OPTIMIZATION OF CONCURRENCY OF PV-GENERATION AND ENERGY DEMAND BY A HEAT PUMP – COMPARISON OF A MONITORED BUILDING AND SIMULATION DATA

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ABSTRACT

Monitoring data of a small, well-insulated residential building shows that the electricity consumption of the heat pump amounts to approx. 30% of the total electricity consumption of the building. Shifting duty cycles of the heat pump into the daytime would therefore be a possible means to greatly increase the concurrency of electricity production and consumption and reduce the grid interaction without an expensive technical effort. Experimentally, the duty cycle of the heat pump is limited to daytime from 10 am through 7 pm. The monitored data shows this is sufficient to heat the building and the domestic hot water.

Interesting questions that arise are e.g. if such run-time limitations can also be used with a heavy (concrete) and a lightweight (wood) construction and if further reduction of the run-time is possible. Reducing run-time even more would further increase self-consumption and reduce grid interaction. The impact of the thermal mass of the construction and the limiting of the run-time are investigated by transient thermal building simulation. The simulation model with constructions "as built" is calibrated based on measurement values from temperature sensors in the living rooms and the measured heating demand of all three apartments. Simulation results are evaluated based on thermal comfort criteria in the living rooms of each apartment.

The results obtained show that for the construction types "as built" and "heavyweight" no differences in resulting thermal comfort are to be expected. Construction types "as built" and "heavy weight" show good robustness in regard to the limitation of the run-time of the heat pump. The construction type "lightweight" cannot be used with limited run-times of the heat pump without a significant drop in thermal comfort as defined by the metrics used. The paper gives detailed results for the mentioned construction types and 4 different run-time scenarios.

Keywords: Building simulation, self-consumption, heat pump, energy flexibility, thermal mass

INTRODUCTION

Due to the necessary increase of renewables the amount of volatile electricity based on solar and wind power being fed into the grid must be expected to increase, also. This will lead to big challenges in regard to the stability and capacity of the grid. In order to mitigate this effect, the direct consumption or storage of electricity based on renewables at the site of production seems prudent. In order to be able to increase the self-consumption of buildings, these must have certain flexibility in regard to their energy demand. Such flexibility must consider thermal comfort.

Measurement data gained from a small, well-insulated multi-family dwelling shows that the self-consumption of electricity generated on site by photovoltaic panels (PV) was approx. 28 % between September 2011 and April 2012 during daytime hours from 10 am to four pm each day [1]. During the remaining hours of the day, approx. 27 % of the overall electricity consumption could be attributed to the heat pump. This shows that the heat pump is the largest single consumer of electricity and therefore most promising in regard to shifting loads

into daytime hours and thus increasing self-consumption. Consequently, the run-time of the heat pump was constrained to 10 am through seven pm starting February 2013. This resulted in a shift of approx. one MWh from nighttime to daytime hours. The overall self-consumption was thus increased from 21 % (winter 2011/2012) to 34 % (winter 2013/2014). Also, the efficiency of the heat pump was increased. This is due to a reduction in the number of on-off cycles. The heating efficiency increased from 3.8 to 4.9 and the DHW efficiency increased from 3.6 to 3.9 [2]. No decrease in thermal comfort was found, even though the restriction meant that the heat pump was off 15 consecutive hours per day. The temperature decrease in the building was found to be about 1 K [1].

In the work described below, the potential of heavy weight and lightweight buildings in regard to run-time constraints is evaluated. The work is based on transient thermal building simulation. Simulation model details can be found in [3].

