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Analyses of thermal storage capacity and smart grid flexibility in Danish single-family houses

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Abstract

This paper describes theoretical analyses of typical detached Danish single family houses' ability to provide thermal capacity and thus flexibility, in an electricity grid, if they were heated by individual heat pumps.

A set of archetype house models have been set up for analyses of their ability for moving energy use in time by dynamic simulations in BSim (Wittchen et al., 2000-2019). The archetypes was established in order to analyse single-family houses constructed in different periods, usually related to shifts in building regulations or building traditions.

Finally, results from archetype modelling are scaled to the total number of Danish single-family houses located outside district heating areas to estimate the future thermal capacity in these houses. Analyses showed that up to 99 % of the energy demand for space heating within peak hours can be moved outside peak hours, with acceptable influence on the indoor temperature.

The paper describes the simulation approach and the results for different archetype houses as well as upscaling to nation-wide thermal storage potential. Moreover, the paper describes flexibility studies on selected houses based on both peak response and price signal response.

Introduction

In the near future, where fluctuating renewable energy, e.g. from wind turbines dominates the electricity grid, flexibility will be essential for a stable electricity grid and maximum utilization of the renewable energy resources (Ministry of Climate, Energy and Buildings, 2013). One source for this flexibility is buildings heated by heat pumps (Dréau and Heiselberg, 2016). Around 50 % of Danish detached single family houses are located outside district heating grids (Statistics Denmark, 2020) and will, in the near future equipped with heat pumps (Danish Ministry of Climate, energy and Utilities, 2020).

This transformation towards electric heating of single family houses using heat pumps is the perspective of this study. Put otherwise, we presuppose that Danish single family houses were heated by heat pumps and on this background estimate thermal capacity and flexibility in an electric grid (Hedegaard and Balyk, 2013). A simple approach for the energy flexibility potential has been used (Reyndres et al. 2018) to evaluate the houses' ability to move heating energy use away from peak periods, utilising the houses' thermal storage capacity (Reynders et al. 2017). The houses thermal capacity has been simulated with the current energy performance level and heating system capacity.

Six archetype models, representing Danish single-family houses, have been set up to analyse the thermal storage potential The archetypes represents differences in building tradition and historical changes in energy requirements stated in shifting Danish Building regulations (Wittchen et al., 2016), covering the following age categories:

- 1850-1930
- 1931-1950
- 1951-1960
- 1961-1972
- 1973-1978
- 1979-1998

These age categories are typically constructed of heavy building materials, have reasonable insulation levels due to carried out renovation and are reasonable air-tightness (Danish Energy Agency, 2020). These are all parameters that support the houses in maintaining an acceptable indoor temperature during periods without heat supply.

The reasoning for not analysing houses older than 1850 is that these houses are normally poorly insulated, leaky (Danish Energy Agency, 2020) and represent a very small share of the total housing stock (Statistics Denmark, 2020). Houses constructed after 1998 have also been excluded as these houses are normally made of light constructions (little thermal energy storage possibility) and are highly insulated and airtight (Wittchen et al., 2016). They do thus not offer a large thermal energy storage potential.

The analyses did not aim at exploring the potential CO_2 emission reduction by utilising the thermal capacity of single family houses in an electric grid. The aim was solely a simple quantification of the amount of energy and in second hand electricity that can be moved away from daily peak periods (breakfast and cooking peaks).

Extrapolation to total energy flexibility is limited to Danish single-family houses located outside district heating areas constructed in 1850-1998, assuming they will be heated by individual heat pumps in the future.

In parallel, existing, high frequency measurements of energy consumption and indoor temperatures from 140 detached single-family houses in a night setback experiment (Jensen, 2016) were used to validate if the archetype models performed as expected (Palmer et al. 2020). Data from this experiment can be used to characterise the houses' dynamic behaviour as any change in the heat supply for a house will result in a dynamic response. Measurements of the indoor and outdoor temperatures can be used to estimate the time-constants of the house. Time constants are one of the key parameters to understand the dynamic thermal behaviour of a system (house) and thus its potential flexibility (Jakobsen and Kolarik, 2018). The measurements were used to estimate time constants for houses corresponding to each archetype and compared to time constants estimated from simulation results of the archetype models (Palmer et al., 2020).

