The potential for utilizing energy flexible buildings to reduce district heating peak demand

The transition towards a less environmentally damaging energy system requires not only increased energy efficiency, but also requires an increased energy production from renewable energy sources. The volatile nature of the most prevalent renewable energy sources (wind, solar) introduces a much higher need for balancing services than the conventional energy production based on burning biomass of fossil fuels. In this article, we demonstrate how buildings in heating-dominated climates can contribute with flexibility in district heating systems.

Keywords: Energy flexibility, Demand response, District heating, Demand modelling, Smart-meter data

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Our need for flexibility

Building energy efficiency has been a societal priority in Denmark for almost five decades. The oil crisis in the early 1970s was the starting point for what would become a series of revisions made to the national building regulations, each increasing the requirements for the energy performance of building envelopes. These requirements have now reached a point where the agenda is set by our climate ambitions more than the real financial gain associated with the last centimetre of insulation material in the outer walls. Despite these strict requirements of the current building regulations, the reality is that for many years a large part of the building stock will continue to be characterized by the much more lenient requirements of previous building regulations. For the majority of these buildings, it will be expensive or practically impossible to achieve significant reductions in energy consumption through energy renovation measures. It is therefore clear that we cannot hope to solve our climate issues by further insulating and air tightening our buildings alone, but that our efforts to improve energy efficiency must also be complemented by other measures such as the ongoing transition to a greener energy production.

The challenge of an energy system based on a large share of renewable energy is that the production is directly dependent on weather phenomena and thus fluctuating by nature. The fluctuating supply of energy necessitates a high degree of flexibility in the rest of the energy system. This may be achieved by either establishing a large capacity for short-term storage of energy, or by making parts of the energy consumption itself flexible. In recent years, researchers have therefore investigated which energy-consuming activities in our society that could potentially deliver this flexibility. Since a degradation of consumer comfort is rarely a successful route to take, the task is therefore to identify the parts of consumption that can be manipulated without imposing additional costs or a loss of comfort for the consumer. Some of these potential sources of energy flexibility include chargers for electric vehicles and home appliances that can be configured to start only when production is sufficient, and the electricity grid is not overloaded. Research is also being conducted on the extent to which the heat consumption in our buildings can be made flexible due to the large amounts of energy involved; 27% of all energy use in European Union is for space heating according to euroheat.org. Since the electricity grid is particularly sensitive to imbalances between production and consumption, most of the research on the potential of energy flexibility focuses on the electricity-based heating forms. Nevertheless, flexibility is also relevant in district heating, where, for example, flexible consumers can help to reduce peak loads, thereby lowering the necessary capacity in the heat production and the associated distribution networks. Freeing up capacity in distribution networks is highly relevant as it opens up the possibility for lowering the supply temperature in the district heating network, thereby lowering heat losses in the distribution grid and increasing the efficiency of the overall district heating system.

Energy flexible buildings

In district heating systems, the morning peak caused by the many coincidental showers of consumers is a recurring daily phenomenon. The morning peak on the dimensioning day results in a direct increase in the necessary production and distribution capacity in the district heating network. Since the consumption of domestic hot water, which together with night setback schemes is the primary cause of the morning peak, is closely related to the daily routines in the household, we do not consider this part of district heating consumption to be flexible in practice. Therefore, if we want to reduce the morning peak in order to lower the necessary capacity in the system, we must do so by creating a corresponding valley in the second of the main components of district heating consumption: space heating. Part of this consumption can be made flexible if we part with the practice of setting a *temperature set point* for our heating systems, but instead specify the *range of temperatures* that we as consumers consider comfortable. Such a comfort range can be adapted to the preferences of the individual consumer, and could for instance define that room temperatures should be maintained between 20°C and 23°C at all times throughout the heating season. The fact that such a comfort range allows us to use advanced control schemes to impose subtle and controlled temperature fluctuations in the building creates opportunities for shifting heating consumption in time - for example by preheating the building prior to the morning peak in consumption. The Danish building tradition's large use of heavy building materials such as bricks and concrete creates favourable conditions for this passive storage technique where thermal energy is stored directly in the thermal mass of the heavy building components.

