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Numerical investigation of the energy flexibility of different heating and cooling systems

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Abstract. The significant expansion of intermittent renewable energy sources can compromise the stability of energy grids due to the mismatch between instantaneous energy use and production. Buildings have a large potential for energy storage and demand-side management, which can offer energy flexibility to a Smart Grid system. Smart control of heating, ventilation and air conditioning systems is a great solution for improving flexible energy use, load shifting and power peak shaving. This numerical study compares the energy flexibility potential of three different heating and cooling systems implemented in a nearly zero-energy office building. The energy flexibility strategy consists in the modulation of heating / cooling indoor temperature set points according to an energy price signal. The energy flexibility assessment was performed based on the energy shifting ability, indoor thermal comfort level and economic benefits. This article establishes a better understanding of the flexibility potential of common and innovative heating / cooling technologies. Lindab Solus system has the highest load shifting ability with a flexibility index of 67.41%, followed by the radiator heating system, scoring a 59.92%, and the underfloor heating system with 56.65%. It is clear that the selection between different heating/ cooling systems can have a great impact on the energy flexibility of the grid system.

1 Introduction

A global rising trend for decarbonification of the energy production mix can be observed in most countries [1, 2]. These increasing efforts to reduce the impact of climate change, pollution and risks of energy crisis are leading to a significant continuous expansion of renewable energy sources (RES). However, production from RES is mostly intermittent and difficult to modulate. An energy grid with a large share of RES can thus experience a problematic mismatch between the instantaneous energy production and usage, which leads to stability and reliability issues [3, 4].

To tackle these problems and prepare for the realization of a fossil fuel-free society, researchers are striving to develop a Smart Energy Grid system able to bear 100% RES. The latter couples buildings, industries, transportations and various energy storage solutions within interconnected electrical, thermal and gas grids, which are all supervised by a smart metering and control network [5].

Within this framework, the building sector, which is the largest global energy end-user, has a predominant role to play to enable demand side management and energy flexibility strategies. Buildings offer various forms of energy storage possibilities. They can be employed for local or global load shifting measures to preferably use energy during RES overproduction, and retrieve or conserve energy when the latter is scarce, expensive or highly carbonated. In addition, peak saving can largely reduce the cost of energy production and distribution by eliminating the extreme power peaks of demand that the

grids can sometimes face [6]. It is therefore essential to realize the importance of the building sector as a major active actor of the future Smart Energy Grids.

Among the various technics to adapt the power usage profile of buildings to fulfil grid requirements and reduce excess production from RES, thermal energy storage in the indoor environment by means of temperature set point modulation has been found to be a cost-effective solution [7]. Several numerical studies showed that this energy storage in the thermal mass of residential buildings allows a large energy shift over time: from a couple of hours to more than 24 hours [3, 8, 9].

The study presented in this paper aims at exploring further the potential of buildings for energy shifting. The energy flexibility of indoor space heating and cooling of office buildings in Denmark is assessed for different configurations of HVAC systems. The investigated systems are a traditional convective heating system equipped with radiators and mechanical ventilation for fresh air supply and cooling, a radiant floor heating system, also combined with mechanical ventilation, and finally a novel single circuit convective heating and cooling system designed by Lindab.

Firstly, the methodology for calculation of the energy flexibility index is explained. The different building cases are then presented followed by the results and discussion of the numerical investigations about the energy flexibility of the former. Finally, a conclusion and suggestions for further research close the article.

2 Methodology: calculation of the energy flexibility of a building

The recent concept of energy flexibility in buildings is gaining a lot of attention. It is commonly defined as the ability of a building to adapt its energy use profile to the grid requirements without jeopardizing technical and comfort constraints [10]. However, there is no scientific agreement yet about how to calculate the energy flexibility of a building.

