Simulation and Monitoring Results of two MFHs in PH Standard with Heat Pump, Solar Thermal and PV

Fabian Ochs[1], Georgios Dermentzis[1], Alexandra Ksiezyk[1]

[1] University of Innsbruck, Unit Energy Efficient Buildings, Innsbruck

Abstract

In the city of Innsbruck, the project Vögelebichl of the social housing company Neue Heimat Tirol (NHT), consists of two multi-family houses (MFH) in Passive House (PH) Standard and aims at operation with minimum CO_2 emissions for heating and domestic hot water (DHW) preparation. Net zero energy building (NZEB) was the goal of NHT for this project. The heat emission system, a floor heating with very low flow temperature, together with very well insulated heat distribution network allows a high performance of the ground water sourced heat pump (HP). The separate DHW distribution with flat-wise fresh water preparation is also designed for minimum possible flow temperature. DHW preparation is covered by solar thermal (ST) to a large extend. The electricity demand of the HP should be covered as much as possible by on-site PV. The optimum configuration of ST and PV with respect to energetic and economic performance was determined by means of simulation in a previous study Ochs et al. 2014. This paper presents the technical details of the two MFHs, the hydraulic concept and monitoring results after the first two years of operation, and a monthly primary energy evaluation.

Keywords: nearly zero energy building, Passive House, Multi-Family House, Heat Pump Solar Thermal, PV

1. Introduction

1.1 EPBD - Heat pump and PV for nZEBs

The recast of the European building directive (EPBD Recast, 2010) defined the path to nearly zero energy buildings (nZEB). Three aspects are addressed:

- New buildings will have a very high energy performance.
- The remaining very low energy demand will be provided to a very significant share by renewable energies and
- Cost-optimal levels for minimum energy performance are requested.

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

However, the implementation of the EPBD in the member countries is far less ambitious (see 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 nearly Zero Energy Building (nZEB) is the combination of solar PV systems and heat pumps. In the IEA HPT Annex 49, 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.

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1.2 nZEB vs. NZEB

The goal of both, nZEBs and NZEBs are comparable in the sense that CO_2-emissions and non-RE primary energy use shall be minimized, nevertheless, the definitions differ quite much in detail and the performance might be quite different eventually.

nZEB: nearly zero Energy Building according to EPBD, 2010, see above. Each member state has a national definition, with significant differences with respect to the energy use considered (heating, cooling, DHW, auxiliary, appliances), the maximum limits, the conversion factors etc. (see BPIE, 2016).

NZEB: Net Zero Energy Building, generally a NZEB is a "grid-connected building which produces the same amount of energy on-site by renewable energy sources as it consumes on annual basis." (IEA SHC Task 40, IEA HPT Annex 40). There is a fuzziness in this definition regarding the interpretation of the system boundary, the energy flows, the weighting/conversion factors etc.

Usually, Net Zero includes

- Heating (and cooling)
- DHW
- aux. energies (MVHR, pumps, control, etc.)

but excludes appliances. Even though appliances, have a large contribution to the overall electricity consumption (1500 kWh/a to 4500 kWh/a depending on the number of persons per household for a typical central European household, Statistik Austria 2016, BEDW 2013).

According to this definition, a NZEB can consume relative high amount of (electric) energy in winter, when correspondingly a large PV area produces this amount as excess electricity in summer. This means, that according to the NZEB concept, the electric grid is considered as a loss free seasonal storage, which is obviously not the case. In order to account for this weakness in this concept, additional performance indicators such as the load match factor or fraction of PV own consumption are suggested.

Remark: „net-zero“ as a goal can be a misleading concept, anyway as optimization for net-zero may lead to one storey buildings, because reaching the net zero balance is more difficult compared to a multi-storey 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 et al. 2014.

1.3 Monthly primary energy values

A possible approach of balancing primary energy demand and CO_2 emissions of a building with renewable energy generation is shown schematically in Fig. 1.Solar thermal (ST) energy is used to reduce the energy demand (heating, DHW + storage and distribution losses) that has to be covered by e.g. a heat pump (HP). Onsite PV can be used directly for appliances and auxiliary energies or to drive the HP, for higher own consumption a battery storage is required, which is subject to losses.

