Thermal storage capacity in the entire building stock of Denmark for energy flexibility strategies and building-to-grid services

HICHAM JOHRA
Aalborg University,
Department of the Built
Environment, Denmark

MAXIME GOUPY
Aalborg University,
Department of the Built
Environment, Denmark

KIM B. WITTCHEN
Aalborg University,
Department of the Built
Environment, Denmark

Building-to-grid services by means of short-term demand response (shifting energy demand in time, peak power demand shedding or load profile reshaping) are key to decarbonising and optimising energy grids comprising an ever-growing share of intermittent renewable energy sources.

Keywords: Demand response, building energy flexibility, building stock thermal storage, load shifting, building-to-grid services

Buildings have an enormous untapped potential to perform demand response thanks to their energy flexibility. These building energy flexibility actions mainly rely on different forms of energy storage (e.g., electric batteries, water tanks) or dispatchable on-site energy supply and services. The thermal inertia of the indoor environment also holds a large energy storage capacity, which can easily be leveraged with heating/cooling temperature setpoint modulation. If this approach has proven promising for building demand response, large-scale capacity estimates are lacking. This article gives an estimate of the heat storage capacity in the indoor environment of the entire building stock in Denmark. The latter is comparable to that of all combined batteries in large fleets of electric vehicles or the entirety of industrial-size storage tanks in district heating plants. The indoor environment of the building stock is a readily available and massive thermal storage tank awaiting to be used to help the grids at minimum costs.

Motivations

In the current challenging energy and environmental context with climate change, the need to decarbonise and electrify the different energy grids (electrical grid, district heating and cooling networks), the transition from fossil fuels to fluctuating renewable energy sources (RES) and the tightening sustainability constraints, an important paradigm shift is needed and currently initiated.

The operation of energy infrastructures is drastically changing: CO_2-intensive peak power generators must be phased out while maintaining grid stability with a large share of intermittent and decentralised RES. It was demonstrated that demand-side management (i.e., the modulation of the energy demand) can alleviate the aforementioned challenges. Demand response and energy flexibility measures are short-term demand-side management strategies. They can, e.g., help stabilise voltage and frequency in electrical grids, eliminate peak power limitation and local bottlenecks in energy networks, reduce the use of CO_2-intensive peak power generators, lower costly needs for reinforcement and extension of energy infrastructures and prevent the deterioration of hydronic networks caused by the unstable operation.

Buildings are the largest energy end-users. For a long time, they were considered as immutable and non-responsive loads. In reality, the building stock can change and adapt its energy demand. It also performs sector coupling between the different energy grids and transportation. Buildings are becoming more energy efficient. Decentralised prosumers and energy communities are emerging everywhere. The future of the built environment is pointing towards grid-interactive smart buildings performing demand response to provide services to the grids and match demand and energy supply from intermittent RES (**Figure 1**).

Demand response and energy flexibility for building-to-grid services

Building energy flexibility is the ability of a building to adapt or modulate its short-term (a few hours or a couple of days) energy demand and energy generation profile according to climate conditions, user needs and energy network requirements without jeopardising the technical capabilities of the building systems and the comfort of occupants [2]. Building energy flexibility/demand response thus allows load control and modulation to provide building-to-grid (B2G) services to the local energy grids and support matching the energy demand profile with the energy supply profile in smart grids dominated by RES.

The potential for buildings to provide B2G services is colossal. In Australia, it is estimated that 50% of the dispatchable capacity on the electrical grid will come from the building stock [3]. In the USA, B2G services are expected to reduce CO_2 emissions of the electricity grids by 6% and generate \$100-\$200 billion in cost savings by 2030 [4]. The global demand response capacity from the building stocks is currently only 1% of the total electric supply. However, it should reach 10% by 2030 [5].

