Identifying promising use cases for a novel heat battery in Dutch residential buildings

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Abstract. Owing to the recent breakthrough in thermochemical storage technology, a novel closed-loop thermal energy storage (TES) system, the heat battery (HB), has been introduced. With higher energy density and no storage loss, this system is believed to have a greater potential of helping the energy transition in the built environment compared to other conventional TES systems. To identify the most promising use case of the HB, this research proposes a simulation approach to predict and assess how the HB will influence the performance of Dutch residential buildings. Based on a literature review and discussions with developers of the HB, a list of potential use cases is defined and the most important stakeholders are identified (homeowner, distribution system operator, and district heating system operator). Next, the simulation approach was conducted. The results show that the HB has the potential of both reducing the operational energy cost for the homeowner and reducing the peak heating load from the building to the district heating system.

Keywords. Thermochemical storage, building simulation, demand-side management.
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1. Introduction

Energy storage in buildings has attracted many research efforts because of the growing challenge of both managing the building energy demand and the fluctuating production of renewable energy sources. Various energy storage technologies are used in buildings, such as electrical batteries (chemical storage) [1], [2], water tanks (sensible heat storage), PCMs (latent heat storage) [3]. Thermochemical heat storage is another promising type of energy storage as it shows high energy densities, high round-trip efficiencies, and high flexibility of charging/discharging temperatures [4], [5], [6]. However, the technological readiness level [7] of solutions based on thermochemical heat storage is still between conceptual development and industrial application.

The heat battery is a novel thermochemical heat storage solution. It absorbs/releases heat from/to the heating system in the building based on the dehydration/hydration reactions of potassium carbonate (K_2CO_3), as can be seen in Fig. 1 [8]. It employs an electricity-based circulating system to maintain continuous charging/discharging powers of heat.

To support the further development of the heat battery (HB), this paper investigates which use cases of the HB are promising for Dutch residential buildings. The section 2 of this paper explains the simulation-based approach adopted by this study. In Section 3, the investigated use cases are described. The predicted performance of the use cases are analyzed in Section 4, and Section 5 concludes this paper with a discussion and conclusion.

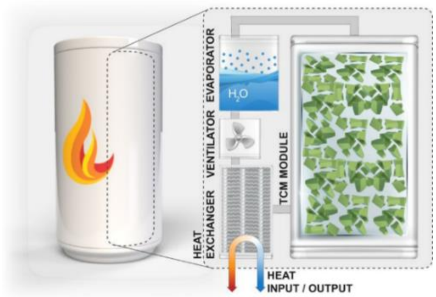

Fig. 1 – Schematic diagram of the HB [8].

2. Methodology

2.1 Defining potential use cases

This study defines the potential use cases of the HB based on the following five use case elements: WHO

– WHY – WHERE – HOW – WHEN. For the HB, this means that we need to identify the main stakeholders (WHO) and their main purpose of using the HB (WHY). Moreover, we need to specify various design options of buildings (WHERE) and their energy systems including several relevant operational strategies (HOW) and certain scenarios (WHEN), e.g., for the building occupants and the electricity price. This research firstly includes a review of previous literature to define the proper options of these five aspects, then combines suitable ones according to the practice of Dutch residential buildings to form diverse use cases.

2.2 Modeling and simulation approach

The second part of this methodology is a simulation approach for the performance prediction of the HB in each use case. As shown in Fig. 2, this approach firstly includes modeling the building based on the design options and occupant's scenarios selected in each use case, then the heat consumption for space heating, domestic hot water (DHW) usage, and other electricity consumptions (e.g., lighting, plug-in appliances, etc.) of the building will be simulated in EnergyPlus. The simulation employed the weather file of a typical reference year in Amsterdam [9], and generated the time series (with a 15-minute timestep) of the heat demand and other electricity demand for a whole calendar year.

