danish Technology Catalogue and IEA data and the used data is presented in tables below.

The costs of district heating network

In Balmorel district heating (DH) network costs are added per unit (kWh) of heat supplied by heat and/or cogeneration plants. The length of the Danish district heating network is 29 thousand kilometres, consisting of transmission and distribution pipelines. One average cost is used in the model for the whole district heating network in Denmark. Clearly, the actual costs of the network differ for transmission and distribution pipes due to differences in pipe diameters and network utilisation time. Distribution pipes are used 2000 hours during a year while transmission network is exploited for 5000 hours annually [2]. The cost of heat supply by DH network in Table 4 is calculated based on data available in Heat Plan for Denmark [2].

Table 4. Cost of district heating network.

	Existing DH network	Expanded DH network[a]	DH for new buildings[b]	Cost data for Balmorel[c]
Total value of DH net (M€)	14,500	24,970	1,210	26,200
Total DH production (GWh)	35,800	55,000	2,400	57,600
Annuitized value of DH net[d] (app. €/year)	563,000,000	970,000,000	46,900,000	1,020,000,000
DH system cost per produced heat (€/kWh)	0.016	0.018	0.019	0.018

[a] Expansion of the existing network to cover 70 % of heat market in Denmark.

[b] District heating infrastructure for new buildings, build before 2030.

[c]Weighted average cost of 'Expanded DH network' and of 'DH for new buildings'

[d] 3 % discount rate and lifetime of 50 years are assumed.

Heat saving costs

Costs of heat saving measures, included in the model, are based on the costs of building element improvements (Table 5) and current state of 175 types of buildings by purpose and construction year.

Table 5. Average costs for energy efficiency improvements of building envelope[a].

	Improvement cost[b] (€/$m^2_{element}$)
Insulating walls	47.3-82.8
Insulating floor	47.0
Insulating roof	26.9
Replacing windows	40.3

a Based on [3].

b Incremental costs for energy efficiency improvements only.

Calculation of heat savings potential is described in [4] and modelling of heat savings in Balmorel is documented in [5] and [3].
The resulting heat saving costs included in the model span from around 2 €cent/kWh to around 60 €cent/kWh depending on building type and heat saving measure.

Technologies for individual heating

In a 100% renewable energy scenario without district heating, heat supply will be based on individual biomass boilers, electric boilers, solar thermal and different types of heat pumps. In addition, investment in individual heat storage is possible in the model (see Table 6). Heat storages in the model will only be relevant for solar thermal due to the variability of solar radiation and heat pumps due to electricity price variations.

Table 6. Technologies available for investment in individually heated areas [6].

Technology	Life time	Inv. cost[a] (€/unit)	Inv. cost[b] (M€/MW-th)	O&M (% of inv.)	Fixed O&M (k€/MW-th)	Fuel eff./ COP
Heat pump ground-water	15	13400	1.89	0.6	11.3	3.2
Heat pump air-water	15	6700	0.88	0.6	5.3	2.6
Biomass boiler	15	6700	0.88	2.8	22.6	1
Electric boiler	20	1100	0.13	0.9	1.2	1
Heat storage[c]	40	860-1490	0.089	-	-	0.98

[a] Costs for a typical house with a heat demand of 15 MWh/year.

[b] Based on assuming a heat pump dimensioning covering 80 % of heat demand at an outdoor temperature of -12°C and an indoor temperature of 20°C [7] and [8].

[c] Estimated average investment costs for heat storage tanks (M€/MWh) in the size interval of 300-1000 litres based on [9].

Power and heat supply technologies

The relevant renewable power and heat producing technologies included in the model database for both process energy in industries and for power and district heat production are listed in Appendix 1. The model database includes several generations of each technology, but here only the best technologies available in 2050 are included, from which the model chooses when only running it for 2050.

For power production, the main technologies are wind power, photovoltaic, wave power and biomass (also municipal waste) based CHP, but also fuel cell technologies are available. For district heating, the main technologies are heat pumps, biomass based boilers and solar heating. Industrial process energy can be covered by electric boilers, biomass based boilers or solar heating (only low temperature).

RESOURCES AND FUEL PRICES

Some resources are limited, and therefore restrictions are added on some of these resources in the model. As we only include renewable energy in the scenarios for Denmark biomass can be a limiting resource, but also wind has restrictions on how much can be installed onshore and offshore. The surrounding countries are still allowed to invest in fossil fuel based energy production and hydro power in Norway, Sweden and Finland is kept at the same level as today.

Table 7. Resource restrictions for Denmark in the scenarios.

	Max usable resource
Offshore wind	20,000 MW
Onshore wind	5,000 MW
Biomass straw	15 TWh
Biomass wood	22 TWh
Biomass wood waste	5 TWh
Municipal waste	13 TWh

The transport sector is not included in this Balmorel model, therefore 33 TWh biomass, not included in Table 7, are reserved for the transport sector to be transformed into bio-fuels and assumed not to be available to the rest of the energy system.

Ground heat potential for individual heat pumps

The ground heat resource available for individual ground heat pumps is implemented based on estimates in [10]. In this report, data on heat demand, ground area and built area have been collected for existing detached houses in Denmark and it is assumed that heat demand in houses with heat demand below 57 kWh per m^2 available ground area can cover their heat demand with ground heat pumps. The available ground area, i.e. area available for installing ground heat pipes, is here defined as half of the difference between ground area and built area. Taking also the ground heat potential for new buildings into account, the ground heat potential for 2050 is estimated for the different scenarios (see Table 8).

Table 8. Ground heat potentials (GWh).

	Ground heat potential 2008[a]	Ground heat potential 2050	
		DH-scenario[b]	NODH-scenario[c]
Eastern Denmark	1361	2438	3242
Western Denmark	2383	3812	6939

[a]Source: [10].
[b]All new houses built from 2008 to 2050 are assumed to have sufficiently low heat demands to make possible that heat supply can be based on ground heat pumps. Total heat consumption for residential houses in individually heated areas is estimated to increase 17 % from 2008 to 2050.
[c]Based on data extraction from heat atlas by Bernd Möller, Aalborg University.

Fuel prices

The used price scenarios are based on the fuel price scenarios from the Danish Commission on Climate Change Policy [11] where the case with high fossil fuel prices, low CO_2-price and high biomass prices represents a world without a global climate agreement. This leads to increased demand for fossil fuels and thereby higher prices, on the other hand the global demand for biomass is low and the CO_2-market is not working very well. The case with low fossil fuel prices, high CO_2-price and high biomass prices resembles a situation where an ambitious global climate agreement are in place, forcing the CO_2-price up and increasing biomass prices due to high demand for biomass in the energy sector. The demand for fossil fuel decrease as result of the global agreement and therefore market prices on fossil fuels are low.

Table 9. Fuel prices and CO_2 price used in the scenarios.

	Low fossil fuel price scenario (€/GJ)	High fossil fuel price scenario (€/GJ)
CO_2-price (€/ton)	320	106
Coal	1,9	3,3
Natural gas	8,7	11,7
Fuel oil	15,0	21,0
Biomass wood	17,7	14,3
Biomass straw	15,6	9,0
Municipal waste	-2,3	-2,3

RESULTS

The combination of two set of fuel price assumptions and a system with and without district heating give four scenarios. The naming convention for the scenarios used in result tables and figures can be seen in Table 10.

Table 10. Name convention for scenarios.