As illustrated in **Figure 2**, building energy flexibility/demand response actions can consist of, e.g., peak shaving (reduction of the power peak demand),

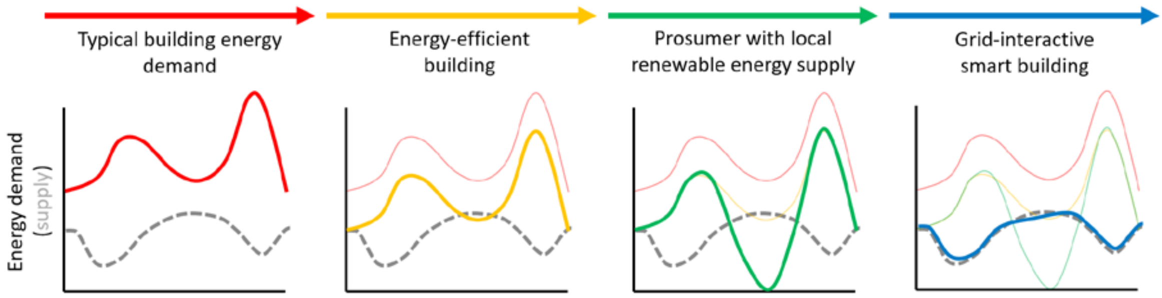

Figure 1. Paradigm shift: Toward smart building-to-grid services sustainable grids dominated by RES [1].

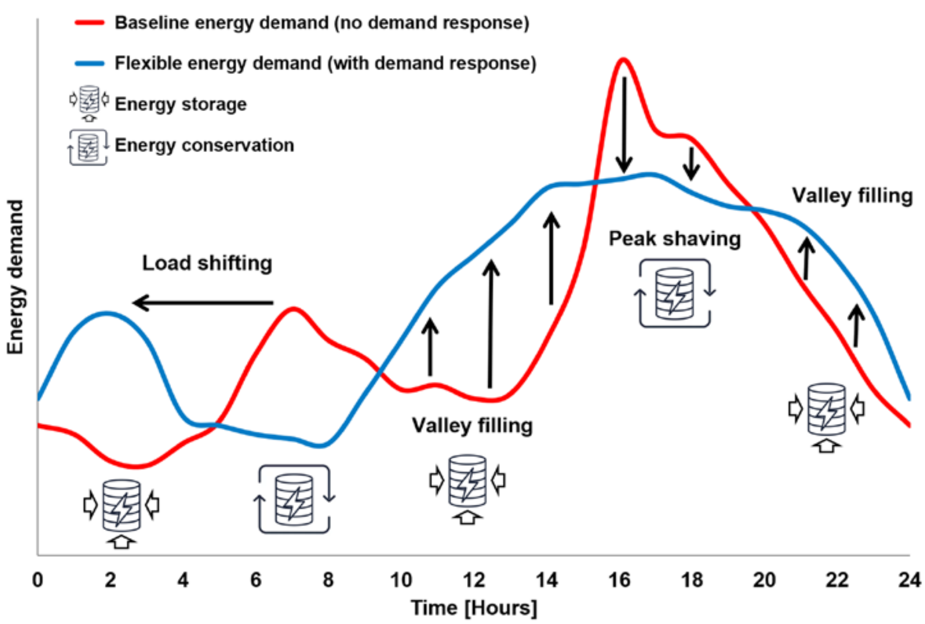

Figure 2. Examples of building energy flexibility/demand response actions [6].

load shifting (anticipating or delaying the energy use over a short period of time) or valley filling (increase energy use when the energy demand is lower than the energy supply).

Many of these building demand response strategies rely on different forms of energy storage at the energy end-user side, such as electric batteries (including batteries of electric vehicles connected to a building), hot water storage tanks, phase change material storage units or ground source heat exchangers (boreholes). Demand response can also be achieved by curtailing on-site renewable energy supply (e.g., solar panels) or shifting the operation of certain appliances in time (e.g., washing machine or dishwasher).

Another significant energy storage capacity of the built environment resides in the thermal inertia of the indoor environment and structural elements. This storage capacity can easily be exploited using heating/cooling indoor temperature setpoint modulation strategies. This approach has been proven promising for building demand response [7][8]. However, there is an apparent lack of large-scale thermal storage capacity estimates at entire building stock levels.

Indoor thermal storage capacity in the entire Danish building stock to perform demand response

To remedy the limitation above, the effective thermal storage capacity of the different typologies of buildings in a given country could be estimated. Those typologies or archetypes are representative of a large number of similar buildings throughout an entire country. Combined with statistical information regarding the total number of each archetype in the whole building stock, a nationwide estimate of large-scale demand response can be made.