METHODOLOGY

General

The building performance simulation model is set up based on design values and wherever possible actual values taken from the known building usage (ESP-r [4]). The measurement data available consists of various electricity consumption values in a time-step resolution of 15 minutes. The simulation model is calibrated and validated with measurement values from the period February 10th 2013 through March 11th 2013. The ambient air temperature in this period is 1.8 ± 4.7 °C with minimum and maximum values of -12 °C and 17 °C, respectively. For validation purposes, the values measured with the temperature sensor "living room" (Figure 1) and the measured useful heat consumption are used.
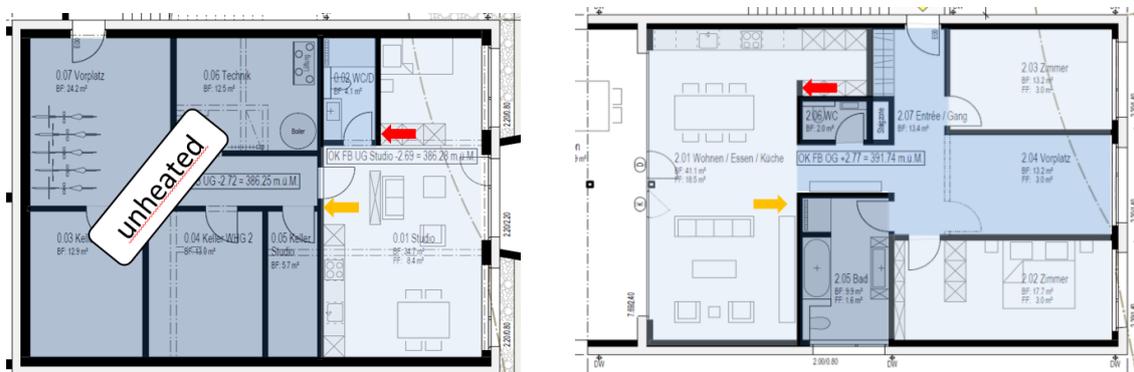

Figure 1: Layout of thermal zones for ground floor (left hand side) and first/second floor (right hand side). Positions of the temperature sensor (red) and the heating thermostat (orange) in the living rooms are given (© Setz Architektur).

Building Details

The building considered in this paper is a well-insulated small multi-unit dwelling in the Canton of Aargau, Switzerland. The two-story building has a cellar and an overall heated floor area of 320 m^2. The ground and first floors are each one flat with a heated floor area of 135 m^2. The cellar is partially above grade to the east and features a small studio with a heated floor area of 50 m^2. Detailed information in regard to the building can be found in [1, 2]. Heating and DHW is covered by a ground source heat pump (GSHP) with a nominal power of 8.9 kW. The building also features a mechanical ventilation system with heat recovery. A PV system with 20 kW peak is mounted on the roof facing south with a 10° angle to the horizontal and has a design electricity production of 18 MWh per year (Figure 2).

Figure 2: View of the multi-family dwelling studied (© Setz Architektur, FHNW IEBau).

Transient building performance simulation

The building performance simulation model is set up with 15 thermal zones, one for each room of the building (Figure 1). The non-heated area in the cellar is modelled as one thermal zone, though. Regardless of the availability of quite detailed measurement data, various necessary inputs for the building performance simulation are unknown and must therefore be based on assumptions. Specifically, the the following main assumptions are made [3]:

- The solar protection device (external venetian blind) is up at all times during the heating period.
- There is no thermally relevant air exchange between thermal zones (internal doors are closed).
- The occupation schedule in each unit is based on the current (at the time of this study) tenant situation.
- The split of electricity consumption between lighting and small power is set room-wise.
- The thermal mass of furniture and other non-constructive fittings is taken into account based on an approximate amount of clutter.
- The ventilation rate is set to a fixed, constant value room-wise. This ventilation rate includes the mechanical ventilation (w/ 80 % heat recovery) and a fraction taking occasional opening of windows into account.
- The temperature sensor "living room" is let into the wall and thus is assumed to measure a mix of air- and wall temperatures. It is assumed that this split is 33 % air temperature and 67 % wall temperature [5].

In the **actual building** ("as built"), floor and ceiling slabs, cellar walls and the roof are made of reinforced concrete. The external walls are made of aerated concrete and the internal walls are made of sand-lime brick or plasterboard. For the **heavyweight model**, external and internal walls are changed to reinforced concrete, as well. Standard wall thickness values for cast-in-place concrete are used (i.e. external walls 250 mm, internal walls 200 mm). For the **lightweight model**, above grade external walls, the ceiling/floor between first and second levels and the roof are changed to wood frame constructions. For both variants, the U-values for external walls and the roof are equal to the values of the actual building. Detailed information on the constructions used can be found in [3].

The overall heat capacity is found to be 17 kWh/K for the actual building, 21 kWh/K for the heavyweight construction and 11 kWh/K for the lightweight construction (values derived with the transient method according to [6]). The heat capacity of the furniture is calculated to be 1.8 kWh/K (derived with the simplified method according to [6] with a time period of 24 h including heat transfer coefficients).

The only changes in the models considered in the results given below are the changes to the building elements mentioned above and the run-time of the heat pump. In all other respects, the models are identical to the calibrated model of the actual building.