For the electricity mix, the share of renewables within the time frame of consideration (e.g. 20 years) should be included and not as usually done the current or past status. A significantly increased share of renewable electricity can be expected in the near future in particular in summer (PV), while in winter only a moderate increase is likely (further extension of wind power) unless seasonal storage capacities are strongly build up.

If a large number of buildings use heat pumps (and ST) for space heating and DHW preparation and produce electricity (with PV), both, the purchased electric energy and the share of renewables in the electricity mix and thus the CO_2 conversion factor of the electricity are dependent. Electricity that is used on site is not available in the grid and an increased share of fossil fuels in the energy mix have to be considered. PV electricity sold to the grid will replace fossil fuels more likely in winter, spring and autumn than in summer.

Heating and DHW preparation do not yet contribute significantly to the electric grid load in central European countries such as Germany and Austria (electric heating and heat pumps have a share in the range of 5 %, BEDW 2013, Statistik Austria, 2016)

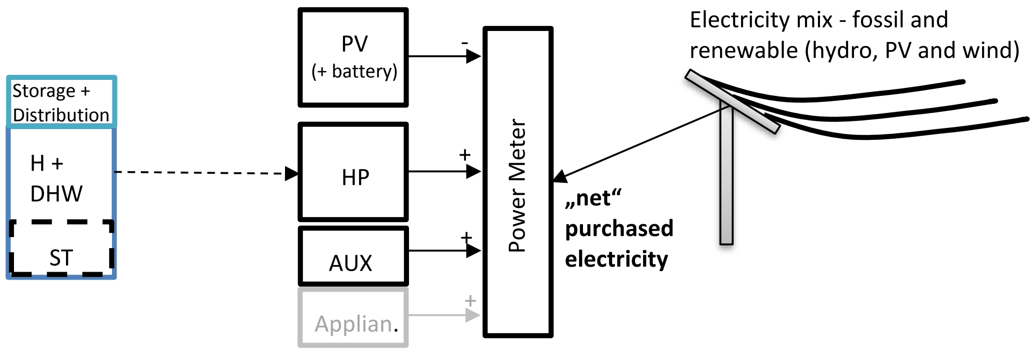

Fig. 1. One of different possible approaches for the energy balance for the calculation of the net energy balance with Heating (H) and domestic hot water (DHW) demand covered partly by ST; the remaining demand is covered by a heat pump (HP), which is partly powered by onsite PV, the remaining electricity demand for the HP auxiliary energies (and appliances) is covered by the grid with volatile shares of renewable electricity

Due to the volatile share of renewable energy in the grid (see e.g. the energy balance for Germany in 2015 (e.g. data from ENTSO-E), a net energy balance to evaluate different efficiency and energy concepts can be misleading.

National conversion factors for PE/CO_2 are not purely based on facts, but are partly politically motivated. They differ significantly between the EU member states and are subject to change, e.g. Germany (ENeV) 1.8 since 2016 (2.4 before), Austria 1.91 since 2015, 2.62 before (OIB-6, 2015, (OIB-6, 2011). Seasonal variations are not considered at all. Instead, a monthly evaluation based on monthly primary energy factors is proposed, which can be used to calculate a more representative environmental impact. The specific primary energy e_{PE} is

$$e_{PE} = f_{PE} \cdot w_{el} \qquad \text{(eq. 1)}$$

With different shares of hydro, wind, PV and fossil energy the primary energy conversion factor can be calculated on monthly basis.

$$f_{PE} = f_{PE,hyd.} \cdot \frac{w_{el,hyd.}}{w_{el}} + f_{PE,wind} \cdot \frac{w_{el,wind}}{w_{el}} + f_{PE,PV} \cdot \frac{w_{el,PV}}{w_{el}} + f_{PE,fos.} \cdot \frac{w_{el,fos.}}{w_{el}} \qquad \text{(eq. 2)}$$

