Quantifying Thermal Flexibility of Multi-Family and Office Buildings

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Abstract

The increased feed-in of solar electricity into the grid needs to be counterbalanced by an increase in self-consumption of buildings. This paper addresses the differences in thermal flexibility between a multi-family house and an office building and the implications to thermal comfort. It looks into the operating time of both heating and cooling and gives simplified design criteria for residential buildings. The findings of the thermal simulations suggest that it seems easier to utilize thermal flexibility in residential buildings than in office buildings. Transferred to the Swiss building stock, it is estimated that roughly 10% of the dwellings could offer some thermal flexibility to the grid.

Introduction

The feed-in of solar energy based electricity into the grid can have detrimental effects due to an excessive supply during daytime. Ideally, buildings that consume electricity for space heating or cooling should align their demand with times of excessive supply. In the case of the aforementioned solar energy based electricity, this would be during the day in order to ensure a high self-consumption. Requiring only short windows of time for energy demand is advantageous, here. The prerequisite are buildings, which allow this flexibility without any severe drawbacks for the user.

In a more general sense, flexibility can be assessed in multiple ways. A literature review (Marszal-Pomianowska, Reynders, Lopes, & Aelenei, 2017) outlines that the diverse approaches found fall into three categories:

1) *"the temporal flexibility,*
2) *the amount of energy or power that can be shifted and*
3) *the associated cost of activating this flexibility."*

The extent of the achieved flexibility depends predominantly on (see Figure 1)

- the building: heating/cooling demand, thermal capacity, appliances (electricity consumption and internal loads),
- the heat generation: installed capacity of the boiler / heat pump,
- the available storage for heat and/or electricity and
- the amount of electricity produced.

As the feed-in of solar energy into the electrical grid is a central issue, the temporal flexibility is a relevant property for the investigations. Restriction of the operation of major appliances to daytime hours is beneficial. Ideally, these time slots should be short enough so that a flexible shifting of these core times during daytime is possible. User acceptance of the flexible operating times exerted by energy providers is crucial and can be gained only if a satisfactory thermal comfort is assured. For this reason the investigation focuses on thermal comfort. The consequence on the operative temperature during occupancy when deviating from the usual operating times of the heating / cooling system is evaluated.

Methodology

Scope

This paper mainly addresses the thermal flexibility provided by the building mass. The necessary operating times during daytime for an electricity driven heating/ cooling device, for instance a heat pump, while ensuring comfort requirements during occupancy are evaluated.

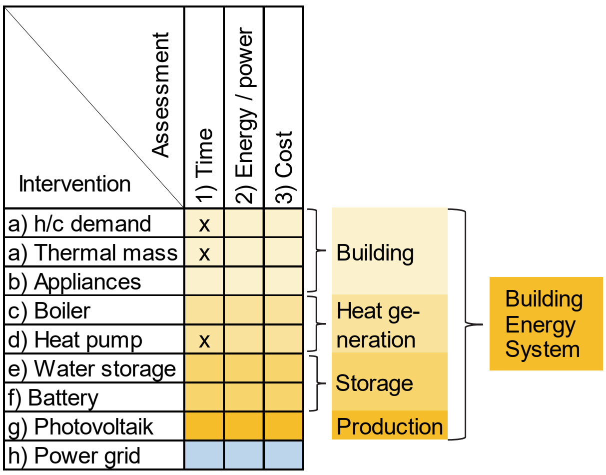

Figure 1: Possible zones of intervention in a building a) to h) and possible properties for assessing the energy flexibility. Abbreviations used: h = heating, c = cooling, x = considered in this paper

Electricity storage or the general grid compatibility of the building is not considered. Figure 1 shows the project scope in an extended "building energy flexibility map".

Questions

In this paper, it is explored whether it is possible to operate a certain building type with heating and cooling power available only for short intervals during daytime while maintaining thermal comfort. The analysis is done for a residential building and an office building.

Because of the different building uses, the analysis has two different emphases. For the residential building, focus is on building envelope and structure related topics. For the office building, focus is on different operation modes. This is due to the fact that internal loads in office buildings are typically more than twice as high as in residential buildings (SIA 2024, 2015).

