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Impact of Weather and Occupancy on Energy Flexibility Potential of a Low-energy Building

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Abstract

The introduction of renewable energy sources in the energy market leads to instability of the energy system itself; therefore, new solutions to increase its flexibility will become more common in the coming years. In this context the implementation of energy flexibility in buildings is evaluated, using heat storage in the building mass. This study focuses on the influence of weather conditions and internal gains on the energy flexibility potential of a nearly-zero-energy building in Denmark. A specific six hours heating program is used to reach the scope. The main findings showed that the direct solar radiation and the outdoor temperature appeared to have the larger impact on the thermal flexibility of the building. Specifically, the energy flexibility potential of the examined apartment can ensure its thermal autonomy up to 200 h in a typical sunny winter day.

Introduction

The high share of Renewable Energy Sources (RES) expected in the energy market for the coming years will lead to lower stability of the energy system itself due to the high dependence on weather conditions (e.g. solar radiation and wind). Consequently, there will be problems with matching the production side with the demand side. To overcome this issue, new solutions have to be implemented to increase the energy flexibility of the energy system (Lund and Lindgren et al., 2015) (Rotger-Griful and Hylsberg Jacobsen, 2015). Few decades ago, Gelling coined the term "Demand-Side Management" (DSM) to indicate all actions that can be taken to influence the users' consumption profile in order to adapt it to the energy production (Gellings and Parmenter, 1985). Such solutions (e.g. peak shaving or load shifting) are becoming more relevant in the energy management field. For instance, energy storage devices can be implemented at final-user level, in this way, when there is surplus of energy from renewable production, it can be stored and used in a second moment when there is a lack of it (Lund and Lindgren et al., 2015).

The integration of RES in the energy system also leads to a more decentralized structure, since these sources are distributed in the territory. For this reason, a "smart city" model has to be used to allow communication between energy producers, loads and components (Aduda et al., 2016) (Lund and Lindgren et al., 2015). The aim of the new energy system is to improve the flexibility on the demand side, since, due to the high maintenance and operational costs, it would be more expensive to act on the supplier side (Aduda et al., 2016) (X. Xue et al., 2015) (Labeodan et al., 2015). In the building sector, a certain amount of storage capacity can be installed while ensuring good indoor comfort for the occupants (Zheng et al., 2015). Referring to the Danish energy market, its correlation between energy price and amount of renewables production ensures that flexible consumers can benefit from lower electricity prices (Neupane et al., 2015).

As the previous studies presented by Marin et al. (2016) and Ling et al. (2006) state, the thermal mass of buildings can be used to store energy. For example, the thermal inertia of the floor heating system allows the use of intermittent heating strategies, achieving load shifting. On the other hand, the envelopes of refurbished or new buildings lead to lower heating demand and higher influence of internal gains on the heating consumption. Firląg et al. (2013) presents a first assessment of the influence of the internal gains on the energy consumption. In new buildings, heat gains can cover up to 60% of the heat losses and therefore considerably affect the energy consumption. They can affect the indoor comfort and with a dedicated heating control strategy, it is possible to take advantage of them, with the consequent reduction in energy consumption, up to 30%. In Lazos et al. (2014) it is described how heat gains prediction from occupancy and weather conditions could be used to reduce the energy consumption in a range 15-30%, highlighting the importance of heat gains prediction in the energy management of a building. Sikula et al. (2012) found that the highest impact is given by solar gains that can affect the energy consumption around 20%. In Chen et al. (2012) it is explained that the energy consumption of a building could be forecasted based on weather forecast. Le Dréau and Heiselberg (2016) showed that a single-family passive house can be totally autonomous in terms of heating demand up to 48 h, while ensuring the operative temperature was always kept above 20 °C. In the same way, Ingvarson and Werner (2008) investigated the energy storage capacity in the building mass. The results show that the heating system can be switched-off in newly built or renovated dwellings, while ensuring acceptable indoor temperature for more than 24 h.

The aim of this paper is to investigate energy flexibility in a newly constructed building through energy storage in building mass during the heating period. The building investigated follows the Danish building regulation (BR10) for a low energy building in class 2015. The energy supply for heating, ventilation, cooling and domestic hot water per m^2 of heated floor area does not exceed 30.1 kWh/m^2/year. An important step of the evaluation is the definition of a dedicated flexibility indicator, evaluated with regards to different weather conditions and internal gains. Furthermore, two heating strategies are implemented: the first one is used to define the flexibility indicator and the second one is used to assess the effect of achieving energy storage on a daily basis with a specific heating program. The relevance of this study is based on the type of building chosen for the investigation. Due to its design characteristics, it ensures a unique contribution in terms of energy flexibility.

Methodology

Model description

The reference building is located in Copenhagen, Denmark, and is newly constructed. It consists of 85 apartments of different sizes, divided in five storeys. In this case study, a reference apartment is chosen, which is 95 m^2, located at the 4th floor and facing the waterfront on the south-east façade. The apartment has three bedrooms, a kitchen-living room, two bathrooms and a storage room. Figure 1 gives an overview of the apartment.

