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Analysis of energy flexibility of an efficient positive energy apartment building in a Nordic climate by thermal mass activation

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Abstract
The necessity to transition to a net zero economy has led to legislation that seeks to fully decarbonise the building stock in the European Union by 2050. The aim of this study is to investigate various strategies for utilising the thermal mass of a building to reduce its energy costs while ensuring the occupants' comfort in a first-of-its-kind multi-apartment positive energy building located in a Nordic climate. The findings of this simulation-based study suggest that a combined storage-conservation strategy, with a heating setpoint of 21.5°C during low energy price periods and 19°C during high energy price periods, results in the highest cost savings. Furthermore, this study highlights the importance of using such controllers in the current high and fluctuating energy prices scenario.

Highlights
- The current work contributes to the knowledge repository of studies on positive energy buildings in cold climate conditions using advanced control techniques.
- The novelty of this research lies in its examination of the energy flexibility potential of multi-apartment positive energy buildings in a cold climate by activating the building's thermal mass. Additionally, the study also demonstrates that a reduction in heating demand resulting from a high-performance building envelope leads to a decrease in the potential for energy flexibility.
- The study involves developing an economic, rule-based controller (RBC) to modify the indoor air temperature heating setpoint, resulting in cost savings. It is highly relevant in the current energy price scenario, where prices are high and volatile.

Introduction
The International Energy Agency (IEA) has released the world's first comprehensive assessment on pathways to transition to a net-zero energy system by 2050 while ensuring an affordable and secure energy supply for all and fostering robust economic growth. According to the findings of this analysis, the fulfilment of the existing national commitments does not accomplish net-zero emissions by the target year (International Energy Agency (IEA), 2021). Over 190 countries signed the Glasgow Climate Pact, which advocated for a commitment to review emission reduction measures annually to attain the 1.5°C Paris Agreement target, phase down unmitigated coal use, and climate finance for developing economies (UNFCCC. Conference of the Parties serving as the meeting of the Parties to the Paris Agreement (CMA), 2022). The COP27 ruling underlined the urge for Parties that have yet to do so to examine and reinforce their targets to comply with the Paris temperature goal (Alayza, et al., 2022).

In the past year, the operational energy demand in buildings reached an unprecedented high of 135 EJ, accounting for 30% of worldwide final energy consumption (UNEP, 2022). In the European Union (EU), the building sector contributed to 40% share of the total energy consumption (European Commission, 2020). HVAC systems, which are required to maintain optimal indoor climatic conditions, consume significant energy in buildings. The use of HVAC systems for space heating and cooling alone accounts for more than 40% of a building's total energy consumption in the United States, China, the United Kingdom, and the European Union (IEA, 2015; United States Environmental Protection Agency (US EPA), 2022; United States Energy Information Administration (US EIA), 2018; Eurostat, 2022).

As economies expand and populations grow at a rapid pace, this translates into increased demand (European Commission, 2020). This conclusion is supported by the United Nations Environment Programme (UNEP) and the IEA's 2019 study, which shows an increasing trend in global building stock energy use and commensurate growth in emissions (UNEP & IEA, 2019). The impacts of climate change are exacerbated by such an increase in energy consumption, which imposes an additional strain on the environment and the resources. With rising energy demand and increasing uncertainty about its future availability, it is imperative to develop measures to reduce consumption and transition to renewable energy sources. Governments mandate such efforts through legislative frameworks and regulations such as the 'Energy Performance of Buildings Directive’ (European Parliament & Council of the European Union, 2018).

The COVID-19 pandemic, climatic factors, Russia's curtailment of natural gas export to the EU, and European sanctions drove global energy prices to a record-breaking...
These high energy prices emphasise the advantages of energy efficiency improvements in building structures and encourage behavioural changes and technological developments to reduce energy consumption (IEA, 2022).


In accordance with this regulation, all new buildings after 2020 must be Nearly Zero Emission Buildings (NZEB), having high energy efficiency, nearly zero energy demand, and primarily powered by renewable energy sources. A further proposal to revise the directive in 2021 argues for progression from NZEB to Zero-emission buildings (ZEB), taking a step ahead towards a climate-neutral economy (European Commission & Directorate-General for Energy, 2021). Despite these improvements, an even further step along the road to a decarbonised building stock is Positive Energy Buildings (PEB). A PEB could be characterised as an energy-efficient building that produces more energy via renewable sources than it uses over a defined time span.