In the current study, the building energy flexibility is defined as the ability to shift in time the heating and cooling energy utilization from high and medium energy price periods to low energy price periods. The yearly energy use distribution between the different price categories for the case with flexibility strategy (temperature set point modulation) is compared to the one of a reference case without any energy flexibility measures (constant temperature set points). The energy flexibility index “F”, representing the load shifting for a specified building, is thus calculated according to equation (1) as the change of energy repartition between the reference case and the flexible case [9].

$$F = \left[\left(1 - \frac{\%High}{\%High_{ref}} \right) + \left(1 - \frac{\%Medium}{\%Medium_{ref}} \right) \right] \times \frac{100}{2} \quad (1)$$

Where *%High* and *%Medium* are the percentages of yearly heating and cooling energy (relatively to the total yearly heating and cooling needs) used during high and medium price periods respectively, when the energy flexibility strategy is operational. Equivalently, *%High_{ref}* and *%Medium_{ref}* are the percentages of yearly heating and cooling energy for the reference case.

The energy flexibility index takes the value of zero if the repartition of the energy use is the same as in the reference case: the building did not provide any energy flexibility. The index becomes negative if the share of high and medium price periods is larger than the reference values. If there is no remaining energy usage during the periods of high and medium price, the energy flexibility index takes the maximum value of 100% [9].

3 Description of the study cases

3.1 Building study case

The building used for the study is a new office building of Aarhus Municipality. In 2012, this was the first nearly zero-energy building to be constructed in Denmark. It consists of three floors and a basement, with a total floor area of 2924 m².

A large share of the building’s façade is glazed. In order to avoid high transmission losses, the envelope is composed of energy efficient windows, special vacuum insulation elements and polyurethane thermo-panels. The main characteristics of the building elements can be found in Table 1 [11].

Table 1. Building and load properties.

Construction elements		
U-value [W/m ² K]	Roof	0.085
	Ground floor	0.077
	External walls	0.107
	Slab	4.773
	Opaque partition walls (internal)	4
	Window	0.64
Window g-value [-]		0.49
Window light transmittance coefficient [-]		0.71
Ratio windows to wall [%]		38
Effective thermal mass [Wh/Km ²]		100
Ventilation		
ACR infiltration [l/sm ²]		0.041
ACR mechanical ventilation [l/sm ²]		1.23
ACR natural ventilation [l/sm ²]		1.21
η ventilation [-]		0.88
Other		
Shading coefficient (external shading) [-]		0.1
People load [W/m ²]		4
Equipment load [W/m ²]		6

3.2 HVAC systems

3.2.1 Convective heating with radiators and mechanical ventilation system

The first system combines radiators for heating and a mechanical ventilation system for cooling and supply of fresh air. The ventilation system is equipped with a variable air volume fan, a cooling and a heating coil, while the air from the room is not being recirculated or mixed with the primary air. Figure 1 presents the layout of the system.

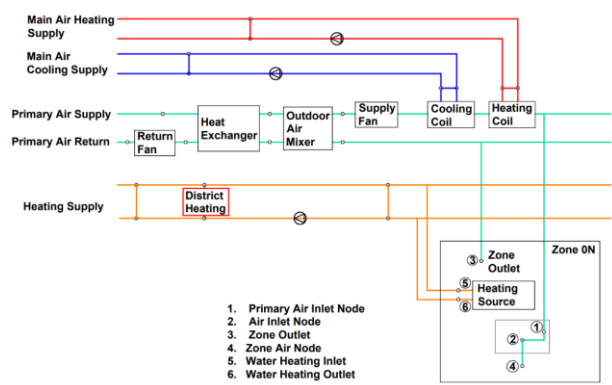


Fig. 1. Schematic diagram of radiator heating system or radiant floor heating system with mechanical ventilation.

3.2.2 Radiant floor heating and mechanical ventilation system

The second system layout is similar to the previous one, with the difference that instead of radiators, it is equipped with an underfloor heating system (UFH). The hydronic tubing is embedded within the concrete of the existing floor construction.

