DESIGN AND MONITORING OF A SOLAR THERMAL, PV AND HEAT PUMP SYSTEM

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Abstract

Two new, residential, and high-performance buildings were constructed in Innsbruck, Austria (with cold winters and mild summers) aiming to achieve net-zero energy building (NZEB) standard. The design was supported by the Passive House design tool PHPP. A groundwater heat pump, solar thermal collectors, photovoltaic panels (PV), and heat recovery ventilation units were installed. On one building a solar thermal system of 74 m^2 and a PV system of 52.5 m^2 and in the other building a PV system of 99.8 m^2 were installed. Four years of monitoring data are available. In this study, a monthly comparison between the monitoring data and the design values (PHPP) is presented concerning the performance of solar thermal, PV, and the heat pump. In addition, the efficiency of the solar thermal system is compared against the one of PV driven heat pump system, and the direct exploitation of onsite electricity generation is analyzed.

Keywords: solar thermal, PV, heat pump, in-situ monitoring, PHPP, NZEB

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 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 a 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 an annual balance between the electricity from and to the grid. Several studies about nZEB (Ascione et al., 2016; Attia et al., 2013; Becchio et al., 2015; Deng et al., 2014; Kneifel and Webb, 2016; Tsalikis and Martinopoulos, 2015) and NZEB (Attia et al., 2017; Goggins et al., 2016; Guillén-Lambea et al., 2017; Kurnitski et al., 2011; Lu et al., 2017; Paiho et al., 2017; Santoli et al., 2014) 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 an nZEB and NZEB is the combination of solar PV systems and heat pumps. In the IEA HPT Annex 49 (A49, n.d.), a follow-up of 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 the storage of electricity. Storage is relevant 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 the 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 this paper, the results of the monitoring of four seasons are highlighted and the monitored energy

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performance is compared to the designed one based on a steady-state calculation using the Passivhaus Planning Package (PHPP). The focus is on solar thermal, PV, and heat pump. The present study enhances the discussion about the design and evaluation of NZEBs using solar energy with a monitoring example from central Europe.

2. Concept

Two residential Passive House buildings were constructed in Innsbruck, Austria. The two multi-family houses consist of 26 apartments - 16 in the north building and 10 in the south building. In this project, the goal was to reach the NZEB standard, which was defined as the annual balance between the electricity consumed for heating (space heating and domestic hot water) and ventilation (excluding household appliances), and the electricity produced by renewable sources. Fig. 1 presents a simplified hydraulic scheme of the heating system. A two-stage groundwater source heat pump with a power of 58 kW (at W10/W35) including a desuperheater was used. 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 m2 (16 kWp) was placed on the roof of the south building. The ventilation units were centralized (three in total) including heat recovery. In combination with floor heating and a heat exchanger in each flat for domestic hot water (DHW), 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.

Through a simulation study, the share of PV (max 19 KWp) and solar thermal collectors (ST) was varied to determine the maximum possible energy yield considering PV and ST system efficiencies including heat pump performance and distribution losses (Tab. 1). The optimal design (from an energetic point of view) was found to be 74 m² ST and correspondingly 53 m² PV on the north roof (Ochs et al., 2014).

During the final design process and the construction of the two buildings, some parameters changed concerning the original planning. The floor heating flow temperature is 30 °C (30/26 °C instead of 28/24 °C) and the DHW flow temperature is 55 °C. A 3-pipe system with a common return pipe of floor heating and DHW was installed instead of the initially proposed 4-pipe system.

Tab. 1: Characteristic data of the two buildings NHT Vögelebichl according to the design (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	

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 focus was on energy performance. The thermal comfort of the south building is monitored, too. The operation of a monitoring system has started in November 2015, thus, monitoring data of four years are available.

During the design phase of the project, PHPP (Feist, 1998) was used as an energy calculation tool. PHPP uses monthly energy balance (ISO, 2008) with a detailed description of the building envelope including thermal bridges, ventilation, DHW (incl. distribution losses), etc., and also includes the prediction of the performance of air or ground-coupled heat pumps using an improved bin method. It includes an algorithm to predict the use of solar thermal energy. In addition, it calculates the electricity produced by a PV system. Finally, it is cross-validated against measured data and simulation results.