Ever since the world’s first PEB was constructed in Freiburg in 1994 (Rolfdisch, 2017), there has been a steady rise in the number of PEBs across the globe. As of 2020, 58 positive energy buildings were identified across Europe, with increased traction since 2009. Jaeger et al., in their work (Llorente, et al., 2021), classified the location of the 58 PEBs based on their climate zone: Oceanic climate zone (26), Continental climate zone (13), Mediterranean climate zone (8) and Nordic climate zone (5). Of particular interest to our work is the Nordic climate, and among the 5 PEBs in the climatic zone, namely Powerhouse Kjørbo (Norway), Lantti-talo (Finland), Powerhouse Brattorkaia (Norway), Svart Hotel (Norway), New Montessori School (Norway), only the Lantti-talo is a residential PEB (single-family). To date, there has not been any record of a positive energy multi-apartment building in the Nordic climate zone. Consequently, this makes this work unique, as it involves studying an upcoming multi-apartment residential building that is also a PEB in the EXCESS project in the Finnish Nordic climatic conditions.

**Novelty**

The contribution of this research lies in its examination of the energy flexibility potential of multi-apartment positive energy buildings in a cold climate through the activation of the building’s thermal mass, where similar studies are scarce in the existing literature. Furthermore, this study showcases the interplay between energy efficient new buildings, characterised by reduced energy consumption resulting from a high-performance building envelope, and their capacity for energy flexibility.

**EXCESS Building**

The EU project EXCESS (fliXible user-CEntric Energy poSitive houseS) aims to test, evaluate, and disseminate PEB solutions that have the potential to be replicated in the four climate zones mentioned earlier. These pilot cases are located in Austria, Belgium, Finland, and Spain (EXCESS: fliXible user-CEntric energy poSitive houseS, 2020). The Finnish positive energy apartment building in Helsinki’s Kalasatama neighbourhood is the subject of our interest (60.19° N, 24.94° E). It consists of seven storeys and 51 units with a total heated area of 4000 m², including common spaces for sauna, laundry, storage, a 2-storied office, and a couple of shops. The building’s volume is 12800 m³, and the overall roof area is 400 m². The simulated building with shading neighbouring buildings, as well as the floor layout of the 1st apartment floor, is presented in Figure 1.

![Figure 1: The simulated building with neighbouring buildings and the 1st floor layout from IDA ICE simulation tool](image)

The main thermal characteristics of the simulated pilot building and the reference values of the Finnish national building regulations are presented in Table 1. From the table, it can be observed that the building was designed not just to meet but also exceed the requirements of the national building regulations, especially for windows, exhaust air heat recovery and air tightness of the envelope. This underscores the presence of a high-performance building envelope, which plays a pivotal role in reducing heating demand and subsequently impacting the potential for energy flexibility.

In 2018, Helen Oy, the energy company responsible for district heat production in Helsinki, relied on coal for 53% of its energy production (Pöyry Management Consulting Oy, 2020). However, in order to adopt a more environmentally friendly and energy-efficient approach to space heating, the work of Tom Allen Senera Oy and Gebwell Oy was utilised (Järvinen & Manner, 2020). This involved implementing a secondary circuit to distribute heat recovered from the ground during the colder months to the space that needs to be heated, and during the summer months, it cools down the building. This way, a
low-temperature underfloor heating serves as the basis for space heating. The ventilation heating coil is also designed to operate at low temperatures (supply/return of 35/30°C). Hot water demand and circulation losses constitute the Domestic hot water (DHW) load, and the daily profile takes into account the user’s behaviour. Cooling is based on underfloor cooling, as has been the case with a few other NZEB buildings in Helsinki (Kivirinne, 2021).

Table 1: Thermal characteristics of the simulated building and the reference values of the building regulations.

<table>
<thead>
<tr>
<th>Construction</th>
<th>Design value</th>
<th>Building code</th>
</tr>
</thead>
<tbody>
<tr>
<td>External wall U-value, W/(m²K)</td>
<td>0.15</td>
<td>0.17</td>
</tr>
<tr>
<td>Roof U-value, W/(m²K)</td>
<td>0.09</td>
<td>0.09</td>
</tr>
<tr>
<td>Floor, U-value, W/(m²K)</td>
<td>0.16</td>
<td>0.16</td>
</tr>
<tr>
<td>Window U-value, W/(m²K)</td>
<td>0.60</td>
<td>1.0</td>
</tr>
<tr>
<td>Ventilation air flow, dm³/(s·m²-floor)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apartments</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Offices and Shops</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Exhaust air heat recovery efficiency</td>
<td>75%</td>
<td>55%</td>
</tr>
<tr>
<td>Air tightness, m³/(h·m²-external surface)</td>
<td>1.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

The COP (Coefficient of Performance) and EER (Energy Efficiency Ratio) of the heating and cooling system are presented in Table 2. Being located in a cold climate, the heating load of the building is considerably higher than the cooling load, and the results of the annual energy simulation reflect this as well (Lara, et al., 2020).

