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Expanding Building Archetypes to Estimate the Indoor Environment Thermal Storage Capacity in the Danish Building Stock when Performing Demand Response

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Abstract

Short-term demand response leveraging the energy flexibility of the building stock is a key solution to decarbonise and ensure the reliability and sustainability of smart energy grids dominated by intermittent renewable energy sources. Most of the building demand response capacity depends on different forms of energy storage in the built environment. In addition to electric batteries, hot water storage tanks, ground source heat exchanger or dispatchable on-site renewable energy sources, buildings possess a tremendous thermal storage capacity within the thermal inertia of their structure and indoor environment. The latter can easily be harnessed with heating/cooling indoor temperature setpoint modulation strategies. However, there is a clear lack of large-scale estimates of this indoor environment thermal storage capacity in the different building stocks. To tackle this issue, detailed dynamic numerical models of the different building typologies in European countries are generated to assess the potential of demand response strategies at nationwide levels. The current paper presents the preliminary results on the thermal storage capacity in the Danish building stock when performing heating temperature setpoint modulation. These results are based on estimates of the effective thermal inertia of the different building archetypes in Denmark. They show that the Danish building stock contains immense thermal storage capacity, which is comparable to all combined batteries in a large fleet of electric vehicles or all industrial-size storage tanks in district heating plants.

Introduction

With the current massive deployment of intermittent renewable energy sources (RES), the different energy grids will require much higher flexibility and storage capacity to operate correctly. For instance, the flexibility requirements in the European Union's electricity grid are expected to double by 2030 and septuple by 2050, reaching 25% and 80% of today's electrical power demand in 2030 and 2050, respectively [Koolen et al., 2023]. In the U.K., in 2023, the electricity storage capacity is 6.6 GW, but it should reach 38.4 GW (+480%) in 2035 [ESO, 2024].

In this context, Building-to-Grid (B2G) services in the form of demand response are key solutions to provide energy flexibility and storage capacity, thus enabling reliable, efficient, decarbonised, cost-effective, and sustainable energy grids [Jensen et al., 2019].

Building energy flexibility is the ability of a building to adapt or modulate its short-term (from a few hours to a couple of days) energy demand and energy generation profile according to climate conditions, user needs and energy network requirements (B2G services) without jeopardizing the technical capabilities of the building systems and the comfort of its occupants [Jensen et al., 2019; Johra et al., 2023].

This building energy flexibility can be leveraged to perform short-term demand response actions, such as peak shaving (reduction of the peak power demand), load shifting (anticipating or delaying the energy use) or valley filling (increase energy use when the energy demand is lower than the energy supply) (see Figure 1).

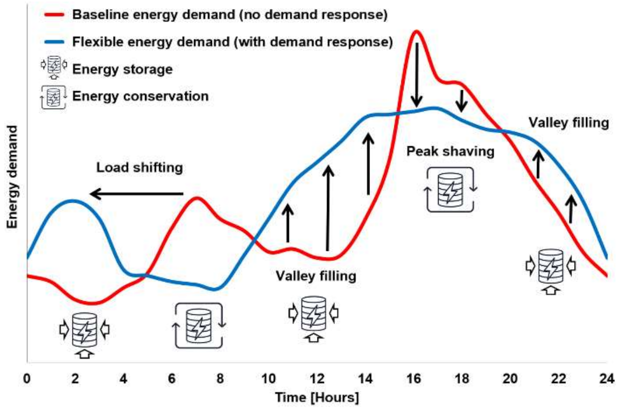

Figure 1: Examples of building energy flexibility measures and demand response actions [Johansen and Johra, 2022].

If employed appropriately, building demand response can help match the end-user energy demand to the RES supply, stabilize the voltage and frequency of electrical grids, decrease supply temperature and minimize return temperature for district heating networks (and vice versa for district cooling networks), minimize expensive reinforcements or extensions of the networks, mitigate local distribution bottlenecks, limit the needs for operating costly and CO2-intensive peak power generators, and reduce necessary installation of additional energy storage infrastructures.