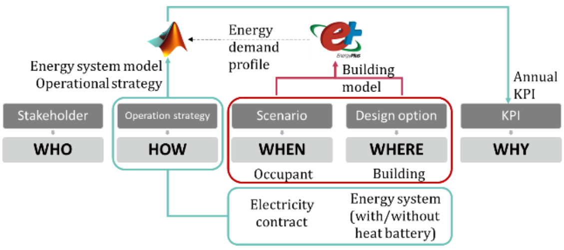

Fig. 2 – Workflow of the simulation approach.

With the predicted energy demand profiles, the energy systems and their operational strategies are then modeled and simulated in MATLAB to calculate the annual key performance indicators (KPIs) based on the energy contracts chosen in the use case. Many performance indicators related to the building's operational energy performance, e.g., the operational energy cost or peak load, can be estimated based on a model with a conceptual complexity level [10]. An example of the conceptual model is to represent a heat pump system with its coefficient of performance or heating seasonal performance factor. This modeling approach can avoid unnecessary long simulation time. Therefore, both the heat supply systems and the HB are modeled at this complexity level. If the defined performance indicators require a more detailed model, then the complexity can be increased accordingly [11].

Appendix A lists the conceptual level models used for possible heat supply systems in this study.

The heat balance of the HB is calculated by:

$$Q_{HB}(t) = Q_{HB}(t-\Delta t) + q_c(t)\cdot\Delta t - q_d(t)\cdot\Delta t \qquad (1).$$

Here, Q_{HB} is the heat stored inside the HB, kWh. q_c and q_d are the thermal charging and discharging powers, kW. The t is the time and Δt is the timestep of simulation (=15 minutes).

The HB is assumed to be loss-free of storage but still needs electricity to drive the circulation of the closed air loop. Its electricity consumption is calculated by:

$$E_{HB}(t) = q_c(t)\cdot\Delta t\cdot COP_c + q_d(t)\cdot\Delta t\cdot COP_d \qquad (2).$$

In Eq. (2), E_{HB} means the electricity consumed by the HB, kWh, while the COP_c or COP_d is equal to the charged or discharged heat divided by the electricity consumed by the HB itself. The charge and discharge powers are related to the storage capacity of the HB and the operational strategy defined in each specific use case.

3. Definition of use cases

Based on discussions with developers of the HB and a literature study ([3], [12], [13], [14]), the scope of use cases are defined as follows (see also Fig. 3). Three stakeholders are considered: the homeowner, the electricity distribution system operator (DSO), and the district heating (DH) system operator. Moreover, six operational strategies are defined (S1~S6, see Fig. 3).

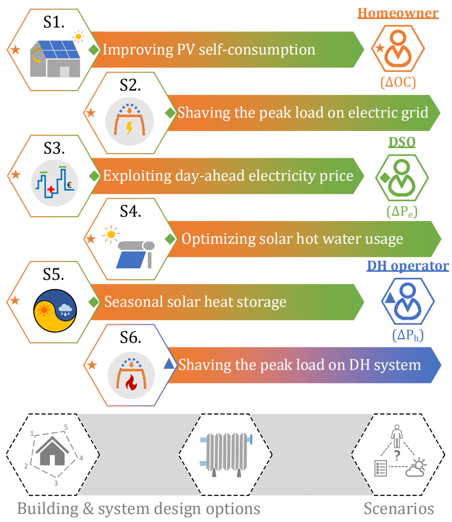

Fig. 3 – Scope of use cases in this research.