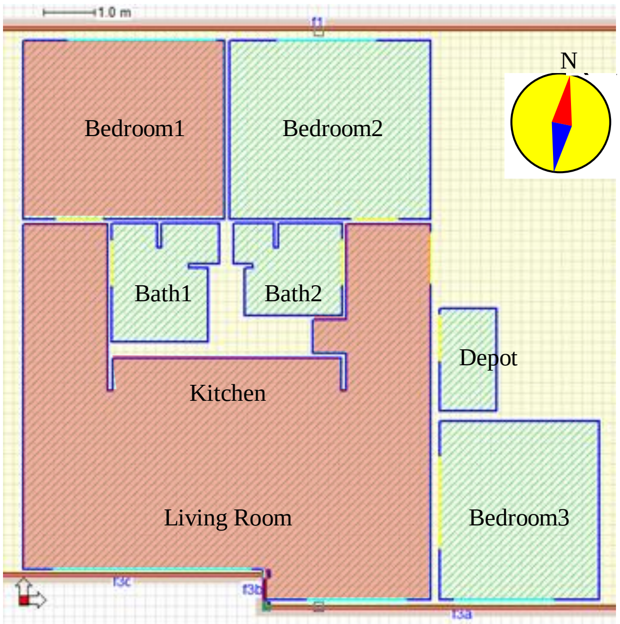

Figure 1: Floor plan of the apartment investigated

The rooms used for the analysis in this study are the Kitchen-Living Room (45 m^2) and bedroom 1 (14 m^2), highlighted in red in Figure 1. The building itself has a concrete-structure, where both internal and external bearing walls are reinforced concrete walls. Information about the composition of the building's components can be found in Table 1. The external walls have a U-value of 0.12 W/m^{2}K, while for the internal walls is 3.43 W/m^{2}K. Triple glazing windows are used with an overall U-value equal to 0.8 W/m^{2}K. The glazing-to-wall ratio is 0.42.

Table 1: Material layers

	Layer material	Thickness (m)
External walls	Concrete (inside)	0.150
	Mineral wool	0.275
	Air gap	0.025
	Brick (outside)	0.108
Internal floor	Oak planks (top)	0.030
	Concrete	0.060
	Termotec insulation	0.146
	Hollow concrete (bottom)	0.220
Bathroom floor	Concrete (top)	0.100
	Air	0.126
	Hollow concrete	0.220
	Lightweight concrete (bottom)	0.060
Bearing internal wall	Concrete	0.200
Non-bearing internal wall	Aerated concrete	0.100
Bathroom wall	Lightweight concrete	0.080

The building is connected to the local district heating network with supply water temperature at 60 °C and return at 40 °C. The space heating (SH) system is a hydronic floor-heating system with a heating design power of 16 W/m^2 (excluding the storage room) and a supply water temperature of 40 °C. The pipes are embedded in the 10 cm concrete slab (1 cm depth from the top), which is covered by a 3 cm wooden covering. The mechanical ventilation is a balanced constant air volume (CAV) system with heat recovery of 80% efficiency. The air is supplied in bedrooms and living room and is exhausted from kitchen (20 l/s) and bathrooms (15 l/s each). The supply air temperature is set at 17 °C. No mechanical cooling is implemented in the building. The external infiltrations are considered constant and are set to 0.1 l/s m^2.

The domestic hot water system (DHW) is not considered in the simulations. In the building, the system is equipped with a water tank, which provides hot water to the entire building. Since this study focused on one apartment, a scaling procedure of the water tank would have led to not precise results. Moreover, the DHW system is decoupled from the SH system, therefore this assumption does not influence the results.

The study is performed using the simulation software IDA ICE and a multi-zone model of the apartment is created with it. The simulations are run for one month, focusing on the heating season, with specific settings for weather conditions, heating schedule and occupancy characteristics as described in the following paragraphs.

Weather file

To assess the influence of the weather conditions on the flexibility potential, it is decided to vary only two weather parameters (outdoor temperature and solar radiation). For each case, three specific weather files are created based on realistic conditions of Denmark's heating season. The Test Reference Year (TRY) file representing the weather conditions in Vanløse, suburb of Copenhagen, is used as reference file to create the new ones. The outdoor temperature pattern during the heating period is analysed and three representative constant temperatures are selected. The temperatures chosen are 5 °C, 0 °C and -12 °C, respectively the highest, the average and the lowest temperature in January (coldest month in Denmark). In order to limit the influence of temperature variations, the three selected temperatures are kept constant during the simulation period.

The second parameter considered is the direct solar radiation. Similar to the temperature profile, three typical conditions are selected from the TRY file: large solar radiation, narrow solar radiation and no direct solar radiation, based on the hours that direct solar radiation is available. The large solar radiation considers 8 h of direct solar radiation, with a peak of 500 W/m^2 in the middle of the day and 0 W/m^2 at the beginning and the end of it; the narrow solar radiation considers 4 h of direct solar radiation with the same pattern. Regarding the diffuse radiation, it is assumed to have a peak of 50 W/m^2 in the middle of the day, in accordance with the direct solar radiation. These three cases are considered to occur on daily basis throughout the simulation period. The relative humidity is kept constant at 80% in all cases and absence of wind is considered.