For instance, it has been estimated that demand response and B2G services could generate $100-$200 billion of cost savings and a 6% CO2 reduction for the US power sector by 2030 [Satchwell et al., 2021]. Moreover, 50% of the dispatchable capacity on the Australian electricity network could be provided by B2G services [Australian Energy Market Operator, 2022]. Globally, it is estimated that commercial and residential energy storage systems could supply 510 GW of flexible power modulation (10% of the total electricity supply) in 2030 [International Energy Agency, 2022].

The majority of building demand response actions depend on different forms of energy storage in the built environment. The most common sources of building energy flexibility are listed below:

- Flexible loads from heating-ventilation-air-conditioning (HVAC) systems, sanitary hot water production, charging of electric vehicles (EVs) connected to the building, or white good appliances with shiftable operation, e.g., dishwashers or washing machines.
- Dispatchable on-site RES production, e.g., solar panels.
- Active energy storage systems, e.g., electric battery kits, batteries embedded in connected EVs, hot water storage tanks, phase change material storage, or ground source heat exchangers.
- Passive heat storage in the thermal mass/inertia of the building elements and indoor environment.

The current paper focuses on this last point: the untapped and readily available storage capacity that is intrinsically present in each building within the thermal inertia of its structural components, indoor environment, indoor air, furniture, and other indoor items [Johra and Heiselberg, 2017].

This indoor thermal inertia can be leveraged to store thermal energy by means of short-term indoor temperature setpoint modulation for the heating and cooling systems. Smart thermal management via temperature setpoint modulation can easily be implemented in commercial, public, and office buildings equipped with a building management/automation system, and in residential buildings that have smart home automation systems, such as a smart thermostat. The heating/cooling activation in the building can thus be locally optimised based on the occupants' comfort requirements and an incentive signal broadcasted by the energy grids (e.g., energy spot price or grid CO2 intensity), which only requires a one-way communication infrastructure. A more complex control architecture could consist of a bidding market for demand response, which would require a bi-directional communication system with an aggregator and a bidding/clearing platform.

This demand response strategy was found promising and more cost-effective than other storage solutions to balance the intermittence of RES [Le Dréau and Heiselberg, 2016; Johra et al., 2019; Hedegaard et al., 2012]. It has the potential to provide significant energy storage capacities at 20% of the price of equivalent electric battery alternatives.

Despite the proven potential of demand response by temperature setpoint modulation and the growing interest in aggregated energy flexibility at building cluster scales, there is a clear lack of large-scale estimates of the energy storage capacity an entire building stock can offer [Le Dréau et al., 2023]. To tackle this issue, the present research aims at creating detailed dynamic numerical models of the different building typologies in European countries and uses these models to test and assess the potential of demand response strategies at nationwide levels. This paper presents the preliminary results on the thermal storage capacity in the indoor environment of the Danish building stock when performing heating temperature setpoint modulation.

Methodology

The main workflow of this study consists in expanding the description of the building archetypes identified by the TABULA project [IEE Project TABULA, 2012] for assessing the energy demand of 13 different European building stocks. Based on these archetype characteristics and corresponding statistics from national building registries, more detailed descriptions of these archetypes are generated. Dynamic numerical models of these archetypes are then created and calibrated with different modelling tools (e.g., EnergyPlus, IDA ICE or BSim). These models are intended to be readily available for the building community for all sorts of numerical investigations and will be used to test different demand response strategies on entire national building stocks in the near future.

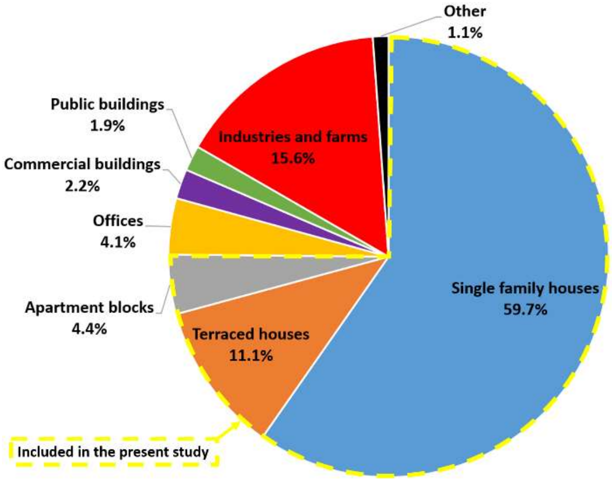

Figure 2: Overview of the Danish building stock: Distribution of the number of different building types in the Danish stock (heated buildings only) [StatBank Denmark BYGB40].