3.1 The homeowner

The homeowner is assumed to use the HB mainly for reducing operational energy costs. For those buildings unconnected to the local DH system, it is expected that in the future these costs will mostly come from electricity consumption as the residential sector in the Netherlands is moving towards electrification [15]. Therefore, the operational energy cost is calculated as follows:

$$OC = E_{im} \cdot p_{im} + \sum_{m=1}^{12} E_{p,m} \cdot p_p - (E_{ex} \cdot p_{ex} + E_{self} \cdot p_{self}) \quad (3).$$

Here, OC is the annual operational electricity cost of the building without HB, €. E_{im} is the electricity imported from the grid, kWh, and E_{ex} is the electricity exported to the grid, kWh. Their basic prices are assumed to be p_{im} and p_{ex}, €/kWh. Especially, OC includes an extra peak load cost [16] and an extra PV-self-consumption incentive. The extra peak load cost is calculated by the electricity consumed with an electric load above 2.5kW (E_p, kWh) every month (m) and its related price (p_p, €/kWh/kW). The OC also includes an extra PV-self-consumption incentive calculated by the locally consumed electricity from PV (E_{self}, kWh) and its incentive rate(p_{self}, €/kWh).

Based on (3), the HB's reduction on OC can be calculated by:

$$\Delta OC_{HB} = OC - OC_{HB} \quad (4).$$

Here, OC_{HB} denotes the operational electricity costs of buildings with HBs, it uses the same algorithm as OC and has a unit of €. The ΔOC_{HB} is exactly how much annual electricity cost the HB will reduce for the building.

To reduce OC, the homeowner can use the HB under five different strategies (S1~S5) as mentioned in Fig. 3. The first three strategies (S1~S3) require an air-to-water heat pump and S1 needs PV modules, while the other two strategies (S4~S5) use solar thermal collector as the main heat source with an electric water heater as a backup. In addition, three different scenarios of electricity contracts (both importing and exporting) are considered, as shown in Tab. 1.

Tab. 1 – Scenarios of different electricity contracts.

No.	Importing		No.	Exporting	
	p_{im}, €/kWh	p_p, €/(kW·kWh)		p_{ex}, €/kWh	p_{self}, €/kWh
1	0.25	0.00	1	0.25	0.00
2	Day-ahead [17]	0.00	2	0.06	0.00
3	0.20	0.08	3	0.00	0.06

According to the current situation in the Netherlands, various building design options (building type, and insulations' values) and occupant scenarios (occupancy patterns, heating setpoints, etc.) are defined. Details can be found in Appendix A.

3.2 The electricity Distribution System Operator (DSO)

The second stakeholder is the electricity DSO. Different from the homeowner, DSO normally will not directly install the HB in its system. It will adjust its pricing strategy to encourage the demand side to manage the peak load by itself. In this way, the DSO is assumed to encourage the homeowners to use the HB to reduce the peak load of importing and exporting electricity from the grid ($P_{e,im}$, kW and $P_{e,ex}$, kW). The reduction can be described as:

$$\Delta P_{elec,im,HB} = P_{elec,im} - P_{elec,im,HB} \quad (5).$$

The $P_{elec,im}$ is the peak load of importing electricity from the grid in the building without HB, kW. It is the maximum value in the annual time series with a 15 minutes timestep. $P_{elec,im,HB}$ is the peak load in building with HB, kW, so $\Delta P_{elec,im,HB}$ is the reduction, kW.

3.3 The district heating system operator

The third stakeholder is the operator of the DH system. It is assumed to directly use the HB to reduce the peak heat load on its system, as described in [18]. In this study, the HB is assumed to be installed in a DH system serving a residential neighborhood consisting of 50 houses, and all the houses in one neighborhood are assumed to have the same building designs and occupant scenarios as mentioned in Appendix B. The KPI for the operator is the reduction of the peak load of supplying heat from the DH system to the 50 houses, and it can be calculated by:

$$\Delta P_{heat,im,HB} = P_{heat,im} - P_{heat,im,HB} \quad (6).$$

Here, The $P_{heat,im}$ is the peak load of supplying heat from the DH system without HB to the 50 houses, kW. It is the maximum value in the annual time series with a 15 minutes timestep and includes a coincidence factor of 0.3 [19]. $P_{heat,im,HB}$ is the peak load in the DH system with HB, kW, and $\Delta P_{heat,im,HB}$ is the reduction, kW.