Model set-up

Archetype models were set up in the building simulation tool BSim (Wittchen et al., 2000-2019). To meet the special needs for this study, BSim was extended with a "parasite" that controls the program and among others makes it possible to extract simulation results on sub-hourly level rather than the normal hourly output (Jensen et al., 2020).

Archetype models were defined with focus on accurate modelling of the thermal mass, window-to-floor ratio, thermal performance of the building envelope, and size of heating system. Ventilation was estimated based on experiences form measurements in multiple Danish single-family houses (Bergsøe, 1996) and internal loads (persons, lighting and auxiliary electricity) was estimated using national standards (Aggerholm, 2018) for energy certification of buildings. The heated floor area and the heating supply of the archetype houses is extracted form information in the Danish Building and Dwelling stock Register (BBR).

The focus was on simulation of existing houses in in their current stage in terms of energy performance and heating system installation in order to evaluate the thermal storage potential of the existing housing stock.

Due to the simplifications in ventilation rates and internal loads, all archetype houses only had one zone, except for those archetypes that has two floors. All internal walls however, are modelled in order to maintain the correct thermal capacity of the house.

The building model do not take into account thermal storage capacity in the technical building systems and therefore neither a potential water tank. Inclusion of a water tank will potentially be able to increase the total thermal storage capacity of the house. Heating systems in all archetypes are adjusted to match the actual power of the representative example houses.

Figure 1 show a wireframe drawing and a photo of an example archetype house with 180 m² gross heated floor area representing the construction period 1961-1972.

Due to the daily routines of Danes, there are normally two daily peak periods (Figure 2): two hours in the morning (breakfast peak) and three hours in the evening (cooking peak).

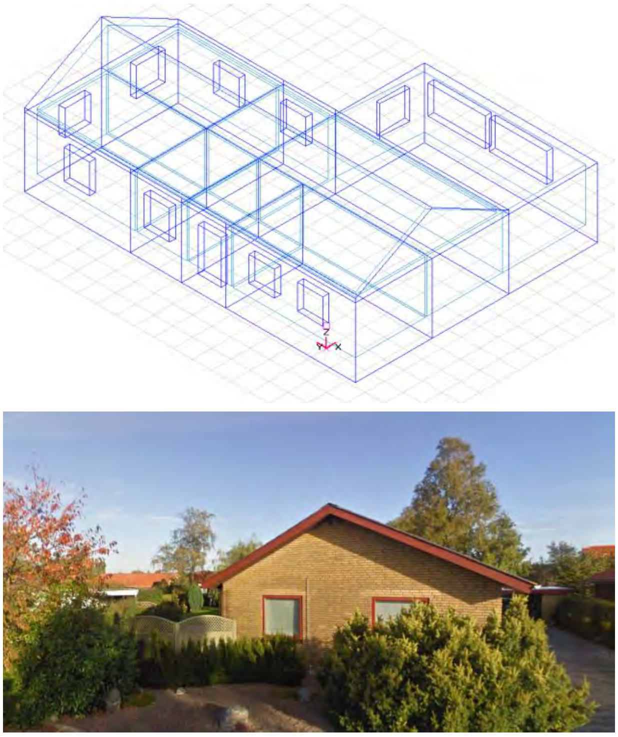

Figure 1. Wire-frame drawing of 1961-1972 archetype house in simulation tool and photo of corresponding example house (1966).

The idea behind the simulation experiment, was to move as much energy demand for space heating away from the peak-periods, still maintaining an acceptable indoor temperature (20-22 °C). This is done by three different control strategies.

1. Fixed indoor temperature of 22 °C (reference).
2. Turn off heating at the start of the peak-periods and let the indoor temperature drop towards 20 °C, i.e. 2 degree temperature setback.
3. Pre-heating or charging of the thermal mass to 23 °C the house 1 and 2 hours in advance of the peak-periods with temperature setback to 20 °C during peak-periods.

The first control strategy (2) is almost the same as a traditional night set-back strategy aiming at reducing the energy use, but carried out over a shorter periods (2 and 3 hours) and during daytime. In the time after the set-back period there is an increase in power uptake compared to the control with a fixed indoor temperature. The second demand control strategy (3) may result in an annual increased energy use. This control strategy is, in contrast to Knudsen and Petersen (2016), a simple strategy, which do not aim at minimising the CO_2 emissions, but only move energy uptake away from peak periods. Fluctuating wind result in fluctuations in the CO_2 emission from the Danish electricity production and these fluctuations are thus not synchronous with the fixed peak periods (Clauß et al., 2019) used in this study. Analyses of the potential for moving energy use away from peak hours is an example on how thermal storage capacity in Danish single-family houses can be utilised as flexibility. This capacity is studied for, but not limited to, peak-periods. Both strategies (2 and 3) may be able to decrease the total CO_2 emissions as a result for less fossil-fuel based energy in the energy mix during peak periods or other periods with a large share of fossil fuels in in the energy mix.