GSHP run-time constraints

Initially, the heat pump run-time is restrained to 10 am through 1 pm and 2 pm through 7 pm for heating purposes. In accordance with the measurement results, DHW is produced in the intermediate interval of 12 am through 1 pm. This basic setting corresponds to the setting in the actual building where eight hours were available for heating purposes in the time period considered. Subsequently, the run-time is further reduced in three steps to five hours (10 am through 1 pm and 2 pm through 4 pm).

RESULTS

Evaluation of the simulation results and comparison between run-times is based on the calculated operative temperatures of the living rooms in the three units. Also, thermal comfort criteria according to SN EN ISO 7730 [7] and SIA 180 [8] are evaluated. The following specific criteria based on hourly mean values are considered:

- SN EN ISO 7730:2006 [7]: The operative temperature must be in an interval according to the desired comfort class A (22 ± 1 °C), B (22 ± 2 °C) or C (22 ± 3 °C).
- SIA 180:2014 [8]: The operative temperature must be between 20.5 and 24.5 °C during occupied hours if the 48-hour running average of the ambient temperature is less than or equal to 12 °C, which is the case, here.

Model validation

The simulation model with constructions "as built" is calibrated based on measurement values giving useful heat supplied and values from the temperature sensors in the living rooms of all three apartments. Table 1 shows that the agreement between measured and calculated values is very good. Thus, the simulation model is considered validated.

Table 1: Measured/calculated useful heat demand and average measured/calculated temperatures at the temperature sensors "living" (actual construction, heat pump run-time: 10:00-13:00/14:00-19:00 hours).

Floor	Heat [kWh]		Average temperature at sensor „living" [°C]	
	Measured	Calculated	Measured	Calculated
Ground	311	306 (-2%)	21.9 ± 0.4	21.9 ± 0.4
First	580	560 (-3%)	21.6 ± 0.3	21.7 ± 0.4
Second	728	710 (-2%)	22.8 ± 0.4	22.9 ± 0.4
Total	1'619	1'576 (-3)		

Operative temperatures

Figure 3 shows the cumulated frequency of calculated hourly values for operative temperatures in the zone "living room" of each floor for the three different construction types and four different run-time constraints considered. The comfort class achieved according to [7] corresponds to the level of the highest or lowest operative temperature found. Table 2 summarizes the resulting comfort classes. It can be seen that the construction "as built" and the heavyweight construction show identical results in regard to comfort class. Only in the second floor can the lightweight construction achieve a "C" for the longest run-time of the GSHP considered.

Table 2: *Comfort compliance for the living rooms according to SIA 180:2014 and SN EN ISO 7730:2006 (gf: ground floor, ff: first floor, sf: second floor).*