To demonstrate the potential of energy-flexible buildings, we have modelled the district heating consumption in 159 detached single-family houses located in the city of Aarhus, Denmark. We have used time series of hourly consumption data has been made available to us for research purposes by the local district heating supplier *AffaldVarme Aarhus*. This consumption data, derived from remotely read *Kamstrup* heat meters, is used to calibrate and validate mathematical models of the thermodynamic properties of each individual building together with an associated model for the daily distribution of domestic hot water consumption. The building model thereby describe the weather-dependent consumption, while the models for hot water consumption describe the weather-independent consumption. **Figure 2** presents the consumption predicted by the models and compares it to the measured consumption – first for two individual single-family houses and finally for the aggregated 159 buildings. In the case of the depictions of individual buildings, we have highlighted some of the peculiarities that inevitably make their way into consumption data from in-use buildings. The highlight in the first graph shows an event where the consumption seizes for a short dura-

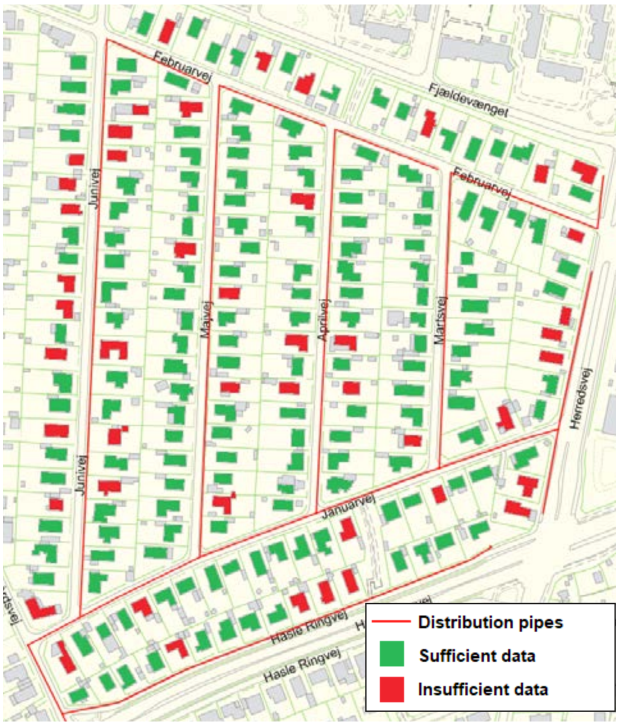

Figure 1. Map of the modelled residential area.

tion followed by a kickback where the heating system is likely reheating the building. Since this temporary drop in consumption was seen for multiple buildings simultaneously, we assume maintenance work in the district heating network a likely cause. The highlight for the second building marks a Danish holiday week, where the sudden absence of domestic hot water peaks would suggest that the building is indeed vacant.

From comparing the measured and predicted time series on the single-building scale, it is clear that the stochastic nature of especially the domestic hot water consumption is a cause of discrepancy between the models and the actual measurements. A part of this is due to the assumptions made in the model of domestic hot water consumption, in which we assume that the domestic hot water consumption follows the same daily pattern on all weekdays. Similarly, we assume a separate consumption profiles to apply to all weekend days. While the method of calibrating the average daily weekday and weekend profiles inevitably simplifies the true stochastic consumption patterns of residential occupants, these effects are averaged out once we move to a larger scale. This is evident from the third graph in **Figure 2**,

