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Detailed Monitoring Analysis of two Residential NZEBs with a Ground-Water Heat Pump with Desuperheater

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ABSTRACT

Two new, residential, and high performance buildings were constructed according to Passive House standard in Innsbruck, Austria (with cold winters and mild summers). The two multi-family houses consist of 26 apartments - 16 in the north and 10 in the south building. The goal of the project was to achieve net zero energy building (NZEB) standard, which was defined in this project as the annual balance between the electricity consumed for heating and ventilation (excluding household appliances), and the electricity produced by renewable sources. Thus, a heat pump, solar thermal collectors, photovoltaics (PV) and ventilation units with heat recovery were installed. The two stage ground-water source heat pump with a power of 58 kW (at W10/W35) includes desuperheating. The available roof space of the north building was covered by a solar thermal system with 74 m^2 and PV with 52.5 m^2 (8.5 kWp). An additional PV system of 99.8 m^2 (16 kWp) was placed in the roof of the south building. The ventilation units were centralized (three in total) including heat recovery. The heating distribution system was floor heating, and a heat exchanger was installed in each flat for domestic hot water (DHW) supply. A four pipe distribution system was used to minimize the distribution losses; two pipes for the DHW (flow temperature of 52°C) and two pipes for the space heating (with flow temperature of 35°C). Therefore, stratification was obtained in the 6000-liter storage to improve energy performance, since the heat pump can operate at a low sink temperature for supplying space heating.

A detailed monitoring system was installed consisting of 58 temperature sensors, 12 humidity sensors, 2 pressure sensors, 37 signals (e.g. controllers, valves, pumps, etc.), 22 heat meters, 7 electricity meters, and 2 volume flow meters. The main focus was the energy performance of the HVAC systems. The thermal comfort of the south building was monitored, too. The operation of a monitoring system has started in November 2015.

In this paper, two years of monitoring results are analyzed and discussed. The energy performance of the technical system and each subsystem is presented in detail. The importance of quality assurance control e.g. with monitoring is highlighted. In addition, the difference in annual heating demand showed the importance of at least two years of monitoring for the new constructions. Moreover, the present study enhances the discussion about evaluation of NZEBs with a monitoring example from central Europe.

Keywords: NZEB, ground-water heat pump, monitoring, Passive House

1. INTRODUCTION

The recast of the European building directive (Directive 2010/31/EU 2010) defined the path to nearly zero energy buildings (nZEB). Three aspects are addressed: (a) new buildings will have a very high-energy performance, (b) the remaining very low energy demand will be provided to a very significant share by renewable energies, and (c) cost-optimal levels for minimum energy performance are requested.

Hence, the aim of the EPBD recast was the minimization of the residual energy demand and of CO_2-emissions, while economics should be considered. Thus, future buildings should have a very high-energy performance, such as Passive Houses and should be operated e.g. with a heat pump together with significant amount of energy from cost-effective renewable energy sources (PV and/or solar thermal).

As Ochs et al. (2017) described, the definition of nZEB varies among the different EU member countries, while net zero energy buildings (NZEB) is the building with annual balance between the electricity from and to the grid. Several studies about nZEB (Attia et al. 2013; Deng et al. 2014; Becchio et al. 2015; Tsalikis and Martinopoulos 2015; Kneifel and Webb 2016; Ascione et al. 2016) and NZEB (Kurnitski et al. 2011; de Santoli et al. 2014; Goggins et al. 2016; Lu et al. 2017; Guillén-Lambea et al. 2017; Paiho et al. 2017; Attia et al. 2017) can be found in the literature. However, the implementation of the EPBD is far less ambitious in some of the European member countries (BPIE 2016). The more important is it to demonstrate best practice examples and highlight non-renewable primary energy and CO_2-savings.