In this paper, however, the investigations are limited to directly estimating the indoor environment thermal storage capacity of the single-family houses, the terraced houses and the apartment blocks in the Danish building stock. Although not covering all building typologies, this represents around 75% of all conditioned buildings in Denmark and about 70% of the entire heated floor area in the Danish building stock (see Figure 2 and Figure 3).

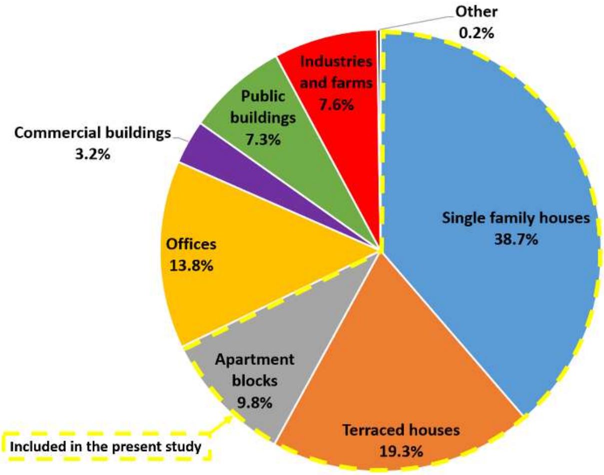

Figure 3: Overview of the Danish building stock: Distribution of the total heated area for each building type in the Danish stock [StatBank Denmark BYGB40].

Clear descriptions of all construction elements composing the different archetypes for the Danish residential building stock are generated, including dimensions, occupancy schedules, material thermal properties of the different construction layers, windows' characteristics, envelope performance and HVAC systems. These detailed archetype descriptions are based initially on the simplified descriptions from the TABULA registry for Denmark [Wittchen and Kragh, 2012]. They are slightly adjusted so that, when implemented in the developed dynamic numerical models (BSim, IDA ICE, EnergyPlus), the transmittance of the building envelop elements is in good agreement with that of the corresponding building categories in the Danish building registry [Kragh and Wittchen, 2010].

Those envelop transmittance adjustments mainly consist of slightly altering the thickness and thermal conductivity of the insulation layer and claddings (ensuring that the adjusted values are realistic and close to what can be found in real buildings). Despite matching the envelop transmittance, the total heating demand simulated by the numerical models might differ significantly from that of a corresponding building archetype in the Danish building registry. These discrepancies are expected and relatively common. They can be explained by the differences in the actual boundary conditions for the weather, the occupancy schedule and the internal loads, as well as the uncertainties in the modelling of the geometries, heat, air and moisture transports, solar radiation distribution and building systems' operation.

From these detailed descriptions of the construction elements, it is possible to calculate the effective thermal inertia of all surfaces in contact with the indoor environment (internal sides of the external walls, ceilings and floors; both sides of the interior partition walls and floor separations). The calculation of the effective thermal inertia of each planar building element is thus conducted according to the dynamic thermal characterisation method of the ISO 13786:2007 standard. Three different

Table 1: Key characteristics of the analysed building archetypes in the Danish stock.