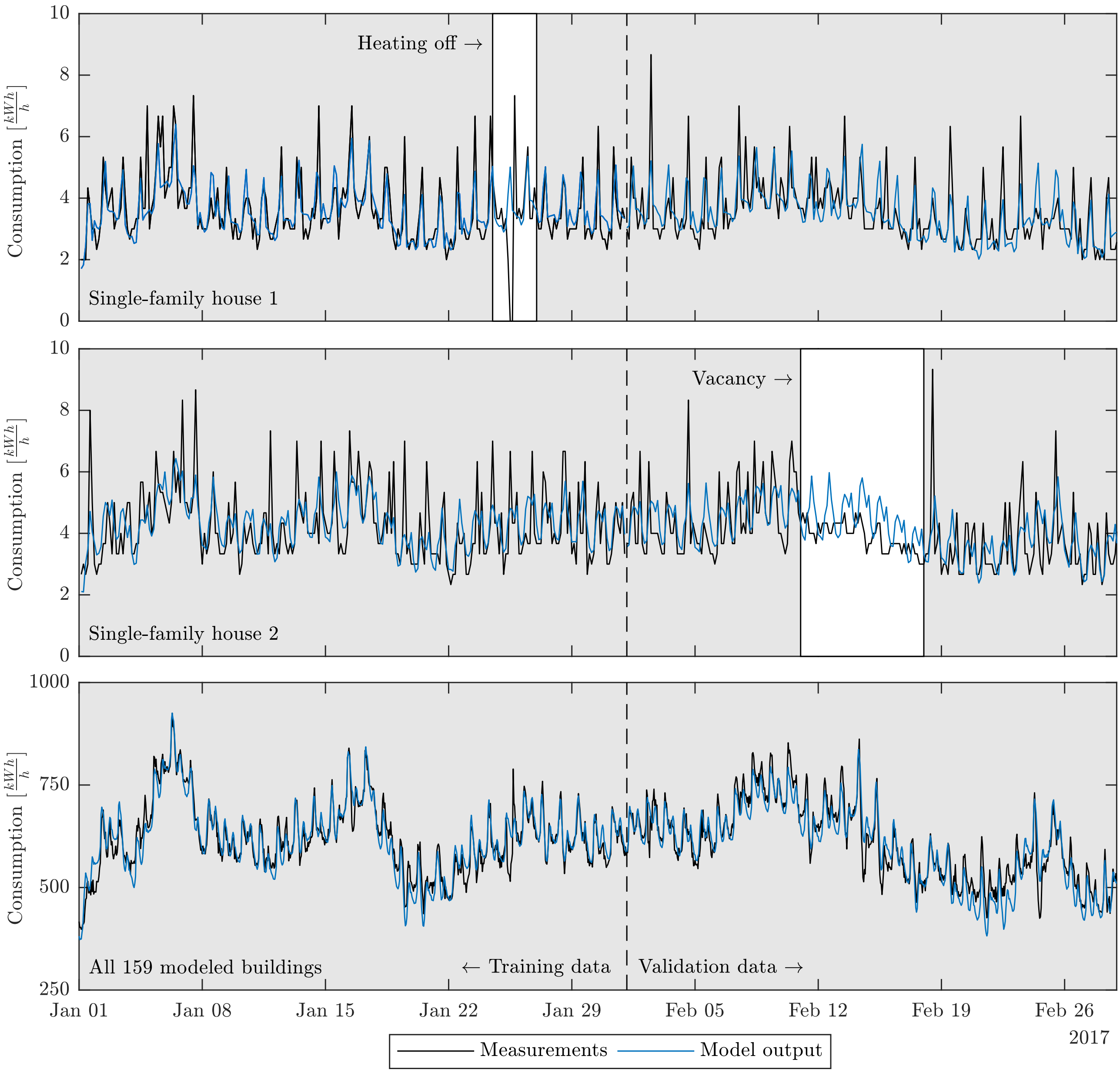

Figure 2. Comparison between measured consumption and model predictions. The top and middle graphs depict time series for two single-family houses, while the third depict the aggregated neighbourhood (159 single-family houses). The vertical dashed line separates the data used to calibrate the models (left side), and the data used for validation purposes (right side).

in which we depict the combined consumption of all of the 159 buildings. Here, the models are capable of predicting the daily variation caused by domestic hot water consumption with a high level of accuracy. Since the combination of the models of building thermal dynamics and domestic hot water usage describes the district heating consumption in the single-family houses quite accurately, we can use them to test different strategies for utilizing energy flexible buildings and thereby map the potential associated with them.

Smoothing the morning peak

In Aarhus, the coldest hour of the 2016/2017 heating season fell in the early morning hours of January 6, 2017. **Figure 2** shows a simulation of the 159 single-family houses' total district heating consumption in the surrounding days, separated into the space heating component and the hot water component respectively. The figure shows the starting point where all the buildings are heated to a constant temperature throughout the day and where the highest aggregated consumption for the group of buildings reaches an hourly average of 925.3 kW. The red mark indicates the proportion of space heating consumption that is moved as we utilize flexible consumption to reduce the buildings' maximum district heating demand by 10 percent.