Because the paper addresses thermal comfort as well as heating/cooling demand in detail, heat injection and extraction are modelled in detail. In the residential building, a floor heating is simulated and in the office building a concrete core conditioning (embedded in the centre of the floor/ceiling construction) for heating and cooling is considered. In both cases, heat injection/extraction occurs in the appropriate layer of the construction considered Thus, both heat and cold distribution take thermal inertia and resistivity of the actual layer structure into account.

For the residential building, only wintertime is looked into, because an active cooling is unusual. Parameters considered are the insulation standard, thermal capacity and installed heating capacity. It is evaluated how each of these parameters affect the necessary operating time of the heating. No cooling is analysed, here.

For the office building, different operation modes are analysed. Operating times for heating or cooling necessary to maintain thermal comfort are evaluated. In the winter, the duration, the onset time and the supply temperature of the heating as well as the electric lighting are varied. In the summer, an active discharging of the thermal capacity (by concrete core conditioning) is considered. The cooling power can be provided by a heat pump, for example. In the simulations, the duration, the onset time, the set point, the supply temperature and the mass flow rate of the cooling is varied. Additionally, the electric lighting and the internal loads are altered and night-time ventilation is considered.

Tools and general simulation setup

The thermal simulations are performed with ESP-r ("ESP-r," n.d.). Both building types are defined as geometric models within a certain environment (climate data), use detailed schedules of building operation and feature building /plant control. The plant is based on an explicit component approach. The simulations have a pre-simulation period of 60 days, to allow transient oscillation of the building model. The basic settings of each building model are described in the following sections. For the simulated variants, the parameters of interest are changed as described in chapter "Thermal flexibility of the residential building" and in Tables 3 and 4.

Buildings

The residential building

The basis of the investigations is an existing multi-family house, which comprises three apartments (ERA of 320 m^2) and is built to MINERGIE-P Standard, which means it has a very high level of thermal insulation (Table 1). The building can be viewed as a "light" heavyweight construction. It features external walls in lightweight concrete and ceilings/floors as well as a flat roof in heavy weight reinforced concrete. A ground-source heat pump (geothermal probe) heats the building with an installed capacity of 8.9 kW. The heat is distributed by a floor heating. The supply temperature is 35 °C with a set point temperature θ_{air} = 20 °C. A mechanical extract and supply ventilation system with heat recovery (80 %) is installed. A photovoltaic system (PV) with 20 kW peak design capacity is installed on the roof.

Table 1: Properties of the residential building. Remarks: ^{a} = mechanically ventilated spaces in the flats, ^{b}= calculated according to (SN EN ISO 13786:2007, 2007)*, ^{c} =* (SIA 2028, 2010)*,*

Property	Value
U-value, ext. walls	0.119 [W/(m^2 K)]
U-value roof	0.089 [W/(m^2 K)]
U-value windows	0.75 [W/(m^2 K)]
g-value, windows	50 [%]
Glazed part of wall (area weighted)	23 [%]
Solar control (blinds)	Not applicable
Shading (surrounding buildings)	yes
Thermal capacity (with R_{si})	63 [Wh/(m$^2_{NFA}$ K)]^b
Air exchange rate ^{a}	0.39 [1/h]
Climate	DRY Buchs-Aarau (CH)^c

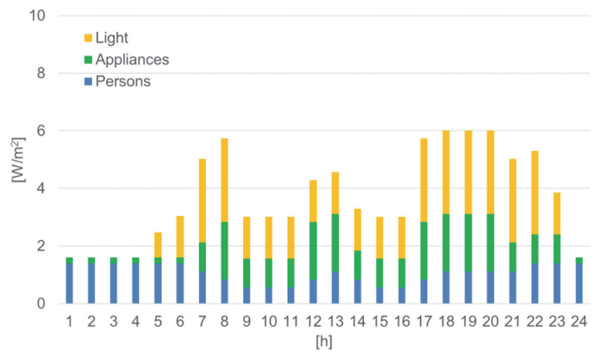

Figure 2: Internal loads (occupants, appliances, light) for residential buildings according to Swiss building standard SIA 2024 (SIA 2024, 2015). Generally, the run time for the EL is adapted, as the standard would suggest 16 hours full use of the light (installed capacity: 9.4 W/m^2). The graph shows the adapted values for wintertime

Further information on the building and related research can be found in (Hall, Dorusch, & Geissler, 2014) and (Hall & Geissler, 2015).