Internal gains

In addition to solar radiation, the influence of the occupancy is investigated, simulating with two, three and four occupants. Table 2 gives a detailed description of the schedule applied to the occupants

Table 2: Schedule for four occupants working

Room	Time	No. People [MET] Weekdays	No. People [MET] Weekend
Living Room-Kitchen	7:00 - 9:00	2.1 [1]	2.1 [1]
	9:00 - 17:00	0 [0]	1.2 [1]
	17:00 -23:00	2.1 [1]	2.1 [1]
	23:00 - 7:00	0 [0]	0 [0]
Bedroom 1	7:00 - 17:00	0 [0]	0.4 [1]
	17:00 - 23:00	0 [0]	0.4 [1]
	23:00 - 7:00	2 [0.7]	2 [0.7]
Bedroom 2/3	7:00 - 17:00	0 [0]	0.2 [1]
	17:00 - 23:00	0 [0]	0.2 [1]
	23:00 - 7:00	1 [0.7]	1 [0.7]
Bathrooms	7:00 - 9:00	0.5 [1.2]	0.5 [1.2]
	9:00 - 17:00	0 [1.2]	0.2 [1.2]
	17:00 -23:00	0.5 [1.2]	0.5 [1.2]
	23:00 - 7:00	0 [0]	0 [0]

The occupancy schedule applied to the occupants evaluates two different configurations. The first one considers working people that are not at home during weekdays and the second one considers retired people that spend more time at home throughout the week. For the schedule of retired people, the weekend pattern is applied for all the weekdays.

Heating program

The aim of the heating program is to allow the possibility of load shifting. Two cases are created in order to achieve two different aims during the investigations:

- Cut-off program
- Daily heating program

The first one is used to assess the flexibility potential in terms of the number of hours of acceptable indoor comfort that can be maintained in the apartment once the heating is switched-off. It is related to the first flexibility indicator explained in the next paragraph, and it is used to evaluate the flexibility potential using different internal gains. This heating program is called "cut-off program" since it considers the complete switch-off of the SH system. More specifically, it considers a continuous control of the heating from the 1st of January until the 14th of January, with the room set point at 20 °C. Afterwards, on the 15th of January, from 0:00 until 6:00, the heating set point in the rooms is risen to higher values (21 °C, 22 °C, 23 °C and 24 °C), in order to enable heat storage in the building mass. Afterwards, the heating is switched-off and the temperature drop in the apartment is analysed.

The second program implemented considers a daily pattern. It is used to determine whether a daily heating program could provide flexibility by storing heat into the building mass. The heating pattern used is the same as the one used for the cut-off program, but in this case after the 15th of January, the SH system is set to work every day from 0:00 to 6:00. As previously, different set points are tested during the six hours heating period (21 °C, 22 °C, 23 °C and 24 °C).

Flexibility indicator

In a residential apartment, it is necessary to guarantee the occupants' comfort. In this study, the thermal comfort, and in particular the operative temperature is used as indicator to evaluate the flexibility potential of the building. The requirements provided by the European Standard DS/EN 15251 (Dansk Standard, 2007) for a building in comfort category II are followed, that require minimum operative temperature at 20 °C during the heating season.

The first flexibility indicator represents the number of hours that the operative temperature is kept above the lowest limit recommended by the standard (20 °C), once the heating is switched-off according to the cut-off program. Figure 2 shows a simplified representation of the first flexibility indicator.

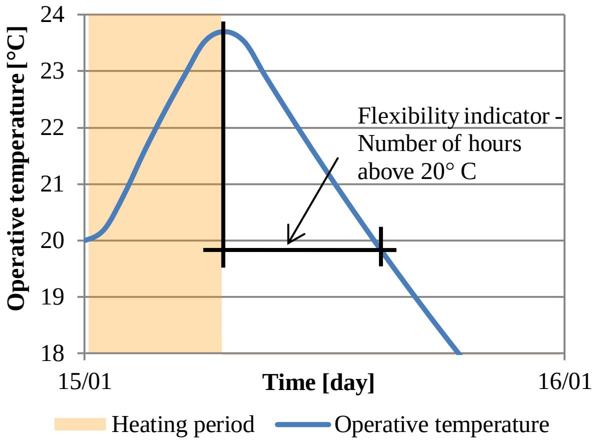

Figure 2: Representation of the flexibility indicator

The following formula (1) explains the concept adopted.

$$Ind_1 = min\ \{t \mid T_{op}(t) \geq 20\ °C\} \qquad (1)$$

where,

t is the time with a temperature above 20 °C after the heating cut-off,

T_{op} is the operative temperature in the room.

The indicator quantifies the time that the building can be independent of the heating supply, which corresponds to a period when the renewable energy is not available.

