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

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ABSTRACT

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 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.

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

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 25-30 % of annual electricity demand [1], and the Government plans to increase this share to 50 % in 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 applying a large-scale energy system model. Papaefthymiou *et al.* [17] assess the system benefits of operating large scale installations of individual heat pump 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 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 in 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 Section 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[1]. Thermal storage tanks for space heating and hot water are also covered, representing other options of enabling flexible heat pump operation. The model 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 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 installation of individual heat pumps affect the energy system, when not operated flexibly. The difference between the scenarios iHP and iHP-Flex reveal 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:

[1] In addition, heat can be stored passively in the rest of the building structure [65].

- *Intelligent heat storage in the building structure*: investment in digital thermostats[2], 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 foremost 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 litres per house and in a central controller communicating with the power system [18].

A small hot water tank of around 180 litres [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 & district heating sectors in 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,

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

representing the bulk, 78 % [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).

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 (94 %) of the individually heated one-family houses by 2030.

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 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

variations in indoor temperatures for the households [44] (measured in living room/kitchen), an interval of 20-23 °C is 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].

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 realistic or 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 & waste potentials

Use of straw, wood chips/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.

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 (NOiHP 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 investment in individual heat pumps are allowed (iHP and iHP-

Flex scenario), air-water heat pumps are installed in all individual heating areas. This represents a significant electricity demand of 4.3 TWh.

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.

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 buildings with a high share of concrete). 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 each individually heated area is modelled on aggregated level. This means that a given heat storage capacity can be utilised 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. 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 when the heat pumps are operated flexibly (440 MW, 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 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 & 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 reduction 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 with flexible heat pump operation 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.

If forcing through investments in both 1000 litres 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 19 % 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 on annual level is increased from 0 TWh to 2-3 TWh 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 litres [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 flexible heat pump installations, 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 0.45-0.80 % found in [17]. If forcing through investment in intelligent heat storage in the building structure and in 1000 litres 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] and [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 and analysing 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 around 50-60 % wind power 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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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.

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			Ref.
			1850-1960	1961-1978	1979-2005	
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.

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	-	-

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 & power generation.

Table 6. Power & 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 litres)[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.

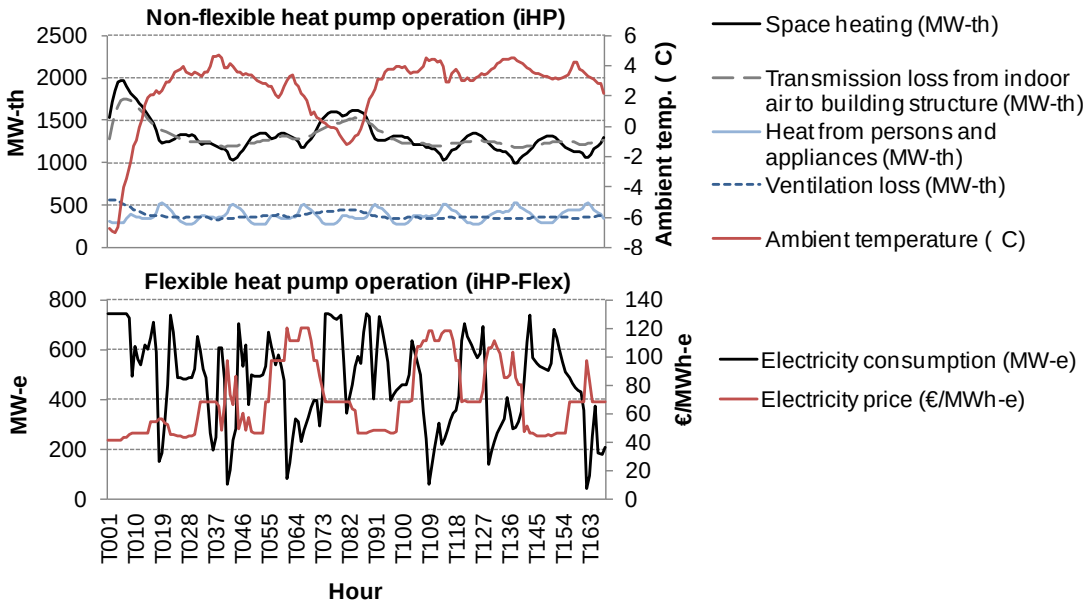
Non-flexible heat pump operation (iHP)
MW-th
Ambient temp. (C)
Space heating (MW-th)
Transmission loss from indoor air to building structure (MW-th)
Heat from persons and appliances (MW-th)
Ventilation loss (MW-th)
Ambient temperature (C)
Flexible heat pump operation (iHP-Flex)
MW-e
€/MWh-e
Electricity consumption (MW-e)
Electricity price (€/MWh-e)
Hour