3.2.3 Novel two-pipe convective heating and cooling system

Lindab Solus system, a novel energy system introduced by Lindab, consists of a two-pipe hydronic system with common inlet temperature for both heating and cooling. The key feature of this system is the combination of low-temperature heating and high-temperature cooling, supplying the different building thermal zones simultaneously. The desired inlet temperature of approximately 22 °C can be achieved through the mixing of the return water from the different zones [12]. Fresh outdoor air is supplied to each zone through an active beam. A water loop is connected to the heating/ cooling coil of each active beam unit and heats up or cools down the secondary air coming from the room, before being mixed with the fresh air (primary air) and supplied in the zone. The inlet of the primary air through the nozzles creates a low-pressure zone in the mixing chamber, resulting in the induction of secondary air from the room [13]. The system is equipped with a constant air volume fan. The schematic diagram of the system is presented in Figure 2 [11].

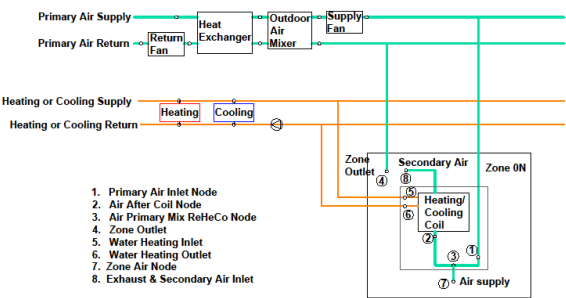


Fig. 2. Schematic diagram of the Lindab Solus system [11].

3.3 Energy flexibility control strategy

The main goal of Smart Energy Grid systems with energy flexibility measures is to improve the integration of RES. In Denmark, a large share of the electricity production comes from wind turbines. It is thus considered here that the Danish electricity spot price is a good indicator of the RES production availability and the energy demand. Consequently, the former is used as control signal for the temperature set point modulation of the energy flexibility strategy.

The latter consists in maximizing heating and cooling use during low price periods when there is a RES excess production, and minimizing it during high price periods when the energy production is insufficient for the demand.

For each hour, a low-energy price limit and a high-energy price limit are defined as the lowest and highest quartile of the electricity market spot price (Denmark, 2015) over the previous 14 days. If the electricity price is lower than the low price limit, temperature set point for heating is increased to 25 °C and the temperature set point for cooling is decreased to 22 °C. Reciprocally, if the electricity price is above the high price limit, the temperature set point for heating is decreased to 19 °C and the temperature for cooling is increased to 27 °C. When the electricity price is in between the low and high price limits, the temperature set points are kept at a neutral level of 22 °C and 24.5 °C for heating and cooling, respectively. The set points for the different cases are summarized in Table 3. In all situations, the temperature set points are always within the boundaries of the occupants’ thermal comfort [14].

Table 3. Heating and cooling set points for Reference and Flexibility cases during occupied hours.

Case	Price category	Heating set point [°C]	Cooling set point [°C]
Reference	-	22	24.5
Flexibility	Low price	25	22
	Middle price	22	24.5
	High price	19	27

3.4 Numerical modelling

The entire building systems were modelled and tested with the well-known simulation tool, EnergyPlus. The building model is a simplified version of the actual building, excluding the basement. The building is divided in 11 thermal zones based on orientation and use [11] (see Figure 3).

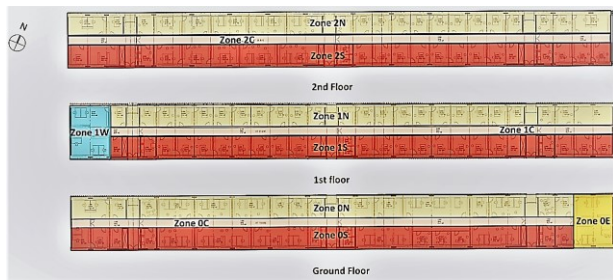


Fig. 3. Floor plans and thermal zones [11].

The schedules and internal loads from people, lighting and electrical equipment are selected to approach the operation of an office building. Likewise, the selection of building materials is intended to match the actual construction of the building [14]. Natural ventilation is automatically triggered when the operative temperature is above 23 °C and the building is not occupied, while shading is activated when operative temperature is higher than 24 °C. Electricity price and the weather data from Copenhagen, during the year 2015, are presented in Figure 4 [11].