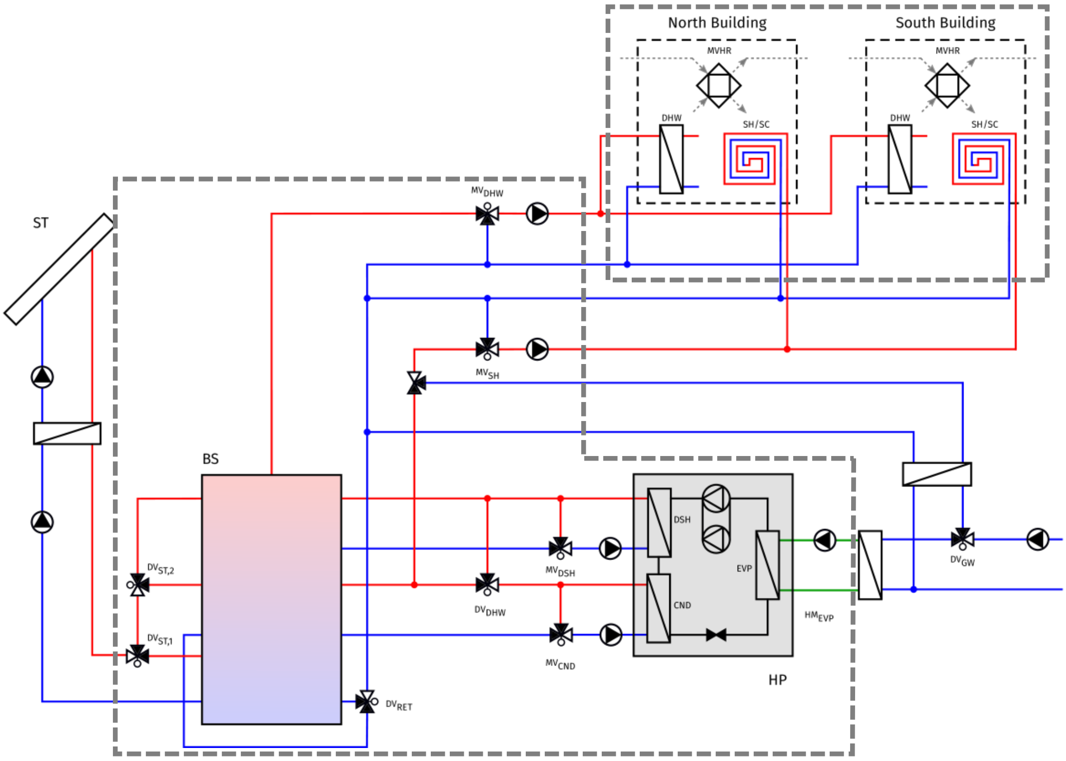

Fig. 1: Simplified hydraulic scheme with Solar Collectors (SC), Buffer Storage (BS), 2-stage ground-water heat pump (HP) with desuperheating (DSH) in heating mode with floor heating and decentral heat exchanger for domestic hot water (DHW) supply (Franzoi, 2020)

3. Design and monitoring results

3.1. Solar thermal

In Fig. 2, the monthly thermal energy production of the ST system is depicted. The bars show the monitoring values of the four years, and the lines, the calculated values in PHPP. Two cases are presented using PHPP: the ‘design’ one that corresponds to the values during the design phase, and the ‘calibrated’ one in which the heating and DHW demands are calibrated to the monitoring data (this has been done since the algorithm for the ST production depends on the heating and DHW demand, which is an input). It can be observed that the ‘PHPP design’ is on the safe side compared to the monitoring results, especially during the summer months. However, ‘PHPP calibrated’ is in a good agreement with the monitoring data, e.g. in 2018, PHPP calculated 12% less energy compared to the measured one.

