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

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ABSTRACT

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

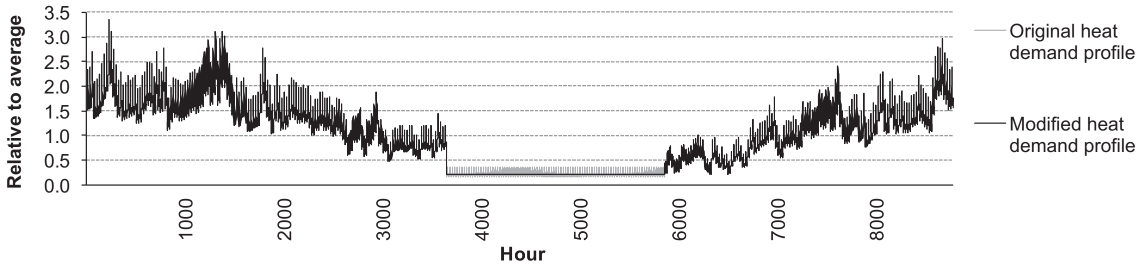

Fig. 1. Hourly heat demand profile applied for the aggregated building stock of existing detached houses.

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.

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

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

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

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

$$\mathrm{HP}_{\mathrm{heat}}(t) \le \mathrm{CF} \cdot \mathrm{HD}_{\mathrm{max}} \quad \forall t \tag{5}$$

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

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 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.

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.

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

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

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

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

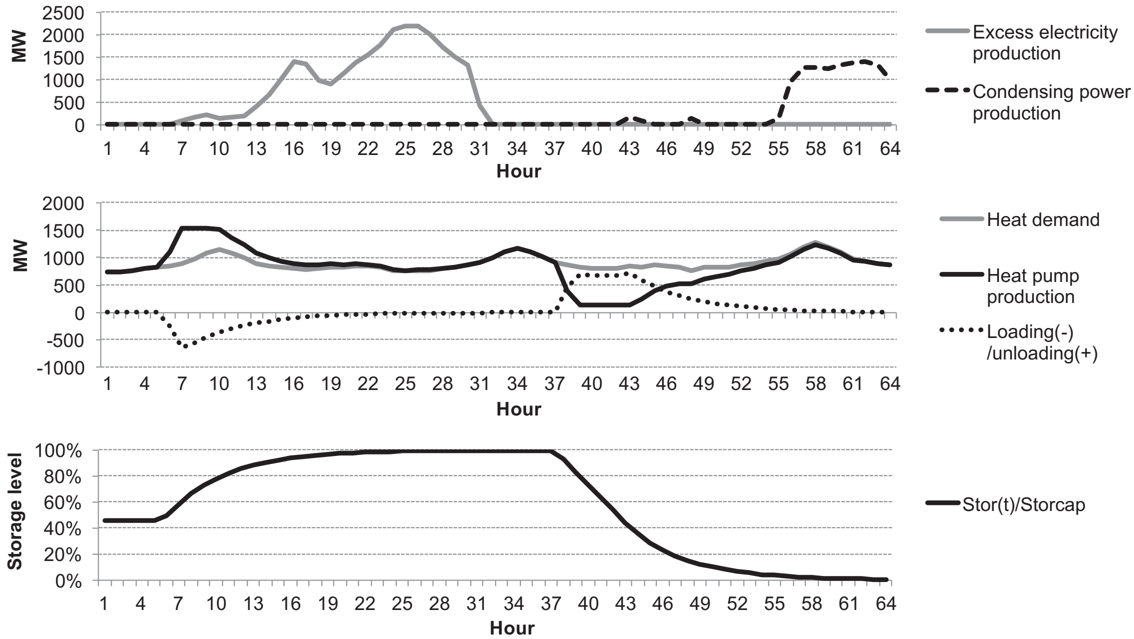

Fig. 2. Optimisation of a large-scale installation of heat pumps using passive heat storage, modelled in integration with the energy system (allowing ∓1 °C indoor air temp. var. and assuming a passive heat storage cap. of 120 W/m^2 floor area/K). A loading and subsequent unloading period is shown, together 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).

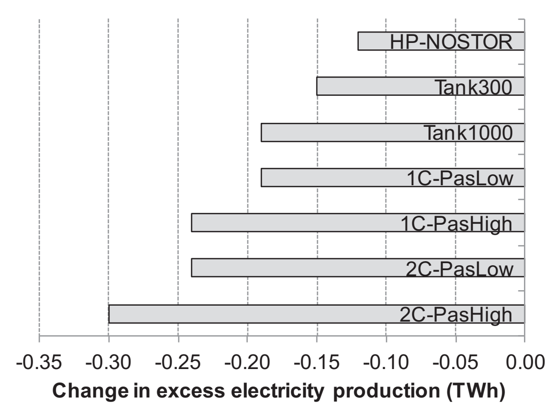

Fig. 3. Change in excess electricity production depending on type and size of heat storage available for individual heat pumps, compared to a system without heat pumps.