Archetype	Number of buildings (% of entire building stock)	Total heated area [m^2] (% of entire building stock)	Yearly energy need [kWh/m^2]	Effective thermal inertia 1h modulation [Wh/K.m^2]	Effective thermal inertia 5h modulation [Wh/K.m^2]	Effective thermal inertia 24h modulation [Wh/K.m^2]
Single-family house (<1850)	35 500 (1.4%)	17 200 000 (3.2%)	199	5.3	19.7	51.3
Single-family house(1851-1930)	335 000 (13.6%)	48 500 000 (9%)	151	6.7	26.7	79.5
Single-family house (1931-1950)	150 000 (6.1%)	21 000 000 (3.9%)	167	6.8	27.6	81.5
Single-family house (1951-1960)	121 000 (4.9%)	14 900 000 (2.8%)	183	8.3	32.6	80.8
Single-family house (1961-1972)	340 000 (13.8%)	44 650 000 (8.2%)	129	5.5	24.9	71.3
Single-family house (1973-1978)	175 000 (7.1%)	24 300 000 (4.5%)	86	5.7	25.1	76.3
Single-family house (1979-1998)	178 000 (7.2%)	48 900 000 (9%)	98	5.5	23.5	72.0
Single-family house (1999-2006)	74 000 (3%)	9 745 000 (1.8%)	81	5.5	21.9	63.4
Single-family house (2007-2013)	58 500 (2.4%)	8 836 000 (1.6%)	61	4.9	20.4	63.2
Terraced house (<1850)	4 000 (0.2%)	517 000 (0.1%)	125	8.4	33.1	100.9
Terraced house (1851-1930)	26 000 (1.1%)	3 518 000 (0.6%)	121	8.4	33.1	99.1
Terraced house (1931-1950)	15 000 (0.6%)	1 973 000 (0.4%)	128	7.4	28.8	84.4
Terraced house (1951-1960)	16 000 (0.6%)	2 260 000 (0.4%)	134	4.7	19.1	54.9
Terraced house (1961-1972)	32 000 (1.3%)	4 675 000 (0.9%)	109	7.7	32.4	98.5
Terraced house (1973-1978)	25 000 (1%)	3 800 000 (0.7%)	97	7.1	26.1	65.4
Terraced house (1979-1998)	82 000 (3.3%)	13 000 000 (2.4%)	80	5.2	22.3	63.3
Terraced house (1999-2006)	25 000 (1%)	4 120 000 (0.8%)	73	5.4	22.4	63.1
Terraced house (2007-2013)	18 000 (0.7%)	2 800 000 (0.5%)	64	5.3	21.8	61.1
Apartment block (<1850)	2 400 (0.1%)	1 100 000 (0.2%)	131	5.3	21.1	54.1
Apartment block (1850-1930)	45 000 (1.8%)	28 500 000 (5.3%)	174	5.3	21.5	56.0
Apartment block (1931-1950)	17 400 (0.7%)	15 610 000 (2.9%)	150	7.2	28.2	70.6
Apartment block (1951-1960)	17 400 (0.7%)	8 705 000 (1.6%)	120	4.8	18.3	60.8
Apartment block (1961-1972)	7 700 (0.3%)	15 225 000 (2.8%)	113	5.3	23.6	74.4
Apartment block (1973-1978)	2 900 (0.1%)	5 656 000 (1%)	88	5.3	24.5	80.3
Apartment block (1979-1998)	10 500 (0.4%)	9 600 000 (1.8%)	101	5.3	23.6	74.8
Apartment block (1999-2006)	4 200 (0.2%)	2 630 000 (0.5%)	88	5.3	24.5	81.5
Apartment block (2007-2013)	3 000 (0.1%)	4 600 000 (0.8%)	80	5.3	23.9	75.9
All archetypes of current study	1 820 500 (73.7)	366 320 000 (67.7%)	127 *	5.9 *	24.6 *	71.5 *
Remaining buildings	648 700 (26.3%)	174 999 000 (32.3%)	-	5.9 *	24.6 *	71.5 *
Entire heated building stock	2 469 200	541 319 000	-	5.9 *	24.6 *	71.5 *

* Area-weighted average of all assessed archetypes

sinusoidal temperature variation (modulation) periods are considered for calculating the effective thermal inertia: 1 hour, 5 hours and 24 hours, respectively. These modulation periods correspond to very short, typical and long temperature setpoint modulation, respectively. If most of the dynamic price-based control setpoint modulations typically occur for only a couple of hours, well-insulated buildings with appreciable thermal mass and large time constants can shift their heating demand over more than 24 hours [Le Dréau and Heiselberg, 2016; Johra et al., 2019].

The effective thermal inertia of the entire building archetype is obtained by summing up the effective thermal inertia of each of its components. The thermal storage capacity of the indoor environment of each archetype is then calculated by assuming a temperature setpoint modulation for heating/cooling of 4 K (±2 K modulation from the neutral setpoint) [Johra et al., 2019].