Table 2: COP and EER of the heating and cooling system for the building under study.

<table>
<thead>
<tr>
<th>Process</th>
<th>COP/EER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating</td>
<td>4.5</td>
</tr>
<tr>
<td>DHW</td>
<td>4</td>
</tr>
<tr>
<td>Cooling</td>
<td>3</td>
</tr>
</tbody>
</table>

The electricity load profiles for appliances and lighting adhere to the national recommendations of the Finnish Association of HVAC societies and are adjusted to ensure that the annual energy consumption matches the values specified in the Finnish building standards (1010/2017 Decree of the Ministry of the Environment on the Energy Performance of New Buildings) (Ympäristöministeriö, 2017). Electricity usage in apartments, offices and shops comprises lighting and appliances. The property loads include elevators, saunas, a laundry room, property lights, and outdoor lighting. HVAC systems comprise supply and exhaust air fans, pumps, and auxiliary equipment.

The setpoints of the various zones (Table 3) in the building were assigned according to the National Building Code of Finland D3 2012 (asuinkerrostalo and liikerakennus) (Ympäristöministeriö & Rakennetun ympäristön osasto, 2011). In addition to the building’s mass elements, the associated energy system, which can provide further flexibility, includes buffer tanks, hot and cold tanks, borehole thermal energy storage, and heat pumps besides solar-thermal panels and photovoltaics. However, in this work, we investigate energy flexibility through the activation of the building’s thermal mass alone.

Methodology

IDA Indoor Climate and Energy (IDA ICE) is a simulation tool developed to design and optimise buildings and associated energy systems. It enables users to create detailed and dynamic multi-zone simulations for studying the indoor climate and the energy consumption of the entire building and building systems, including HVAC components (EQUA Simulation AB, 2017). IDA ICE has been widely utilised in the study of energy-efficient structures such as passive houses and positive energy buildings (Weinberger, et al., 2021; Johari, et al., 2022; Vujnović & Đović, 2021). Therefore, it has been chosen as the tool to simulate this building.

In households in Finland, space and water heating alone account for a large share of total energy consumption (~81%) (Statistics Finland, 2022). Hence, in the current work, we vary the heating setpoint alone to activate the thermal mass using three control strategies:

- Storage strategy: Increasing the setpoint temperature during low energy price periods
- Conservation strategy: Decreasing the setpoint temperature during high energy price periods
- Mixed storage-conservation strategy: Depending on the classified energy price at each time step, the heating setpoint is increased or decreased.

Figure 2: Deployment of the control strategy on the basis of energy price classification, as implemented through the RBC.

Table 3: The setpoints of the various zones in the simulated building.

<table>
<thead>
<tr>
<th>Zone Type</th>
<th>Zones</th>
<th>Heating setpoint (°C)</th>
<th>Cooling setpoint (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crawl spaces/Garage</td>
<td>6</td>
<td>12</td>
<td>99</td>
</tr>
<tr>
<td>Stairs</td>
<td>15</td>
<td>21</td>
<td>27</td>
</tr>
<tr>
<td>Office/Shops</td>
<td>5</td>
<td>21</td>
<td>25</td>
</tr>
<tr>
<td>Sauna</td>
<td>19</td>
<td>23</td>
<td>27</td>
</tr>
<tr>
<td>Apartments</td>
<td>59</td>
<td>21</td>
<td>27</td>
</tr>
</tbody>
</table>
The heating setpoint is varied between 19-23°C for various cases. Figure 2 illustrates the control strategies corresponding to the price classification as a flowchart.

The energy price classification technique used in this study is derived from the work of Delgado et al. (2018). By classifying energy prices based on past and future values, it is possible to optimise energy consumption and reduce costs by taking advantage of lower energy prices. The RBC implemented in this work considers the energy price in the preceding and succeeding 12 hours and categorises the energy price at the current time step as ‘high’ or ‘low’ based on varying percentiles (50, 60, 70 and 80). A percentile-based classification is more reactive with price changes, and a 12-hour window provides more data for the controller to process before flexibility measures are implemented. Based on the classification, the control action is executed.