Tab. 1: Monthly primary energy factors calculated exemplarily for two cases, A: a share of 10 % hydro, 10 % wind and 10 % PV, and the load of a PH with a HP for heating and DHW preparation as shown in Fig. 2 and B a share of 10 % hydro, 10 % wind and 10 % PV; $f_{PEhyd.}$ = 0.01 kWh_{PE}/kWh_{el}; f_{PEwind} = 0.05 kWh_{PE}/kWh_{el}; f_{PEPV}= 0.1 kWh_{PE}/kWh_{el}; $f_{PEfos.}$ = 2.4 kWh_{PE}/kWh_{el}

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	av.
A: 10-10-10	2.01	1.96	1.89	1.60	1.33	1.20	1.18	1.28	1.53	1.78	1.92	2.01	**0.8**
B: 10-30-30	1.53	1.42	1.23	0.50	0.08	0.08	0.08	0.08	0.33	0.98	1.33	1.54	**1.6**

Remark: A more detailed paper showing in detail the approach and the method of the PE-model and discussing the assumptions and implications is under preparation. The method can be applied to CO_2-emissions in the same way.

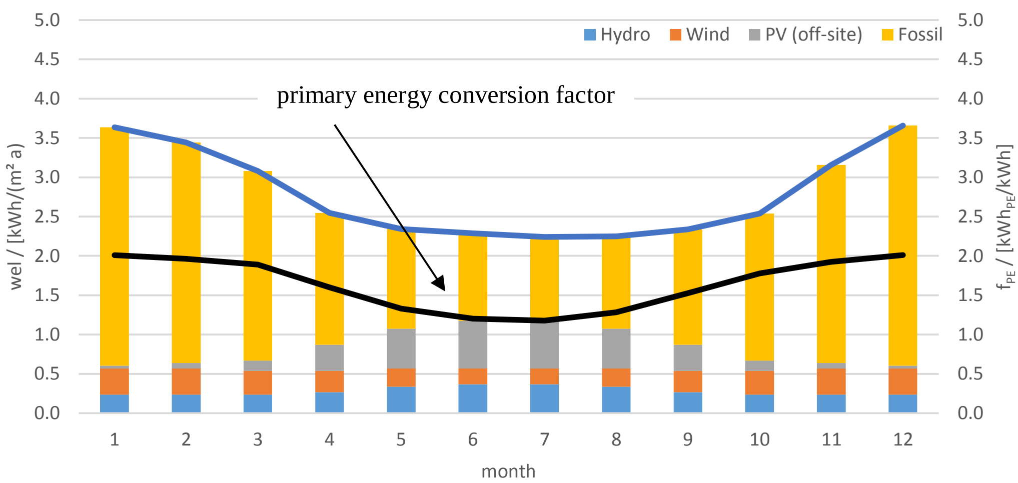

Fig. 2. Monthly share of renewables (hydro, wind, PV, fossil) and corresponding primary energy conversion factor, example of a PH with a HP for heating and DHW preparation with a share of 10 % hydro, 10 % wind and 10 % PV in the electricity mix

2. NZEB Project NHT Vögelebichl in Innsbruck

For the Passive House project Vögelebichl in Innsbruck (two multi-family houses with together 26 flats of the social housing company NHT see Fig. 3 and Fig. 4) the optimum share of PV and Solar Thermal (ST) was determined for the given boundary conditions. One roof of the multi-family houses is covered by PV (16 KWp) only. 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 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. Instead of the initially proposed 4 pipe system a 3 pipe system with common return pipe of the DHW and the heating loop was installed.

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, see Ochs et al. 2014.

Tab. 2: Characteristic data of the two buildings NHT Vögelebichl (as planed)

	North	South
No. of Flats	16	10
Treated area	1269.8 m²	818.8 m²
Heating Demand (PHPP)	13.5 kWh/(m² a)	17.0 kWh/(m² a)
Heating Load (PHPP)	12.0 W/m²	13.9 W/m²
PV size	8.5 kWp	16 kWp
ST area	50 m² (ca. 35 % of roof area)	-