As mentioned above, the effective thermal inertia estimate is currently limited to 27 archetypes for detached single-family houses, terraced houses and apartment blocks for multi-family dwellings in Denmark. Office, public, commercial, farm and industrial buildings will be thoroughly described, modelled and assessed in the near future. To estimate the effective thermal inertia of those remaining buildings, it is assumed that their specific effective thermal inertia (respective to the heated surface area) is equal to the area-weighted average specific thermal inertia of all previously calculated 27 archetypes (see Table 1).

The thermal storage capacity of each archetype is then multiplied by the number of corresponding buildings in the entire Danish stock and all summed up to obtain the total thermal storage capacity of all heated buildings in Denmark for different indoor temperature setpoint modulation durations.

For the sake of useful comparison, the different estimates of indoor environment thermal storage capacity are presented side by side with the total heat capacity of all industrial-size hot water storage tanks in all Danish district heating plants [Jessen, 2015], and the storage capacity of electric batteries of all passenger cars in Denmark if the entirety of the fleet would be EVs (i.e., 2 594 000 vehicles)[Eurostat, 2020].

Finally, the time constant is another essential characteristic that is linked to the capacity of a building to perform demand response and load shifting using heating/cooling temperature setpoint modulation. In the present study, this building's (theoretical) time constant has been estimated from the effective heat capacity, the envelope transmittance and the ventilation/infiltration heat losses calculated from the enriched description of each archetype.

Results and discussion

The main result of the present paper is the nationwide estimate of the total indoor environment thermal storage capacity in the entire Danish building stock when performing demand response by means of heating temperature setpoint modulation. One can see in Figure 4 that this thermal storage capacity is quite significant, ranging from 13 GWh (for a short-term modulation of 1 hour) to 130 GWh (for a longer modulation of 24 hours).

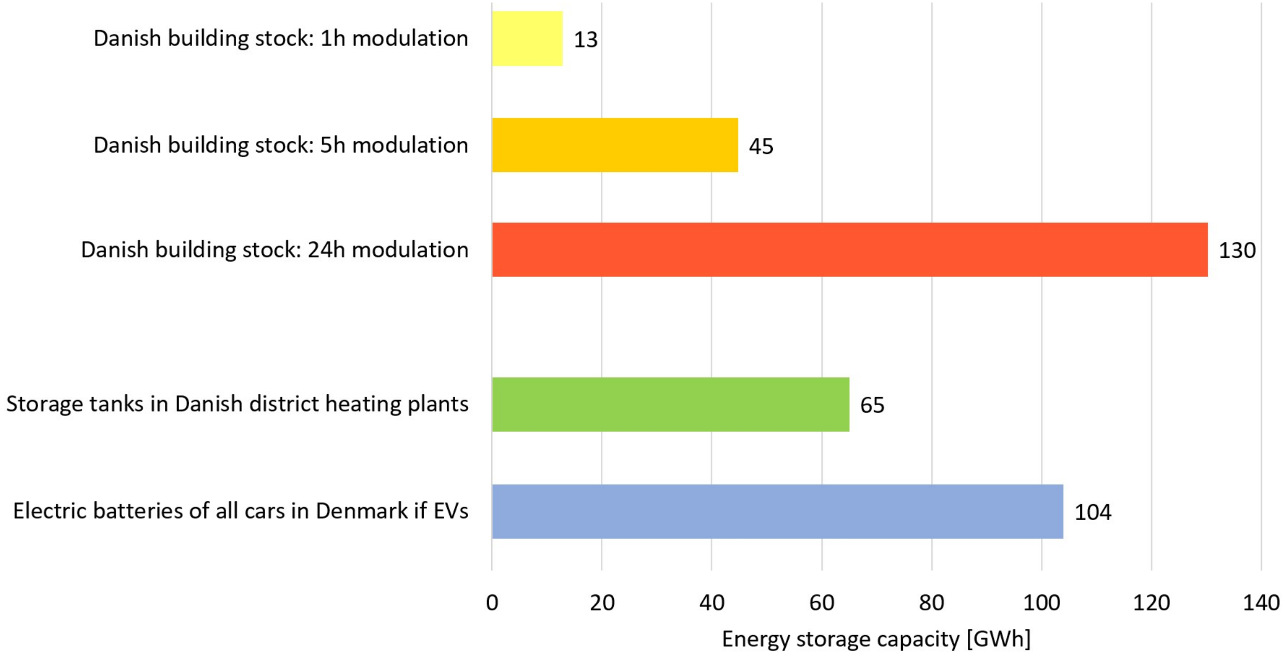

Figure 4: Estimates of the thermal storage capacity in the indoor environment of the entire Danish building stock compared with other key storage sources.