Pre-heating demand control strategy (3) takes advantage of the houses' ability to act as a thermal storage for electricity grid. The storage capacity of houses will be able to increase the grid's resilience towards fluctuations as wind power delivers an increasing share of the total electricity production.

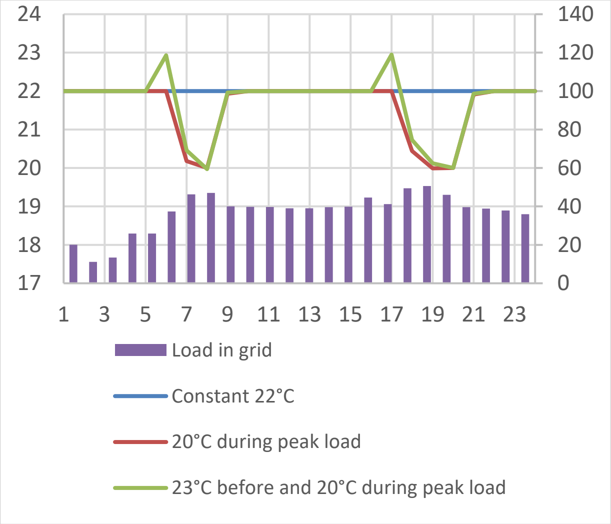

Figure 2. Example indoor temperature in a house that offers flexibility to the grid.

Example 1966 house

Measurements in the Middelfart dataset (Jensen, 2016) include high frequency (between 1 and 5 minute intervals over 2 years) measurements of indoor and outdoor temperatures as well as energy consumption in 140 Danish detached single-family houses in a night setback experiment.

Within the archetype period 1960-1972 is data from one single-family house from 1966 in the Middelfart dataset of good quality, i.e. data is of sufficient granularity and with enough un-interrupted sampling periods. This makes it possible to use the data for statistical studies of cooling characteristics, i.e. time-constants, of the house.

Even though this house is heated by district heating, data from night setback cool-down periods can be used as representative for such houses' dynamic behaviour. Use of data from a house with district heating are equally valid for use in the statistical analyses and estimation of time-constants as data from a house with another heat source.

The selected house was renovated in 2006 with addition of cavity insulation in the brickwork walls and replacement of windows. The heat capacity of the house is maintained during this operation as the internal leaf of the brick walls are unchanged. This kind of post insulation work is common in Denmark. Due to the low price of this work, compared to the energy savings, the intervention is widespread for this age of houses. This kind of renovation works are typical for houses from this period (Danish Energy Agency, 2020), thus the house is considered typical for the period. The house is thus assumed to be representative for the archetype of this period.

Estimating time-constants

Night indoor temperature curves for this house shows that a typical setback is about 2.5 degree. The night temperature is decreasing until about 18 °C and towards 8 AM the temperature increases to a little above 20 °C. In this house there is not much difference between weekdays and weekends. Figure 3 depict the night setback as measured indoor temperature for a selected period.

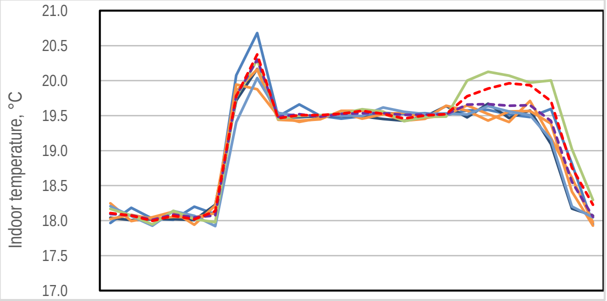

Figure 3. Examples of temperature 24h curves for night set-back in house from 1966. Red dotted line indicates the average for weekdays while the blue dotted line is the average for weekends.

Based on measurements of the indoor temperature during periods with night set-back in a house, it is possible to estimate the time-constant for using a first order auto-regressive model (Bacher & Madsen, 2011). In Figure 4, time-constants for all analysed archetype representatives are shown.

