Monitoring results of the energy consumption behaviour of two highly solar-powered apartment buildings

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Abstract

The CO_2-neutral self-supply of heat and electric energy is an important objective for new buildings. Two new apartment buildings (7 units each) built in 2018 according to the solar house concept will achieve solar fraction of up to 77% electrically and 65% thermally through solar thermal and photovoltaic systems and thermal and electrical storages. The residents receive all energy services, independent of consumption, financed by a flat-rate rent. Within this article, the first results of two years monitoring with the effects of the user's behaviour on the energy balance of the apartments and building is analyzed. It is clear that users prefer high room temperatures that are up to 5K above the German average. The electricity consumption, on the other hand, is average and the measured consumption matches the results of a residents survey conducted. Nevertheless, different user behaviour in terms of when they purchase electricity leads to a different load on the electricity storage and to a different individual electricity mix.

Keywords: energy efficiency in buildings, solar energy, energy storage, solar fraction, NZEB, measurement

1. Introduction

In the EU the nearly zero-energy building-standard (NZEB) is obligatory for all new buildings by 2021 (Directive 2010/31/EU). Therefore, an improvement of the energy efficiency of buildings and their evolution to new integrated building concepts with solar systems is necessary. Over the past 30 years, various low energy house concepts have been developed with different, mostly regenerative, energy supply systems. Nevertheless, in the literature, there exists a big leakage on detailed scientific measurement data to proof their efficiency under real user behaviors, see also Storch and Wilde 2018. This paper focuses on first measurement results of two identical new solar apartment buildings (see table1) with high solar fraction in electrical and thermal energy.

Table 1: Parameters of one partially self-sufficient apartment building at the Cottbus location (* approx. 2400 kWh/apartment; ** from EnEV-certificate 2013)

effective area / heated house-volume	853.5 m² / 2921 m³
Area of solar thermal- / PV –collector / roof pitch	100 m² / 29.6 kW_p (facade & roof)/ 50° (S)
Volume of heat storage tank/ storage battery (Li-Ion)	24.6 m³ / 52 kWh
Auxiliary heating (gas)	48.2 kW
Solar fraction el./ heat	~ 77% / ~ 65%
Annual demand in electrical energy* / thermal heat**	18,665 kWh/yr / 15.58 kWh/m²
Annual primary energy consumption**	8.40 kWh/m²yr

2. Results

The main heat source for the buildings is the solar thermal system. These can be temporarily stored in a hot water tank. In addition, it is possible to use a gas boiler if the heat demand is higher than the yields of the solar thermal system. Table 2 compares the heat demand for heating and hot water for building 1 with the planned values. It is clear that the planned values are significantly exceeded during operation.

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Table 2: Comparison of measured values and planning (for 6 residential units) for building 1, Measuring period 2020/21 (Heating consumption and hot water consumption related to effective area, solar thermal yields related to area of solar thermal-collectors)

	Measurement house 1	Compared to planned values
Heating consumption	52,365 kWh / 61.4 kWh/(m²a)	344 %
Hot water consumption	23,425 kWh / 27,4 kWh/(m²a)	234 %
Hot water tap volume	180 m³	82 %
Solar thermal yields	52,365 kWh / 523,6 kWh/(m²/a)	201 %

Various reasons were identified for this strong deviation from the planned values. In addition, it should be noted that the planning was carried out for a building with 6 residential units; the buildings that were finally constructed each comprise 7 residential units.

During the heating period the measurements showed that the room air temperatures of the individual rooms are about 2.5 to 5 K above the average temperatures in living rooms and bedrooms according to Techem 2017 and thus also above the assumptions for the pre-calculation of the EnEV energy certificate. Figure 1 on the left shows an example of the room temperatures of three apartments. In all apartments, the bedroom is kept slightly cooler than the living room, which may be due to more frequent and longer window ventilation in addition to the setting of the room thermostat. In figure 1 (right), the presence of the residents is clearly indicated by the increase in CO_2 and humidity. The continuous drop in room temperature suggests that the window is open throughout the night from 11 p.m. to 6 a.m. This caused a cooling of the bedroom temperature of about 5 K due to a low outside temperature of about 0 °C. This means heat losses from the room with underfloor heating through uncontrolled air exchange and cooling of the walls. By comparing the heat consumption quantities in the respective periods with an apartment without window ventilation, the heat that escapes in this way can be quantified at approx. 27.2 kWh. A nightly regulation of the heating operation alone can thus avoid about half of the additional consumption. A further influence is the reduction of the room set point temperature. However, it cannot be safely concluded that the cause of this behavior is due to the flat-rate energy billing. Ignorance and convenience can also influence user behavior.