A second indicator is defined to evaluate the effect of implementing a dedicated heating program to take advantage of the flexibility potential in terms of power peaks. In fact, the new heating program created, considers raising the set point for a limited period and then switching-off the heating system. Usually, in buildings the heating set point is constant and the SH system controls the indoor temperature throughout the day. The consumption peak obtained when implementing a continuous control of the SH system is compared with the one obtained using the daily heating program presented in the previous paragraph. The indicator is defined as:

$$Ind_2 = \frac{P_{\max\_daily}}{P_{\max\_cont}} \qquad (2)$$

where,

P_{max_daily} is the consumption peak obtained with the daily heating program,

P_{max_cont} is the consumption peak obtained with the continuous control.

The flexibility indicator gives an evaluation of the impact that the implementation of energy flexibility has on the dimensioning of the heating system.

Results

Flexibility potential

The results of two reference rooms are plotted in the following graphs, Bedroom 1 and Kitchen-Living Room, since they have opposite orientation and they represent two "end-use" cases, with different occupancy schedules. In terms of thermal comfort, they represent the best and worst case respectively. The results shown refer to heating set point of 21 °C, since for higher set points, the same pattern is found and the difference is only in the magnitude of the indicator. It is important to mention that a basic case is created, and every time a single parameter is changed. The basic case considers narrow solar radiation, outdoor temperature at 0 °C and three occupants following the schedule for working people.

Figure 3 presents the flexibility indicator as number of hours above 20 °C. In this particular case, it quantifies the time that the building can be independent of the heating supply for the three different direct solar radiation cases.

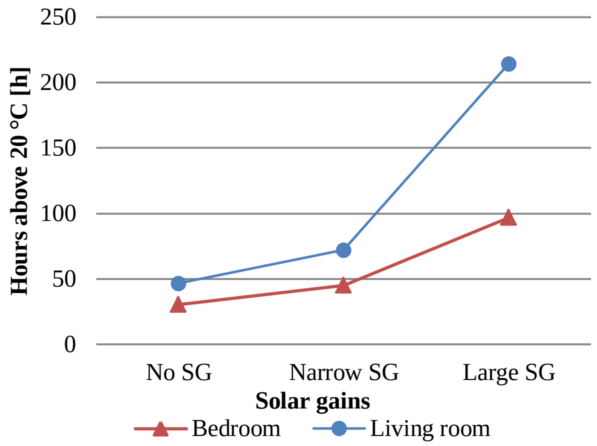

Figure 3: Flexibility indicator with different solar radiation

The impact of solar gains in the two rooms is presented with regards to the first indicator. This impact is higher in the living room than in the bedroom, mainly due to the orientation of the room that is facing south. Moreover, the glazing area is larger in the living room. It can be seen that the impact of the narrow solar gains compared to the absence of solar gains, increases the number of hours above 20 °C with a factor of 1.47 in the bedroom, while in the living room with 1.54. On the other hand, when considering the transition from narrow solar gains to large solar gains, the increasing factor is 2.14 in the bedroom and 2.96 in the living room. Therefore, it can be deduced that the indicator is affected more in case of large solar gains and that the living room is more sensitive to this change since it faces south.

In Figure 4, the results of the first flexibility indicator for different outdoor temperatures are presented. It is noticeable that the outdoor temperature influences the indicator with an exponential pattern. The results obtained with the outdoor temperature at -12 °C show that the temperature in the rooms drops rather faster and a lower flexibility can be achieved compared with the other temperatures tested. The decrease of the flexibility indicator, when the temperature at -12 °C is considered, is about 4.51 times for the bedroom and 3.93 times for the living room. On the other hand, when the temperature is changed to 5 °C, the indicator increased with a factor of 2.14 for the bedroom and 2.05 for the living room. Therefore, it is seen that the outdoor temperature is an important factor for the thermal comfort in the rooms as it was expected, and this is revealed from the flexibility indicator. In extreme outdoor conditions (-12 °C), the flexibility of the building is limited (i.e. 10 hours in the bedroom). As it is noticed also in the solar gains analysis, the living room always ensures a higher indicator due to the fact it faces south and it is more affected by the solar radiation.

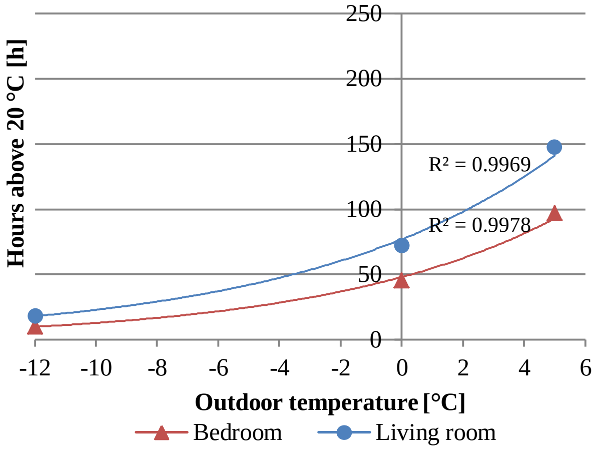

Figure 4: Flexibility indicator with different outdoor temperatures

Figure 5 shows the flexibility indicator results when different numbers of occupants are present in the apartment.