When aggregated at a large scale, this readily available storage capacity is thus equivalent to that of all industrial-size water storage tanks installed in district heating plants or what could be provided by the batteries of an entire fleet of EVs if all passenger cars in Denmark were electrified.

Moreover, the storage capacity with a 1-hour modulation is about half of the daily residential electricity demand, the storage capacity with a 5-hour modulation is about half of the daily electricity demand in the entire Denmark, and the storage capacity with a 24-hour modulation is equivalent to the daily heat production from all district heating plants in Denmark combined, or the entire heating demand from the Danish residential buildings during a winter day [Danish Ministry of Climate, Energy and Utilities, 2015; Danish Energy Agency, 2021].

It should be noted that the energy storage in the buildings' thermal mass is available at all times, while the electrical storage in EVs is only possible when the latter are connected to a building or a charging station. On the other hand, energy stored in the form of electricity has a higher usefulness (high-grade energy) than low-temperature (low-grade) thermal energy.

In addition, one should be aware that the thermal storage capacity and thermal storage efficiency of the indoor environment in a building are highly dependent on the energy performance of the building envelope. The insulation class of the building is the primary factor influencing its heat storage capacity and load-shifting efficiency [Johra et al., 2019]. It is thus expected that the global indoor thermal storage performance and, therefore, building energy flexibility of the entire stock will tend to increase with the continuous renovation efforts in the different countries and the tightening of the building regulations pushing for more energy-efficient building envelopes.

However, the correlation is very weak when comparing the effective heat capacity of the different Danish buildings as a function of their normalized envelope thermal performance or their space heating need (see Figure 5 and Figure 6).

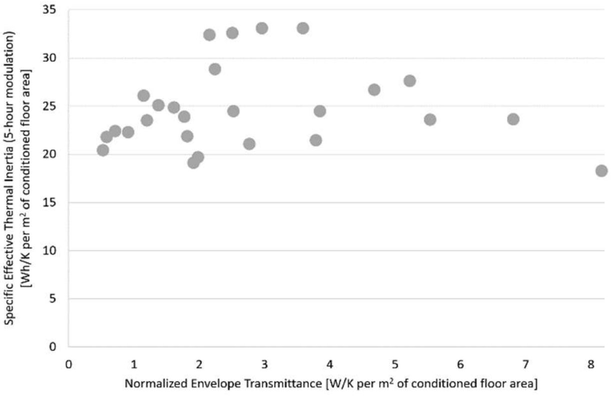

Figure 5: Effective thermal inertia (heat capacity for a 5-hour modulation) as a function of the normalized envelope transmittance in the Danish building stock.

This weak correlation could be explained by the difference in the configuration and composition of the different construction elements in the buildings, with newer ones having slightly less overall thermal mass than old ones.

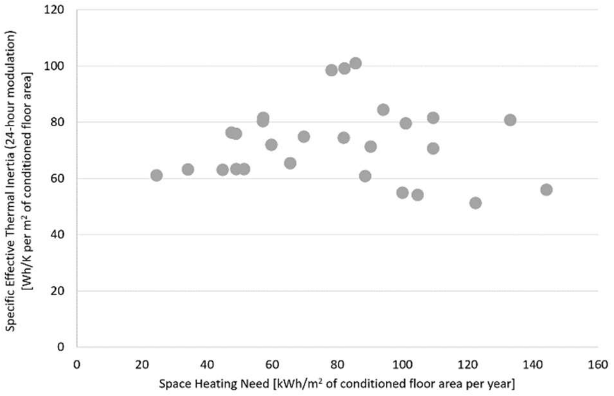

Figure 6: Effective thermal inertia (heat capacity for a 24-hour modulation) as a function of the space heating need in the Danish building stock.