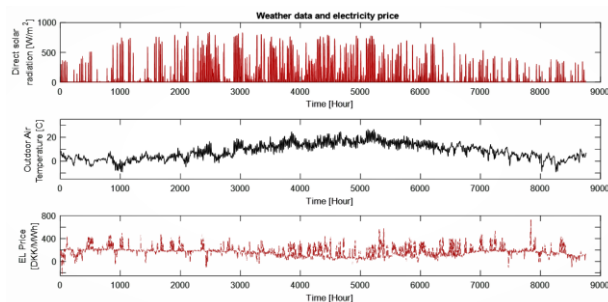


Fig. 4. Weather data (outdoor temperature and solar radiation) of Copenhagen and electricity price of Denmark in 2015 [11].

4 Results and discussion

Simulations were performed for the three different systems for both reference and flexibility cases for an entire year. The calculation results of the energy flexibility index and indoor thermal comfort are presented hereafter.

Figure 5 presents the total amount of energy used for heating and cooling of each scenario. As expected, the cases with set point modulation control have a higher energy consumption compared to the reference cases. This is because the flexibility strategies are based on energy storage. The latter is never perfect and thus induces additional losses and energy needs due to storage inefficiency. The Lindab Solus system demands more energy for cooling compared to the other systems, due to the system's operation, providing low temperature heating and high temperature cooling throughout the entire year. On the other hand, the activation of cooling for the other two systems is restricted to the cooling season. Additionally, the system equipped with radiators consumes the least amount of energy.

In Figure 6 is shown the energy usage repartition in between the different price levels (low, medium and high) for all study cases. The first plot shows the total energy

usage, while the energy used for heating and cooling are presented in the second and third plot, respectively. One can clearly observe that in the flexibility cases the energy utilization is minimised during high price periods, while it is increased significantly during low price periods. During medium price level periods, that there is no implementation of flexibility control, the consumption is altered slightly, as a consequence of the set-point variation for low and high price categories. Furthermore, the energy flexibility index is calculated and presented for the three systems. Lindab Solus system reaches 67.41% flexibility; the radiator heating system reaches 59.92% flexibility, while the UFH system achieves 56.65% flexibility. It is important to note that the flexibility achieved for the systems with radiators and UFH is generated mainly from the energy consumption for heating. That is because the energy consumed for cooling is very small and thus the ability of power adjustment is limited.

The reason why the UFH system has a slightly lower energy flexibility index compared to the radiator system is due to its slow response. The investigated office building is considered to be occupied from 08:00 to 17:00. Therefore, UFH system requires a longer time in order to reach the desired set point, in comparison to the other two systems that have a fast response. As a result, there is a time shifting in the desired temperature range for the reference case, starting late in the morning and lasting long after the end of the occupied period, as seen in Figure 7. Additionally, a higher amount of energy is necessary in order to first activate the building's thermal mass, before the operative temperature starts increasing. Consequently, even though it would be expected for a system with higher heat storage capacity to increase its energy flexibility index [6], the long period of unoccupied hours prevents the exploitation of the building's heat capacity. On the other hand, the radiator heating system can follow more accurately the set point alteration. Finally, the Lindab Solus system can maintain a higher operative temperature, even during non-occupied hours, because of the air recirculation and redistribution during the evening hours.

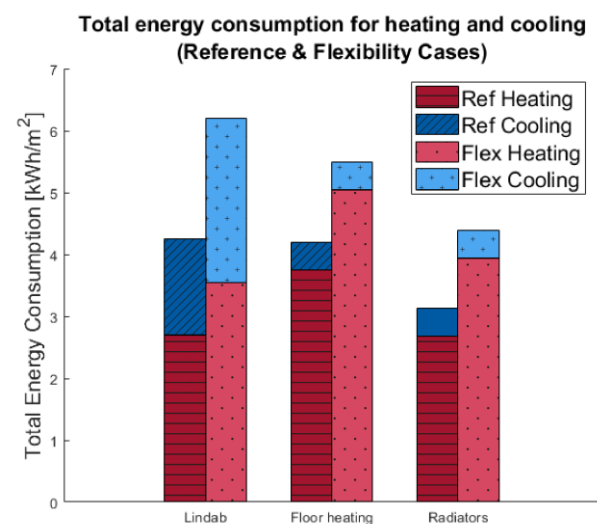


Fig. 5. Energy consumption for heating and cooling of Reference and Flexibility cases.