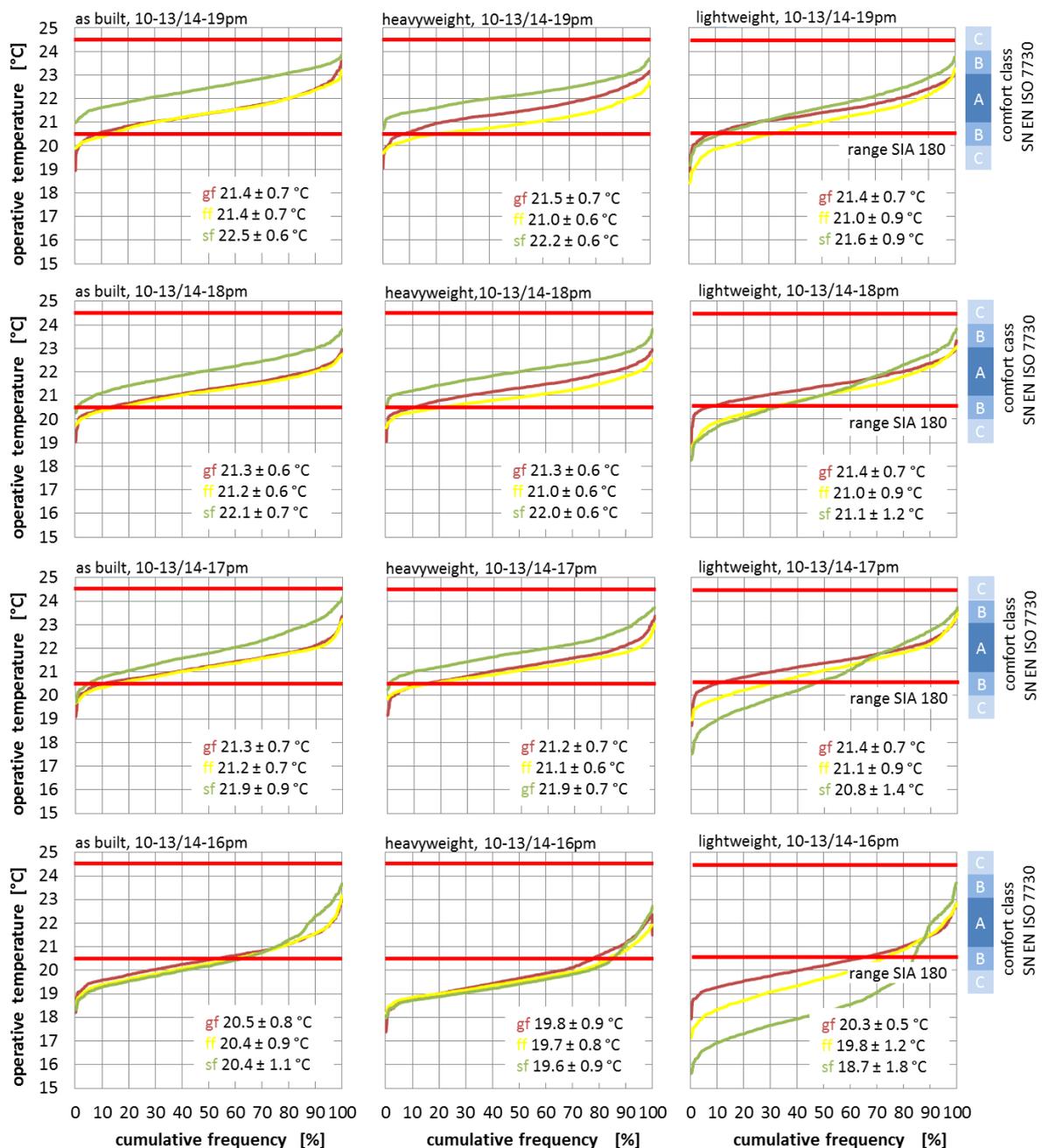| Heat pump run-time schedule	"as built"			"heavyweight"			"lightweight"		
	gf	ff	sf	gf	ff	sf	gf	ff	sf
10 am -13/14-19 pm	C	C	B SIA 180	C	C	B SIA 180	-	-	C
10 am -13/14-18 pm	C	C	B	C	C	B	-	-	-
10 am -13/14-17 pm	C	C	C	C	C	C	-	-	-
10 am -13/14-16 pm	-	-	-	-	-	-	-	-	-

Figure 3: *Cumulative frequency, mean value und standard deviation of simulated operative temperatures for the living rooms in the ground, first and second floor apartments (gf: ground floor, ff: first floor, sf: second floor).*

DISCUSSION

The tenants of the measured building are highly satisfied with thermal comfort in their flats. It must be assumed that in real life the operative temperature – which was not measured – shows a similar range of values as found in the simulation. This could be interpreted such that operative temperatures falling below the threshold values according to standards for short periods of time do not lead to immediate problems in regard to thermal comfort. The tenants obviously easily accept a thermal comfort at level "C" in the highly insulated building considered here. This implies that the tenants seem to accept a shortfall in thermal comfort compared to requirements given by SIA 180:2014 [8]. In order to use the thermal mass of a building to increase energy flexibility it seems necessary to allow for such short-term shortfalls of thermal comfort.

CONCLUSION

The results show that regardless of a very high level of thermal insulation a sufficient amount of thermal storage capacity is necessary in order to be able to limit run-times of the heat pump to daylight hours without unduly compromising thermal comfort. The restriction of run-time for the heat pump (or any other heat source) to daytime hours unavoidably leads to a drop in operative temperature levels despite the high insulation standard. Ideally, thermal comfort requirements set by standards can be met by a building in which a high degree of energy flexibility is sought. The current requirements in regard to thermal comfort defined in SIA 180:2014 [8] do not allow for the degree of flexibility in building operation studied in this paper. It will likely prove desirable to adapt the requirements in said standard in order to be able to meet Swiss political goals in regard to the future power supply.

ACKNOWLEDGMENTS

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