The simulations are performed and evaluated for the period from 1st of January until 28th of February. The building is occupied all the time, thus all hours and all day types are evaluated.

The office building

The office building has an ERA of 1´040 m^2. Open-space (OPO) and cellular (CO) offices equally share 62 % of the area. The remaining space consists of secondary rooms and circulation areas (VDI 3807, 2013). The exterior walls are made of masonry; the slabs and the structural core consist of concrete. Internal walls are lightweight constructions (gypsum cardboard and mineral fibre). The heat and cold distribution is realised by concrete core conditioning (radiant floor/ceiling). The hydronic supply temperature is 35 °C with a set point temperature θ_{air} = 20 °C in winter. In summer, the temperatures are 18 °C and θ_{air} = 26 (or θ_{air} = 24 °C), respectively. As in the residential building, a mechanical extract and supply ventilation system with heat recovery (80 %) is considered. Solar control is by Venetian type blinds. In summer and winter these are closed (deployed, slat angle horizontal) when façade insolation is greater than 180 W/m^2. The blinds retract when façade insolation falls below 150 W/m^2.

Table 2: Properties of the office building. Remarks: [a]= The difference is due to higher occupancy in the OPO, [b]= calculated according to (SN EN ISO 13786:2007, 2007), [c] = (SIA 2028, 2010)

Property	Value
U-value, ext. walls	0.17 [W/(m^2 K)]
U-value roof	0.17 [W/(m^2 K)]
U-value windows	0.61 [W/(m^2 K)]
g-value, windows	50 [%]
Glazed part of wall (area weighted)	40 [%]
Solar control (blinds)	Yes (summer and winter)
Shading (surrounding buildings)	no
Thermal capacity OPO / CO (with R_{si})	50 / 62 [Wh/(m$^2_{NFA}$ K)] [b]
Air exchange rate OPO / CO	0.308 / 0.246 [1/h] [a]
Climate	DRY Zürich (CH) [c]

The simulations are performed for one level in middle of the building. They are evaluated in winter for the period from 1st of January until 31st January (coldest month) and in summer from 1st of July until the 31st of July (hottest month). The building is occupied on 5 days per week between 8 am and 6 pm. The evaluation considers occupied hours, only (in January and July 230 h each).

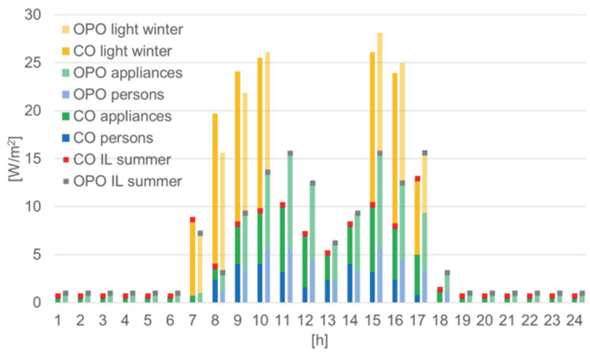

Figure 3: Internal loads (persons, appliances, light) for office buildings discriminating between OPO and CO according to (SIA 2024, 2015). The bars represent the loads in winter, the squares the lump sum in summer. The difference is due to the reduced use of EL in summer. Generally, the run time for the EL is adapted in summer and winter, as the standard would suggest 11 hours full use of the EL (installed capacity OPO: 12.5 W/m^2, CO 15.9 W/m^2).