The 1966 house show the longest time-constant, 50.8 hours, which indicates a thermally heavy house with good insulation level and air-tightness. This matches the expectations for a house constructed from heavy building materials (brickwork) that has been insulated in the cavity walls and with new windows.

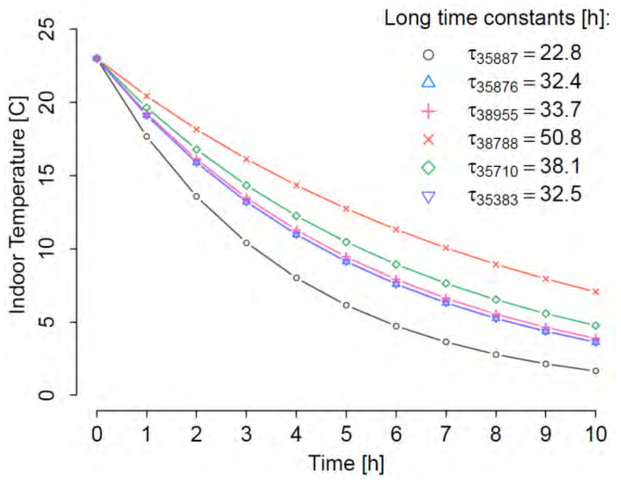

Figure 4. Estimated cooling curves for six selected houses (the six archetype categories) in the Middelfart dataset. The 1966 example house has a time-constant of 50.8 (red curve marked with x).

Simulating peak periods' flexibility

The annual simulated net heating demand with a constant indoor temperature at 22 °C is 26 729 kWh with a maximum power demand of 10.7 kW (Table 1). By cutting off heating during peak periods (control strategy 2) and letting the indoor temperature float towards 20 °C, the annual net heating demand decreases to 26 140 kWh but at the same time the maximum power demand increases to 14.4 kW. If the house is pre-heated to 23 °C one hour in advance of the peak-period (control strategy 3), the annual net heating demand becomes 26 322 kWh and maintaining the maximum power demand at 14.4 kW. Preheating 2 hours before peak-periods increases the annual heat demand to 26 633 kWh.

Table 1. Annual net space heating demand and max power demand for 1960-1972 archetype simulations.

	Heat kWh	**Power kW**
Constant indoor temperature 22 °C (reference)	26 729	10.7
Maximum 2 degree set-back during peak-periods	26 140	14.4
Pre-heating 1 hour before peak-periods to max 23 °C and 2 degree set-back during peak-periods	26 322	14.4
Pre-heating 2 hours before peak-periods to max 23 °C and 2 degree set-back during peak-periods	26 633	14.4

Summarising the hours that are within the peak-periods the annual net heating demand becomes as shown in Table 2. It is clear that the relative reduction in annual net heating demand within the peak-periods is significantly higher than for the whole year. In this way, it is possible to move up to 99 % (5 480 kWh) of the net heating demand away from the peak-periods.

Table 2. Annual heating demand within peak-periods for archetype 1960-1972 simulations.

	Heating kWh	**Reduction %**
Constant indoor temperature 22 °C (reference)	5 514	-
Maximum 2 degree set-back during peak-periods	86	98
Pre-heating 1 hour before peak-periods to max 23 °C and 2 degree set-back during peak-periods	34	99
Pre-heating 2 hours before peak-periods to max 23 °C and 2 degree set-back during peak-periods	34	99

Indoor temperature during peak periods

The internal loads is set to increase during peak-periods with a factor 3 e.g. due to cooking. This increase reflects the increased activity in the house during peak-periods.

Even with a control strategy aiming at a constant indoor temperature of 22 °C, there are some hours with indoor temperature in the living area below the set-point (Figure 5 and Table 1). This points to a slightly undersized heating system. That is a normal situation in houses constructed in this period as the heating system is laid out for a constant indoor temperature of 20 °C when the outdoor temperature is -12 °C. In the Danish reference year used in the simulations, the outdoor temperature reaches -15 °C at the depth of winter (Wang et al., 2013). Introducing periods with heating cut-off will naturally challenge the power of the heating system, but the situation is realistic for existing houses where such dynamic control strategy are introduced.

Figure 5 show the number of hours with indoor temperature below 22 °C.