In order to avoid creating a new peak in the hours when we preheat the buildings, it is important to coordinate which buildings to preheat - and just as importantly when to begin preheating them. The blue marking in **Figure 3** shows how our preheating efforts may be coordinated such that we can eliminate the consumption in the red making on **Figure 4** without causing a formation of new peaks, and thereby achieve the 10 percent reduction of the maximum demand for district heating. The energy stored in the thermal mass in the activated buildings during the preheating process is released slowly as soon as the space heating is lowered and the room temperature begins to drop towards the lower limit of the comfort range. When the lowest permissible temperature is reached, the building's heating system ensures that the temperature does not drop any further. One consequence of this storage technique is that some of the stored heat is released only after the morning rush is over, as can be seen by the elongated tail of the red marking in **Figure 4**.

The example shows that energy-flexible buildings are not only relevant in the smart electricity supply of the future, but can also contribute to value creation in the district heating sector and, by extension, district heating consumers. One challenge associated with activating the flexibility potential associated with space heating in buildings is that predictive control schemes are necessary to ensure that the flexibility is utilized in the most appropriate way. One of the reasons for this is that it is not free to move energy consumption in time: in the example, it required on average 1.31 kWh preheating (the blue mark) to move 1 kWh out of the morning peak (the red mark). This energy loss is due to

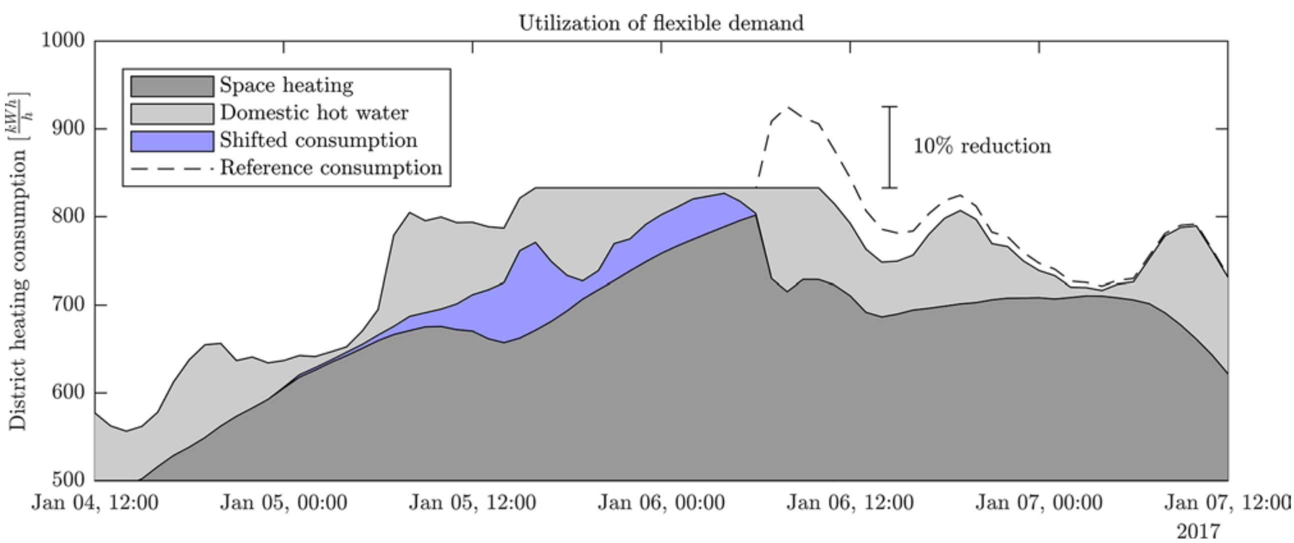

Figure 3. Simulated consumption under utilization of flexible consumers. The blue marking highlights the consumption dedicated to preheating a group of the buildings in the area in such a way that a 10% decrease in the peak demand is achieved.