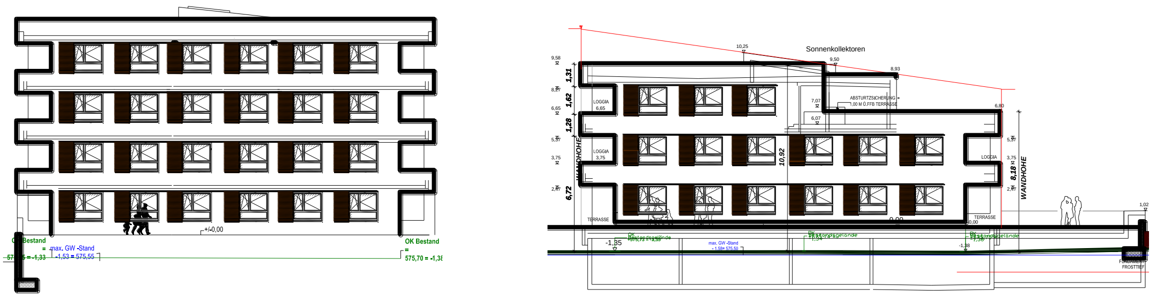

Fig. 3. West view of the two multi-family houses in Innsbruck Vögelebichl, NHT Tirol; two multi-Family PHs with ground water heat pump and PV (and opt. ST for DHW) with 4 pipe distribution system, low temperature system and fresh water modules in each flat

Fig. 4: Photos of the two MFHs in PH Standard (source: NHT)

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 (common return flow of floor heating and DHW) was realized (instead of the proposed 4-pipe system).

Fig. 5 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 preparation (DHW plate HX). The double stage heat pump is equipped with a hydraulic circuit enabling hot gas (HG) de-superheating. Depending on the operation mode (heating or DHW preparation), the flow of the heat pump enters the buffer store (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 store depending on the temperature level either at the bottom or at about 1/3 of the height of the store in order to enhance stratification. The electric backup heater (BH) is currently not used.

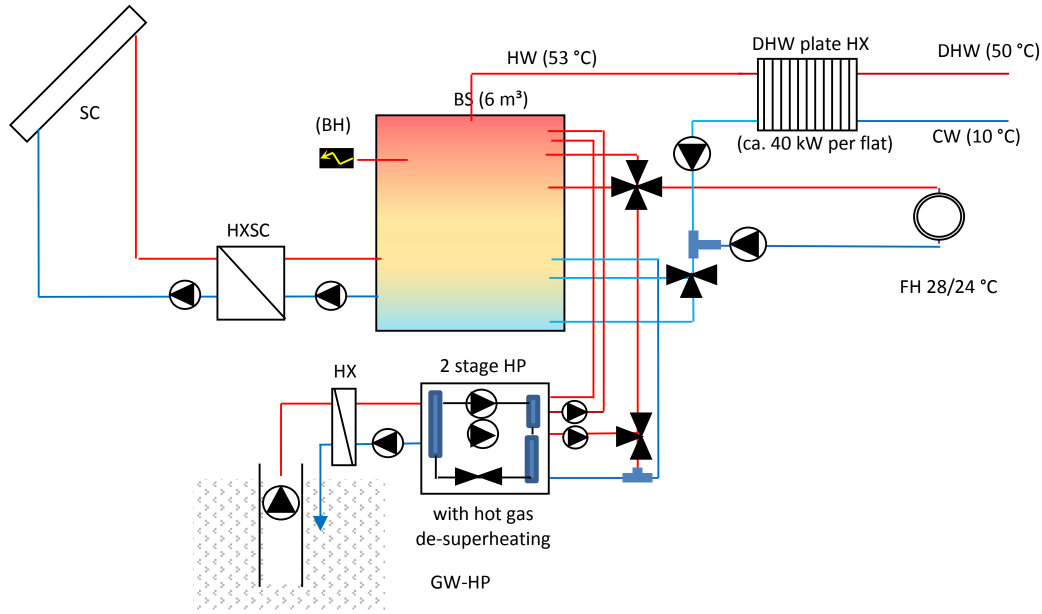

Fig. 5: Simplified Hydraulic Scheme with Solar Collectors (SC), Buffer Store (BS), 2-stage ground water heat pump (HP) with hot gas HG) de-superheating in heating mode with floor heating (FH) and decentral heat exchanger (HX) for domestic hot water (DHW) preparation

3. Monitoring Results

3.1 Climate

The climate during the monitoring period was rather typical. However, there was a relative cold January in 2017. The other months were in the range of average years. During the heating period in average the measured ambient temperature was 2.6 K higher than the design climate used in PHPP. The measured global horizontal solar radiation was with 1192 kWh/(m² a) very close to the design values.