A dominating concept to reach the zero energy balance over an annual period for a nZEB and NZEB is the combination of solar PV systems and heat pumps. In the IEA HPT Annex 49 (A49), a follow-up of the Annex 40 heat pump integration options for nZEBs are investigated as well as the design and control for heat pumps in nZEB and the integration into energy systems. Solar thermal can be relevant as it is technically and economically less challenging to store heat compared to storage of electricity. Storage is relevant in order to reduce the remaining electricity usage in winter, which has generally a higher fossil (and/or nuclear) share. Hence, nZEBs should be evaluated considering the time of electricity usage from the grid.

"NZEB" as a goal can be a misleading concept, since an optimization for net-zero may lead to one story buildings, because reaching the net zero balance is more difficult compared to a multi-story building (with smaller roof and façade area related to treated area). However, MFHs, which are more compact, are favorable from the overall energetic and macro-economic point of view, compare also (Feist 2014).

In the present study, a monitoring analysis of two multi-family houses designed according to NZEB is presented and the lessons learned are discussed.

2. CONCEPT

For the Passive House project Vögelebichl in Innsbruck (two multi-family houses with together 26 flats of the social housing company NHT, see Figure 1) the optimum share of PV and Solar Thermal (ST) was determined for the given boundary conditions. One roof of the multi-family houses is completely covered by PV (16 KWp). The other roof space was partly used for PV and partly for solar thermal (ST). The primary energy demand was determined for different shares of solar thermal collectors with regard to the maximum available unshaded roof space. For the optimal performance of the ground-water heat pump a low temperature distribution system (floor heating) and separate domestic hot water (DHW) loop with decentral heat exchanger was proposed. Compared to the 2-pipe system, the 4-pipe system allows better performance of the HP and offers the possibility for some cooling in summer.

By means of a simulation study, the share of PV (max 19 KWp) and solar thermal collectors (ST) was varied in order to determine the maximum possible energy yield considering PV and ST system efficiencies including heat pump performance and distribution losses. The optimal design (from energetic point of view) was found to be 74 m² ST and correspondingly 53 m² PV on the north roof (Ochs et al. 2014).

Figure 1: Outside southeast view of the two multi-family houses in Innsbruck Voegelebichl, NHT Tirol

During the final design process and the construction of the two buildings, some parameters changed with respect to the original planning. The treated area is 1295.6 m² (North) + 853.2 m² (South). The ST area is 73.6 m² (North) and the PV area is 52.5 m² (North) + 99.8 m² (South). The floor heating flow temperature is 30 °C (30/26 °C instead of 28/24 °C) and DHW flow temperature is 55 °C. A 3-pipe system with common return pipe of floor heating and DHW was installed instead of the initially proposed 4-pipe system.

Table 1: Characteristic data of the two buildings NHT Vögelebichl during design phase (Ochs et al. 2014)

	North building	**South building**
Number of Flats	16	10
Treated area	1269.8 m²	818.8 m²
Designed Heating Demand (PHPP)	13.5 kWh/(m² a)	17.0 kWh/(m² a)
Designed Heating Load (PHPP)	12.0 W/m²	13.9 W/m²
PV size	8.5 kWp	16 kWp
Solar Thermal (ST)	50 m² (ca. 35 % of roof area)	-
Buffer storage	6000 Liters	

Figure 2 shows a simplified hydraulic scheme including the GW heat pump (two stage), solar thermal collector field (SC) as well as the low temperature heat distribution and the separate decentral fresh water supply (DHW plate HX). The double stage heat pump is equipped with a hydraulic circuit enabling hot gas (HG) desuperheating. Depending on the operation mode (heating or DHW supply), the flow of the heat pump enters the buffer storage (BS) at the top or at 1/3 of the height from the top. The combined return of the heating and DHW loop enters the large 6 m³ buffer storage depending on the temperature level either at the bottom or at about 1/3 of the height of the storage in order to enhance stratification. The electric backup heater (BH) is currently not used.