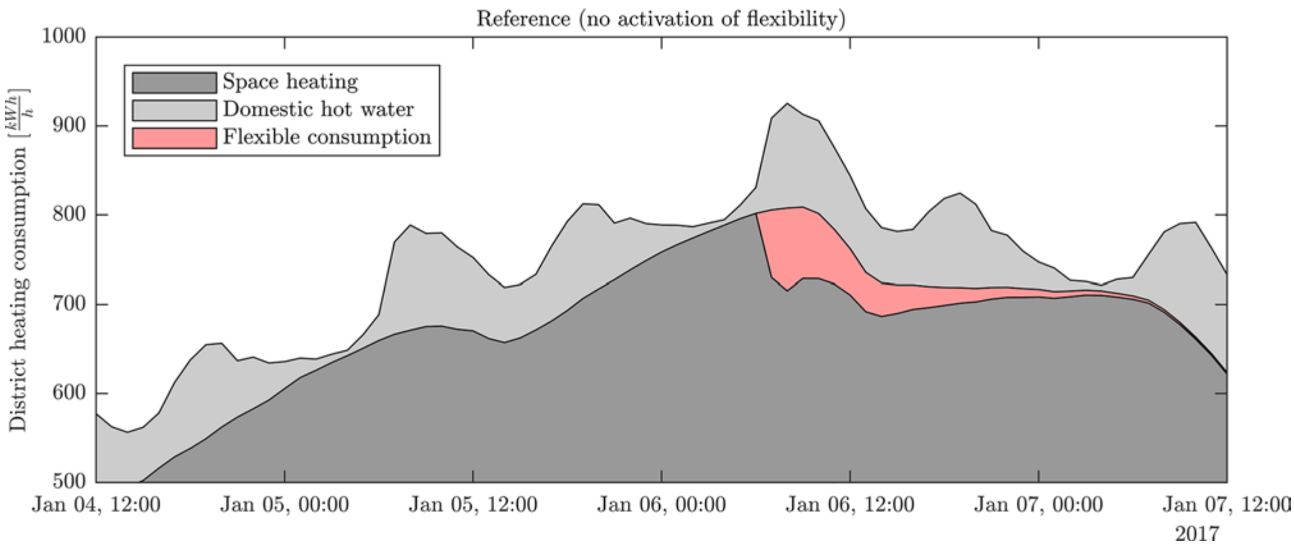

Figure 4. Simulated district heating consumption in the modelled 159 residential buildings. The models of building thermal dynamics and domestic hot water consumption are used to depict the consumption as the potentially flexible demand for space heating and the inflexible demand for preparation of domestic hot water. The red marking shows the part of the reference consumption that will be shifted in time in this example (see **Figure 3**).

increased heat loss during preheating, and thus depends both on the energy efficiency of the buildings and on how early it is necessary to start preheating. Another reason is that, especially during transitional periods, we can easily risk that preheating of the building in the early morning hours will end up causing the building to overheat in the afternoon due to solar heat gains, thus resulting in comfort-issues for the occupants. To avoid these issues, predictive control strategies combine a model of the building's thermal dynamic properties with forecasts of weather and internal heat loads to optimize the control strategy in terms of both economy and thermal comfort. Obtaining models sufficiently precise for control purposes is therefore a concrete obstacle to realizing this so-far untapped flexibility potential. As seen in this article, the availability of time-resolved consumption data is a good starting point to be able to map the potential in more detail and develop methods for establishing the necessary building models. ■

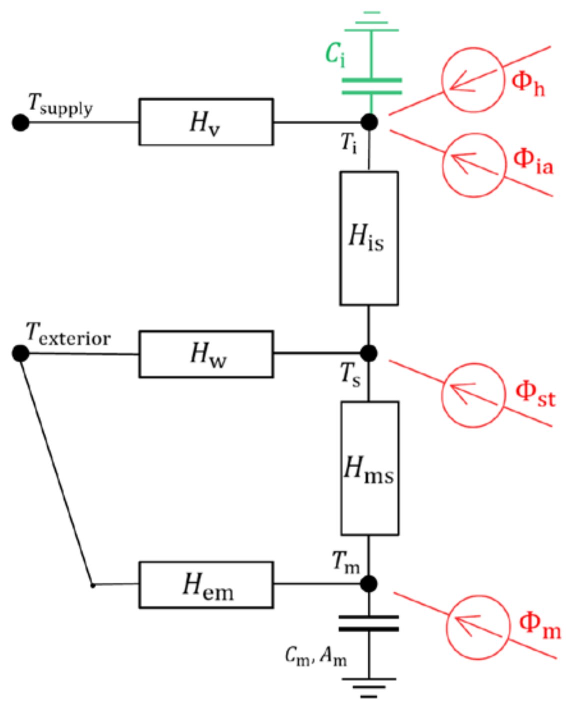

Figure 5. Second order resistance-capacitance model structure used to describe space heating demand.

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