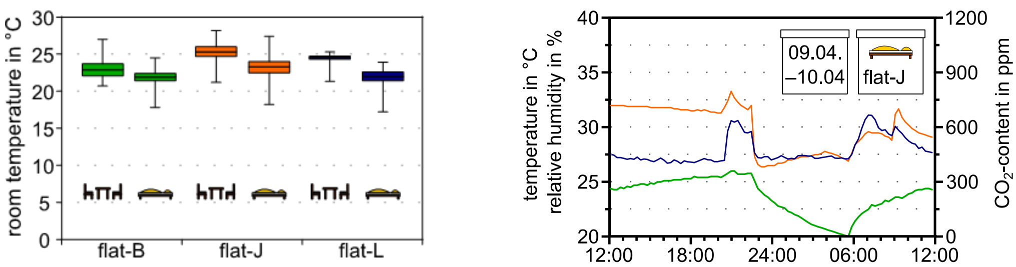

Fig. 1: Left: average room temperatures of apartments (living / bedroom, 19.03. to 14.05.2019); right: air properties of 1 bedroom, with green = temperature; blue = CO_2; orange = humidity (09.04. to 10.04.2019), Oppelt 2019

The hot water consumption is also significantly above the planned values. Here, too, a major cause is that the planned values were prepared for a building with 6 residential units. Figure 2 clearly shows that there is a more or less normal distribution across all residential units. The high and low consumers roughly balance each other out. The averaged hot water consumption in Germany is about 33 – 36 l/ person. There is no particular outlier to be seen, which could indicate possible abusive behaviour. The measured values also fit relatively well with a tenant survey that was conducted with the residents from this building. In this survey, 7 out of 14 units estimated their water consumption as average, 3 estimated it as very high and 4 as very low. Table 2 also showed that the planned hot water volume was undercut. Only the heat quantity for hot water is above the planned values. The reason for this is that the planned hot water temperature of 50 °C was not implemented, but the hot water is provided at 60 °C during operation. In addition, it must be considered that the washing machine and dishwasher have a hot water connection and thus there may be a higher hot water consumption compared to other residential units.

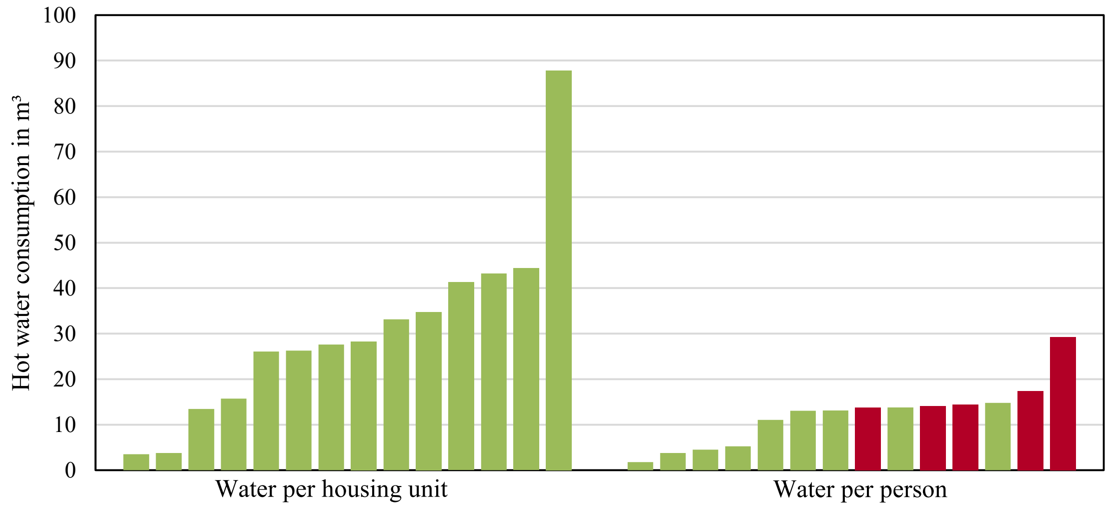

Fig. 2: Individual hot water consumption of the flats of both buildings related to the residential unit and related to one person