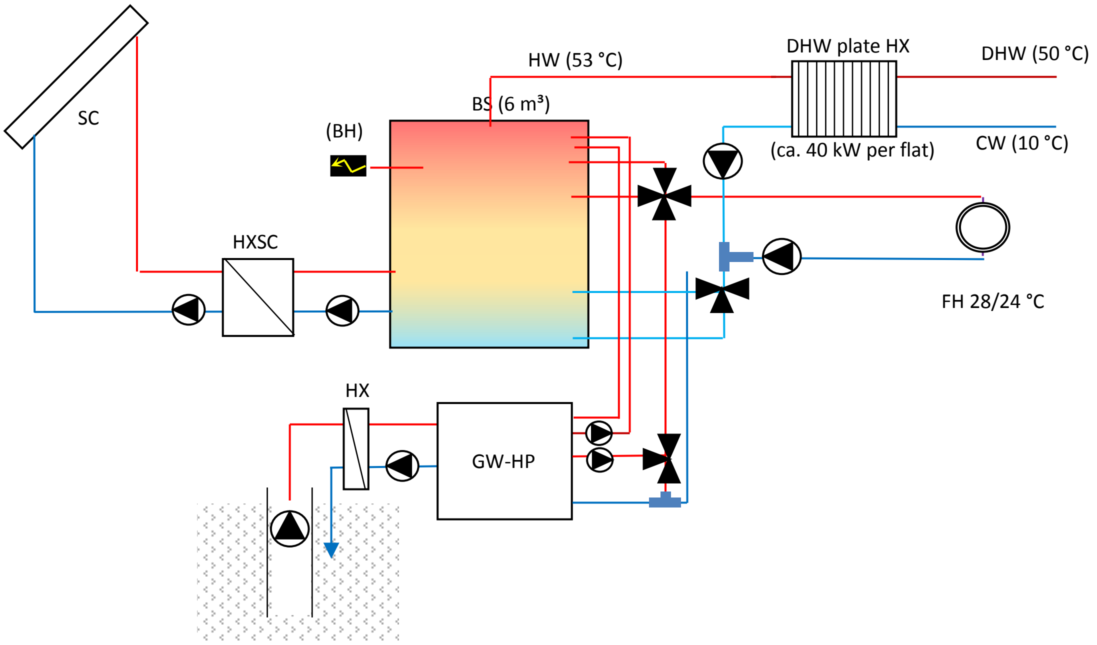

Figure 2: Simplified Hydraulic Scheme with Solar Collectors (SC), Buffer Storage (BS), 2-stage ground-water heat pump (HP) with hot gas HG) desuperheating in heating mode with floor heating (FH) and decentral heat exchanger (HX) for domestic hot water (DHW) supply (Ochs et al. 2017)

3. MONITORING RESULTS AND DISCUSSION

3.1 Heading and DHW demand

As shown in Figure 3, The heating demand (HD) in the first year was significantly higher than in the second year with a value of 31.1 kWh/(m^2·a) and 20.5 kWh/(m^2·a), respectively (see also Figure 3). Figure 3 also shows the monthly average ambient temperature, which was similar in the two years. The indoor temperature in the heating season, which was only measured in the south building, was 1 K lower in 2017 than in 2016. Similarly, the extracted air temperature in the ventilation systems was also 1 K lower in 2017 in both buildings. The main reason for the high heating demand in 2016 is the construction moisture.