On the other hand, one can observe in Figure 7 and Figure 8 the very strong correlation between the building's theoretical time constants and the space heating need of the different archetypes in the Danish stock. A higher time constant for the indoor environment is related to a higher building energy flexibility for heating/cooling setpoint modulation. Once the indoor space is "charged" (pre-heated or pre-cooled), the heating or cooling system can be modulated down or switched off. The higher the building time constant, the longer it will take for the indoor temperature to significantly change to the point that it compromises the occupants' thermal comfort. It can thus be concluded that newer or renovated buildings with better envelope thermal performance (i.e., lower space heating needs) offer a higher and more efficient thermal storage capacity in their indoor environment to perform load shifting and peak shaving.

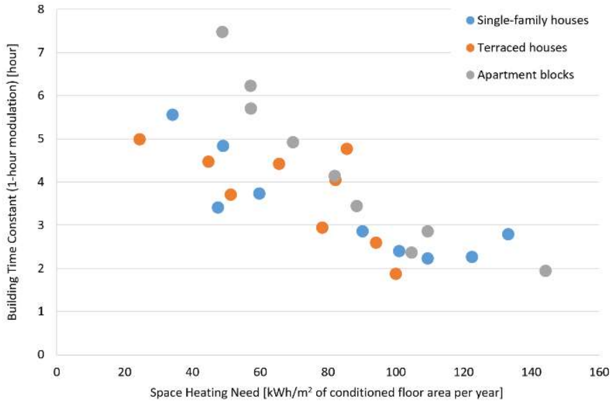

Figure 7: Building's theoretical time constant (indoor environment for a 1-hour modulation) as a function of the space heating need in the Danish building stock.

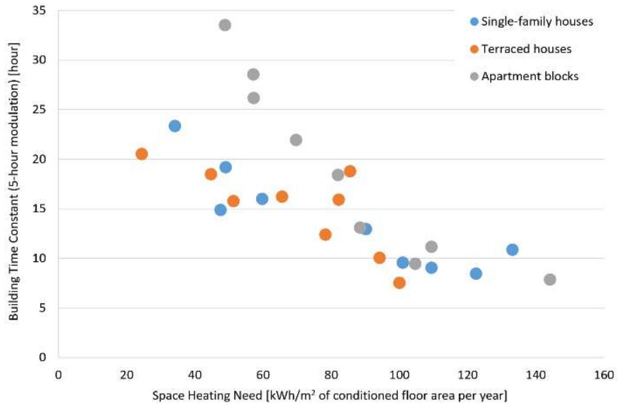

Figure 8: Building's theoretical time constant (indoor environment for a 5-hour modulation) as a function of the space heating need in the Danish building stock.

Conclusions and future work

The present preliminary estimate of the nationwide thermal storage capacity in the indoor environment of the Danish building stock clearly shows the massive demand response potential that the latter can provide. This untapped and already existing energy storage capacity is comparable in size to that of all industrial-size storage tanks in the district heating plants or that of a future large fleet of EVs.

A large share of the energy demand/supply from/for the building sector could be stored over short periods in the built environment by pre-charging (increasing indoor setpoint temperatures) before peak hours and reducing heating demand (decreasing indoor setpoint temperatures) during peak hours. This can be deployed at low costs within existing building automation/management systems and new smart home technologies to leverage the dynamic tariff structures that are more and more commonly offered by the different utility companies, energy providers and demand response aggregators.

Although currently limited, the authors of the present study hope that these preliminary results and the following detailed investigations on the matter will support and foster the development of building energy flexibility strategies and the rapid deployment of B2G services at a large scale to support optimal, reliable and sustainable operation of smart energy grids.

This study will continue with the systematic development of detailed archetype descriptions for the different building stocks of Europe. Although the TABULA project provides typologies for a large share of the building stocks, there are no archetypes of office buildings, public facilities, commercial buildings, farms and industrial infrastructures. This gap will be bridged.

For each archetype, dynamic building models will be created and calibrated with various popular building simulation tools (e.g., EnergyPlus, IDA ICE, BSim or low-order RC networks state-space models as grey-box models). These descriptions and models will then be used to assess different building demand response strategies and calculate B2G service performance and energy storage capacities in multiple ways and at large scales.

Acknowledgement

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