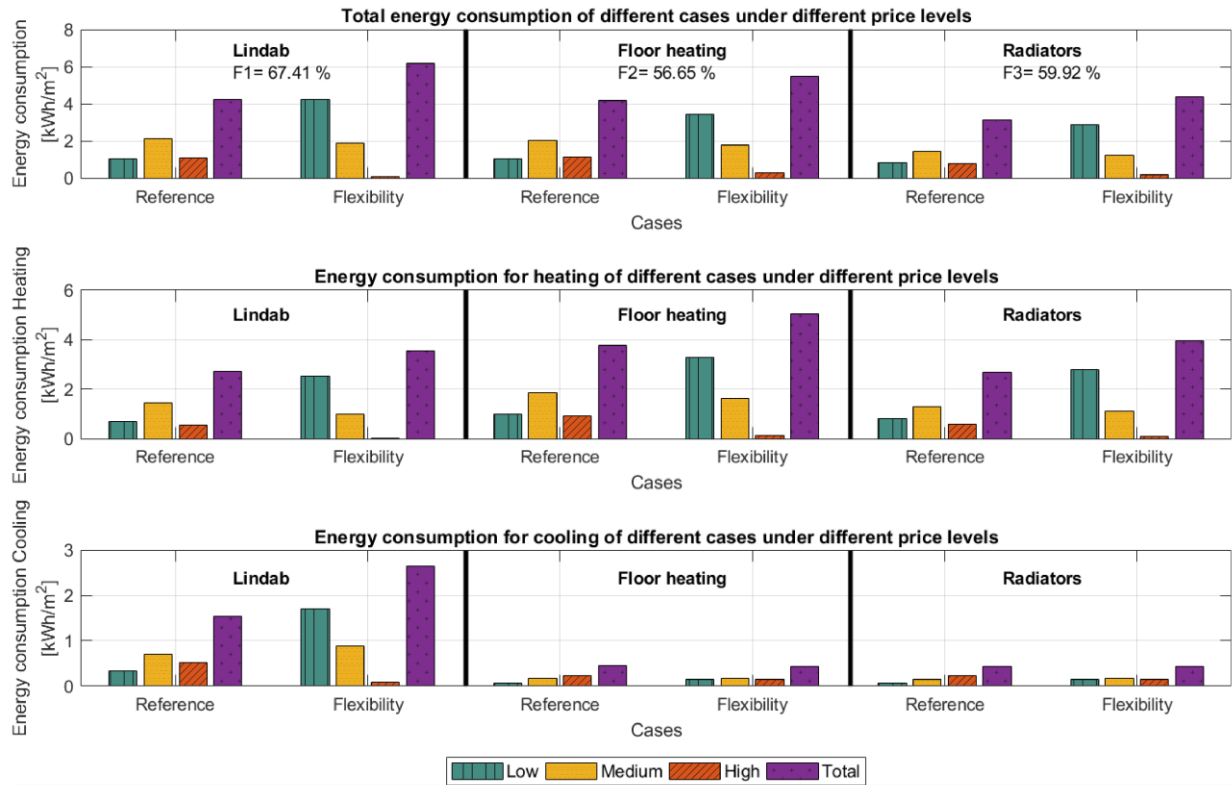


Fig. 6. Energy consumption during different price level periods of reference and flexibility cases.