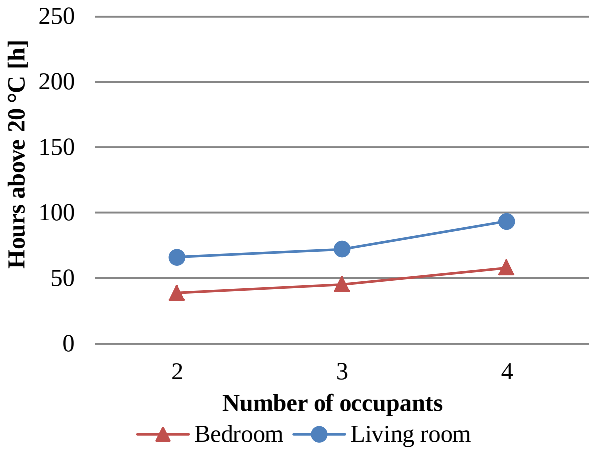

Figure 5: Flexibility indicator with different number of occupants

It can be seen that the increase in number of hours above 20 °C is almost linear for different number of occupants. The decrease of the flexibility indicator is about 1.18 times in the bedroom, when it is considered to decrease from three to two occupants, while it is about 1.09 in the living room. On the other hand, when four people are considered, compared to the case of three occupants, the flexibility indicator increased with a factor of 1.28 in the bedroom and 1.29 in the living room. It can be deduced that increasing the number of occupants by one unit can influence almost linearly the indicator. As it is seen in the previous cases, the living room guarantees a higher indicator due to the higher solar gains.

Figure 6 shows the results of the first flexibility indicator for the two different occupancy schedules. It is observed that for the schedule of retired people the flexibility indicator is higher. In particular, it increases with a factor 1.44 in the bedroom and approximately 1.26 in the living room. This is due to the time that the people spend in the apartment, which is assumed longer for retired people.

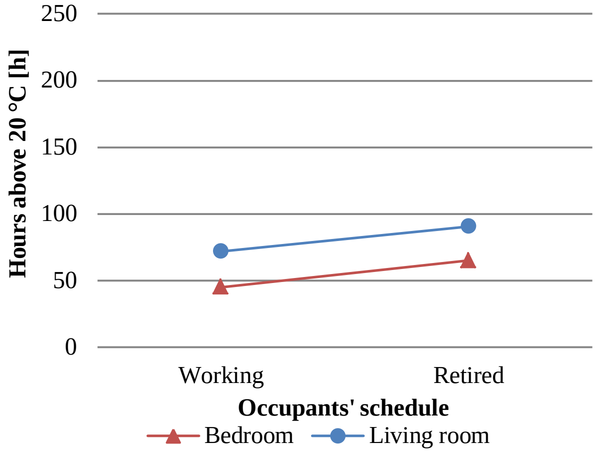

Figure 6: Flexibility indicator with different occupancy schedule

The following two analyses give an overview in case a different apartment in the same block is chosen as reference. In the first case, the building is rotated by 180°, in order to have the main façade oriented towards the north, while keeping the same allocation of the rooms. In the second one, the reference apartment is moved from the fourth floor to the ground floor and the top floor.

Figure 7 shows the flexibility indicator for two different orientation of the building.

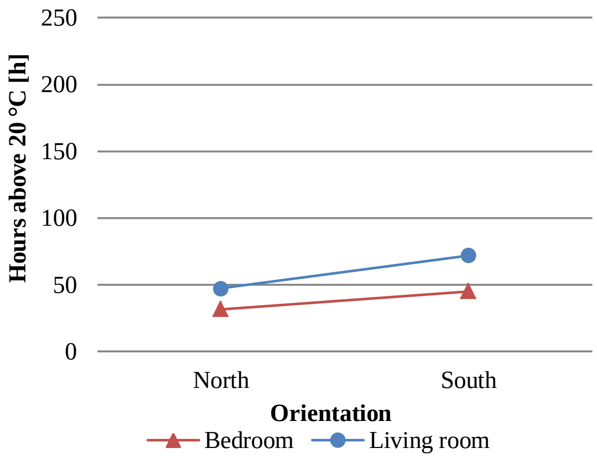

Figure 7: Flexibility indicator with different orientation of the building

When the main façade is oriented towards the south, the living room faces south and the bedroom faces north. The large glazing area of the first room guarantees the highest flexibility indicator, due to the high solar gains in the apartment. Consequently, the highest flexibility indicator is found in the living room. On the other hand, when the main façade faces north, the solar gains in the apartment are lower, resulting in a lower flexibility indicator. In this case, it is expected to get a higher indicator in the bedroom, since it is facing south. However, the room faces the internal yard, and the opposite side of the building creates shading thus reducing the solar gains in the room and attenuating the effect of being oriented to the south. Furthermore, higher internal gains in the living room still ensure a higher flexibility indicator in this room. This can be seen in Figure 7, where the indicator increases for the south orientation, 1.52 times higher than the north once, while in the bedroom the difference is lower, where the indicator is 1.43 times higher in the south oriented case.