Simulation results

Thermal flexibility of the residential building

All thermal simulations are evaluated under the condition that the operative room temperature should never drop below θ_{op} = 20 °C. In order to assess the flexibility of the necessary time slots of the heating, parameters such as thermal capacity, heating demand and capacity of the heating are varied. Figure 4 shows the correlation between the operating time of the heating (y-axis) and the thermal capacity. Five different insulation levels leading to different heating demands (represented by different colours) are analysed. The initial building as characterised in Table 1 has a heating demand of 18 kWh/(m^2 a). Two different installed capacities of the heat generation system are symbolised by line styles (solid, dashed). The graph only takes the heating's operating time for space heating into account. Hot water generation requires approximately one additional hour run-time (which was included in the simulations by blocking the space heating between 12 am and 1 pm). Figure 4 leads to following conclusions:

- reduction of the heating demand is paramount for a reduction of necessary run-times of the heating
- increase of installed capacity of the heat generation system also allows for a reduction of run-times
- A thermal capacity exceeding 60 Wh/(m^2 K) does not reduce the necessary operating time of the heating significantly. Thus, the simulations suggest that less thermal capacity is usable within 24 h periods than the calculation according to SN EN ISO 13786:2007 indicates.

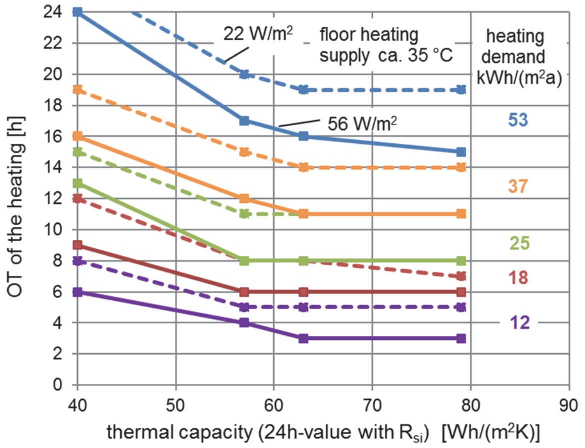

Figure 4: OT of the space heating vs. thermal capacity. Heating demand (colour) and the heating's capacity (line style) are varied. Thermal capacity is calculated according to SN EN ISO 13786:2007

Figure 5 gives simplified correlation equations for run-time of the heat pump vs. heating demand for two levels of thermal capacity (with an installed heat generation capacity of 40 W/m^2 as a basis). These simplified correlations can be used to assess design parameters in a more comprehensible way.

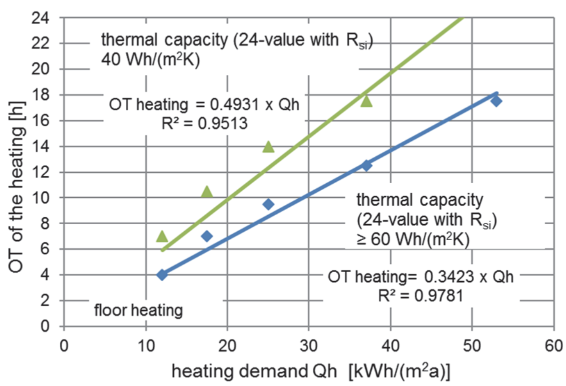

Figure 5: OT for space heat vs. heating demand for different thermal capacities. Thermal capacity (24h value with R_{si}) is calculated according to SN EN ISO 13786:2007

So far, the discussed running modes of the heating were consecutive time blocks of different lengths at daytime. The logical consequence would be to examine shorter time sequences of the heating within 24 h periods. The economic background for this approach is that the utility could shift the runtime of the electricity driven heating (e. g. heat pumps) according to its needs. Taking Switzerland as an example, certain utilities already include this rationale within their tariffs for heat pumps. These utilities are able to cut the volume of purchased electricity for certain times, e. g. 3x2 hours per day. The longest possible shut down period is two hours. The duration of the following on time must be at least as long as the previous shut down period. The simulations show that if the heating is allowed to run in time sequences between one and three hours, the equally long shut down periods do not cause a comfort problem. It is found, that such an intermittent activation of the heating allows to reduce the overall run-times according to Figure 4 by one to two hours. A reason could be that with shorter time sequences between the on and off mode of the heating, the building cools down less than with the long shut down period.