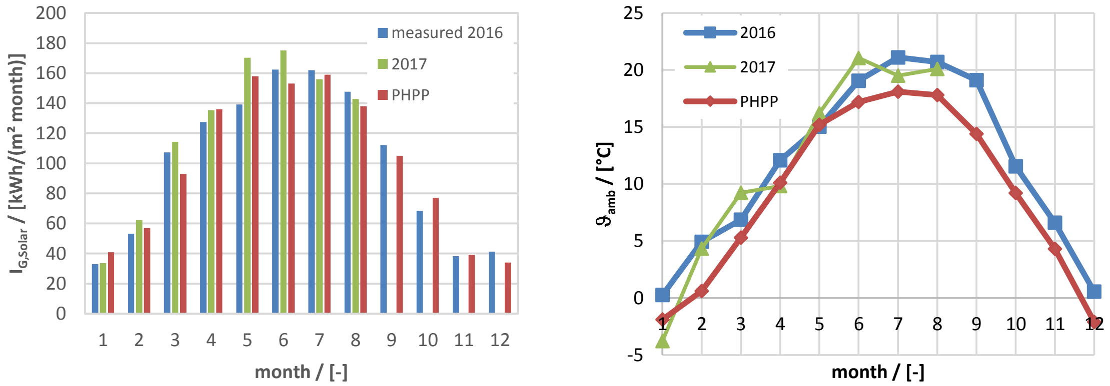

Fig. 6: Measured and design (PHPP) global horizontal solar radiation (left) and ambient temperatures (right)

3.2 Indoor Temperatures

The monitoring system is connected to the building management system (BMS), data of every relevant flow and return temperature, mass flow and energy flow is stored every 15 min. In addition, the temperature is recorded in each flat of the south building. The average temperature of the north building can be estimated by comparing the measured extract air temperature of the south and the north building. The monthly temperatures are reported in the following figure:

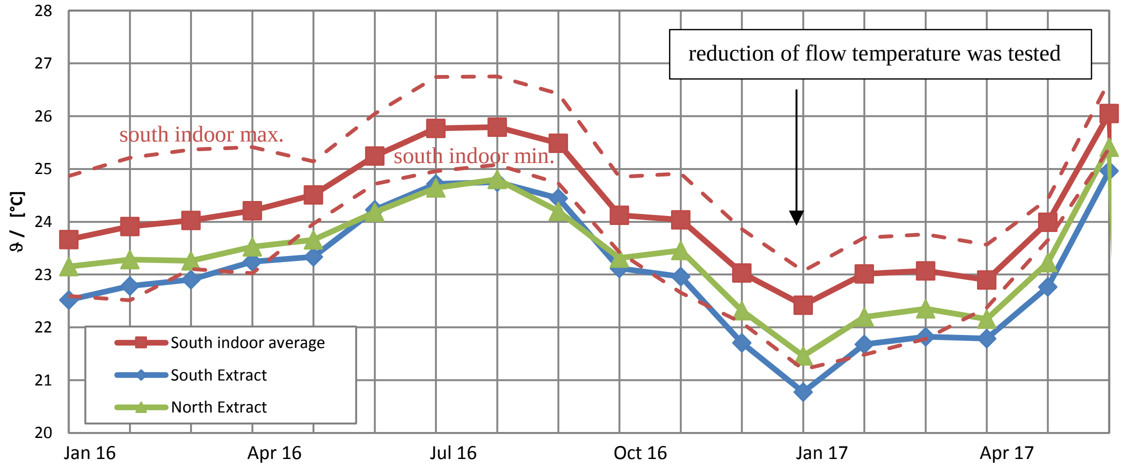

Fig. 7: Measured average, max. and min. indoor temperatures of 9 (of 10) flats of the south building and the corresponding extract air temperature as well as the extract air temperature of the north building

By comparing the average south building temperature and the extract air temperature of the south building and seeing that the extract air temperature of the north building is in winter about 0.5 K higher than the extract air of the south building, it can be expected that the average indoor temperatures were also slightly higher in the north building. In winter 2017, the average indoor temperature of the south building was in the range of 23 °C, while it can be expected that the temperature of the north building was in the range of 23.5 °C, which is 3.5 K higher than the design value. The difference between maximum and minimum indoor temperature of the flats of the south building was reduced significantly in the second winter (with 1.1 K compared to 2.4 in the first months).