Figure 8 represents the flexibility indicator when the apartment is moved at different floor levels.

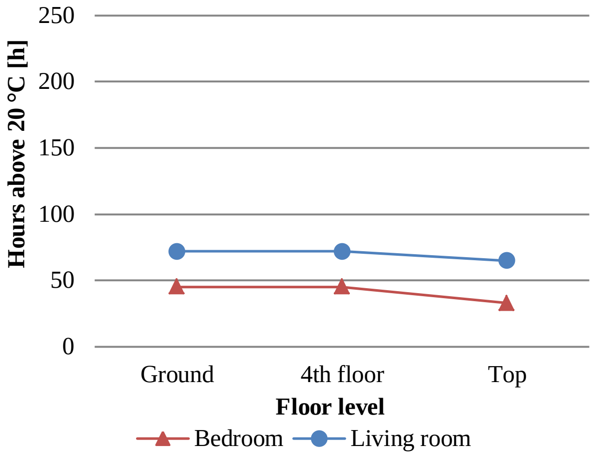

Figure 8: Flexibility indicator with different heights of the apartment

It is noticeable that for the cases at the ground floor and in the fourth floor, the results obtained are the same. Since the building has a heated basement, the losses in the ground floor are limited. However, the flexibility potential decreases 1.12 times in the living room and 1.37 times in the bedroom, when the apartment is located at the top floor. In this case, the apartment has higher heat losses since the exposed wall and roof area towards the ambient are bigger compared to the other cases.

Heating programs

In the second part of the study, the flexibility potential is investigated with particular attention to the heating system. Firstly, the flexibility potential is tested for different heating set points (20 °C – 24 °C) with the cut-off program for the basic case. Afterwards, the daily heating program is implemented and the possibility of implementing load shifting is investigated. Figure 9 shows the results of the flexibility indicator *Ind1* when the cut-off program is applied.

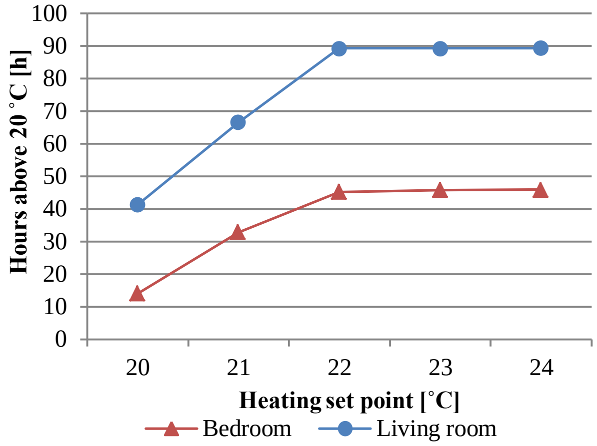

Figure 9: Flexibility indicator obtained with the cut-off program at different heating set points

It can be noticed that the heating set point used in the rooms during the heating period influences the flexibility indicator. In particular, for both the bedroom and the living room, the maximum amount of hours is reached with a set point of 22 °C, namely 89 h for the living room and 45 h for the bedroom. When higher set points are used (23 °C or 24 °C), the same results in terms of flexibility indicator are achieved, due to the thermal inertia of the floor heating system, namely that the temperature set point cannot be reached within the six hours of pre-heating. Thus, higher set points would not make any difference in the energy stored in the thermal mass. On the other hand, a set point lower than 22 °C, i.e. 20 °C and 21 °C, leads to a lower number of hours above the comfort limit. When the set point is increased from 20 °C to 22 °C in order to obtain the maximum result in terms of flexibility, the indicator increases with a factor of 3.22 for the bedroom and 2.16 for the living room.

Figure 10 shows the operative temperature pattern from January 14th until January 20th in the bedroom when the cut-off program is applied.

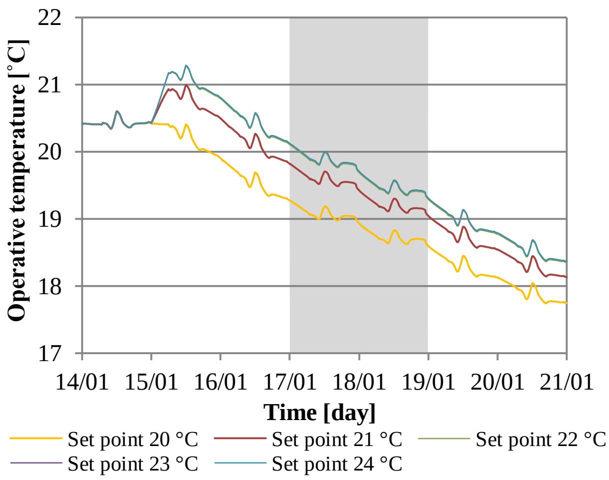

Figure 10: Temperature pattern in the bedroom for the cut-off program

As expected from the evaluation of the flexibility indicator, for set points 22 °C, 23 °C and 24 °C set points, the temperature pattern overlaps. It is possible to notice the influence of the solar radiation, which can be observed in the temperature peak in the middle of each day. The weekend is highlighted (grey area) and it can be seen that the operative temperature drop slightly decreases, due to the fact that the occupancy schedule considered that people spend more time at home. It is also noticed that the initial temperature in the beginning of the heating program is 20.4 °C. This is a bit higher than the set point (20 °C) for the period before the 15th of January. The reason is the proportional controller implemented in the model that introduces this error. It has a bandwidth of 2 °C and it stops the heating supply only when the operative temperature reaches the set point plus half of the bandwidth. The temperature pattern in the living room shows similar behaviour to the one in the bedroom with the only difference of higher temperatures, due to larger influence of the solar gains.