The number of low indoor temperature hours increases dramatically when the set-point is decreased during peak-periods. Therefore, the influence of pre-heating to 23 °C two hours in advance of the peak-periods was analysed for this archetype. A two hour pre-heating strategy proved to have limited influence on the overall heating demand and maximum power demand (Table 1 and Table 2), but significant influence on the number of hours with indoor temperatures below 22 °C (Table 3).

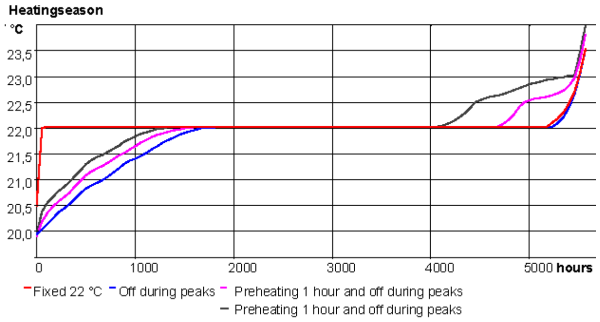

Figure 5. Distribution curve for the indoor temperature during the heating season in the four simulated cases.

In all control strategies, the number of hours during the heating season with an indoor temperature below 20 °C is limited.

In Wittchen et al. (2020) results from simulations and time-constant estimates of all archetypes are described.

Table 3. Number of hours during the heating season with indoor temperature below 20 and 22 °C respectively in the living area for four simulated control strategies.

Number of hours	**<20°C**	**<22°C**
Constant indoor temperature, 22 °C (reference)	0	50
Maximum 2 degree set-back during peak-periods	14	2 677
Pre-heating 1 hour before peak-periods to max 23 °C and 2 degree set-back during peak-periods	9	2 321
Pre-heating 2 hours before peak-periods to max 23 °C and 2 degree set-back during peak-periods	2	1 903

Storage capacity on national level

Based on BSim simulations and the accompanying calculations of the heating demand in widespread Danish single-family houses, it has been possible to estimate the potential for thermal energy storage capacity (flexibility).

If Danish single-family houses outside district heating areas, are equipped with heat pumps and a control favouring flexibility, the total flexibility potential can be estimated. This was done by a simple conversion from thermal energy to electricity in heat pumps using an annual COP of 3

Table 4 shows an upscaling of the total annual flexibility for Danish single-family houses located outside district heating areas, if they were heated by heat pumps. The total flexibility (conversion from thermal storage capacity) in these houses sum to a total of 544 GWh, for the fixed (morning and evening) peak-periods only.

Table 4. Flexibility in archetype houses and upscaling to Danish houses outside district heating areas, assuming they are heated by heat-pumps (COP=3).

	Flexibility per. house kWh	Houses in BBR -	Total flexibility GWh
1850-1930	487	110 596	53.82
1931-1950	1 266	68 739	87.00
1951-1960	851	50 356	42.87
1961-1972	1 827	142 275	259.89
1973-1978	933	73 940	68.96
1979-1998	489	65 402	31.98
Total			544.53

If energy use is being moved away from peak periods, then there will be a new, but smaller peak just after the traditional peak period. The simulations are carried out for single houses, but in reality these are almost 0.5 million individual houses all with their own individual use and dynamic behaviour. The new peak period will therefore be scattered over the hours after the traditional peak. Not considering the wind dependent CO_2 emission over time, this have the potential of resulting in a smaller demand for supplemental fossil fuel for electricity production.

When houses are being renovated, the time-constant and hence the potential for flexibility will increase. A house that are being renovated will typically have unchanged thermal capacity (except for internal insulation), but lower transmission and ventilation losses due to added insulation and potentially implementation of mechanical ventilation with heat recovery.

The total electricity production in Denmark in 2018 from wind turbines was 13 915 GWh, equal to 45 % of the total Danish electricity consumption (Danish Energy Agency, 2019). The potential for flexibility in Danish single family houses in 2018 would have been 4 % of the total electricity production from wind turbines in Denmark.

Utilization of buildings' energy flexibility may result in increased annual energy demand (Déreau and Heiselberg, 2016). In most European countries, a building's energy performance is judged on its annual primary energy demand. This may be a hindrance for utilizing buildings' energy flexibility, unless some kind of "discount" is allocated to buildings offering flexibility to the grid (Edelenbos et al., 2015). This is especially important for new buildings, where a building's energy performance below a certain threshold is one prerequisite for obtaining a building permit. But also in refurbishment of existing buildings, thresholds for the energy demand is of importance.