In early winter 2017 (month 13 in Fig.7) the flow temperature of the floor heating system was reduced in order to reduce distribution losses. However, at least this sudden change in the indoor temperature together with the fact that January 2017 was a very cold month (average temperature -3.8 °C) was not accepted by most of the tenants and as consequence the flow temperature had to be increased again. It remains an open question, whether a smoother change of the temperature would have been recognized or not.

3.3 Energy Balance

The thermal energy balance for both buildings is shown in Fig. 8 for 2016. The HD for both buildings is with 31.1 kWh/(m² a) higher than design value of 12.2 kWh/(m² a) acc. to PHPP calculations (14 kWh/(m² a) for the south (853.2 m²) and 11 kWh/(m² a) for the north (1295.6 m²) building).

The main reason for an increased heating demand in the first year of operation is usually the construction moisture. Hence, it can be expected that the average annual heating demand decreases with respect to the first year of operation and will settle within the second year. In addition, the influence of the actual climate (compared to the reference climate) and the elevated indoor temperatures have to be considered. Furthermore, deviations from design values might be caused by the user (window ventilation, shading, occupation, equipment). Finally, the actual construction could differ from the design in terms of air-tightness, thermal bridges etc., but this can be practically excluded as the principles of Passive House design were followed and quality control such as blower door tests was conducted.

It is obvious that during the first winter of operation of such a building, there are effects that should be considered with care and general conclusions should be avoided. A HD closer to the design value can be expected for the next winter season, which is already indicated by the significantly lower HD in winter 16/17 than winter 15/16.

The domestic hot water demand (DHW) was with 24.7 kWh/(m² a) slightly higher than the design value, distribution losses are included and cannot be quantified by the available measurement equipment. Storage losses can be determined by energy balancing of measured heat flows from HP, ST, DHW and heating, and were relatively high: 1030 kWh/month in average throughout the measurement period, which is about a factor of three higher than expected even when a storage with relative poor insulation is assumed.

ST covers summer load including losses, so there is (theoretically) no need for HP operation in summer and PV electricity production can only be used for auxiliary energies and appliances (theoretically).

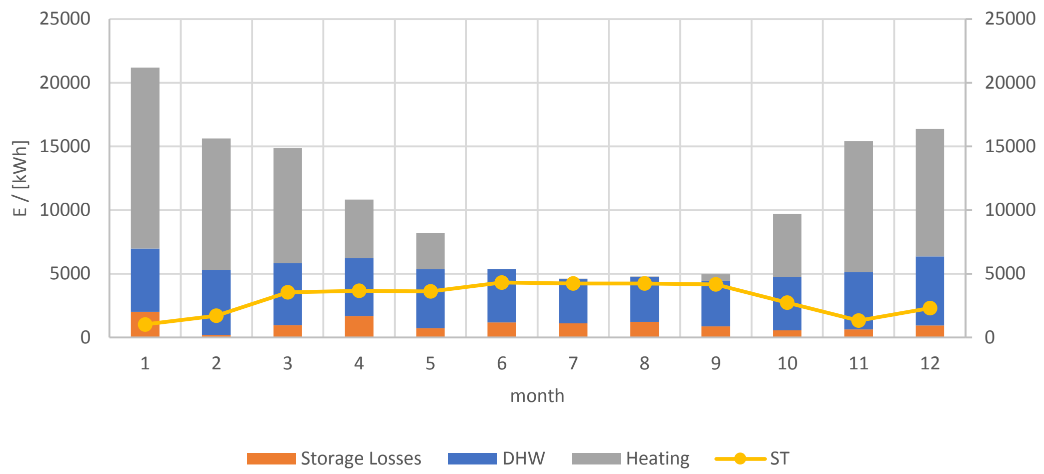

Fig. 8: Thermal energy balance (year 2016), DHW and heating is measured at storage outlet and this includes distribution losses