The simulation period for the cases is one year, and the weather data is from two years, 2015 and 2022, of Helsinki Kumpula station, illustrated in Figure 3 (Ilmatieteen laitos, 2018). The energy prices for the corresponding years are obtained from the European Network of Transmission System Operators for Electricity (ENTSO-E) (ENTSO-E, 2016; ENTSO-E, 2023) (Figure 4).

As observed from Figure 4, the electricity prices in 2022 were high and volatile compared to 2015. Therefore, a comparative study was conducted to examine the effect of smart control on the HVAC system’s energy usage and how it helps to balance energy consumption in response to energy prices for these two years.

In total, four cases of setpoint variation (by 0.5°C, 1°C, 1.5°C and 2°C) were simulated. A further study is conducted by assuming to double the thermal resistance to examine its effect on the heat losses through the building’s envelope. The proposed strategies are evaluated and contrasted with the PI control. The energy flexibility and cost savings potential are then assessed.

Results and Discussions

The simulation results for different setpoint variations and percentiles of price classification are presented in this section. The heating and cooling system regulated by a PI control is considered the baseline scenario (represented as a black arrow in the figures) and is compared with the other cases that utilise cost-based RBCs.

Results for the year 2015

Case 1(a): Setpoint increase and decrease by 1°C

For Case 1(a), i.e., increasing the heating setpoint to 22°C when the electricity price is low and decreasing the setpoint to 20°C when the price is high, it can be observed from Figure 5 that the savings are maximum when the price classification is 60/70 percentile. It is also noted that the storage mode alone results in more cost compared to the only conservation mode and the mixed storage-conservation mode. In this case, the only conservation mode seems slightly more profitable than the mixed storage-conservation mode.

Case 1(b): Setpoint increase and decrease by 1°C with doubled thermal resistance

As observed from Figure 6, the incurred costs of the setpoint increase and decrease by 1°C when the thermal resistance is doubled.
On doubling the thermal resistance and re-running the simulation, the pattern remains the same: the storage mode is more expensive than the other two (Figure 6). Even though the doubled resistance led to relatively lesser costs as compared to Case 1(a) (1.6-2.8% vs 2.6-3.3% more than PI), this indicates that the heat losses through the envelope of the building prevent the storage strategy from being profitable. Therefore, it is concluded that despite the building’s components having low U-values, the heat loss makes the cost savings potential of the storage strategy ineffectual.

Case 2: Setpoint increase and decrease by 1.5°C

For Case 2, i.e., increasing the heating setpoint to 22.5°C when the price is low and decreasing the setpoint to 19.5°C when the price is high, it can be observed from Figure 7 that the savings are the maximum when the price classification is 60 percentile, and are about twice as much as in Case 1(a). Further, the storage mode alone results in more cost compared to Case 1(a) and base case PI. In this case, the conservation mode seems slightly more profitable than the mixed storage-conservation mode.

Case 3: Setpoint increase and decrease by 2°C

For Case 3, i.e., increasing the heating setpoint to 23°C when the price is low and decreasing the setpoint to 19°C when the price is high, it can be observed from Figure 8 that the savings are the maximum when the price classification is 60 percentile and are about three times as much as Case 1(a). In addition, the storage mode alone results in more cost compared to Case 1, Case 2, and the base case PI. The conservation mode appears to be slightly more economically profitable than the mixed storage-conservation mode in this scenario. This could be attributed to the counterproductive heat losses that occur during the storage mode of this mixed approach, resulting in an increased cooling demand.

Figure 7: Incurred costs & cost savings/loss for a setpoint increase and decrease by 1.5°C.

Case 4: Setpoint increase by 0.5°C and decrease by 2°C

A combination of heating the building to 21.5°C during low price periods and decreasing the setpoint to 19°C during high price periods resulted in the maximum savings (Figure 9). When a 70-percentile price-classification method was applied, this resulted in 5.2% savings in annual energy cost (€164). It is found that the low savings are due to the building’s low heating demand, which limits the opportunities for exploiting the energy flexibility.

Results for the year 2022

When the same studies were repeated for the 2022 weather and prices, the following results were observed.

Case 1(a): Setpoint increase and decrease by 1°C

Figure 9: Incurred costs and cost savings for a setpoint increase by 0.5°C and decrease by 2°C.