	Low fossil fuel price scenario	High fossil fuel price scenario
With district heating	WithDH_LowFP	WithDH_HighFP
Without district heating	NoDH_LowFP	NoDH_HighFP

Total Danish system costs

Comparing the total costs of a Danish energy system with district heating with a system without, is not straight forward when the Danish power system is linked up to a common Nordic power market. Changing the situation in Denmark will impact the investments in the other countries and thereby will affect trade of power between the countries. So to compare the system costs we count all investments, operating and maintenance costs, cost of infrastructure, fuel costs and health cost from air pollution in Denmark, and then add the net income from power trade in each of the scenarios. The total yearly cost of running the Danish energy system is around 10 bill. € and the scenarios with district heating have around **2%** higher costs than the scenarios without district heating.

A problem by not having a district heating system is that the municipal waste is not utilised for power and heat production. Then the waste has to be treated in incineration plants not utilising the energy or stored at dump sites. If the negative fuel price on municipal waste is used as the cost of alternative treatment, then the extra costs for the scenarios with district heating drop to **1.5%**.

Energy system configuration and fuel consumption

Balmorel optimises the whole Nordic energy system including Germany and finds the optimal investments in Denmark.

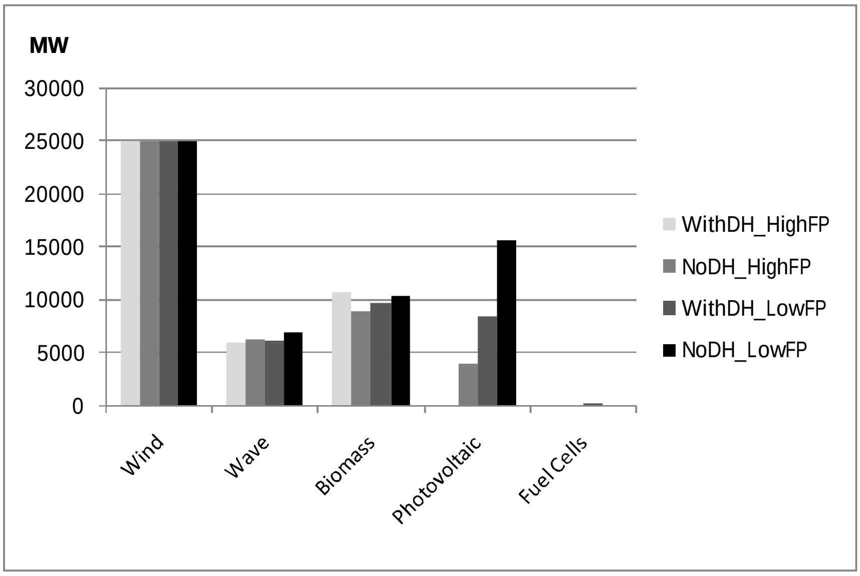

Figure 1. Investment in power producing capacity in Denmark in the four scenarios.

The wind potential is fully developed in all scenarios; wave and biomass are also almost the same between the scenarios. The difference in the power sector is mainly in photovoltaic capacity. In the scenarios without district heating industry is relying more on electricity and therefore has a higher demand for electricity causing increasing investments in photovoltaic.

When it comes to heat production, heat supply in all scenarios is based on heat pumps and biomass together with heat storage. Only one of the scenarios utilises waste for heat production. The district heating scenarios have higher production on the central heat pumps because a part of the district heat is used by industry and therefore counted as heat production. Process energy is not included in the results showed in Figure 2.

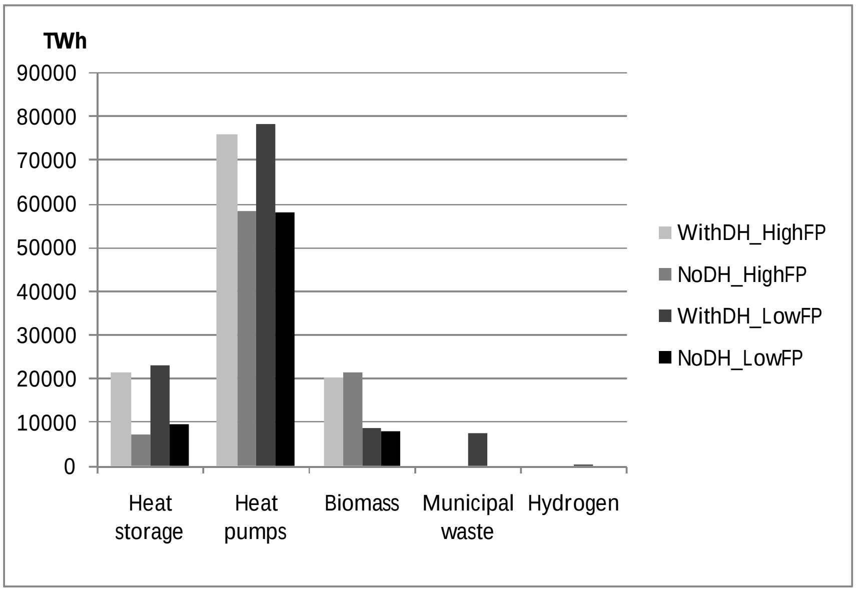

Figure 2. Heat production divided on fuels and scenarios.

Looking at the total fuel consumption for electricity and heat production in Denmark (Figure 3), it is clear that more biomass is used in the cases with lower biomass price and only one scenario (WithDH_LowFP) utilises municipal waste.

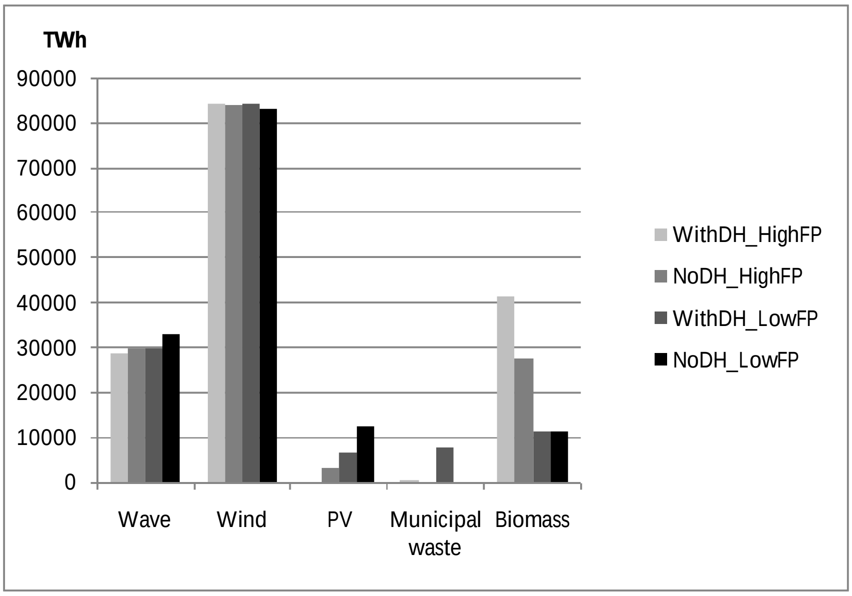

Figure 3. Total fuel consumption for the Danish energy system divided on fuels and scenarios.

Heat savings are not so profitable in areas with district heating, as district heating is a cheap efficient heat source. This can also be seen from our results. In Figure 4 the heat saving potential in Danish buildings today is compared with the heat savings implemented in the different scenarios.