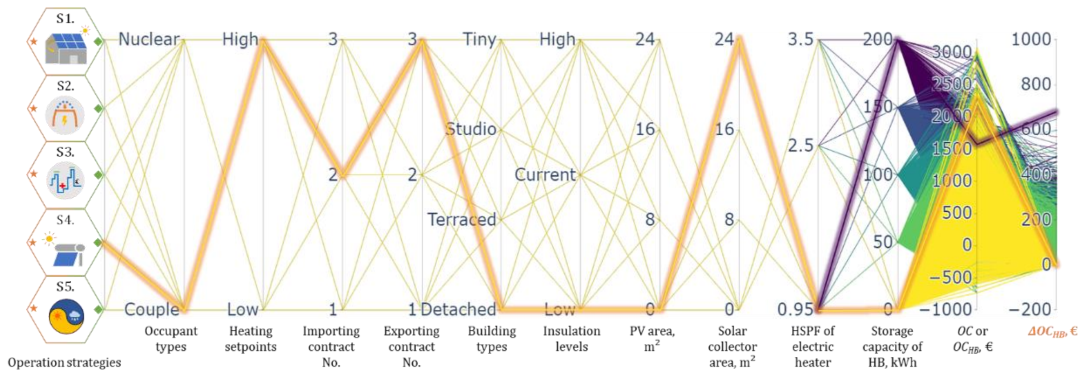

Fig. 4 – Parallel coordinate plot of the annual operational electricity cost (OC and OC_{HB}) and the reductions (ΔOC_{HB}) in all use cases with strategies S1 to S5. The highlighted pair of lines denotes the highest reduction.

4. Performance prediction of use cases

4.1 Predicted performance of use cases for homeowner and DSO

Fig. 4 shows the predicted performance of all considered use cases (more than 28,000 combinations) where the homeowner is the main stakeholder. The colors of the lines distinguish the storage capacity of the HB in each case, and lines (in yellow) connected to zero capacity represent the reference cases without HB. The highlighted lines show the use case with the highest reduction by the HB, where the 200kWh HB can reduce the annual electricity cost approximately from 2100 euros to 1500 euros. Generally, the HB has the potential of reducing the annual electricity cost by 0~400 euros, and this value can be more than 600 euros in some extreme cases.

To further compare the potential of different operational strategies, the predicted annual operational electricity cost with HB (OC_{HB}) and the reduction by HB (ΔOC_{HB}) are then grouped as shown in Fig. 5. Compared with other strategies, S1 and S4 can reach larger values of ΔOC_{HB}, while S1 tends to result in lower values of OC_{HB}. Therefore, use cases with S1 and S4 are selected for further screening of design options.

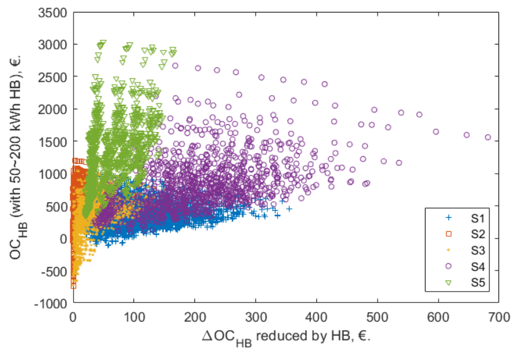

Fig. 5 – Scatter plot of annual operational electricity costs of houses with HBs (OC_{HB}) and reductions by HB (ΔOC_{HB}) grouped by different operational strategies **(the 'HOW').**

Fig. 6 shows how different design options will influence the ΔOC_{HB} in use cases with S1 or S4. Each box in Fig. 6 contains all the use cases with specified design options and operational strategies.