In the second step of the investigation, the heating program is applied on a daily basis. Figure 11 shows the temperature patterns in the bedroom at different heating set points when the daily heating program is applied. For the set points above 21 °C the six hours heating period guarantees acceptable thermal comfort in the rooms, thanks to the heat storage in the building mass. In fact, for all set points higher than 20 °C the temperature increases day by day. This means that during the heating period, the energy accumulated in the concrete slab increases day by day. Only for the set point at 20 °C, the temperature drops below the limit since the energy stored during the heating period is not sufficient to keep the temperature above the limit during the period with no heating. The grey area highlight the weekend, where the occupants spend more time in the apartment.

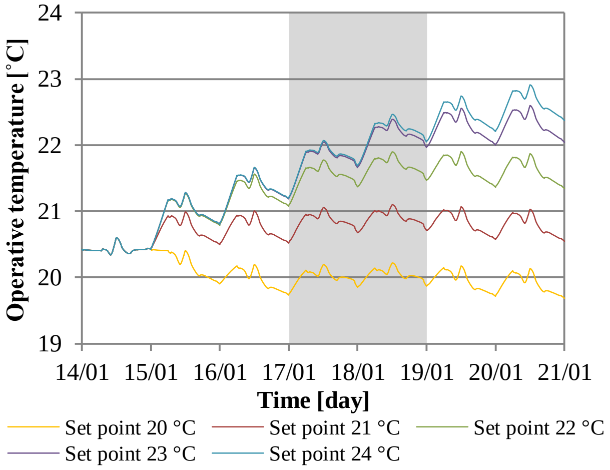

Figure 11: Temperature pattern in the bedroom for the daily heating program

The change of heating program is considered as a DSM solution and it is important to evaluate the effect of its implementation. A higher set point leads to higher power peak, compared to the continuous control of the heating system. Table 3 shows the consumption peaks for the cut-off program on the 15th of January.

Table 3: Consumption peaks for the cut-off program for different heating set points

Continuous control	
Heating set point [°C]	Peak consumption [W]
20	743
Cut-off program	
20	709
21	3785
22	4829
23	4877
24	4877

As it is expected from the operative temperature trends, the highest peak is obtained for the set points of 22 °C, 23 °C and 24 °C. This is due to the higher temperature difference between the operative temperature in the room and the set point temperature which influence the use of the proportional control. For this reason, in case of the 21 °C set point, the consumption is significantly lower, since the room temperature is closer to the set point. The highest peaks measured are slightly lower than 4900 W while for the set point of 21 °C it is approximately 3785 W. For the set point of 20 °C, the peak consumption is much lower, 743 W, but as previously shown, it provides lower flexibility. It can be concluded that, in order to enable the maximum energy storage and flexibility potential in the building mass with the increase of the heating set point, a higher power peak is required. Comparing the highest peak, (set point at 23 °C or 24 °C), with the one obtained with the continuous control of the SH system (set point 20 °C), the increase factor is approximately 6.56 times.

Regarding the daily heating program, in order to assess energy flexibility on a daily basis, the primary energy consumption of the heating system is evaluated. In this case, only the set point at 21 °C is considered, since it is the lowest one that guarantees an operative temperature above 20 °C in all the rooms. Table 4 shows the results in terms of primary energy consumption after one month.

Table 4: Primary energy consumption after one-month simulation

Primary Energy Consumption [kWh/m^2]	
Continuous control	2.89
Daily heating program	2.99

The primary energy consumption obtained with the continuous control is compared with the one obtained with the daily heating program. As it is noticed, the daily heating program leads to 3.5% higher energy consumption. Thus, in order to implement energy flexibility measures in buildings, an overconsumption of the SH system might need to be faced.

Discussion

The results obtained in this study highlighted the energy flexibility potential obtained in a newly constructed building in Denmark. The most updated construction technologies ensure lower energy consumption, lower heat losses and lower infiltration, leading to higher flexibility potential of new buildings, compared to buildings built following older legislations.

As explained also in the work presented by Le Dréau and Heiselberg (2016), which showed heating demand autonomy up to 48 h in a new passive house, new buildings can largely contribute to increase the flexibility of the energy system. In this study, the high amount of hours above 20° C (about 200 h) is found with a specific weather file, where the solar radiation and the outdoor temperature highly contribute to keep an acceptable indoor temperature. The higher flexibility potential, besides the differences in the weather condition, is due to the type of house considered in the two studies. In fact, a single family house, with higher external wall surface, has higher heat losses compared to an apartment.