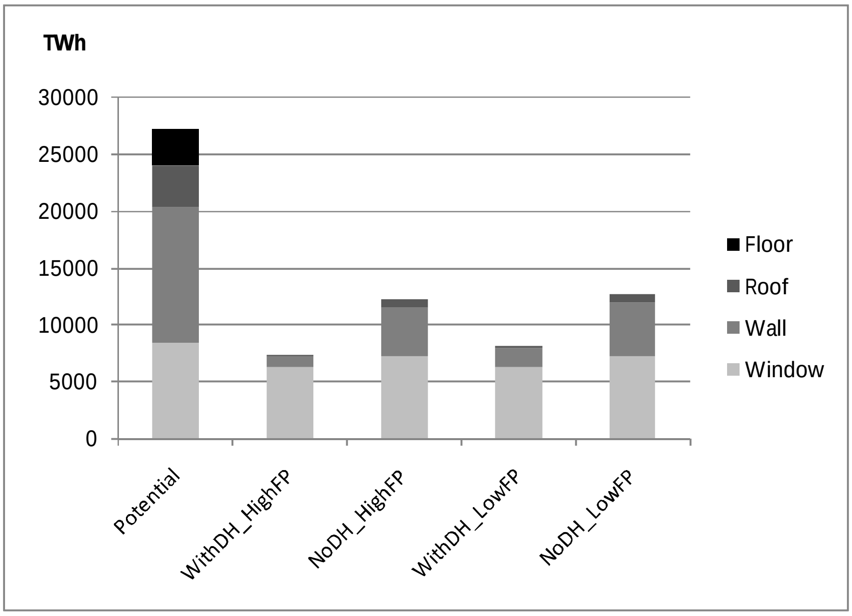

Figure 4. Heat saving potential in Denmark divided on building components and implemented savings in the scenarios.

In the scenarios with district heating around 30% of the potential savings are implemented while it is around 45% in the cases without district heating. We also see slightly more investments in heat savings when the biomass prices are higher (WithDH_LowFP and NoDH_LowFP).

CONCLUSIONS

Based on the modelling results, there is no clear indication whether it is cheaper to run a future renewable based energy system with or without a district heating system. Every model has limitations, and it is important to be aware of these before concluding on the results. In the present analysis, we included all system costs (except from electricity distribution net) and also the costs of building and operating a district heating network, in the cases with district heating. But the district heating piping technologies are not optimised to serve low energy buildings; therefore more optimised district heating technologies would improve the results for district heating. As seen from the results, not all scenarios utilise municipal waste for energy production, which means that the waste has to be removed in another way and this is not included in the modelling. The results are also very sensitive to assumed development in costs and efficiencies for the different supply technologies. Taking all these precautions into account our analysis show that there is no socio-economic argument for building or not building a district heating system in a future 100% renewable energy system.

ACKNOWLEDGEMENTS

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APPENDIX

Technology	Description	Fuel eff.	Invest., M€/MW	Variable O&M, €/MWh	Fixed O&M, k€/MW	Life, year
WI-On-ENS50	Wind turbine size 3.5 MW	1.00	1.16	11.00		30
WI-Of-ENS50	Wind turbine size 8-10 MW	1.00	2.00	14.00		30
HO-BP-WO	Heat boiler (biomass), industry	1.00	0.40		12.00	20
SH-PR	Solar heating, industry	1.00	0.60		0.62	20
EH-BP	Electric boiler, industry	1.00	0.24		2.00	20
ST-WO-ENS50	Steam turbine, wood pellets, advanced steam process, ultra-supercritical, 250-400 MW	0.55	1.40	7.00		40
ST-MW-ENS20	Waste to energy CHP	0.97	8.50	22.00	155.00	20
ST-WW-ENS30	Steam turbine, medium, woodchips, 10-100MW	0.49	1.60	3.20	23.00	30
ST-ST-ENS10	Steam turbine, medium, straw, 10-100MW	1.02	2.20	6.10	38.00	25
ST-STs-ENS20	Steam turbine, small, straw, 8-10MW	0.90	3.90		156.00	20
ST-WWs-ENS20	Steam turbine, small, woodchips, 0.6-4.3MW	1.03	3.50		122.50	20
SE-PV-ENS50	Phtovoltaic cells	1.00	0.95	12.00		30
Wave-ENS50	Wave power	1.00	2.55	7.00		20
EH-PA-ENS50	Large heat pump 1-10MJ/s (heat output), heat source: ambient temperature	3.20	0.50		4.00	20
EH-PW-ENS50	Large heat pump 1-10MJ/s (heat output), heat source: 35C	3.80	0.50		4.00	20
EH-BL-ENS10	Electric boiler, 20 MW, 10kV	0.99	0.06	0.50	1.00	20
EH-BM-ENS10	Electric boiler, 10 MW, 10kV	0.99	0.08	0.50	1.00	20
EH-BS-ENS10	Electric boiler, 1-3MW, 400V	0.99	0.24	0.50	1.00	20
HO-MW-ENS20	Waste to energy, district heating	0.98	1.10	5.30	50.00	20
HO-WW-ENS10	District heating boiler, wood-chips, 1-50MW	1.08	0.50		23.50	20
SH-DH-ENS30	Solar district heating, investment cost are calculated using full load hours for Denmark	1.00	0.21	0.50		20
EH2-AL-ENS10	Alkaline electrolysis (AEC), <3.4MW	0.73	0.23		7.00	15
EH2-SO-ENS30	Solid oxide electrolysis (SOEC), 5MW	0.83	0.57		14.00	20
EH2-SP-ENS20	Solid polymer electrolysis (PEMEC), 0.045MW	0.88	0.16		6.00	20
FC-SO-ENS30	SOFC CHP 2-3MW	0.90	0.50		25.00	15
FC-PE-ENS20	PEMFC CHP 20MW	0.80	0.50	0.60		7
H2-STO-30	Hydrogen storage	1.00	0.01			25
H-STO	Heat storage	0.99	0.00			20

Report chapter

Chapter 9: Balmorel model results – EVs and power system investments.

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Risø-Report, Risø-R-1804 (EN): Electricity for Road Transport, Flexible Power Systems, and Wind power. December 2011. Systems Analysis Department, Risø DTU National Laboratory for Sustainable Energy.

9 Balmorel model results – EVs and power system investments

The overall goal of this analysis is to investigate how a gradual large-scale implementation of plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) in the private passenger vehicle fleet will influence power system investments and operation in the years towards 2030. The analysis covers not only the Danish power system but also the power systems of Germany, Norway, Sweden and Finland. This is due to the importance of electrical interconnections and in order to reveal possible differences in the effects of EVs on different power systems. However, main focus is put on the effects on the Danish energy system.

The idea of the analysis is to investigate how the power system will be affected by the increase in electricity demand due to introduction of EVs and by the flexibility of this demand when assuming intelligent charging of the vehicles. Moreover, the effect of activating vehicle-to-grid capabilities is investigated by assuming that EVs can deliver power back to the system when needed.

In the following, the scope, preconditions and results of the analysis are presented. Input data and further modelling preconditions for the analysis are given in Appendix12.3.

9.1 Scope and preconditions

The assumed implementation of private passenger electric vehicles (EVs) is based on scenarios set up by the Electric Power Research Institute (EPRI) [91] and IEA [92]. In the Medium scenario, EPRI assumes a development in PHEVs new vehicle shares as outlined in Figure 66a. Based on the relative development in sales of PHEVs and BEVs towards 2030 presented by IEA in the Blue Map scenario, we assume additional BEV market shares corresponding to half of the PHEV new vehicle shares. As a result, we consider a development in the vehicle fleet shares towards 2030 as illustrated in Figure 66b. Consequently, EVs are assumed to comprise around 2.5 %, 15 %, 34 % and 53 % of the private passenger vehicle fleet in 2015, 2020, 2025 and 2030, respectively. This development in the vehicle fleet shares is assumed for all the Northern European countries.