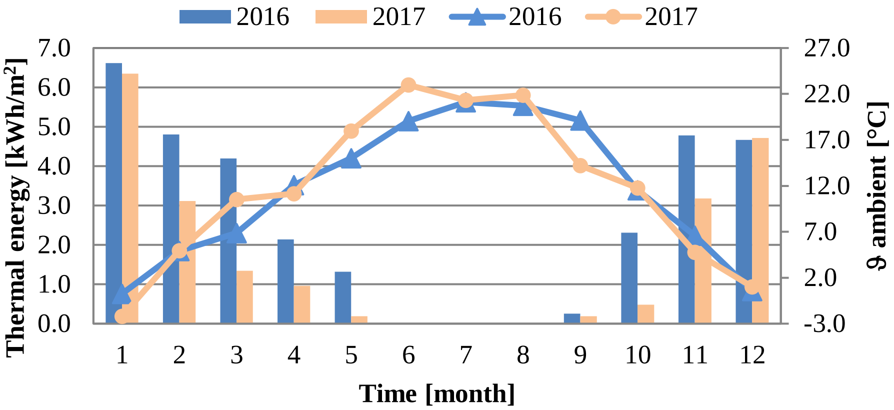

Figure 3: Heating demand and ambient temperature of both buildings in years 2016 and 2017

Only one heat meter was installed in the storage output to measure the DHW consumption, and therefore, the pipe distribution losses were not separately measured. The DHW consumption was 24.7 and 27.2 kWh/(m^2·a) or 2039 and 2250 kWh/flat in the two years. Figure 4 presents the monthly DHW consumption that decreases moderately in the summer months, when the availability of renewable energies is high.

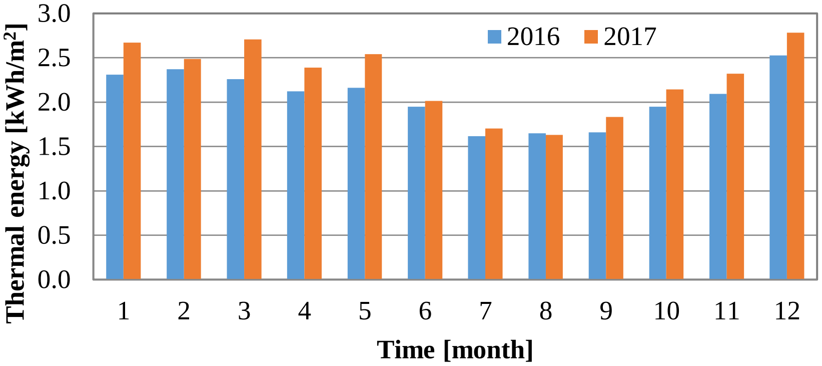

Figure 4: DHW consumption including distribution losses of both buildings in years 2016 and 2017

3.2 HVAC system

Figure 5 demonstrates the energy flow in 2017. The auxiliary energy was the 39% of the consumed electricity, which is significantly higher than expected. The heat pump supplied 65% of the heat to the storage (the rest 35% was delivered by the solar thermal collectors). The supplied energy for DHW and distribution losses was 50%, for space heating was 38% (less than DHW, as is usually the case in Passive Houses) and the storage and distribution losses in the technical room were 12%.