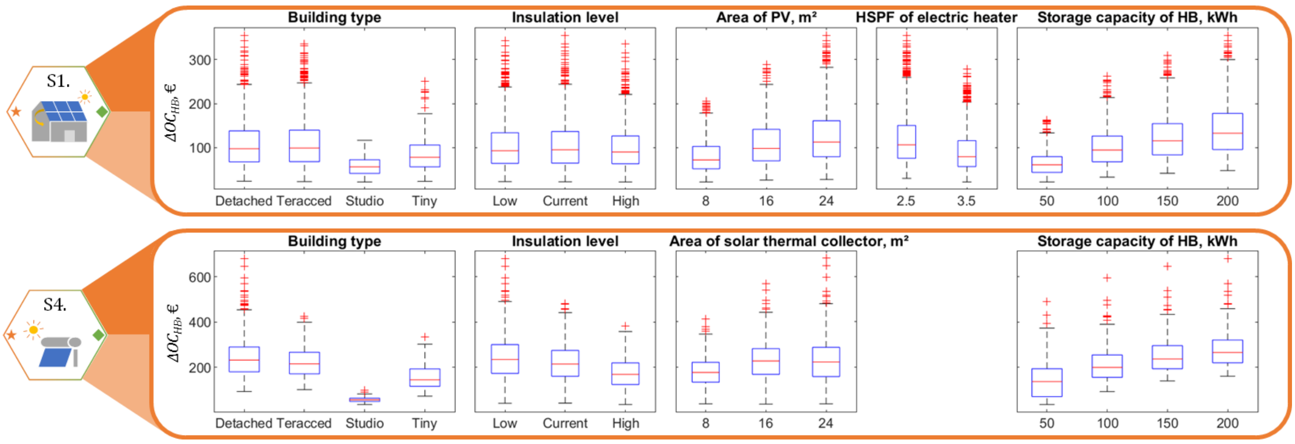

Fig. 6 – Boxplots of the reduction of electricity costs by HBs (ΔOC_{HB}) with different design options **(the 'WHERE')** in use cases with S1 and S4.

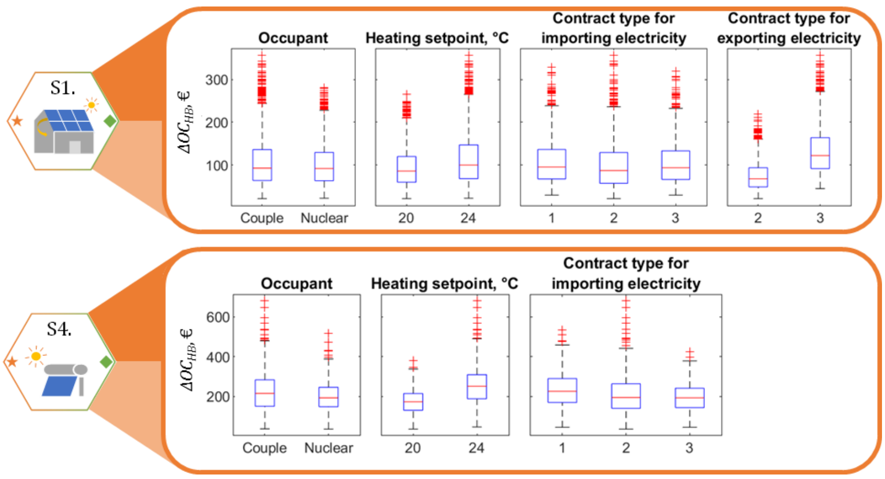

Fig. 7 – Boxplots of the reduction of electricity costs by HBs (ΔOC_{HB}) with different scenarios **(the 'WHEN')** in use cases with S1 and S4.

For use cases with S1, all design options do not change the lower boundary of the ΔOC obviously, but the building type, area of PV, HSPF of the heater, and the storage capacity of HB will shape the upper boundary in different ways. With S1, the HB may reduce more electricity costs when used in larger buildings with more PV modules and heat pumps with lower HSPF.