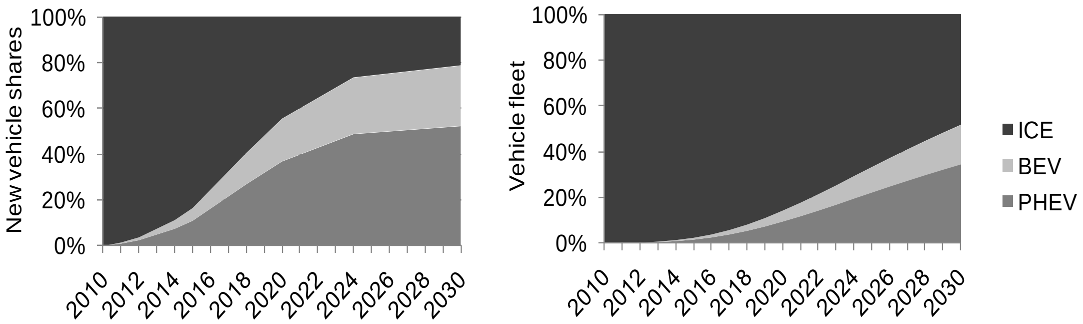

Figure 66 a) Development in plug-in hybrid electric vehicles (PHEV) new vehicle shares in the Medium scenario in *[91]* and illustration of the assumed relation between battery electric vehicle (BEV) and PHEV new vehicle shares based on the Blue Map Scenario in *[92]*. b) Assumed gradual penetration of PHEVs and BEVs in the vehicle fleet *(ICE: Internal Combustion Engine vehicles).*

To analyse the impacts of EVs over the period, two scenarios are set up:

- **Base**: Only internal combustion engine (ICE) private passenger vehicles towards 2030
- **EV:** Gradual implementation of PHEVs and BEVs as private passenger vehicles towards 2030 (as outlined in Figure 66b)

The power, district heat and transport system is modelled in integration using the model Balmorel including the transport-addon developed by Juul and Meibom in [93]. Model development has been made in order to handle the gradual implementation of different vehicle vintages towards 2030. Balmorel is a deterministic partial equilibrium model assuming perfect competition optimising investments in power/heat production, storage and transmission capacities and minimises total costs in the energy system - covering annualised investment costs, operation and maintenance costs of existing and new units, as well as fuel and CO_2 quota costs (the model is further described in the Chapter 12.2). The transport-addon includes demand for transport services, vehicle investment and operation costs and electricity balancing in the integrated road transport and power system. As the gradual implementation of PHEVs and BEVs is fixed, investments in vehicles are in this study not performed as part of the optimisation.
Simulations are made with five year intervals, for 2015, 2020, 2025 and 2030, where optimal investments identified in previous years are included in the optimisations of subsequent years. Plug-in patterns for BEVs and PHEVs have as in [93] been derived from driving patterns obtained from the investigation of transport habits in Denmark [94]. It has been assumed that the EVs are plugged-in at all times when parked and that driving habits are the same for all the countries in the simulation. Optimal vehicle-to-grid and grid-to-vehicle power flows are identified as part of the optimisation.
All EVs are assumed to leave the grid with a fully charged battery, restricting the loading to meet this load factor. The PHEVs are assumed to use the electric storage (the usable part of the battery) until depletion before using the engine. This is considered a reasonable assumption due to the high efficiency of the electric motor compared to that of the combustion engine as well as the low price of electricity (average prices in the neighbourhood of €50/MWh in the simulations) compared to the price of diesel (64-80 €/MWh in 2015-2030 [95]). The model works with a capacity credit restriction ensuring enough production capacity to meet peak power demand as presented in [96]. BEVs and PHEVs are due to V2G capability able to contribute in meeting peak power demand. Modelling of this contribution is taken from the PhD thesis by Nina Juul [97].
Integrating the power and transport systems and introducing intelligent charging/discharging requires a number of additions to the existing system, e.g. communication between vehicles and the power system, vehicle aggregators communicating with power markets, and agreement upon connection standards. All such changes are in the model assumed to be in place and infrastructure costs, e.g. charging stations and hardware, are not included.
In the analysis, investment in the following unit types is allowed:

- Wind turbines (onshore, offshore)
- Coal CHP, steam turbine, extraction
- Natural gas CHP, combined cycle gas turbine, extraction
- Natural gas open cycle gas turbine, condensing
- Nuclear power, condensing (in Finland and Sweden only)
- Biomass CHP, medium, extraction (wood chips), Biomass CHP, small, backpressure (wood chips), Biomass CHP, small, backpressure (straw)
- Natural gas heat boiler, Biomass heat boiler (wood chips)
- Heat pumps
- Electric boilers
- Heat storages
- Transmission capacities between power regions

Data on capacities, efficiencies, operation costs, and technical lifetimes etc. for existing units for power/heat production, storage and transmission are included in the model. Gradual decommissioning of existing power/heat production capacities towards 2030 is thus taken into account. The optimisation is based on socio-economic costs in order to investigate how EVs would affect the power system in the absence of taxes, tariffs and subsidies. The idea behind this approach is that if the outcome does not correspond to what is desired for society, taxes, tariffs and subsidies can then be designed in order to reach the situation wanted.

9.2 Results

In the following, the results are shown covering the effect of EVs on power system investments, electricity generation, CO_2 emissions and costs.

Effects on power system investments

Socio-economically optimal investments in new power production capacities generated by the model in the Base and EV scenario are illustrated in Figure 67 for each of the five countries. As shown, the investments cover on-shore and off-shore wind power, coal based CHP, nuclear power where this option is allowed, and open cycle gas turbines (OC-GT); the latter for ensuring sufficient capacity to cover peak loads.

As a result of increasing fuel and CO_2 prices, the economic conditions for wind power generally improve over the period. This is clearly illustrated for the cases of Denmark, Germany, and Sweden where wind power investments only or mainly occur in the last part of the period towards 2030. Furthermore, existing wind power capacities in Denmark and Germany are significantly decommissioned from 2020 to 2025 (from around 3,200 MW to 0 MW in Denmark and from around 23,000 MW to 11,000 MW in Germany). This is likely part of the explanation for the large wind power investments occurring in these countries in 2025. Norway, Sweden, and Finland, have relatively high onshore wind power resources in terms of obtainable full load hours[1]. Therefore, wind power investments occur earlier in these countries than for the cases of Denmark and Germany.

1 Assumed full load hours for onshore wind power: Norway: 3000 [99.1, 99.2], Finland, Sweden: 2600 [99.1] and based on [99.3], Denmark, West: 2440, Denmark, East: 1960[99], Germany: 1750 (based on [99.4, 99.5]).