Discussion

Dérau and Heiselberg (2016) finds a storage capacity almost 2.5 as high as in this study. Their analyses covers simulation of 365 individual days, i.e. no thermal history from previous charging/discharge cycle, each cycle with a maximum period of 6 hours charging and discharging.

Given this differences in experiment setup, results are judged as comparable.

The nature of the set-back control strategies during hours of occupation (not sleeping) will naturally compromise the thermal indoor climate. The temperature drops from the desired 22 °C towards 20 °C during the peak-periods. This is however not considered a real problem as 20-22 °C is within the comfort band for residential buildings during the heating season (DS/EN 15251:2007). Additionally, almost no hours (Table 3) are in comfort category III for all control strategies.

The indoor temperature are challenged during reheating after peak-hours when introducing a dynamic control strategy in existing houses due to slightly undersized heating systems. But replacement of existing heating systems with heat pumps offers the opportunity of increasing the installed power and in that way reduce the reheating period.

The undersized heating system simulated results in a slightly longer reheating period after peak-period set-back. This affects the indoor temperature and consequently slightly the annual energy use due to the lower average indoor temperature.

Analyses of the five remaining archetypes show similar results, however the selected example show the largest individual annual potential for thermal storage (Table 4). This archetype also have the largest time-constant (Figure 4) and the archetype is representing 27.8 % of the existing Danish single-family housing stock.

In a fluctuating electricity energy grid, primarily based on production from wind-turbines, there may be more periods with need for flexibility, hence the real flexibility from Danish single family houses could potentially be higher.

Increased flexibility

Post insulation of existing houses will increase the time-constant for the house, but the level of flexibility depends on where the insulation is placed in relation to the thermal mass. Internal insulation will decouple the thermal mass from the indoor temperature, and the amount of energy stored in the house for flexibility will decrease. External or cavity-wall insulation however, will increase the time-constant and maintain the contact between the thermal mass and the indoor temperature.

Increased air-tightness of the house, and even better combined with installation of mechanical ventilation with heat recovery, will increase the time-constant of the house. This solution maintain the amount of energy that can be stored in the thermal mass.

Adding thermal mass in the constructions of an existing house is not simple, but the request for floor-heating in combination with renovation works may open for the possibility. To utilize the storage capacity of a thermally heavy floor with floor-heating requires that the control is similar to the room temperature control, i.e. with heat supply cut off during peak periods. On the other hand, pre-heating of a floor with floor-heating installed, and compared to other constructions, more of the thermal mass in the floor can be activated.

Most existing Danish single-family houses have a water tank for domestic hot water and have a water-based heating system. This systems are in most cases reused when converting to a heat-pump heating system, e.g. air-to-water or water/soil-to-water heat-pumps. This water tank can be used as storage for the heating system if reconfigured or replaced at the end of its service life.

Price signal response

Parallel to the analyses of houses' thermal storage capacity, the measured data were used to analyse their flexibility using a price response signal. If the context of flexibility is not only peak response but price signal response all over the day, all year round, the potential of flexibility of single family can be even larger. This will be the case in near future when fluctuating renewable energy, e.g. from wind turbines dominates the electricity grid. A simulation (Palmer et al., 2020) of such a situation was made on three single family houses (Figure 6), H1, H2 and H3 represent three different houses with different characteristics.

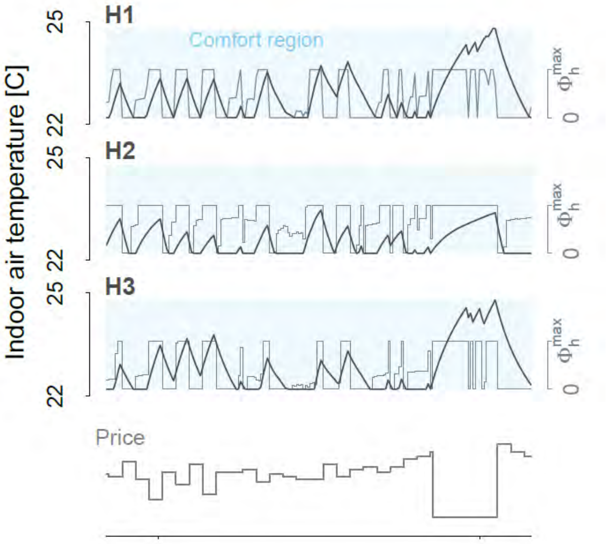

Figure 6. Grey-box simulation of the flexible control scenario for the representative houses (Palmer et al., 2020). Indoor temperature follows the schedule of heat supply, which is controlled by a price signal at the bottom of the plot.