For use cases with S4, the type of building and HB storage capacity will influence both the upper and lower boundaries of ΔOC_{HB}, while the other two design options change just the upper one. So it would be more interesting for the homeowner to use the HB in buildings with higher heating demand. Additionally, the larger the storage capacity of HB, the more OC it can reduce.

Fig. 7 shows how different scenarios of occupants' behavior and energy contracts can alter the ΔOC. Exporting contract type 1 is not included in use cases with S1 because it does not make sense to store heat from PV electricity if the prices of importing and exporting it are the equal. Use cases with S4 do not include PV modules in their energy system so exporting contracts are not considered. For use cases with S1 or S4, types of occupants and contract of importing electricity will not influence the ΔOC as much as the heating setpoint. Especially for S1, the ΔOC is very sensitive to the contract of exporting electricity.

In addition to the homeowner, use cases with S1 to S5 may also interest the DSO because of the interaction between their electric heat sources and the electric grid. Therefore, the 15-min averaged electricity peak load $P_{elec,im,HB}$ and $\Delta P_{elec,im,HB}$ were also calculated and grouped as shown in Fig. 8.

Due to the mismatch between the historical data of the day-ahead prices and the predicted electric demand of building models, the HB will even increase the $P_{elec,im,HB}$ in some use cases with S3. This exactly reveals the risk of applying this pricing strategy for DSO, because the low price might lead to unpredictable peak load. In use cases with S1 and S4, the HB could reduce the P_e more or less despite that the ΔP_e would be less than 0.3 kW. In use cases with S2, where the HB is specially used for shaving electric peak load, the HB brought a better performance of peak shaving (nearly 35% peak load reduction).

Specially, the homeowners can use the HB to reduce the peak load of importing heat from the DH system if they are connected. Based on the same design options mentioned in Appendix B and the operational strategy S6, the $P_{heat,im,HB}$ and $\Delta P_{heat,im,HB}$ were calculated.

Fig. 9 shows how the HB can influence the peak heat load if it is installed in a single house and operated upon S6. It can be seen that the HB can reduce the 15-min averaged electricity peak load $P_{heat,im,HB}$ by more than 1.5kW (because the maximum discharging power of the HB is 1.5kW) and make it less than 2kW in some extreme cases, although the reduction would be less than 0.5kW in some other cases. Hence, if the DH system operator adopts a pricing strategy that can stimulate the homeowner to manage the peak heat load, it will also be a valuable way for the homeowner to use the heat battery.

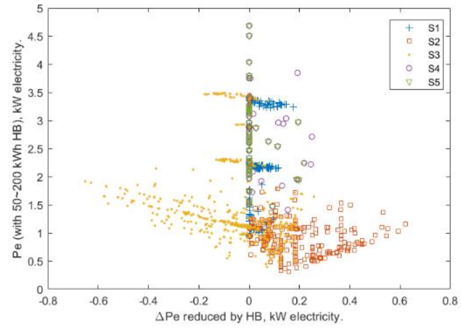

Fig. 8 - Scatter plot of the peak loads of importing electricity to houses with HBs ($P_{elec,im.HB}$) and the peak load reductions ($\Delta P_{elec,im,HB}$). The colors and shapes of dots distinguish the operational strategies from S1 to S5 **(the 'HOW').**

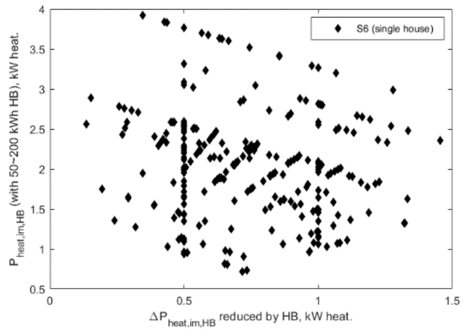

Fig. 9 - Scatter plot of the peak loads of importing heat from the DH system to a <u>single house</u> with HB ($P_{heat,im,HB}$) and the peak load reduction ($\Delta P_{heat,im,HB}$) in use cases with S6 **(the 'HOW').**