Thermal flexibility of the office building

Winter

Table 3 gives a detailed summary of the results for the assessed variants. The open plan office shows more hours with an insufficient temperature than the cellular offices. This is due to the higher air change rate in the open plan offices. The results clearly show that it is not possible to shut down the heating during the whole weekend and maintain an acceptable thermal comfort. Suspending the heating during Saturday is possible in certain cases. Roughly speaking, an operating time of seven hours is enough (#1), although it is crucial that the onset of the heating is aligned with the office hours (#1, #7, #10 shown in Figure 3). If irradiation for the power generation is available, heating should start around 8 am. If the heating is active between 8 am and 5 pm the thermal comfort in the offices is adequate, however, the temperature in the circulation area and the secondary rooms may drop below θ_{op} = 20 °C (but not below θ_{op} = 18 °C). A shutdown of the heating at 4 pm (#7-#10) would be ideal in terms of direct use of PV generation. However, the electric lighting is required as additional heat source. The elevated supply temperature (#10) is only applied for theoretical purposes, as standard SIA 384/1:2009 does not allow supply temperatures for slab heating exceeding 35 °C.

Table 3: Calculated hours θ_{op} < 20 °C with different OT of the heating. The numbers in the coloured boxes are the total number of office hours with θ_{op} < 20°C. Remark: an indicated runtime from 7 am to 8 pm means 7:00 am to 7:59 pm

	Runtime daytime	Runtime during week						Remarks
		Mo - Sun		Mo - Fr		Mo - Fr + Sun		
#	6 am - 8 pm	CO	OPO	CO	OPO	CO	OPO	
1	7-14	0	0	15	26	4	4	
2	7-15	0	0	14	22	3	4	
3	7-16	0	0	12	18	3	4	
4	7-17	0	0	12	16	0	0	
5	8-17	0	0	17	27	3	4	
6	9-17	0	1	26	36	6	13	
7	9-16	1	3	29	38	10	16	
8	9-16	0	0	0	8	0	0	EL 7 am - 5 pm
9	9-16	45	47	126	121	76	72	no EL
10	9-16	0	0	23	25	2	4	supply 45°C
11	10-17	1	7	34	46	14	22	

Summer

Theoretically, summertime seems favourable for direct usage of solar electricity as consumption and generation of solar energy based electricity coincide to a large degree.

Similar to the winter, it is not possible to shut down the cooling during the weekend. The results suggest that even a shut down on Saturday only leads to temperature exceedances. Table 4 shows the results of the thermal simulations with cooling during weekdays and the weekend in detail.

It is found that exclusively cooling by means of the concrete core conditioning is not sufficient. Even if the supply temperature is lowered (#3), or nighttime ventilation is applied, temperatures may exceed θ_{op} = 26 °C. Shifting the cooling set point from θ_{air} = 26 °C down to θ_{air} = 24 °C does not show any effect because the cooling is always on during occupancy, anyway.

The most efficient means to enhance thermal comfort in summer is – as a supplement to active cooling - to lower the internal loads (#9, #13) or to raise the mass flow rate from 100 l/h up to 120 l/h per coil (#14), which is still in the advisable range (Voss et al., 2016). However, if these measures are not possible, active cooling between 6 am and 8 pm is necessary to provide sufficient thermal comfort.

Table 4: Calculated hours θ_{op} > 26° with different operating times of the cooling. The number in the coloured boxes gives the total number of hours with $\theta_{op.}$ > 26 °C.