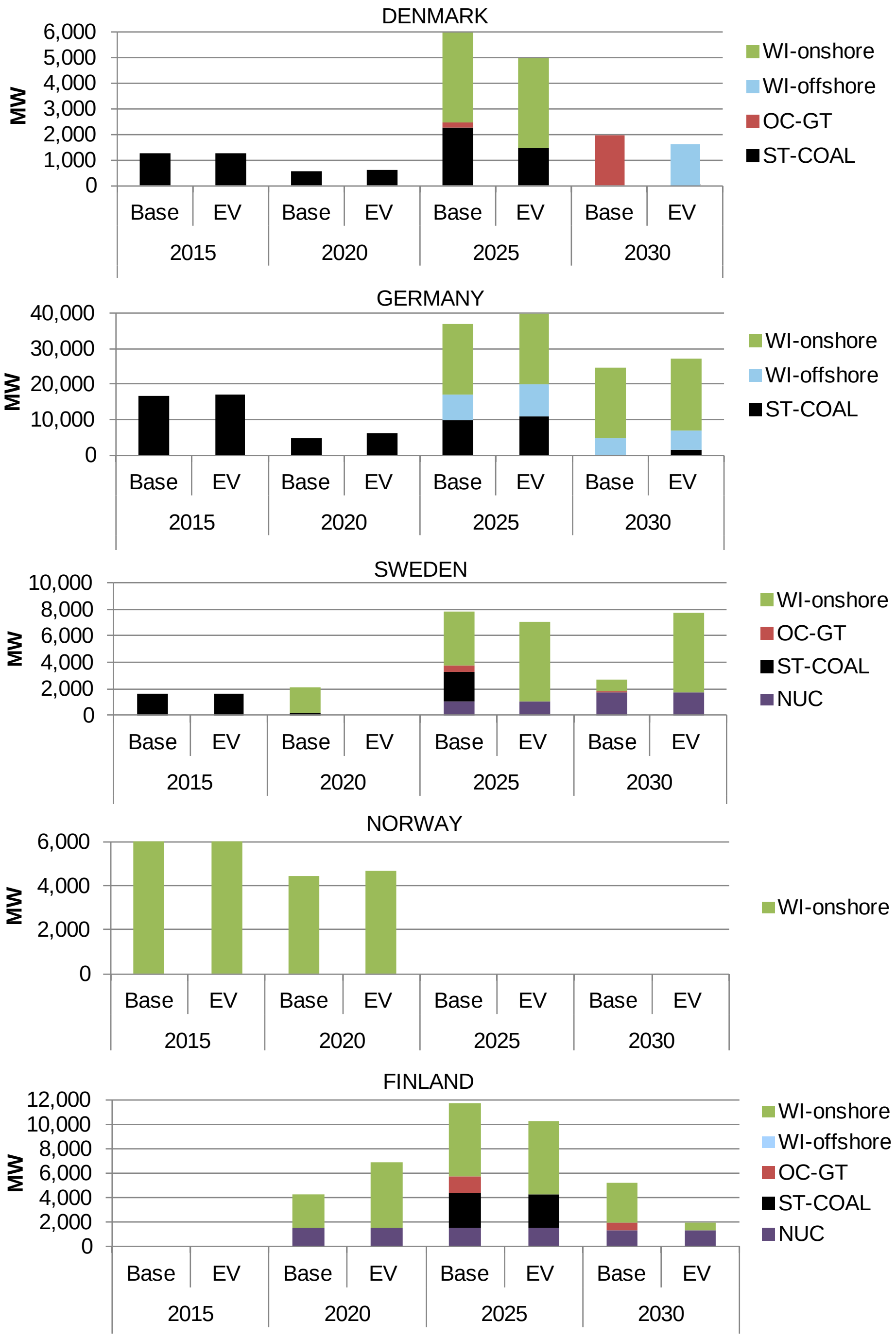

Figure 67. Investments in power production capacities in the Base and EV scenario, representing accumulated investments over each five year period. E.g. investments in 2020 represent accumulated investments from 2016 through 2020. WI: Wind power; ST-COAL: Steam turbine, extraction, coal; OC-GT: Open cycle gas turbine; NUC: Nuclear power.

Comparing the Base scenario with the EV scenario, it can be seen that the gradual implementation of EVs facilitates increased wind power investments in all five countries. The reason is that the flexible charging/discharging of EVs supports the integration of the variable production from wind power into the power systems. For Norway and Finland, this effect is observed from 2020, where EVs comprise 15 % of the vehicle fleet. As such, e.g. Finnish wind power investments are doubled in 2020 with the implementation of EVs. At higher EV fleet shares of 34 % in 2025, EVs generate increased wind power investments in Germany and Sweden and in 2030, where EVs comprise 53 % of the vehicle fleet, increased wind power investments are observed in Denmark and Germany, and particularly in Sweden where wind power investments are increased manifold. In Finland, the assumed onshore wind potential is reached in 2030 in both scenarios. Hence, in this case the EVs push forward the investments in wind power. The Danish wind power investments in 2025 are made in Western Denmark where wind resources are highest. The wind power investments generated in the EV as well as in the Base scenario are constrained by the onshore wind potential for this area (set to 3,500 MW). As a result, identical wind power investments are observed for the two scenarios. In 2030, the effect of EVs on Danish wind power investments is, however, significant, increasing offshore wind power investments from 0 MW to around 1,600 MW. In the EV scenario, the accumulated Danish wind power capacity in 2030 is around 5,100 MW, i.e. significantly lower than the national medium/high wind target for 2030 of 7,300/8,000 MW [98]. As such, the results suggest that a large scale implementation of EVs is not sufficient to facilitate reaching the Danish wind target for 2030 by socio-economic optimality.

As a consequence of the large-scale EV implementation and resulting increase in electricity demand, one might expect a significantly increased need for dispatchable power production capacity. However, the results show that when EVs are charged/discharged intelligently, increased investment in dispatchable power production capacity is only observed in a few cases (Germany in 2020-2030). In fact, rather than increasing investments in thermal production capacity, EVs result in a reduced need for new thermal power capacities for the case of Denmark, Finland, and Sweden. As such, investments in open cycle gas turbines and/or coal CHP capacities are reduced significantly in these countries in 2025-2030 with the implementing of EVs. This is explained by the V2G capability of EVs contributing in covering peak loads. In Denmark, the effect is most significant in 2030 where investments in open cycle gas turbines are reduced from around 2,000 MW to 0 MW.

Effects on electricity generation

By observing electricity generation in the EV scenario relative to generation in the Base scenario, it can be seen how electricity for EVs is produced in the optimisation (see Figure 68). As shown, the electricity demand for EVs is in Denmark largely covered with coal based electricity production in 2015 and 2020. The production increase occurs almost exclusively on existing plants, since the increase in Danish coal power investments caused by EVs is diminishing (cf. Figure 67). From 2025, Danish electricity demand for EVs is partly met by biomass based power production. This is a consequence of the increasing CO_2 prices and the relatively large increase in fossil fuel prices compared to biomass prices over the period. In 2025, electricity demand for EVs in Denmark is partly met by reducing electricity export to Germany and Sweden. This explains the gap in 2025 between the increase in power generation and the electricity demand for EVs. In 2030, EVs is in Denmark generate a significant increase in wind power generation. This is a direct consequence of the increased wind power investment in the EV scenario compared to the Base scenario; i.e. only by increasing wind power capacities, EVs can result in increased wind power generation. The generated increase in Danish wind power production in 2030 is much higher than domestic electricity demand for EVs. As a result, significant displacement of coal based power production occurs and net electricity import from Norway and Sweden is reduced.