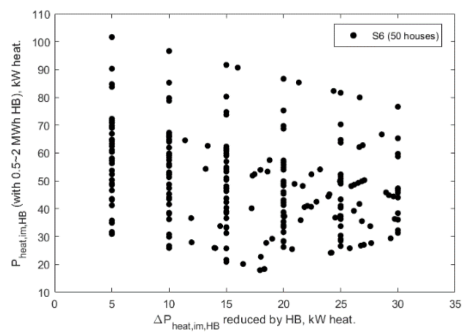

Fig. 10 - Scatter plot of the peak loads of supplying heat from the DH system with HB to <u>50 houses</u> ($P_{heat,im,HB}$) and the peak load reduction ($\Delta P_{heat,im,HB}$) in use cases with S6 **(the 'HOW')**.

4.2 Predicted performance of use cases for DH system operator

Other than the decentralized heating systems mentioned above, the DH system operator is assumed to install the HB in their centralized heating system to reduce the peak load of supplying heat to

50 houses (assumed to have the same design). Based on a coincidence factor of 0.3, $P_{heat,im,HB}$ and $\Delta P_{heat,im,HB}$ were predicted.

Fig. 11 shows the predicted values of all use cases for the DH system operator. In this figure, some dots are clustered on specific values of $\Delta P_{heat,im,HB}$ (5kW, 10kW, 15kW, etc.) which are consistent with the values of the maximum discharging powers of different HB models. This reveals the importance of HB design parameters. Therefore, the values of $\Delta P_{heat,im,HB}$ should be grouped by the design options of both buildings and HBs for further analysis.

As shown in Fig. 11, studios and detached houses imply the higher potential of peak load reduction, and the box of terraced houses contains the highest value of $\Delta P_{heat,im,HB}$, as well. Althought the tiny houses do not reach the top boundary as the other building types, it still allows a peak reduction up to 25kW. But different from building type, the insulation level does not show any obvious impact on $\Delta P_{heat,im,HB}$.

As for the design of the HB, it can be seen from Fig. 11 that larger storage capacity can lead to larger $\Delta P_{heat,im,HB}$., especially from 1MWh to 2MWh. But the maximum discharging power of HB, however, shows different trends. In the boxplot of maximum discharging power, it can be seen that the values of $\Delta P_{heat,im,HB}$ cannot exceed the maximum limit of discharging power.

5. Discussion and conclusion

5.1 Promising use cases

This research defined three stakeholders in the use cases of the HB: the homeowner, DSO, and DH system operator. The homeowner and DH system operator can directly deploy the HB in their systems for performance improvement (reducing operational energy cost or shaving the peak heat load) while the DSO will pay attention to its influence on the peak electric load of the building.

Based on the proposed simulation approach, this research found that solar-related operational strategies (S1 and S4) will be more interesting than those for demand-side management (S2, S3) if the homeowner wants to use the HB to reduce the energy cost. And the reduction will be more obvious where the building has a higher heating demand and larger areas of PV or solar thermal collector. However, the potential of S1 will be limited when the contract of exporting electricity does not provide enough motivation for the self-consumption of PV-generated electricity (as is the case for all types of batteries). The HB also shows the ability to reduce the peak electric load when coupled with an electric heater (electric boiler or heat pump) in some cases, but it may also lead to a higher electric peak load when used with S3 if the fluctuation of the electricity price differs a lot with the electric demand profile of the building.

When using the HB for reducing the peak heat load, the DH system operator can expect a higher reduction by using HB in the neighborhood consisted of larger houses while apartments containing studios may also be interesting. In addition, the value of peak load reduction is sensitive to the maximum discharging power and the storage capacity of HB, so it would be necessary to optimize these two parameters during the design phase of the whole integration.