	Runtime daytime	RTDW		Remarks
		Mo - Sun		
#	6 am - 8 pm	CO	OPO	
1	9-17	177	192	
2	7-18	31	67	
3	7-18	27	63	supply 16°C
4	7-18	41	85	no EL
5	9-17	124	184	no EL
6	7-18	19	53	NV 6 pm - 7 am, 0.5 1/h
7	9-17	67	98	NV 6 pm - 7 am, 0.5 1/h
8	7-18	8	20	NV 6 pm - 7 am, 1.5 1/h
9	7-18	0	0	NV 6 pm - 7 am, 1.5 1/h, IL -20%
10	9-17	25	41	NV 6 pm - 7 am, 1.5 1/h
11	7-18	8	20	NV 6 pm - 7 am, 1.5 1/h, C 24°C
12	8-18	9	18	NV 6 pm - 7 am, 1.5 1/h, C 24°C
13	8-18	0	6	NV 6 pm - 7 am, 1.5 1/h, C 24°C, no EL
14	8-18	0	7	NV 6 pm - 7 am, 1.5 1/h, C 24°C, MF +20%
15	6-20	0	0	NV 6 pm - 7 am, 1.5 1/h, C 24°C

Validation

Both building models are validated by detailed results analysis. The residential building model results are additionally validated by comparison to measurement values derived from the real building (Hall & Geissler, 2015). The office building model results are additionally checked against real-world design values and compared to results from similar models from previous work.

Discussion and outlook

Different assessments of flexibility

The introduction described three different ways to assess flexibility: temporal flexibility, the amount of energy shifted and cost associated with flexibility. In this paper, focus was placed on temporal flexibility. It can be safely assumed that the three aforementioned approaches lead to contradicting requirements. A short outline using the residential building example illustrates this. In terms of temporal flexibility, a well-insulated building with a correspondingly low heating demand and a thermal capacity of roughly 55 Wh/(m^2 K) should be targeted at. If the focus is switched from temporal flexibility to the amount of energy shifted, the absolute amount shifted in a well-insulated building is small compared to a poorly insulated building (Le Dréau & Heiselberg, 2016),(Weiss, Fulterer, & Knotzer, 2017).

Concerning the cost, it depends on the local utility whether it is an economic decision to raise the self-consumption. In terms of grid-stability, the current trend is towards encouraging self-consumption. If no PV-production is possible, electricity consumption during the night is still most cost-effective (Klein, Kalz, & Herkel, 2014).

Residential building

The insulation level (expressed as the corresponding heating demand), thermal capacity and installed capacity of the heat generation system are combined graphically, thus presenting an easy to use tool for the first design stage to determine the potential of thermal flexibility. The graph is based on a residential building with a glazing ratio of the façade of 23 %. Preliminary tests with a highly glazed residential building (albeit with a comparatively high average building envelope U-value) suggest that the graph in its current form might apply only to moderately glazed residential buildings. In order to address a wider choice of buildings, further research is needed.

Another aspect worth mentioning is the user feedback to an “adaptable” thermal comfort. A survey exploring the possible attitude towards a decline of thermal comfort revealed that the majority of respondents seemed only “slightly willing” to reduce the room temperature during high electricity price periods (Li, Dane, Finck, & Zeiler, 2017).

Office building

Thermal comfort in winter can only be maintained if the heating is on between 8 am and 5 pm. For summertime, it is found that cooling must be in operation between 6 am and 8 pm and additionally, nighttime ventilation with a minimum ach of 1.5 1/h must be available. The necessary operation window corresponds roughly to the availability of irradiation in the simulation period considered. In both seasons, the internal loads play a crucial role, although with an adverse effect. While the internal loads are essential to maintain the thermal comfort in wintertime, during summertime they should be as limited as possible. Therefore, reduced turn on times for the electric lighting were introduced, assuming the use of daylight whenever possible. The results show that with 11 h runtime of electric lighting, cooling by concrete core conditioning during daytime hours only does not provide a sufficient thermal comfort. A more efficient lighting, for example LED, could mitigate this issue.