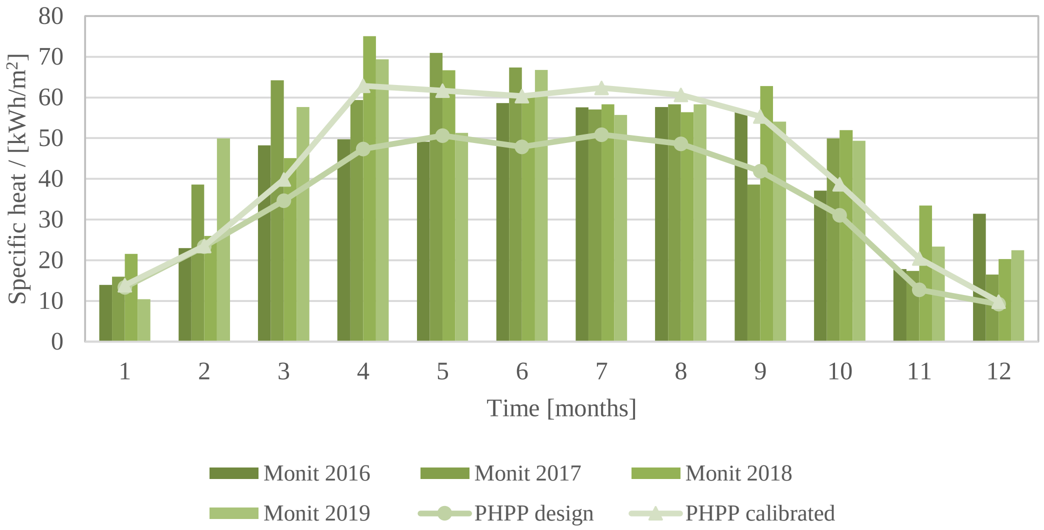

Fig. 2: Thermal energy produced by the solar collectors (ST) from 4 monitoring years and the predicted one by PHPP (once the original design values and once with calibrated heating and DHW demand).

Fig. 3 shows the 'PHPP calibrated' values of the ST versus the minimum, average, and maximum monthly monitoring values. PHPP is close to the minimum values from October to March and close to the average values in the rest months. Thus, PHPP has higher accuracy in summer months (with high ST production) and slightly underestimation in winter months (with low ST production).

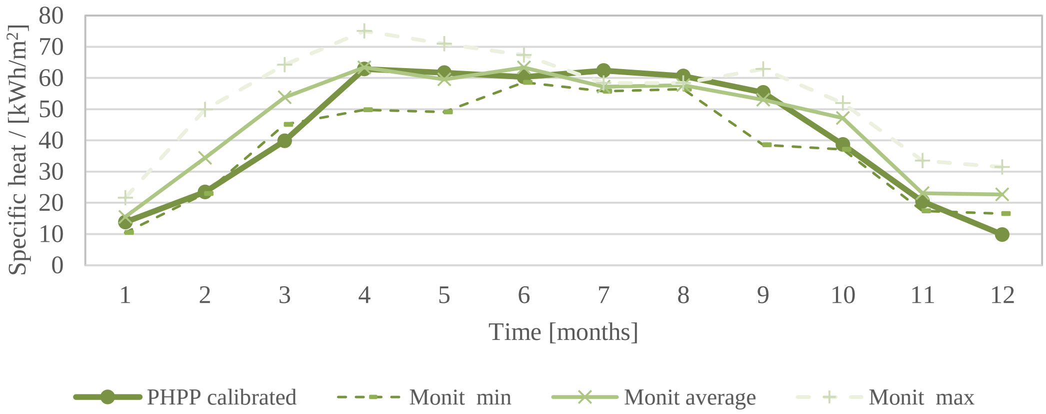

Fig. 3: Comparison of monthly ST production between PHPP and 4 years of monitoring data.

3.2. PV System

The monitored and predicted monthly electricity yield of the PV system is presented in Fig. 4, and in annual values in Tab. 2. PHPP underestimates the PV production in the non-winter months. On an annual basis, PHPP predicted 26% to 35% less electricity production than measured.

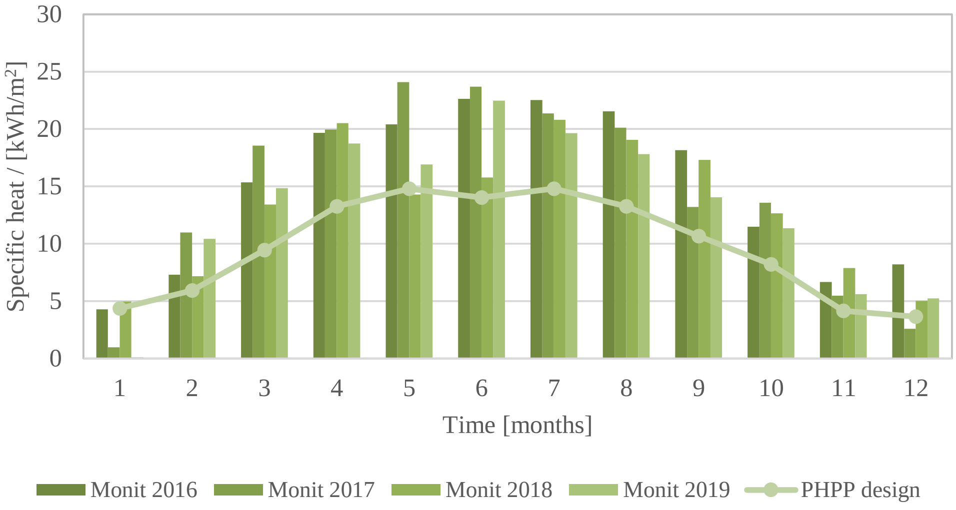

Fig. 4: Monthly measured (of the four monitoring years) PV yield and design PV yield in PHPP.