5.2 Limitation and future work

This research developed a screening approach in order to perform a fast screeing of all the potential use cases. The approach is able to analyze thousands of use cases in several minutes, however it also brings some limits and drawbacks. Firstly, the conceptual models of the energy system and the HB reduce the resolution of the simulation and may lead to distortion of the results. In addition, some detailed practical boundaries, e.g., indoor thermal comfort limits, were not considered in the models, because no data was fed back from the energy system model to the building model.

The promising use cases as identified by the screening approach will be studied in more detail in the future. This requires a more detailed HB model which will be implemented in the building performance simulation tool. In addition, the six operational strategies (S1-S6) will be refined and combined according to the specific design option and future scenario to explore a higher performance improvement by the HB.

6. Acknowledgment

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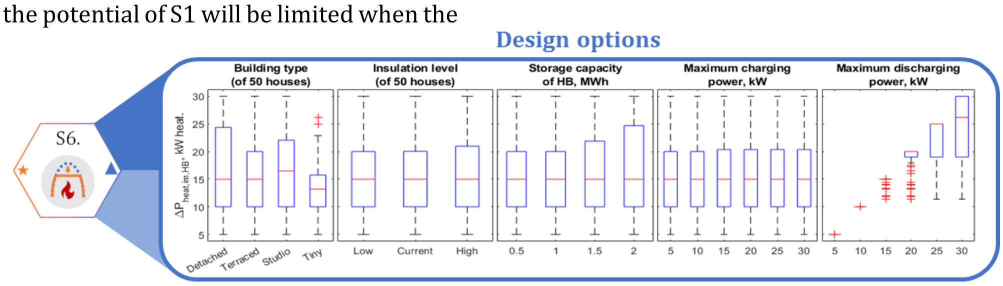


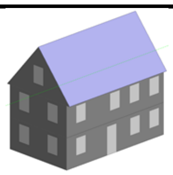
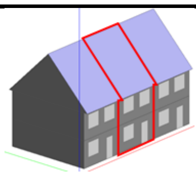
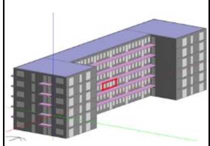
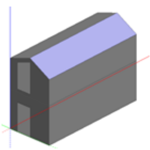
Fig. 11 - Boxplots of peak heat load reduction ($\Delta P_{heat,im,HB}$) with different design options **(the 'WHERE')** in all use cases with S6.

7. Appendices

Appendix A – Design options of energy system and related models.

Energy system designs		Input variables	Models	Output variables
Possible electricity source	Photovoltaic	Solar irradiance, kW/m^2; Area, m^2.	Module conversion efficiency; DC to AC conversion efficiency.	Electric power, kW.
	Electric grid	-	–	Electric power, kW.
Possible heat source	Solar thermal collector	Solar irradiance, kW/m^2; Outdoor air temperature, °c; Inlet temperature, °c; Area, m^2.	ISO efficiency equation [20].	Thermal power, kW.
	Electric boiler	Electric power, kW.	Heating seasonal performance factor (HSPF).	Thermal power, kW.
	Air-to-water heat pump	Electric power, kW.	HPSF.	Thermal power, kW.
	District heating system	-	-	Thermal power, kW.

Appendix B – Design options and occupant scenarios of building models.

Building designs	Possible options			
Building type (gross floor area, m^2)	 Detached house (240) [21]	 Mid-terraced house (135) [21]	 Apartment studio(55) [21]	 Tiny house (39) [22]
Insulation level (Rc value, $K{\cdot}m^2/W$)	Low (Rc- roof = 2.5 Rc - wall = 2.5 Rc- ground floor = 2.5)	Current (Rc- roof = 6 Rc - wall = 4.5 Rc- ground floor = 3.5)	High (Rc- roof = 10 Rc - wall = 8.5 Rc- ground floor = 6)	
Occupancy pattern [23]	Working couple		Nuclear family	
Heating setpoints, °C	20°C		24°C	
DHW [24]	40L/person/day			

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