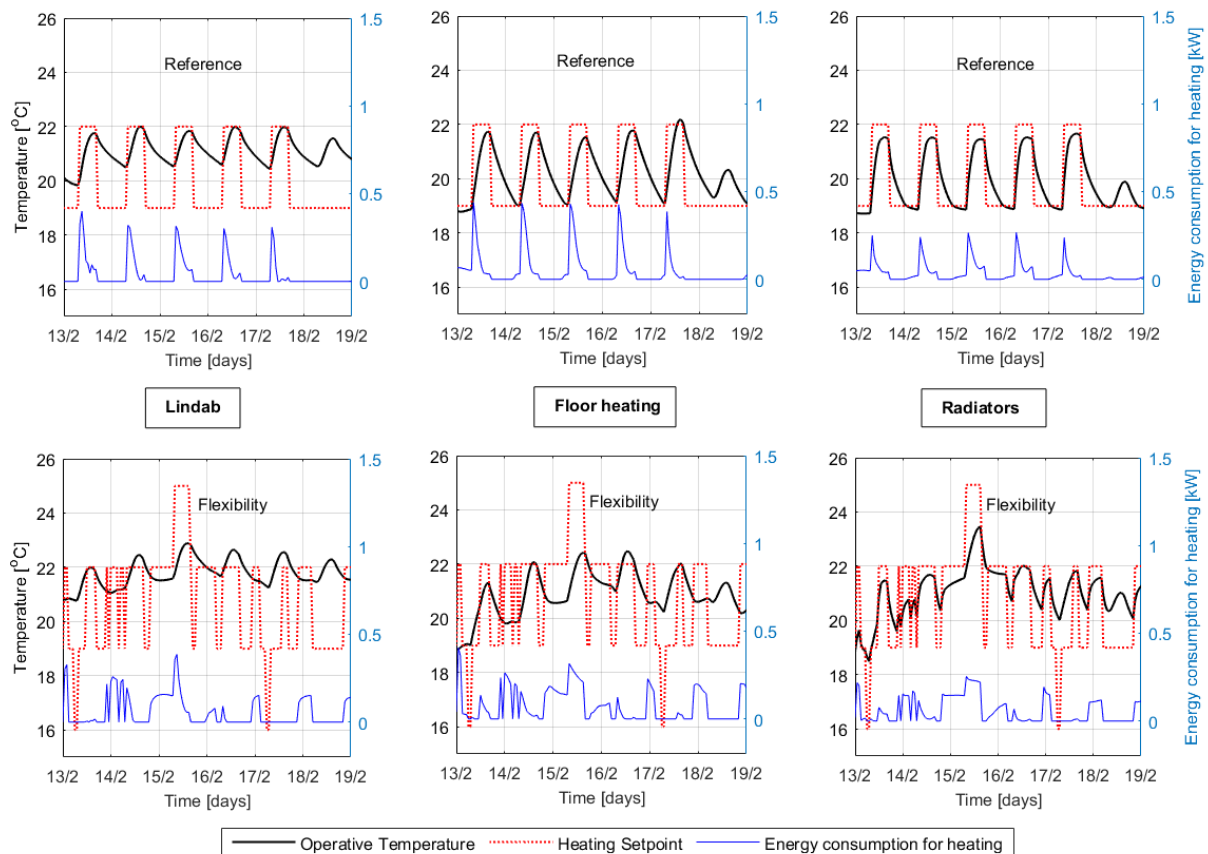


Fig. 7. Operative temperature and energy consumption of reference and flexibility cases during a week in February.

For the evaluation of the systems' efficiency, it should also be taken into consideration the achieved comfort level. Figure 8 depicts the different comfort classes for all the systems and cases. As it can be observed, thermal comfort is not being compromised in any of the cases. Set point modulation strategy maintains the building indoor comfort within Category I and II for the majority of time. The temperature ranges for the thermal categories [14] have been simplified to fit both summer and winter conditions. The percentages in each comfort class are summarized in Table 4.

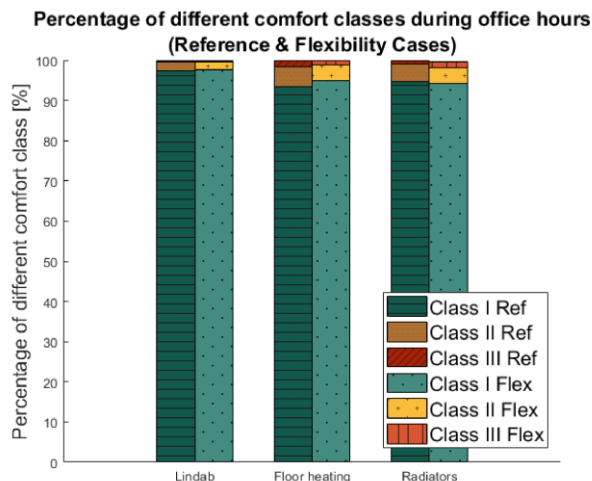


Fig. 8. Percentage of different comfort classes of Reference and Flexibility cases.