Fig. 1

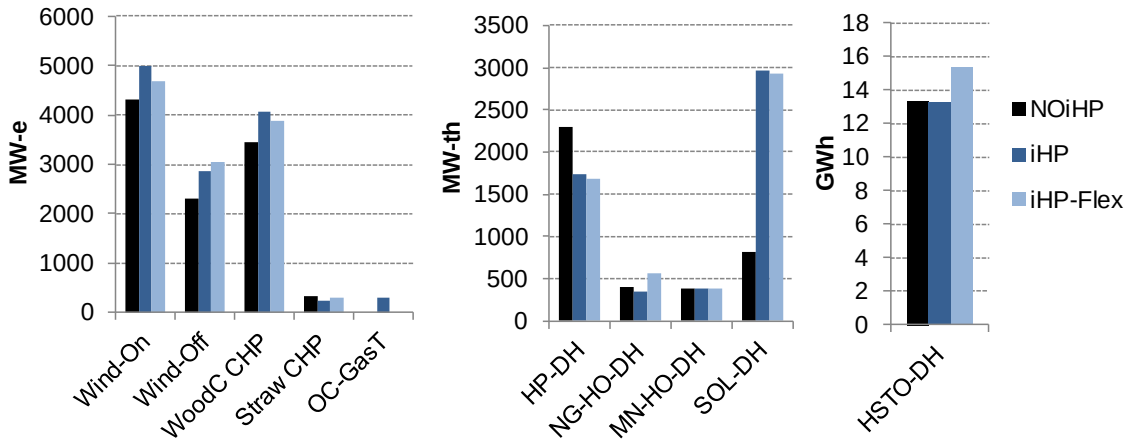
MW-e
6000
5000
4000
3000
2000
1000
0
Wind-On
Wind-Off
WoodC CHP
Straw CHP
OC-GasT
MW-th
3500
3000
2500
2000
1500
1000
500
0
HP-DH
NG-HO-DH
MN-HO-DH
SOL-DH
GWh
18
16
14
12
10
8
6
4
2
0
HSTO-DH
NOiHP
iHP
iHP-Flex

Fig. 2 **a)** **b)** **c)**

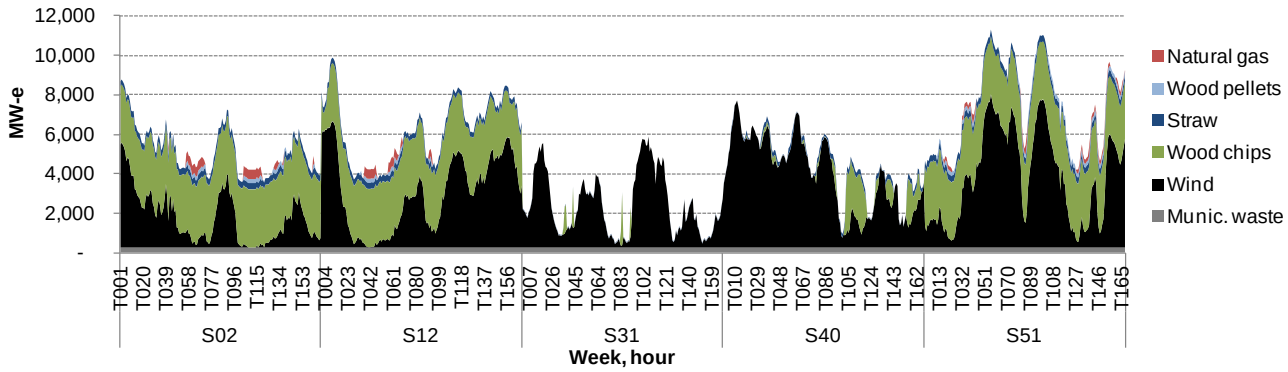
12,000
10,000
8,000
6,000
4,000
2,000
-
MW-e
Natural gas
Wood pellets
Straw
Wood chips
Wind
Munic. waste
T001 T020 T039 T058 T077 T096 T115 T134 T153
T004 T023 T042 T061 T080 T099 T118 T137 T156
T007 T026 T045 T064 T083 T102 T121 T140 T159
T010 T029 T048 T067 T086 T105 T124 T143 T162
T013 T032 T051 T070 T089 T108 T127 T146 T165
S02
S12
S31
S40
S51
Week, hour