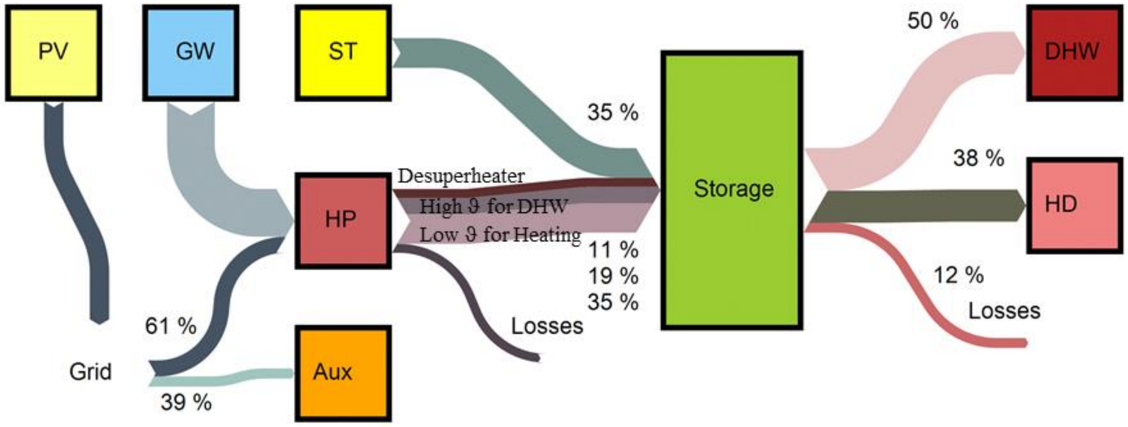

Figure 5: Energy flow for the monitoring year 2017

The delivered thermal energy by the heat pump is distinguished in three categories: (a) condenser at low temperature (for heating), (b) condenser at high temperature (for DHW), and (c) desuperheater (for DHW). The share of the desuperheater was 17% in both years. The heat pump was mainly operating with low sink temperature, which is beneficial for the energy performance. The heat pump losses, which were calculated from the energy balance of the heat pump (see also Figure 5), were 17% and 14% in 2016 and 2017, respectively. The related pumps to the heat pump (located in the condenser, the desuperheater, the evaporator and the ground water) consumed 7% and 4% of the total required heat pump electricity in 2016 and 2017, respectively.

Five different types of seasonal performance factors were calculated including different components, as shown in Table 2. Overall, the performance increased in 2017 compared to 2016. In 2017, the SPF of the heat pump was 3.2 including the pumps (only 0.2 lower when the pumps are excluded). The SPF of the heat pump during operation for supplying space heating (at low temperature) was 4.1 and for supplying DHW (at low temperature) was 2.8. The SPF_{HP+ST} was 4.9 and reduced to 4.4 (SPF_{sys}) when the storage losses were considered. Finally, the SPF_{tot} including also the electricity for the rest auxiliary energy (except the one for the ventilation systems) was 3.4. The heat pump performance with an SPF_{HP} of 3.2 cannot be characterized as very efficient compared to other studies in the literature. For example, Miara et al. (2017) measured 56 ground heat pumps with an average SPF of 3.9, a minimum of 3.1 and a maximum of 5.1, and another 45 ground heat pumps with an average SPF of 4.0, a minimum of 3.0 and a maximum of 5.4.

Table 2: SPF of the ground-water heat pump with desuperheater and of the whole heating and ventilation system including ST

	Equation	**2016**	**2017**
SPF_{HPonly}	$Q_{condenser} / W_{compressor}$	3.1	3.4
SPF_{HP}	$Q_{condenser} / W_{(compressor + pumps)}$	2.9	3.2
SPF_{HP+ST}	$Q_{(HP+ST)} / W_{(HP + HPpumps + ST)}$	4.0	4.9
SPF_{sys}	$Q_{(HD + DHWinc\ pipe\ losses)} / W_{(HP + HPpumps + ST)}$	3.7	4.4
SPF_{tot}	$Q_{(HD + DHWinc\ pipe\ losses)} / W_{(HP + HPpumps + ST + Aux.\ w/o\ ventilation)}$	3.2	3.4

3.3 ST and PV

Table 3 presents the specific energy performance of the ST and PV systems. The ST system showed a high performance, with a specific supplied heat per square meter of collector of 501 kWh/m^2 and 554 kWh/m^2 in 2016 and 2017, respectively. It contributed with 57% to the DHW heat delivery. The PV performance can also be characterized as high for these climatic conditions with more than 1200 kWh/kWp. The specific electricity produced by PV was almost one third of the specific thermal energy produced by ST.

For a comparison with respect to the supplied heat of ST and PV, the monthly PV electricity was multiplied with the SFP$_{HP}$ and then, was compared to the supplied heat by the ST (see Figure 6). Only in November of both monitoring years, the ST production was lower. Even though the HP performance was increased in the second year, the ST still was more efficient than the heat delivered by PV driven heat pump. It has to be noted that the storage losses were excluded in this comparison.