Table 4. Percentages of comfort classes [%].

		Lindab	Floor heating	Radiators
Reference	Class I	97.29	93.40	94.78
	Class II	2.28	5.07	4.38
	Class III	0.42	1.53	0.84
Flexibility	Class I	97.69	94.83	94.16
	Class II	1.91	3.99	3.95
	Class III	0.40	1.15	1.63

Finally, the yearly energy cost for each system is presented in Table 5. The system equipped with radiators achieves the lowest energy cost, before and after the implementation of the flexibility strategy, while Lindab Solus system presents the highest rise in energy cost. It should be kept in mind that the calculated values include the power transmission cost and taxes. It is worth mentioning that the current flexibility strategy cannot generate net profit. The energy tariff variations are therefore not a sufficient incentive to motivate the building owners to enable the energy flexibility techniques that will aid the energy grid.

Table 5. Yearly energy cost for each case [€/m²year].

	Reference [€/m ² year]	Flexibility [€/m ² year]
Lindab	1.057	1.496
Floor heating	1.049	1.342
Radiators	0.778	1.069

5 Conclusion

The increasing share of intermittent renewable energy sources requires energy flexible solutions to support energy grid management. This study examines the potential of different heating and cooling systems to provide energy flexibility to a nearly zero-energy office building located in Aarhus, Denmark. The investigated systems are the Lindab Solus novel two-pipe heating and cooling system, a convective heating system equipped with radiators and mechanical ventilation for cooling and a radiant underfloor heating system, also with mechanical ventilation for cooling.

The results have shown that Lindab Solus system has the highest load shifting ability with a flexibility index of 67.41%, followed by the heating system equipped with radiators, scoring a 59.92%, and the UFH system with 56.65%. More specifically, the radiator heating system uses the least amount of energy for both the reference and flexibility cases. The other two systems have a quite high initial energy consumption, which is further increased after the implementation of the set point modulation. The underfloor heating system requires a high amount of energy in order to activate the building's thermal mass, before the operative temperature can start increasing. The system is operating on its maximum capacity in order to reach the desired set point, even though the operative temperature is not too low. On the other hand, Lindab Solus system consumes less energy for heating, but due to its operation, it also demands a significantly higher amount of energy for cooling, compared to the other two systems. Subsequently, the total amount of energy need is higher compared to the other systems, especially for the flexibility case. Finally, the thermal comfort was not jeopardised for any of the cases. Even though the radiator heating system and UFH system present the highest percentages in Category III, the amount of occupied time within this category is kept below 2%, which can be considered insignificant.

Despite that the UFH system would be expected to have a higher flexibility due to the thermal storage activation of the building's thermal mass, it can be concluded that the applied set point modulation technique does not benefit the operation of this system. The rapid set point modulation, in combination with the system's slow response, does not allow it to fully take advantage of the low price periods. Furthermore, the long non occupied hours result in the waste of the stored energy.

Nevertheless, it is worth mentioning that all three systems can clearly accomplish the main goal of

exploiting the possibility of energy shifting from high to low electricity price. As a result, the mismatch between energy production and usage can be limited significantly, increasing the grid's stability and reliability and thus boosting the share of RES in energy production. Furthermore, changes in the electricity's cost and taxation are necessary in order for these benefits to be also depicted on the economic benefits for the users.

Better insight of the flexibility potential of different HVAC systems has been accomplished through this analysis. However, additional investigation would be of great interest in order to explore further the systems' capabilities. There is space for control optimisation, with the objective of decreasing the energy consumption. In addition, adjusting the control strategy to each system's needs can expand the systems' effectiveness and increase their load shifting ability. Finally, the implementation of weather prediction control for heating and cooling could be of great interest.

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