The annual electricity consumption under full occupancy is about 2,200 kWh (with 2.4 persons/flat) which is within the same range of 2-person households, see stromspiegel. A comparison of the averaged load profiles of all flats of one house with the standard load profiles of BDEW 2017 (figure 3, left) also shows a typical curve shape with regard to the level of the base load and the time distribution of peak loads. However, a comparison of the individual flats with each other reveals a clear heterogeneity, see figure 3 (right). The average daily load curve shape of the individual flats shows that the peak loads mainly fall during times of maximum coverage by direct photovoltaic (pv) supply. Typical peaks in the evening occur in times of higher coverage by battery supply. There is a fluctuation in the degree of coverage of individual flats through direct pv consumption between approx. 28 % to 41 %. Overall, however, a similarly high degree of solar fraction (pv and battery) of 68 % to 73 % is achieved for all flats. Thus, the electrical energy storage leads to a doubling of the solar fraction.

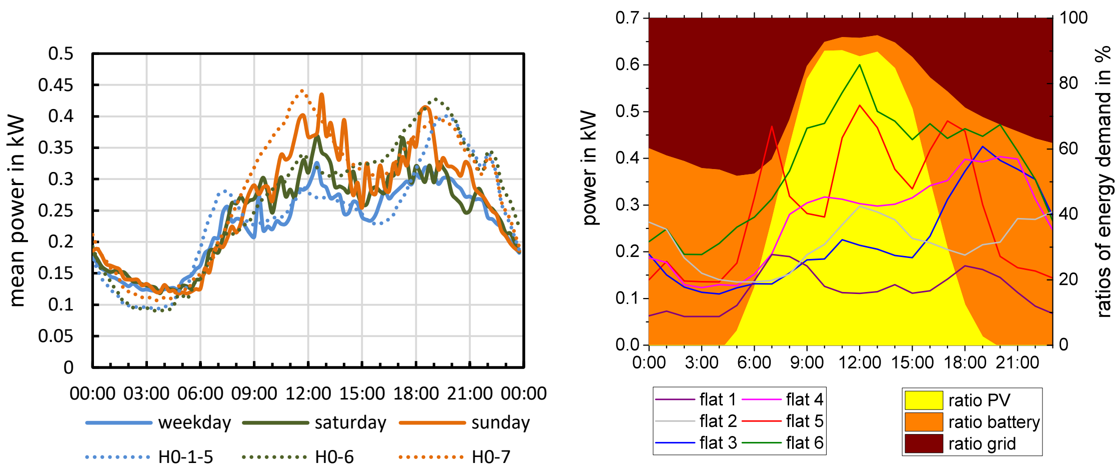

Fig. 3: left: average daily load profile of all apartments with the scaled standard load profile (Germany, H0) according to BDEW; right: day-dependent electricity mix, average values from 15-min. measured values (07/19 to 03/20).

As described in Table 1, both buildings each have electricity storage with a capacity of 52 kWh. Figure 4 shows the battery's state of charge, the PV yield and the current electricity consumption of house 1. As expected, the battery's state of charge is also high in summer when PV yields are high. No seasonal fluctuations can be seen in consumption. Overall, it can be observed that the state of charge hardly drops below 30 % in summer and hardly rises above 50 % in winter. Only in the transitional period is the full capacity utilized. It becomes clear that the accumulator could be significantly smaller without affecting the behaviour of the house. Alternatively, integration into a neighborhood with the surrounding buildings (several apartment buildings and an office building) would reduce the grid feed-in and increases the self-consumption of renewable electricity in the district.

The storage losses of the accumulator are also not negligible. For the measurement period 2020/21, the loss of the accumulator for house 1 was about 2020 kWh, which roughly corresponds to the amount of energy of an additional household. The annual utilization rate was thus around 75.4 %, which also corresponds to the utilization rate observed by Großklos et al. 2016 for other multifamily buildings.