During the investigation procedure, many assumptions had to be made in order to simplify the comprehension of the parameters changed. For this reason, the results need to be treated carefully according to the specific study case. However, they represent a starting point for further investigations, in which all assumptions can be sharpened in order to evolve it to a more generic model.

The specific heating program used during the investigation is based on the evaluation of consumption patterns found in the literature. According to (Fischer et al., 2016) in the daily heating demand, two peaks can be identified: the first one in the morning around 6 a.m. and the second one around 6 p.m. Since the building investigated is located in a district, where there are both residential and office buildings, synergies between the two types of buildings could be developed. The heating operator would supply the two types of buildings at different moments during the day, in order to reduce the peak consumption. Since the lowest consumption of the offices is during night, in this paper it is decided to implement a heating program that ensures the energy supply during night for the residential buildings. This solution could also be applied in case of electrical flexibility, since during the night the electricity price is usually lower due to the night tariffs regulations.

The results obtained from the investigations refer to a new low-energy building; therefore, using different type of buildings (different age of construction or not refurbished) to run the same simulations would lead to different flexibility potentials. In particular, with the perspective of extending the smart grid concept to a larger area, other types of buildings need to be studied to evaluate the impact and the relation of different constructions on the flexibility potential.

The main part of the investigations conducted is based on a simulation model that considered the weather conditions, i.e. outdoor temperature and solar radiation, constant throughout the period. This assumption was made in order to limit the influence of external parameters and it is possible to isolate the effect of each parameter. Definitely, variable weather conditions would have led to different results in terms of flexibility. However, the constant temperature and solar radiation are estimated based on the average conditions during the heating season. This makes the assumption consistent and the results more indicative.

The number of occupants and the schedule that regulate their presence are defined equally for each weekday and for each weekend. In reality, people behave in a random way and this could influence the results. In a further study, it would worth implementing a stochastic model. Moreover, to simplify the investigations, the occupied hours are not distinguished from the non-occupied ones when analysing the results and the minimum indoor temperature is set at 20 °C all times. Finally, the minimum temperature was set according to Category II of the Standard DS/EN 15251, while in reality, each occupant has a different level of acceptability and it could be interesting for further analysis to investigate if different set point temperatures in the rooms can influence the flexibility (i.e. lower set point than 20 °C in bedrooms).

Regarding the apartment's position, it emerged that a different orientation can affect its energy flexibility potential. In the same way, the floor level at which the apartment is located, can affect the indicator due to the different heat losses. Apartment and rooms oriented to the south can ensure higher flexibility as expected, while apartment located at the last floor or at the corners have a lower potential. Therefore, in order to take advantage of the flexibility potential in an apartment block, a dynamic system has to be considered, which evaluates the spatial differences and adapts the heating supply in order to ensure the desirable indoor temperature.

Conclusion

This study gives a first evaluation of how the flexibility potential depends on internal gains and weather conditions. To reach the aim, two flexibility indicators are defined and applied during the investigation. The study highlighted the high influence of solar radiation and outdoor temperature on the indicator, while showed a lower impact of the number of occupants and the occupant's schedule. The analyses about the apartment's position demonstrated that the orientation influences the flexibility indicator the most, while the floor level has a lower impact on it.

The south oriented rooms proved to be more sensitive to solar radiation, as the first indicator is found to be always higher compared to the rooms facing north. The highest impact on the flexibility indicator is given by the large solar radiation and the highest number is found at 215 hours in the living room. In this study case, the number of hours increased around four times compared to the lowest case obtained with no solar radiation. In the same way, the outdoor temperature is found to have high influence on the indoor comfort and therefore, on the possibility of using the flexibility of the building. In particular, for the extreme outdoor condition of -12 °C, the indicator showed the lowest result equal to 10 hours above 20 °C. Regarding the internal gains related to the number of occupants in the apartment and their schedules, it is noticed that increasing the number of occupants by one unit, the increase in hours is almost linear. From the study appears that solar radiation and outdoor temperature have high impact on the indoor comfort in buildings. Therefore, weather forecasts can be used as means to predict the flexibility potential of buildings and if integrated in a smart city network they can be used to achieve results in terms of energy consumption reduction, while maximizing the use of renewable energy.

Implementing flexibility with a dedicated heating program, such as the cut-off program, shows that higher power peaks have to be faced. In fact, the power peak found for the heating systems results 6 times higher than in case of continuous control. This result has to be treated carefully, since it is dependent on the heating control used, as well as it has to be taken into account that only the coldest month was considered. However, despite of the good results in terms of flexibility, changes in heating program need to be evaluated carefully, since due to the higher power peaks, the building's systems might have to be designed accordingly. Furthermore, the primary energy consumption of the heating system with the daily heating program is found to be 3.5 % higher than the continuous control. Therefore, implementing energy storage in the building mass with dedicated heating programs leads to a slight overconsumption, which can be justified if this ensures higher use of energy from RES.

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