Table 3: Specific performance of PV and ST

	2016	**2017**
ST [kWh$_{th}$/m^2]	501	554
PV [kWh$_{el}$/kWp]	1238	1213
PV [kWh$_{el}$/m^2]	178	175
PV plus HP [kWh$_{th}$/m^2]	456	446

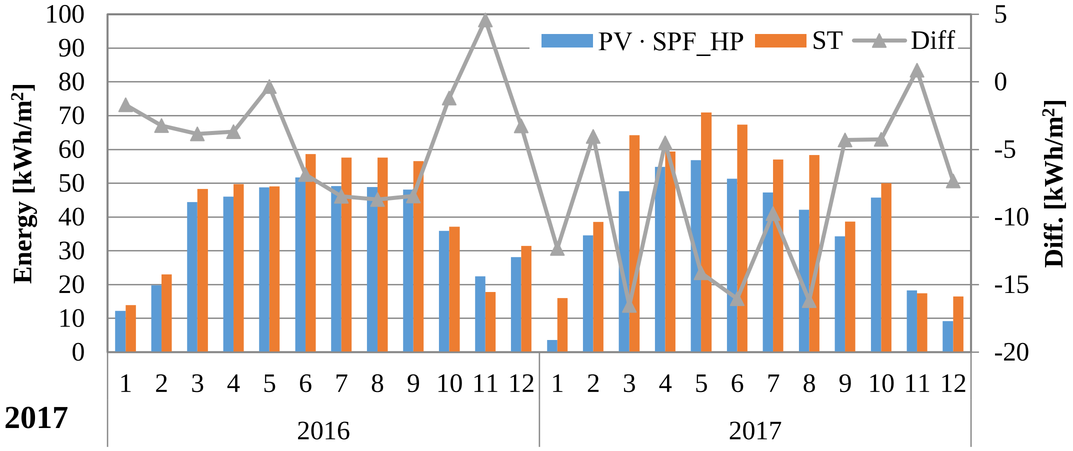

Figure 6: Thermal energy supplied by PV (plus HP) and ST per installed square meter of each system (PV and ST). The produced electricity from PV was multiplied with the monthly SPF of the heat pump (including pumps)

3.4 Thermal energy balance

The storage losses were calculated based on the thermal energy balance between the heat supplied to the storage (by the HP and the ST) and the heat supplied by the storage for space hating and DHW. Thus, the storage losses were 8% and 12% (of the heat supplied to the storage) in 2016 and 2017. The stratification in the storage was not optimal as shown in Figure 7. The part for the DHW supply on the top of the storage (red and blue line in Figure 7), should have similar temperatures (the red line should be similar to the blue line). However, the reason for the high thermal storage losses could be the unexpected water flows in the pipes. Simulations will be performed in future to further investigate the thermal losses and the stratification of the storage.

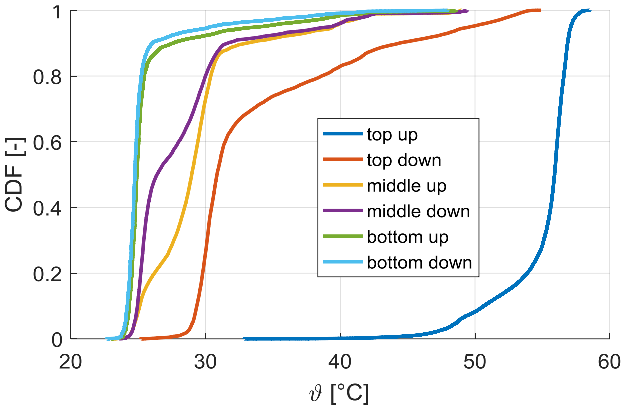

Figure 7: Storage stratification - cumulative distribution function (CDF) of storage temperatures measured every minute in six different heights in December 2017

Figure 8 shows the thermal energy balance of the whole system in 2017. Although the ST performance is high, it can supply the required heat for DHW only in summer months. In the winter months, ST hardly contributes to the space heating. This also applies if the storage losses were significantly decreased.