It can be seen that when the price is low, the heating is switched on and when the price increases the heating is turned off until the temperature approaches the lower boundary. It can be noticed that the heating in H3, due to its high thermal resistance and capacity, is able to keep indoor temperature within the comfort region with the heating system running for a shorter time comparing to the other two houses. <put otherwise the heating could be

turned off for a longer time due to the building's higher time constants. The indoor air temperature in building H2 never reached the upper boundary of the comfort region due to higher heat losses.

So, in addition to the two daily peak-periods in the electricity grid, there will also be periods with insufficient electricity in a wind dominated grid. Flexibility from houses can also help shifting electricity demand from these periods. Periods with overproduction of electricity will occasionally happen during the daily peak-periods and activating houses' flexibility thus call upon some kind of signals from the grid.

Conclusions

In this study (Wittchen et al., 2020), the potential for thermal storage capacity in Danish detached single-family houses located outside district heating areas (approx. 50 % of the houses) was analysed. Analyses were carried out both statistically - based on existing measurements from night set-back experiments in 140 houses - and by simulations of archetype house models. Statistical estimates of time-constants on the simulated results were used to calibrate the archetype models.

In the future, it is assumed that all these houses will be heated by heat pumps and therefore the thermal storage capacity can be converted to flexibility (by demand side control) in the electricity grid. The energy use for houses located outside district heating areas will thus be fully electrical. If the amount of renewable electricity is insufficient during peak-periods, it must be supplemented by fossil fuel generated electricity. Shifting energy use away from peak-periods (or electricity exchange with other electricity grids) is thus needed to reduce the annual CO_2 emissions.

Six archetype models were set up, representing Danish single family houses constructed between 1850 and 1998, which covers approx. 90 % of the Danish detached single-family housing stock. Houses constructed after 1998 are excluded from the study as they are traditionally constructed from lightweight materials and have a good insulation standard. Even though these houses have long time-constants, their total energy demand is low and their individual potential for providing flexibility is limited.

Simulations of archetypes with decreased set-point for indoor temperature during peak periods give an indication of the houses' annual possibility to shift energy demand from these periods. Peak periods are defined as 2 daily periods, 2 hours in the morning and 3 hours in the evening – the latter often denoted cooking peak. Simulations also analysed the effect of pre-heating the houses 1-2 hours in advance of the peak-periods. This control strategy may potentially increase the total energy demand in some houses. This happen if the amount of stored energy during pre-heating exceeds the energy demand for maintaining a constant indoor temperature during peak-periods. Some of the stored energy will be transmitted to the outdoors because of increased temperature of the constructions in the thermal envelope instead of keeping the indoor temperature above the set-point during peak-periods. But as energy use is moved away from peak-periods it may at the same time reduce the total CO_2 emission from the electricity production as the peaks will be lower. Lowering the peaks will reduce the risk for activating fossil fuel power plants to supplement the renewable energy in a wind energy dominated electricity grid.

On this background it can be concluded that almost all Danish single family houses erected before 1998 can contribute to the grid with flexibility. This flexibility is significant and if extrapolated to all single-family houses outside district heating areas it summarises to an annual flexibility of 544 GWh, or 4% or the total Danish electricity production from wind turbines in 2018 (45% of the total Danish electricity use).

Moreover, this flexibility can be increased by simple building renovation like external or cavity wall insulation as well as replacement of windows to new ones with better insulation and air-tightness. Additionally, mechanical ventilation with heat recovery will increase the houses' time-constant and thus flexibility. More exotic, it is possible to increase the house flexibility if domestic hot water tanks are reconfigured or replaced to act as storage for the heating system.

Thus an overall conclusion is that future building renovation should be seen in the perspective of flexibility. Put otherwise energy retrofit of the existing building stock must be seen in quite another perspective than energy performance only.

Future work

The next step in the development of BSim and analyses of energy flexibility of buildings, will be implementation of a model for predictive control of a building's energy systems. The model for predictive control will enable simulating the control of heating systems and indoor climate based on the availability of wind- and/or solar-power in the grid. The control can either be based on price signals or forecasts of the weather and thus an advance simulation of the indoor climate and the availability of renewable energy in the grid.

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