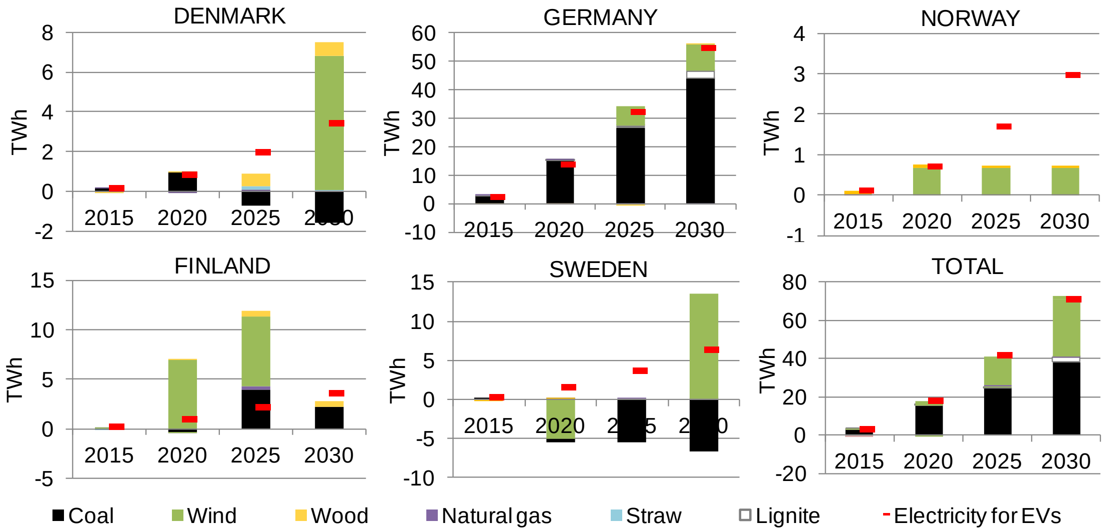

Figure 68. Changes in annual electricity generation due to implementation of electric vehicles. Due to import/export, possible changes in electricity consumption for heat pumps/electric boilers, and in the use of pumped hydro electricity storage, generated power increases in each year will not necessarily correspond to the electricity demand for electric vehicles.

The German case shows similarities with the Danish in the sense that electricity demand for EVs is in 2015-2020 largely met by increased coal based power production while wind power does not contribute in providing electricity for the EVs until in the last part of the period. Also in Sweden, EVs do not facilitate increased wind power generation until 2030. The Finnish case stands in contradiction the trend in Denmark, Germany and Sweden. As such, EVs in Finland generate increased wind power production from 2020 until reaching the assumed onshore wind potential. After that point, the electricity demand for EVs in Finland is largely met by coal fired electricity production. However, estimating the Finnish onshore potential is connected with large uncertainty and the potential might be higher than assumed. If setting the onshore wind potential higher, electricity for Finnish EVs would in the optimisation, also in the last part of the period, most likely be met by wind power. Norway is a large net electricity exporter and to a large extent, the cheapest way of providing electricity for EVs is therefore to reduce the export. Similarly, in 2020-2025 Sweden largely provides electricity for EVs by cutting down export. For this part, the implementation of EVs in Norway and Sweden, thus contributes to the generated increases in power production observed in the other countries.

CO_2 emissions

As result of the EV implementation, Danish CO_2 emissions from the power, heat and transport systems modelled, are more or less unchanged in 2015-2020 while significant emission reductions are obtained in 2025, 7 %, and in 2030, 17 % (see Figure 69 a). The most important factors behind the significant improvement in the CO_2 balance over the period are 1) the increasing share of renewable energy in the electricity mix for EVs, 2) the gradual improvement in the efficiency of the EVs and 3) the increasing shares of EVs in the fleet. As illustrated in Figure 69b, the emission reductions in 2025 and 2030 are mainly caused by displaced fuel consumption for ICEs. In addition, an emission reduction from power&heat production is observed in 2030. This is an effect of the significant displacement of coal based power production that year (cf. Figure 68).

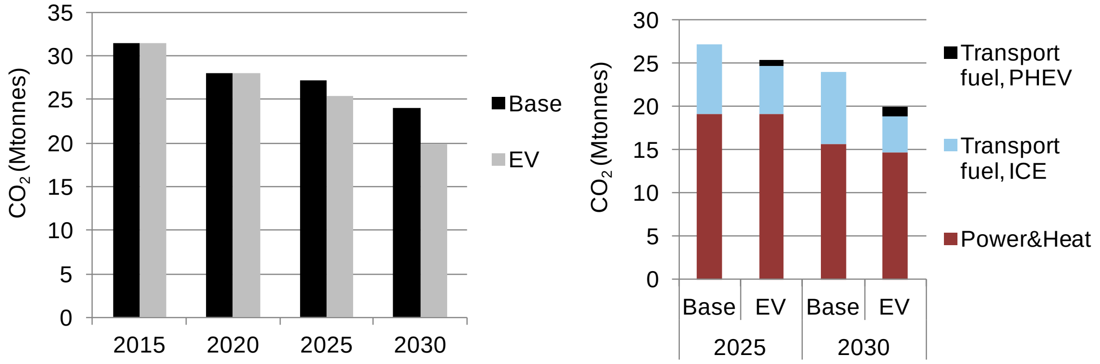

Figure 69 a). Danish CO_2 emissions for the simulated power, heat and transport system in the Base and EV scenario. b) Danish CO_2 emissions in 2025 and 2030, divided on sources for the two scenarios.

For the five Northern European countries as a whole CO_2 emissions are also more or less unchanged in 2015-2020 while reductions of 3 % and 7 % are obtained in 2025 and 2030.

Costs

Figure 70 shows that the implementation of EVs results in an increase in total costs for the simulated power, heat and transport sector of the Northern European countries; around 1.5-7.1 € Billion/yr depending on the year, corresponding to increases of 0.8-3.9 %.
The cost increase is partly due to larger investment costs per vehicle for BEVs and PHEVs compared to ICEs. Moreover, due to the assumed lower annual driving of BEVs compared to ICEs, a larger amount of BEVs are required to provide the same transport demand. Overall, this increases total investment and O&M costs for the transport sector. As illustrated in Figure 70b, the cost reduction from displacing fuel consumption in ICEs is not enough to compensate for this. The cost increase is highest in 2020 (3.9 %) and then lower in 2025 (1.2 %) and 2030 (0.8%); reflecting the influence of expected technical and economic improvements of EVs over the period.

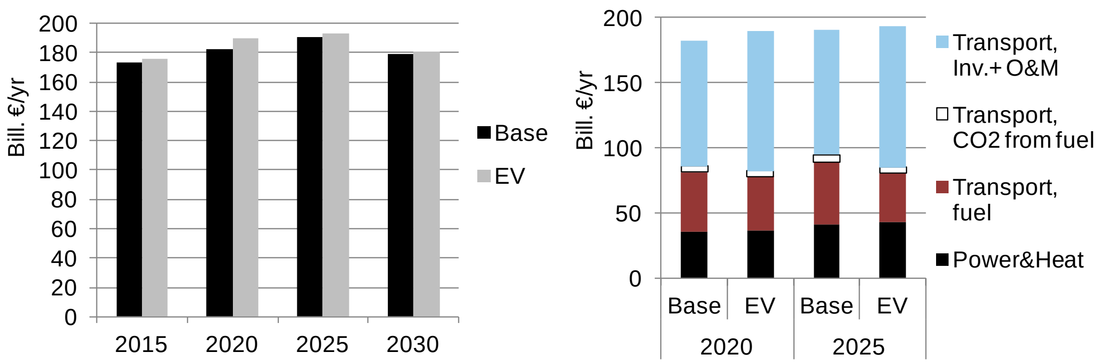

Figure 70 a). Total costs for the simulated power, heat and transport system for the Northern European countries in the Base and EV scenario. b) Total costs in 2020 and 2025, divided on sources.