Tab. 2: Annual comparison of the measured (of the four monitoring years) and designed PV yield

Year	**Design [kWh m^{-2}]**	**Monitoring [kWh m^{-2}]**	**Difference [%]**
2016	117	178	35%
2017		175	33%
2018		159	27%
2019		157	26%

3.3. Solar thermal versus PV driven heat pump

Fig. 5 shows the comparison for the supplied heat of the ST and PV driven heat pump for the 4th year of monitoring (2019). The monthly PV electricity is multiplied with the monthly seasonal performance factor of the heat pump (SPF_HP) and then it is compared to the ST produced heat. The ST production is higher than the heat delivered by the PV driven heat pump in every month. The difference seems to be lower in winter months. In annual values, ST produces 28 % more heat. It is important to note that storage losses were excluded in this comparison.

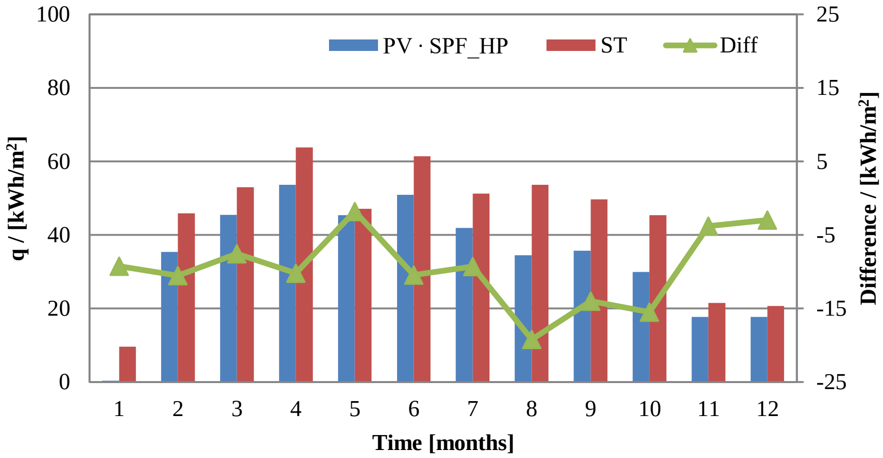

Fig. 5: Thermal energy supplied by PV driven heat pump (HP) and ST per installed square meter of each system (PV and ST). The produced electricity from PV is multiplied with the monthly SPF of the heat pump (including the HP related pumps). Monitoring results of the year 2019

The annual comparison between ST and PV driven heat pump is presented in Fig. 6. Overall, ST is preferable from the energy point of view, since it produces from 6% to 36% more heat compared to the PV driven heat pump. Notice that in 2018 there was a failure of the inverter on the north building, therefore the PV yield is significantly lower than the other years.

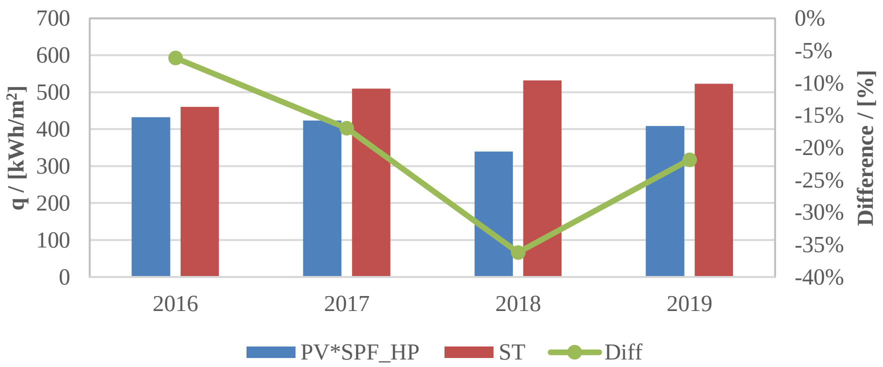

Fig. 6: Monitoring results of four years. Thermal energy supplied by PV driven HP and ST per installed square meter of each system (PV and ST). The produced electricity from PV is multiplied with the monthly SPF of the heat pump (including the HP related circulation pumps).