In the context of aestival comfort, it is worth to comment on the use of shading. In the simulations described here, a relatively high g-value (50%) together with an external Venetian type blind is assumed. On a sunny summer day (29.07.), the shading is deployed in the east from 6 am to 3:20 pm, in the south from 7:30 am to 3:50 pm and in the west from 11:10 am to 7:06 pm. The slat angle of the shading is thereby presumed to be horizontal. The assumption that the electric lighting is mostly turned off during daytime in summer might therefore be too optimistic. Consequently, maintaining thermal comfort in summer might be even more challenging than shown here. If – as it may be the case in office buildings - a glass with a lower g-value is used, the activation times for solar control might be shorter. However, in that case, glare might be an additional trigger. In wintertime, a lower g-value and correspondingly reduced solar gains might result in a higher number of hours for which thermal comfort criteria are not met. In the simulations described in this paper blinds are also operated in wintertime to avoid glare. An additional internal blind to control glare while allowing solar gains should be generally considered. However, this is often discarded due to cost issues and therefore not included, here.

Overall, the simulation results show that thermal flexibility in context with thermal capacity can be utilized fairly effectively in wintertime, but is technically challenging in summertime. This is in good agreement with other recent works ((Klein, Herkel, Henning, & Felsmann, 2017), (Kathirgamanathan, DeRosa, Turner, & Finn, 2017)).

Application to Swiss building stock

The Swiss building stock is documented with inhomogeneous precision. Residential buildings are recorded in detail, non-domestic buildings are covered only by a documentation dating from 1990 (Wüest, Rey, & Steinbach, 1991). At that time, the building stock consisted of 50 % residential buildings and 6 % commercial buildings. The remaining 44 % is composed of farm buildings, subsidiary buildings and industrial buildings (total sum 2.1 million buildings). Today, the entire building stock is estimated at 2.3 million buildings (EnDK, 2014). For residential buildings, some numbers on heating systems used are available (Bundesamt für Statistik BFS, 2017). In 2015, a total of 1.7 million residential buildings existed, of which 12 % (203´000) had a heat pump installed. If it is assumed that only reasonably well insulated buildings are eligible to thermal flexibility, it can be deduced that buildings from 1990 onward are suitable. Altogether, this would be roughly 10 % of the residential buildings. A corresponding statement is impossible for the commercial sector due to a lack of data on the building stock.

Conclusion

In this paper, the temporal flexibility of a residential building and an office building is presented. The results given are based on thermal building simulations. A precondition for a high self-consumption rate and a low feed-in rate to the electricity grid are flexible and short time frames necessary for the operation of the heating/cooling systems.

Residential building

The results show that a low heating demand and a thermal capacity of roughly 55 Wh/(m^2 K) are favourable. Installation of a high capacity heat generation system may additionally reduce the operating times, at the expense of a higher energy demand, however.

Based on a wide range of simulations, a simplified method for the assessment of the necessary operating time of the heating is proposed. Thus, the operating time of the heating can be used as a parameter for flexibility. The shorter the necessary operating time of the electricity driven heating (e. g. heat pump), the higher the flexibility the building can offer to the grid.

Office building

The simulation results illustrate that the thermal capacity provides enough thermal flexibility to constrain the heating's operating to daytime during wintertime. However, it is crucial to maintain heating during the weekend.

In contrast, thermal flexibility is not as high as expected in summertime. Long run-times of the cooling during daytime including the weekend and an additional nighttime ventilation are necessary to create a satisfying thermal comfort. This is due to high internal loads. In both seasons, the internal loads exert a major impact on the thermal behaviour of the building. While in wintertime the internal loads are essential to maintain thermal comfort, in summertime they should be reduced as far as possible.

Both building types can – under certain preconditions – be operated in such a way that heating and cooling is restricted to daytime. Thus, self-consumption can be increased. The results show that this can be achieved more easily for residential buildings, however. In comparison, the office building generally needs longer operating times. Wintertime seems easier to control than summertime.

Acknowledgements

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Nomenclature

C	set point cooling
CO	Cellular office
EL	Electric lighting
ERA	Energy reference area according to (SIA 416/1, 2007)
IL	Internal loads lump sum summer
MF	mass flow rate
NFA	Net floor area, definition according to (SIA 416/1, 2007)
NV	nighttime ventilation
OPO	Open plan office

OT	Operating times
θ_{op}	Operative temperature, 0.5 ($\theta_{air} + \theta_{rad}$)
θ_{air}	Air temperature
θ_{rad}	Mean radiative temperature (long wave)

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