These cost effects are based on an assumed implementation of PHEVs as well as BEVs while it should be mentioned that PHEVs alone have, in [93], shown to provide system cost reductions. Furthermore, potential benefits from using EVs for providing regulating power and power reserves is not included in the cost estimates. Finally, the socio-economic benefit of reducing the transports dependency on oil, increasing security of supply, is not valuated.

When relating the cost increases (excluding CO_2 quota costs) to the CO_2 emission reductions provided by EVs, average CO_2 reduction costs for EVs can be estimated for the five countries as a whole. This shows that CO_2 reduction costs are reduced manifold over the period; from very high levels of around 7100 €/ton in 2015 and 1500 €/ton in 2020, to 110 €/ton in 2025 and 80 €/ton in 2030. However, even in 2030, the CO_2 reductions costs for EVs are rather high compared to the expected CO_2 price level of around 39 €/ton [95]. As such, when comparing with assumed CO2 price levels, the analysis suggests a low cost efficiency of EVs in providing CO2 reductions, particularly in the short term.

Sensitivity analysis

In the analysis above, based on [95], CO_2 prices are assumed to increase from 20€/ton CO_2 in 2015 to 39 €/ton CO_2 in 2030, and the assumed fuel prices correspond to an oil price of $88/barrel in 2015 and $117/barrel in 2030. In a sensitivity analysis, the following low/high fuel price and low/high CO_2 price developments are assumed:

- Fuel prices: set to low at $80/barrel in 2015 increasing linearly to $90/barrel in 2030 and at high increasing linearly from $80/barrel in 2010 to $95/barrel in 2015 and $140/barrel in 2030. Ratios between prices on different fuels are kept constant and are based on [95].
- CO_2 prices: set to low at 15 €/ton in 2015 increasing linearly to 20 €/ton in 2030 and at high increasing linearly from 14 €/ton in 2010 to 26 €/ton in 2015 and 60 €/ton in 2030.

These analyses show that also at low/high fuel and low/high CO_2 prices, EVs facilitate a reduced need for new coal/natural gas production capacities in several of the countries, including Denmark. However, changes in investments and electricity production caused by the EVs over the period are generally found to be sensitive to the development in fuel and CO_2 prices. As such, e.g. for Denmark, at the low fuel price conditions, wind power is not included in the electricity mix for EVs towards 2030. At the low CO_2 price conditions, onshore wind power investments in the Base scenario are reduced below the onshore potential for Western Denmark. As a result, EVs facilitate an increase in onshore wind power investments in 2025. However, no offshore wind power investments are observed and in 2030, wind power only contributes with a small part of the electricity for EVs. Overall, at the low fuel/CO_2 price conditions, electricity demand for EVs in Denmark is in most of the period towards 2030 largely covered by coal based power or through electricity exchange. When assuming high fuel or CO_2 prices EVs facilitate considerable increases in wind power investments from 2025, i.e. five earlier than at the original price conditions. The resulting reductions in Danish CO_2 emissions depending on price conditions are presented in Table 1.

Table 1. Change in Danish CO_2 emissions reductions due to implementation of EVs depending on fuel and CO_2 price conditions

	2015	2020	2025	2030
Fuel and CO_2 prices based on [95]	0.04%	-0.1%	-7%	-17%
Low fuel prices	-0.5%	-0.4%	-6%	-15%
High fuel prices	-0.2%	-2.0%	-14%	-22%
Low CO_2 prices	-0.4%	-1.1%	-9%	-10%
High CO_2 prices*	0.1%	-0.8%	2%	-20%

* The slight CO_2 emission increase in 2025 in the high CO2 price scenario is due to reduced net import, resulting in increased coal based power production in Denmark. Cf. Figure 61 which illustrates the diverse reactions in different countries. For the five considered countries as a whole, CO_2 emissions are in 2025 reduced with 6 % in this scenario.

9.3 Conclusions

- When charged/discharged intelligently electric vehicles (EVs) can facilitate increased wind power investments and can due to vehicle-to-grid capability reduce the need for new coal/natural gas power capacities
- Wind power will likely provide a large share of the electricity for EVs towards 2030 in several of the Northern European countries
- However, if not followed up by economic support for renewable energy technologies other than CO_2 quotas, wind power will, for the case of Denmark (and Germany and Sweden) not contribute in providing electricity for EVs until the last part of the period
- As a result, electricity demand for EVs will in Denmark (and Germany) in the short term likely be met by coal based power
- Large scale implementation of EVs is not sufficient to facilitate reaching the Danish wind target for 2030 by socio-economic optimality
- Effects of EVs on the power system vary significantly from country to country and are sensitive to variations in fuel and CO_2 prices
- In the last part of the period towards 2030, EVs can provide significant CO_2 emission reductions for the Danish energy system as well as for the Northern European countries as a whole.

Supplemental data and model illustrations

Indoor temperature measurements in Danish houses

Measured heat supply in Danish houses

Handling of the summer period

Modelled heat supply over the year

Karsten Hedegaard.

Supplemental data and model illustrations

Indoor temperature measurements in Danish houses

Indoor temperature measurements for 28 Danish houses, with heat pumps (radiator heating) are shown in Figure A and Figure B [1].

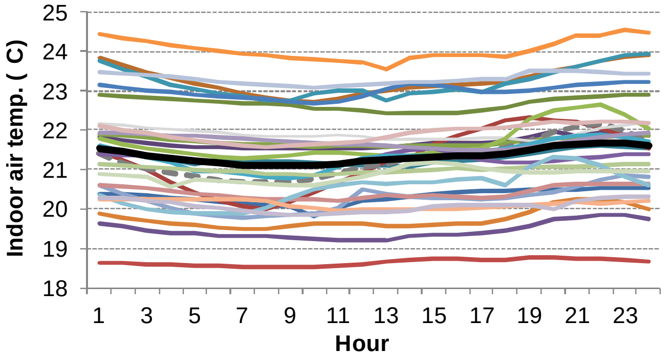

Figure A. Diurnal indoor air temperature profile for an average day in the period November 1 to December 31, 2011, measured in 28 Danish houses with heat pump installations and radiator heating [1] (measured in living room or kitchen). The thick black line indicates the average diurnal profile.

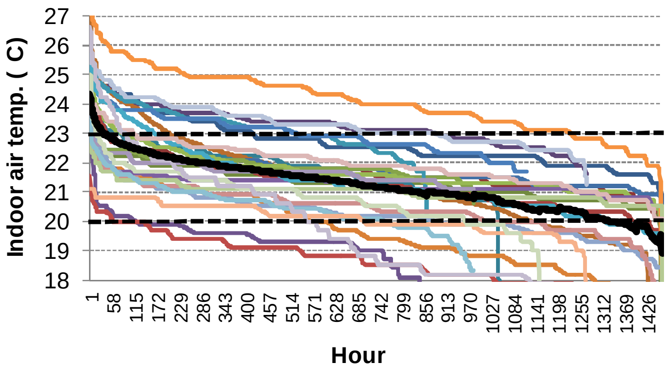

Figure B. Duration curve for indoor air temperatures in the period November 1 to December 31, measured in 28 Danish houses with heat pump installations and radiator heating [1] (measured in living room or kitchen). The thick black line indicates the average duration curve. The dotted black lines indicate the lower/upper indoor air temperature levels applied in the analysis.