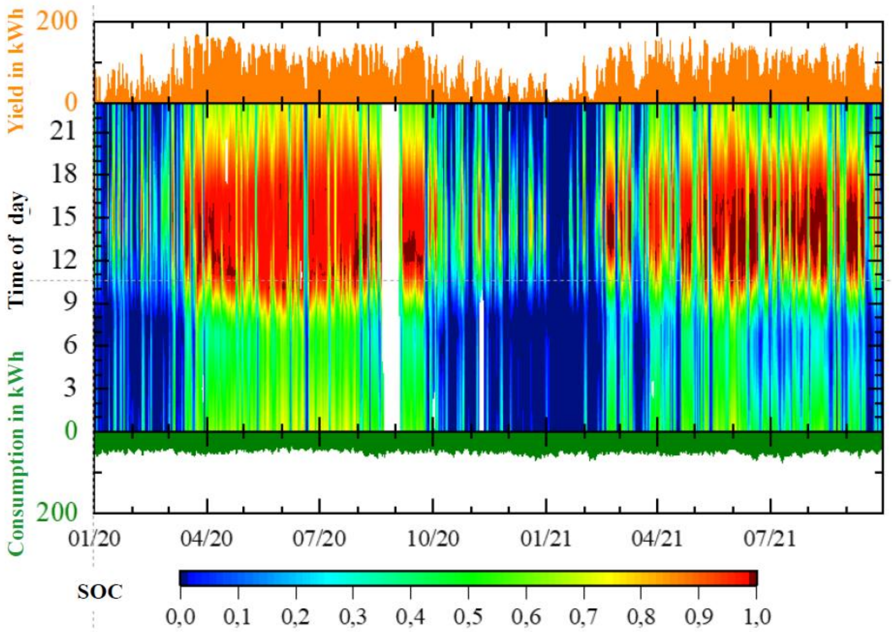

Fig. 4: Yield of PV system, charging status of accumulator, electricity consumption of buildings (house 1)

A detailed look at the consumption of the individual residential units in Figure 5 (left) shows that individual user behaviour has a significant influence on PV use. Residents who are still very active at night (night owls, orange arrow) consume more electricity at night and less in the morning. This means that less PV electricity is consumed directly in these residential units, and more electricity is drawn from the accumulator or the grid at night. This is also shown in Figure 5 (right). The share of PV is lowest for the flat marked with orange arrow, e.g. in April. Due to the accumulator, however, the grid consumption of the flats is almost the same, regardless of user behaviour. The best behaviour for the building is marked in blue: a high share of electricity in the morning (and thus a direct use of PV yields) and a low share at night (and thus a low use of the accumulator).

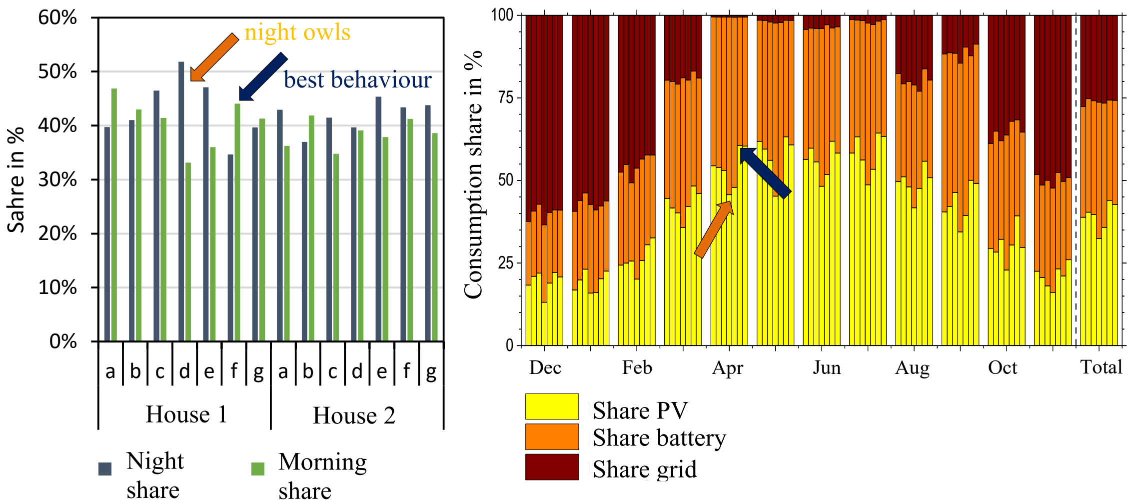

Fig. 5: Left: Electricity consumption by time of day (according to Weniger et al. 2015), Right: User-specific electricity mix, measurement period 12/2019-11/2020