Fig. 3

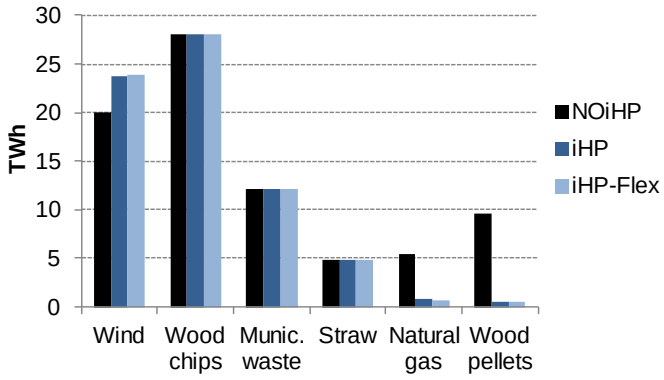
30
25
20
15
10
5
0
TWh
Wind
Wood chips
Munic. waste
Straw
Natural gas
Wood pellets
NOiHP
iHP
iHP-Flex

Fig. 4

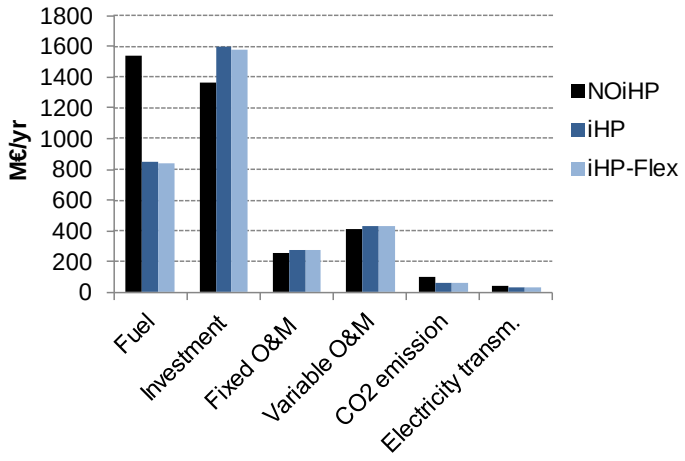
1800
1600
1400
1200
1000
800
600
400
200
0
M€/yr
NOiHP
iHP
iHP-Flex
Fuel
Investment
Fixed O&M
Variable O&M
CO2 emission
Electricity transm.

Fig. 5

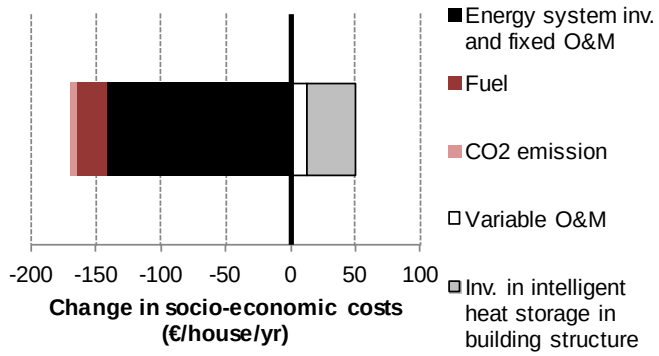
-200
-150
-100
-50
0
50
100
Change in socio-economic costs (€/house/yr)
Energy system inv. and fixed O&M
Fuel
CO2 emission
Variable O&M
Inv. in intelligent heat storage in building structure

Fig. 6