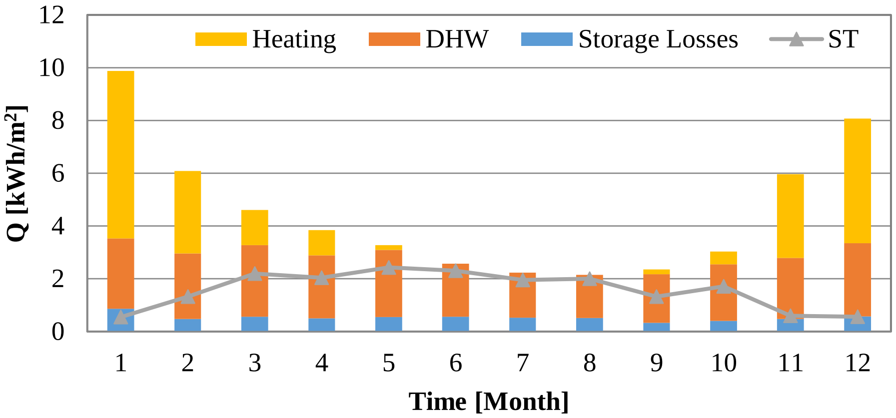

Figure 8: Monthly thermal energy balance in year 2017

3.5 Electricity balance - NZEB

Figure 9 presents the annual electric balance during the two monitoring years. The electricity of the compressor (HP) was significantly decreased in 2017, however the auxiliary electricity was slightly increased by 0.3 kWh/(m^2·a). The goal of NZEB was not reached in the first two monitoring years, mainly because of the unexpected high share of the auxiliary energy. Further optimization of the system i.e. with respect to losses is required. In Figure 10, the share of auxiliary electricity is demonstrated.