4. PV supply and load cover factors

4.1 HP and PV evaluation with PHPP

Within Task 56 ("IEA SHC Task 56/ Building Integrated Solar Envelope Systems, International Energy Agency,"), a new worksheet (add-on) for PHPP was developed to calculate the monthly electricity consumption of a heat pump having as input the annual electricity consumption from PHPP 'HP' sheet, and the monthly photovoltaic (PV) self-consumption (Ochs et al., 2020). The annual electricity consumption of the heat pump is distributed to the months based on the Carnot method in a post-processing step. This is performed separately, once for the use of a heat pump for space heating and once for domestic hot water preparation. Furthermore, the use of a solar thermal system in combination with the heat pump is possible.

As an outcome, the calculation of supply (SCF) and load cover factors (LCF) is possible. The supply (SCF) and load cover factors (LCF) indicate the direct utilization of the onsite electricity generation. The SCF is the ratio of self-consumed energy to the onsite generation energy, therefore representing the percentage of supplied energy directly consumed onsite. The equation representing the SCF is

$$\mathrm{SCF} = \frac{\int \dot{W}_{sc} dt}{\int \dot{W}_{PV} dt} \quad \text{(eq. 1)}$$

where $\dot{W}_{sc}$ is the self-consumed power and $\dot{W}_{PV}$ is the PV generated power.

The LCF represents the fraction of the total consumed energy that is directly provided by the onsite generators being defined as the ratio of the self-consumed energy to the total energy consumption.

$$\mathrm{LCF} = \frac{\int \dot{W}_{sc} dt}{\int \dot{W}_{C} dt} \quad \text{(eq. 2)}$$

where $\dot{W}_C$ is the total consumed power.

4.2 Supply cover factors (SCF) and load cover factors (LCF) in the case study

The SCF and LCF for the heating and non-heating seasons of 2019 and the estimated SCF and LCF of 2018 are reported in Tab. 3. The total energy consumption is considered for the calculation of SCF and LCF. It includes the electric energy needed by the HVAC (from monitoring) and the energy used for the household appliances. As appliances were not monitored, an optimistic annual consumption of 1500 kWh/a per flat is used as annual appliances energy consumption. As a load profile, the average electric energy consumption of 74 residential buildings in Germany was used as reported in Tjaden et al. (2015).

Fig. 7 presents the electricity consumption of the heat pump and the auxiliaries as well as the electricity produced by the PV in 2019. There is a surplus in the summer months, but in winter, the coverage of the consumed electricity by PV is insignificant.

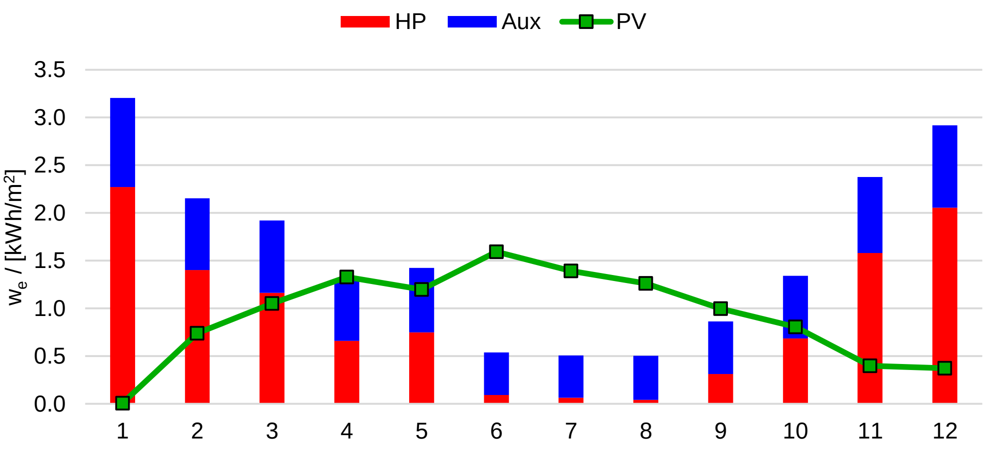

Fig. 7: ***Monthly electricity consumption by the HP and the auxiliaries, and PV electricity yield in 2019*** (*Final report IEA HPT Annex 49 Task 3, Field monitoring in nZEB*, 2020)