In figure 6 an interpolated detailed temperature distribution inside the hot water storage is presented. Two to three facts are visible:

- a high temperature difference over the height of storage is detectable. Thus, a good layering of different temperatures is achieved.
- In 4-5 month per year the storage is unused
- The storage tank could be decreased for next buildings

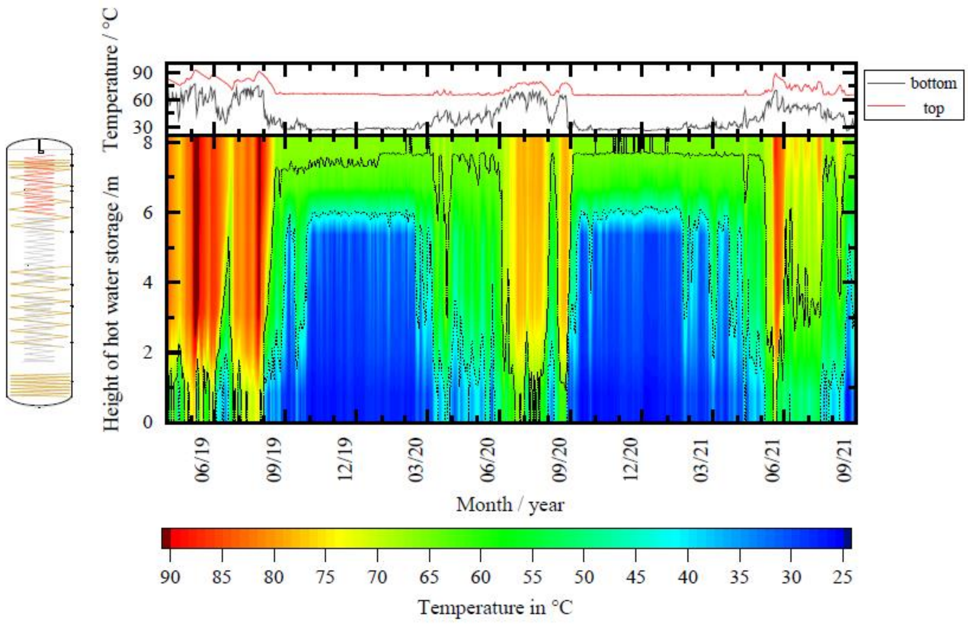

Fig. 6: Storage temperatures of hot water storage (house 1)

3. Conclusion

On the heating side, the first measured values are significantly higher than the planned values, and the user behaviour, among other things, was identified as a possible cause. For example, the users open the windows in the bedroom during the night without turning off the heating mode. Measurement results show that in one night in only one flat, this results in 27 kWh of additional heating demand. In addition, the measured values for room temperatures are between 2.5 and 5 K above the average values for energy demand calculation of living rooms.

The buildings examined in detail achieve the high planned solar fractions for electricity very well due to the generously dimensioned systems. The electricity consumption profile is comparable with literature values and does not show any conspicuous features. In general, it can be stated that a high level of equipment is used sparingly, which corresponds to the sociological tenant profile. In addition to the distribution of typical loads over the time of day, the total consumption of a residential unit can also influence the solar direct consumption share, whereby user behaviour over the time of day has a stronger influence. The installed electric storage tank is only fully used during the transition period between March and October. A smaller capacity would therefore be possible in future buildings with the same concept without restrictions for the residents. Furthermore, the storage tank could be planned some smaller to save valuable space in the building.

In the future, the integration of the buildings into a district will be investigated, e.g. surpluses from the solar thermal system will be passed on to surrounding residential buildings.

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