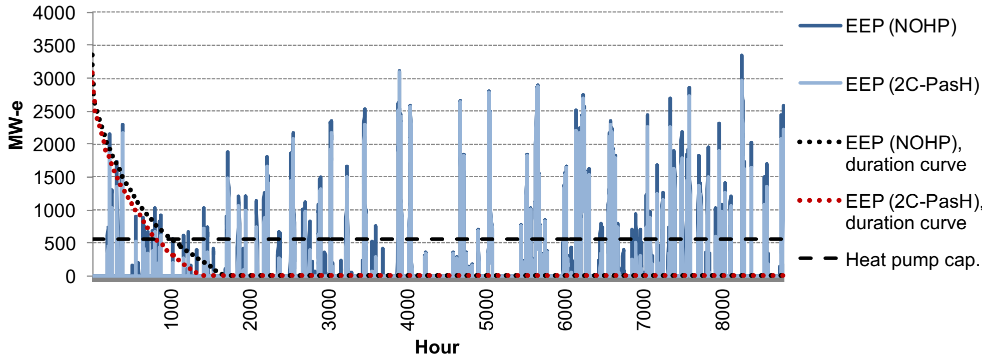

Fig. 4. Excess electricity production (EEP) for a scenario without individual heat pumps (NOHP) and for a scenario with large-scale installation of heat pumps, displacing oil boilers and electric heating, assuming utilisation of passive heat storage (2C-PasHigh).

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.

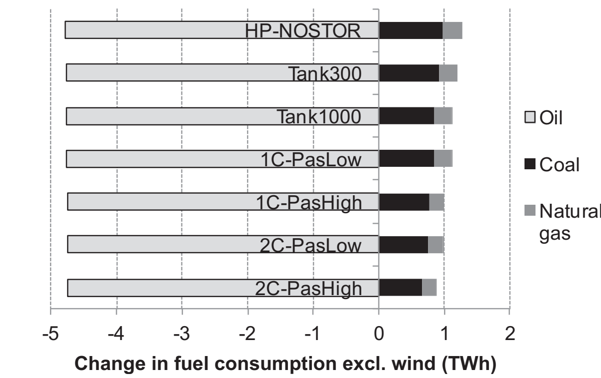

Fig. 5. Changes in fuel consumption excl. wind when installing individual heat pumps and heat storages compared to a system without heat pumps (NOHP).

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.

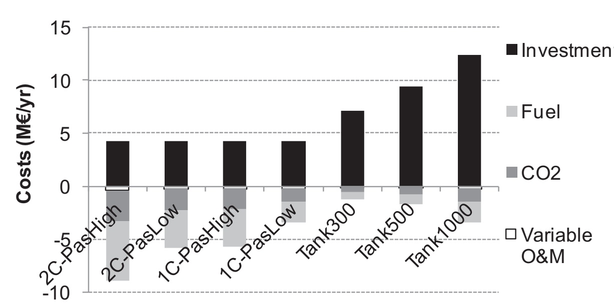

Fig. 6. Changes in socio-economic cost when enabling different types/sizes of heat storages for individual heat pumps.

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

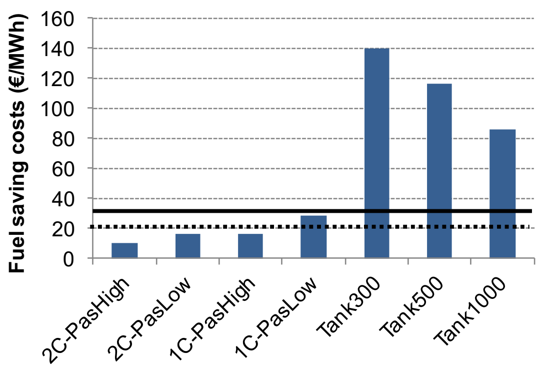

Fig. 7. Average annualised costs per fuel saved for different heat pump storage options. For comparison, the expected coal price, 20 €/MWh (dashed line) and natural gas price, 33 €/MWh (black line) in 2020, including CO_2 costs and fuel and handling costs, is indicated.

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

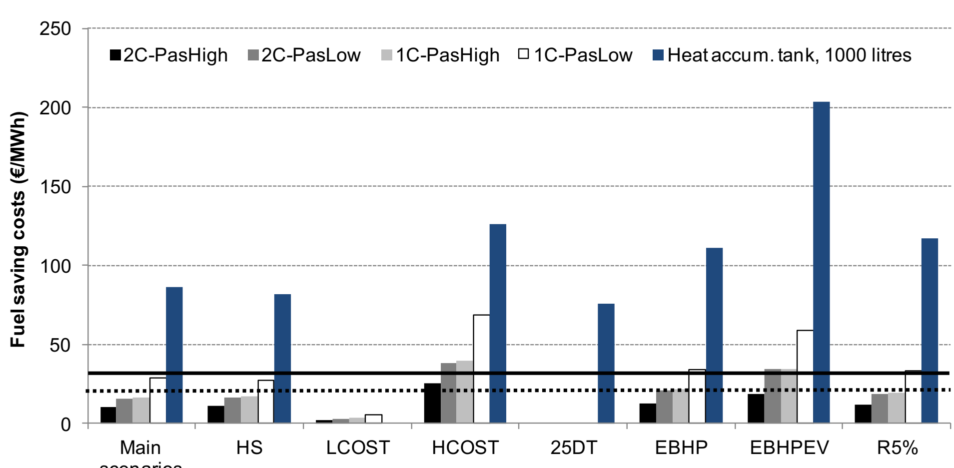

Fig. 8. Average annualised costs per fuel saved for sensitivity scenarios of different heat pump storage options. For comparison, the expected coal price, 20 €/MWh (dashed line) and natural gas price, 33 €/MWh (black line) in 2020, including CO_2 costs and fuel and handling costs, is indicated.

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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