In the present study, pre-existing typologies for the Danish building stock [9] were expanded to calculate the indoor effective thermal inertia for each building archetype. The number of each archetype in Denmark is inferred from the national building registry. Coupling the former and the latter, one obtains an estimate of the combined thermal storage capacity in the indoor environment of the entire Danish building stock when performing heating/cooling temperature setpoint modulation.

One can see in **Figure 3** the results of the stock-scale thermal storage estimate for a temperature setpoint modulation of ±2°C over 1 hour, 5 hours and 24 hours, respectively. One can notice the very appreciable energy storage capacity of the Danish building stock,

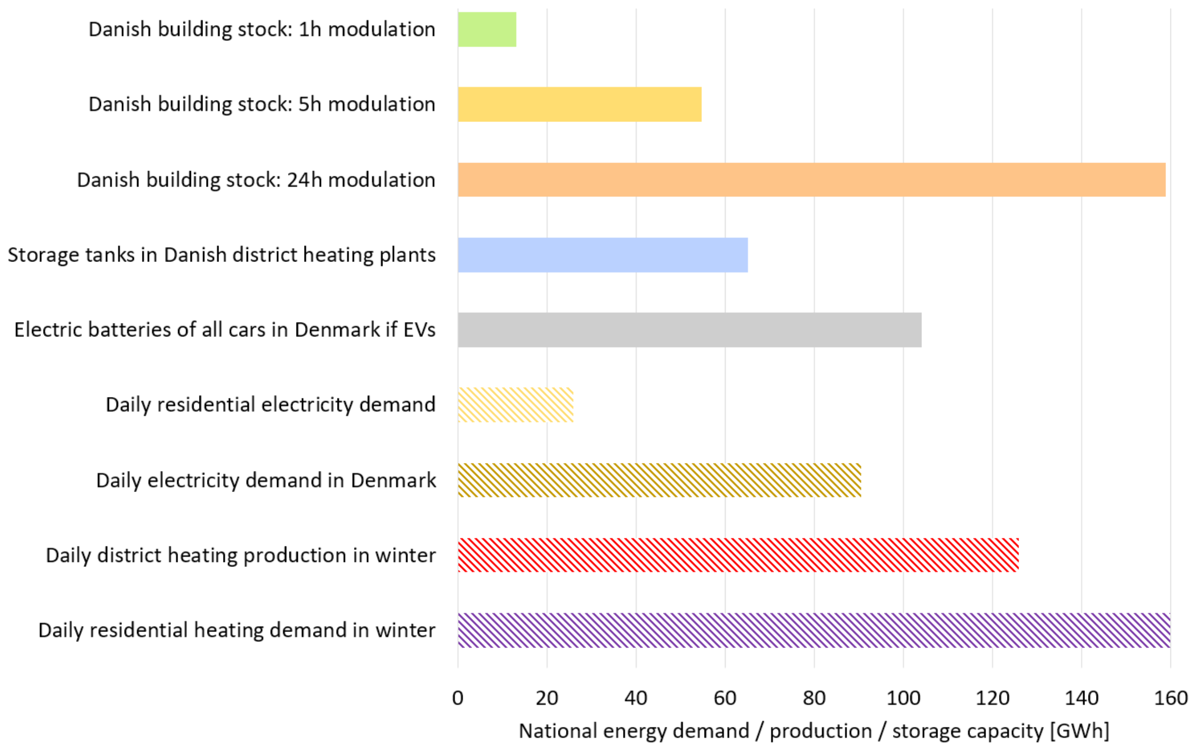

Figure 3. Thermal storage capacity in the indoor environment of the entire Danish building stock compared with key storage sources, energy demands and productions.

which is similar to that of all combined industrial-size storage tanks in district heating plants, or to that of all batteries of a fully electrified fleet of cars. This short-term energy storage capacity is also comparable to the daily electricity demand and the daily heating production during winter.

Although approximated, these results clearly highlight the massive potential for large-scale demand response of the building sector when utilising its readily existing thermal storage capacities embedded in the indoor environment. At the moment, this indoor energy storage is vastly untapped but could easily be leveraged with the help of smart home technologies such as smart thermostats reacting to dynamic energy price signals. Indoor thermal storage by means of temperature setpoint modulation thus forms a cost-effective solution which can be combined with other sources of energy flexibility and enable buildings to counterbalance the intermittence of RES. ■

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