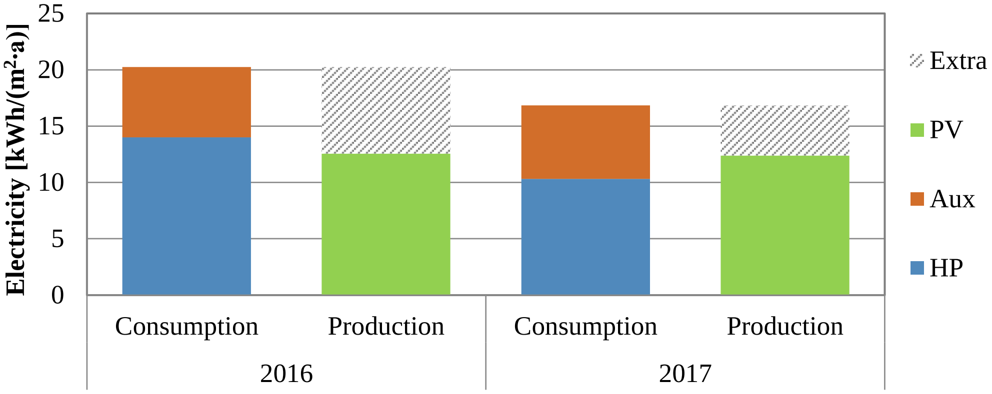

Figure 9: Annual electric energy balance

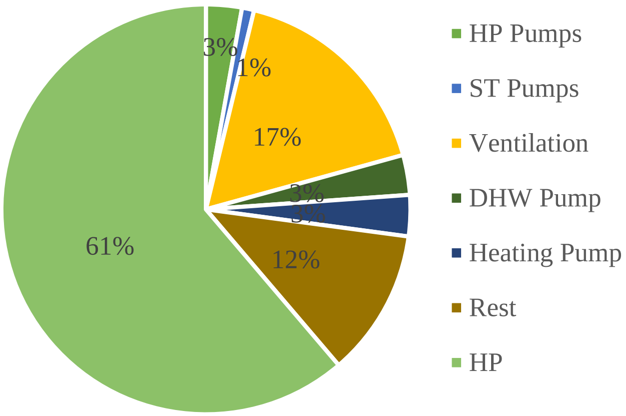

Figure 10: Electricity consumption of each component in year 2017

In Figure 11, the monthly electricity balance in 2017 is shown. Even if the goal of NZEB was reached, the remaining energy in winter is relative high. As Ochs el al. (2017) showed, the electricity that was produced by the PV would not be enough to balance the consumption of the household appliances. Thus, even more PV would have been required e.g. to be installed in the south facades. However, the mismatch between electricity need and PV yield is quite significant. This mismatch can be taken into account by using seasonal or monthly primary energy (PE) factors, as proposed by Ochs et al. (2017) . The combination of high energy requirement and low availability of renewables in winter months can be considered by different PE factors. In this way, the concepts of nZEB and NZEB can be critically discussed.

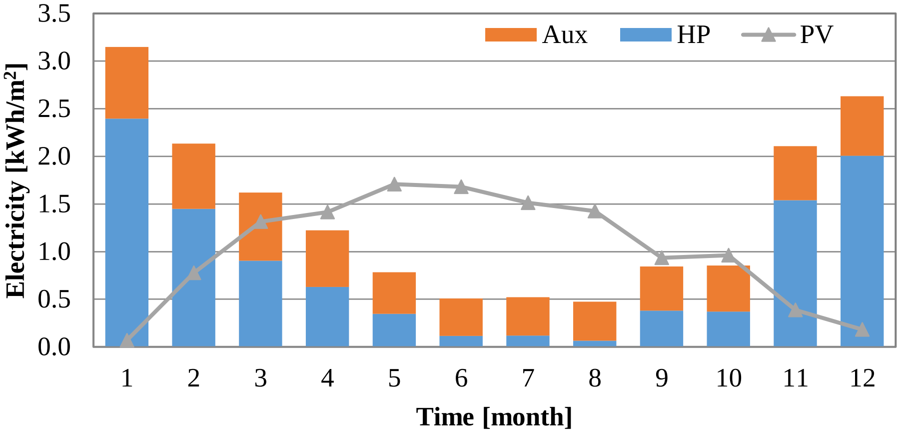

Figure 11: Monthly electric energy balance in year 2017

4. CONCLUSIONS

In this paper, monitoring results after two years of monitoring campaign were presented for a residential project of two multi-family houses designed as NZEB. The energy performance of the photovoltaic (PV) and solar thermal (ST) system was relative high, and the ground-water source heat pump with desuperheater had an SPF of 3.2. High thermal losses were observed in the thermal balance of the storage and unexpected high electricity of the auxiliaries. Thus, there is still a potential for further optimization.

The heating demand was significantly lower in the second year mainly due to the construction moisture. Thus, monitoring for more than one year is recommended for new constructions. The overall energy performance was also improved in the second year due to monitoring analysis. Therefore, quality assurance control is recommended.

The energy gap in the heating season is significant, and renewables cannot really contribute to that without a seasonal storage. Thus, Passive House standard or even better are prerequisite to achieve NZEB. On European level, the implementation of the EPBD has to be more ambitious. In addition, the concept of monthly or seasonal primary energy factors can contribute to the reduction of CO_2 emissions and enhance the critical discussion about nZEB and NZEB.

NOMENCLATURE

Aux	auxiliary electricity
CDF	cumulative distribution function
DHW	domestic hot water
HD	heating demand
HP	heat pump
HVAC	heating ventilation and air-conditioning
nZEB	nearly zero energy building
NZEB	net zero energy building
PV	photovoltaics
ST	solar thermal
SPF	seasonal performance factor

Subscript

sys	system
tot	total

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