The temperature measurements above (measured in living room/kitchen) form part of the background for the temperature settings applied in the analysis of heat pumps and heat storages: 1) the fixed indoor temperature requirement of 21.5 °C in the reference situation without flexible heat pump operation and 2) the allowed indoor temperature interval of 20-23 °C during the day, in the situation where heat pumps are operated flexibly, utilising the heat storage capacity of the building structure (an allowed temperature interval of 19-22 °C at night is assumed when supplementing with other sources, as mentioned in Section 2.2).

A winter period, November 1 to December 31, has been chosen to reduce the influence of solar transmission. Thereby, the measured indoor temperatures best reflect the thermal comfort preferences of the residents. The heat pumps have been operated conventionally, i.e. not flexibly, in the given period [2]. Houses with radiator heating are used as basis, since the bulk of the heat demand for individually heated Danish one-family houses by 2030 are expected to represent radiator heating systems (see Section 2.2). Moreover, radiator heating systems enable a significantly faster regulation in indoor temperatures than (concrete) floor heating systems. Therefore, indoor temperatures measured in houses with radiator heating best reflect the temperature preferences of the residents. The same general patterns in indoor temperatures have however been observed for houses with floor heating systems.

Measured heat supply in Danish houses

Average diurnal space heating profiles for Danish houses with heat pumps and radiator heating are shown in Figure C and Figure D for two different periods. The resulting average profiles (indicated with black bold) are used in the comparison with corresponding model generated space heating profiles in Paper IV.

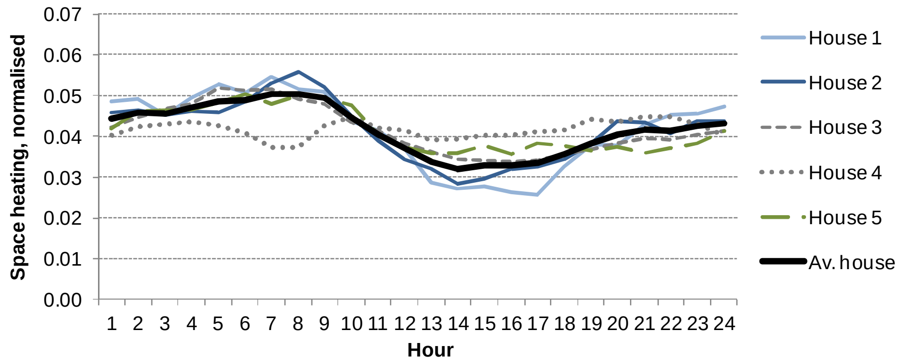

Figure C. Average diurnal space heating profile measured for 5 Danish houses with heat pump installations and radiator heating. The data cover the period March 15 – May 15 and Sep 15 - December 31, 2011.

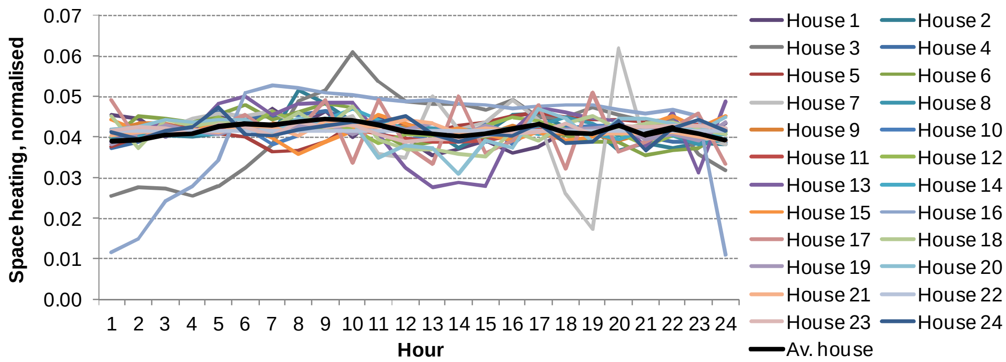

Figure D. Average diurnal space heating profile measured for 24 Danish houses with heat pump installations and radiator heating. The data cover the period 1 November – 31 December, 2011.

Handling of the summer period

Depending on individual comfort preferences and the degree of insulation of the house, Danish households with heat pump installations typically turn off space heating manually in the summer or let the space heating be turned on/off automatically, on a day to day basis, through weather compensation. Weather compensation typically means that when the average ambient temperature for the past day drops below a certain level (15-20 °C depending on the degree of insulation), space heating is turned off [3]. When the average ambient temperature increases above this level, space heating is then turned on again. This mechanism is however not possible to model in a linear optimisation model. Regardless of the type of control, use of heat pumps for space heating in the summer period is however typically very low [3] [1]. Based on the above, it is generally assumed that space heating is only needed in the heating season, which in practice typically covers the period September 15 to May 15 [4]. For computation efficiency reasons, this is implemented in the model by activating the space heating equations, for the heating season only.

Modelled heat supply over the year

Figure E illustrates how generation of space heating and hot water over the year is represented in the thermal building model for an average existing detached house (151 m^2).

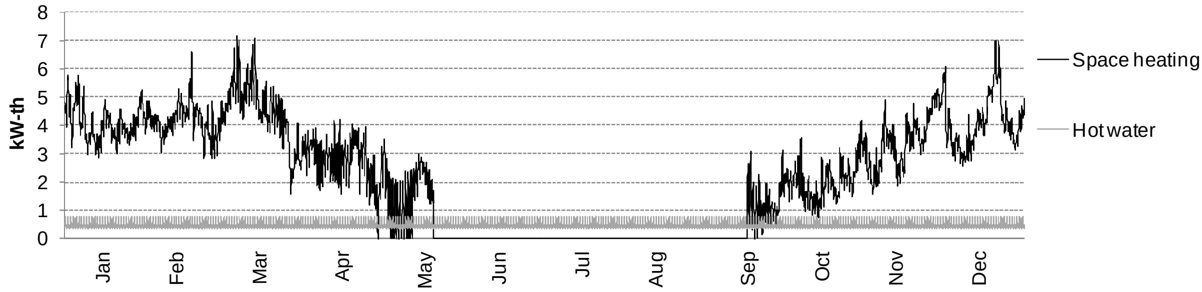

Figure E. Space heating generation and hot water demand profile over the year for an average existing individually heated detached house as generated by the model.

As shown, no space heating occurs in the non-heating season May 15 to September 15. The peaks in space heating represent the few hours of the year where outdoor temperatures are very low (-11 °C to -13 °C). As can be seen, the total heat pump capacity needed for an average existing detached house is around 8 kW-th (for space heating and hot water). This fits well with the capacity of 8.3 kW-th, used in [5] as typical value for individual heating installations.

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The fluctuating and only partly predictable nature of wind challenges an effective integration of large wind power penetrations. This PhD thesis investigates to which extent heat pumps, heat storages, and electric vehicles can support the integration of wind power. Considering the gaps in existing research, main focus is put on individual heat pumps in the residential sector and the possibilities for flexible operation, using the heat storage options available.

Extensive model development is performed that significantly improves the possibilities for analysing individual heat pumps and heat storages in an energy system context. Energy systems analyses reveal that the heat pumps can even without flexible operation contribute significantly to facilitating larger wind power investments and reducing system costs, fuel consumption, and CO_2 emissions. When equipping the heat pumps with heat storages, only moderate additional benefits are achieved. Hereof, the main benefit is that the need for investing in peak/reserve capacities can be reduced through peak load shaving. It is more important to ensure flexible operation of electric vehicles than of individual heat pumps, due to differences in the load profile.

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