SCF and LCF can be evaluated from the monitoring data for 2019, while data gaps in the monitoring in 2017 and 2018 do not allow for a complete calculation of the actual self-consumption. However, for 2018 it is possible to estimate the self-consumption by simulating the power profile of the PVs. Therefore, a model of the PVs was realized in Simulink using the CARNOT library, and parametrized to the monitoring data of 2019, leading to a relative error between the predicted and measured energy of 6%, with the simulation model slightly overestimating the onsite generation. The measured and simulated PV energy yield relative error in 2018 is 8%. Being the estimated energy generation overestimated, the resulting factors for 2018 might be slightly overestimated, too.

Fig. 8 shows the total power and PV generated power profiles for a winter and summer day in 2019, with a shaded area representing the self-consumed energy. During the summer day, it can be noticed that the power consumption is on average lower than the winter day as a consequence of almost no heat pump operation (the DHW demand is covered mostly by ST). In both cases, the peak power generation is not exploited completely, suggesting that a battery or a control strategy properly programmed could improve the self-consumption.

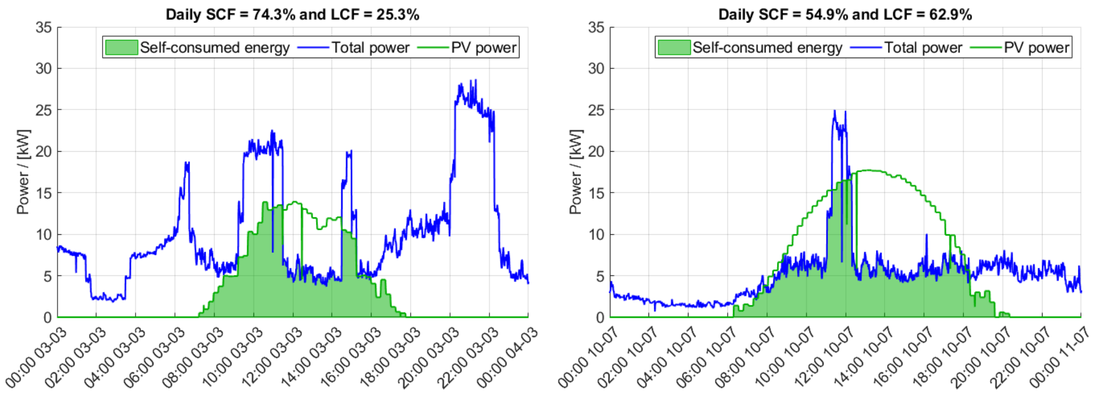

Fig. 8: Left: power profile for a day in the heating season, Right: power profile for a day in the non-heating season, in both figures the share that is self-consumed, is highlighted.

Tab. 3: Load (LCF) and supply cover factor (SCF) in 2019 for the heating and non-heating season and annual

	Heating season		Non-heating season		Annual	
	SCF	**LCF**	**SCF**	**LCF**	**SCF**	**LCF**
2018	84%	13%	62%	40%	67%	24%
2019	84%	6%	60%	31%	64%	18%

The LCF is between 18 % and 24 % (lower in 2019 because of the higher overall consumption) on an annual basis but is only 6 % to 13 % during the heating season, highlighting once more the small contribution of the PV during this season. The SCF is on average 66 % on an annual basis, meaning that throughout the year at least two-third of the generated energy is consumed onsite. Due to the lower consumption during the non-heating season, the SCF results slightly lower than the average and the LCF is significantly higher.

5. Conclusions

The design and monitoring results of a solar thermal, PV, and heat pump system are presented in this paper. The comparison between PHPP and monitoring data showed good agreement in the case of solar thermal energy. PHPP underestimated the PV electricity production, especially in summer months. The solar thermal system produced from 6% to 36% more thermal energy compared to a PV driven heat pump (the monthly PV yield was multiplied to the monthly seasonal performance factor of the heat pump) on an annual basis.

Furthermore, the add-on worksheet in PHPP that calculates among others the supply and load cover factors of PV and heat pump systems (including solar thermal is possible) is presented. The monitoring data analysis showed a load cover factor of 18% and a supply cover factor of 64% in 2019.

6. Acknowledgment

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