For Case 1(a), it can be observed from Figure 10 that the maximum savings are observed when the price classification is in 60-70 percentile range. Although the
storage mode of operation results in higher costs than the other two, all three strategies of thermal mass activation ensued in cost savings compared to the base case PI. In this case, the mixed storage-conservation mode seems slightly more profitable than the other two.

Case 1(b): Setpoint increase and decrease by 1°C with doubled thermal resistance

Figure 11: Incurred costs for a setpoint increase and decrease by 1°C when the thermal resistance is doubled.

Similar to the year 2015, the thermal resistance was doubled, and the simulation was rerun for 2022 as well. It is observed that the pattern remains the same and the storage mode is found to be more expensive than the other two strategies (Figure 11). This is suggestive of heat losses escaping through the building’s envelope, preventing the storage strategy from being more profitable. As a result, it is demonstrated that, despite low U-values, heat loss renders the storage strategy’s cost-saving potential ineffective.

Case 2: Setpoint increase and decrease of 1.5°C

For Case 2, it can be observed from Figure 12 that the maximum savings are when the price classification is in the 60/70 percentile range and in mixed storage-conservation mode. Additionally, it is observed that although the storage mode of operation results in higher costs than the other two, all three strategies of thermal mass activation resulted in cost savings.

Case 3: Setpoint increase and decrease of 2°C

Figure 13: Incurred costs and cost savings for a setpoint increase and decrease of 2°C.

For Case 3, it can be observed from Figure 13 that the savings are the maximum when the price classification is in the 60-percentile range and are approximately 25% higher than the maximum savings of Case 1(a). Although the storage mode of operation results in higher costs than the other two, all three strategies of thermal mass activation resulted in cost savings compared to the base case PI. In this case, the conservation mode seems slightly more profitable than the mixed storage-conservation mode. This could be attributed to the counter-effective heat losses during the storage mode of the combined storage-conservation strategy.

Case 4: Setpoint increase by 0.5°C and decrease by 2°C

Figure 14: Incurred costs and cost savings for a setpoint increase of 0.5°C and decrease of 2°C.

As it was the case for the year 2015, a combination of heating the building to 21.5°C during low price periods and decreasing the setpoint to 19°C during high price periods resulted in the maximum savings (Figure 14). When a 70-percentile price-classification method was applied, this resulted in 7% savings in annual energy cost (€ 377) as opposed to a PI control. The minimal savings in absolute numbers are attributed to the building’s low heating demand, which restricts the opportunities for utilising energy flexibility.
Conclusion

Three strategies are employed in the study of thermal mass activation in a positive energy apartment building located in the city of Helsinki. The energy price is classified as either low or high, and based on this classification, four cases of control were simulated by varying the heating setpoint of the building. These cases were then compared with the base case that employs PI control. The apartment building is in focus because there has not been a multi-apartment positive energy building in a Nordic climate before. Therefore, this work adds to the knowledge in this field.

The results indicated that the storage strategy resulted in a higher overall cost compared to the conservation strategy and the mixed storage-conservation strategy, which is attributed to higher losses taking place through the building’s envelope. The mixed storage-conservation mode resulted in the highest savings while maintaining desirable indoor thermal comfort. This was achieved by raising the heating setpoint of the building to 21.5°C during low-price periods and lowering it to 19°C during high-price periods. The resultant savings were 5.2% in annual energy costs (€164) in 2015 and 7% (€377) in 2022, as compared to the base case PI control for the respective years. Such an economic rule-based controller is highly relevant in today’s scenario, where energy prices are high and fluctuating. This advanced controller that attempts to activate the thermal mass is replicable and could be implemented in other structures that would benefit from cost savings during high-price periods of heating. It is found that the relatively low savings in absolute cost are due to the building’s low heating demand, which is a result of high-quality thermal features applied in the design of positive energy buildings where energy efficiency is a priority. This limits the opportunities for exploitation of the energy flexibility. It is interesting to note that the current volatile energy prices for 2022 led to savings in all three strategies for thermal mass activation of the building’s flexibility.

Not only can building owners/occupants save on operational energy costs through the flexible utilisation of their buildings, but by exploiting the flexibility offered by buildings, high investments in the energy grid during peak load hours can be avoided. Additionally, suitable business models should be introduced along with proper legislation in order to make energy flexibility in buildings attractive to the stakeholders.

Future work would involve the development of an economic model predictive control that takes into account the profile of the energy cost and the weather forecast in the next hours and the status of the building’s flexibility sources, which can result in higher cost savings.

Acknowledgement

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