3.4 Heat Pump Performances

The performance of the ground water heat pump was with an SCOP of 2.9 poorer than expected. HP operation was not optimal for several reasons: heating and DHW flow/return temperatures were higher than planned. The two-stage compressor HP with de-superheating was operated mainly in DHW mode in the first winter. De-superheating contributed with 17 % to the total energy delivered by the HP. Storage stratification was poor in some operation modes and storage (and pipe) losses were too high. The ground water pump (well) was slightly over-dimensioned. Thermal losses of the HP were 16 % in winter and the HP was operated in summer without significant contribution (because of high contribution of ST, see above). The control of the HP and the system was optimized during summer 2016 and in winter 2016/2017 the COP could be increased to 3.4. Further system optimization is possible and an improved sCOP can be expected for 2017.

The average monthly temperature deceases from spring/autumn towards winter because of the higher share of operation in heating mode with flow temperatures of about 35 °C compared to the higher temperatures in DHW mode, see Tab. 3. The calculated monthly average COPs follow the trend of the measured COPs (based on values of 2017) but there is an offset of about 0.7 in average. This remaining difference between the calculation and the measurement can be explained by thermal losses and by the auxiliary electricity demand of the circulation pumps and the well pump and the temperature drop in the heat exchanger. An average COP of 3.6 to 3.7 can be expected based on the calculated values, while from the measurements an average COP of not more than 3.3 to 3.4 can be expected.

Tab. 3: Measured monthly COP in the heating season vs. calculated with Carnot performance factor of 0.5 acc. to data sheet; DHW mode in Mar. and Oct. with 60 °C, 50 % heating and 50 % DHW mode in Jan. and Dec.

	Jan	Feb	Mar	…	Oct	Nov	Dec
Meas. 2016	2.8	2.7	2.9		3.1	3.4	3.4
Meas. 2017	3.7	3.1	2.6				
Calc.	3.9	3.5	3.1		3.5	3.7	4.0
ϑ_{cold}	9	8	7		12	11	10
ϑ_{hot}	50	55	60		60	55	50

3.5 Performance of ST and PV

The performance of both, ST and of PV was relatively good. For a fair comparison, PV electricity has to be converted to thermal energy by means of running the heat pump with PV electricity and charging the storage. So

$$q_{PV} = sCOP \cdot w_{el,PV} \qquad \text{(eq. 3)}$$

Peak power limits and storage losses have to be accounted for. Furthermore, ST delivers temperatures up to 95 °C while with a heat pump the maximum temperature is below 60 °C. The power of the heat pump is limited (here 40 kW_{th}, correspondingly ca. 12 kW_{el}), i.e. for higher power (peak power of PV is ca. 23 kW_{peak}) either direct electric heating rods (with COP = 1) or batteries (with storage losses) have to be used.

A thermal energy storage is required for domestic hot water preparation, but for heating the HP could work directly on the floor heating system (ST contribution to heating is anyway very limited as can be seen in Fig. 8). Assuming 250 l per household, the 26 flats with a simultaneity factor of 0.2 and 50 % distribution losses, a storage volume of about 2 m³ would be sufficient. Hence, the additional volume of 4 m³ can be accounted to the solar thermal system. However, if the electricity generated by the PV area should also be used for DHW preparation (and heating) also in this case thermal energy storage would be required.

In this case, where ST is used for DHW preparation in summer, the monthly COPs of the heat pump should not be taken for further comparisons as the performance of the heat pump in summer was poor because of the very high contribution of ST and correspondingly low contribution of the HP. Therefore, the delivered energy is calculated with the average COP, which is with 2.9 rather low for a ground water heat pump. In this comparison, storage losses are disregarded and then the performance of both ST and PV (+ HP) is in the same order of magnitude as shown in Fig. 9. The specific yield of solar thermal without loses is q_{ST} = 500.8 kWh/(m²$_{ST}$ a) and reduces to $q_{ST\text{-}loss}$ = 336.5 kWh/(m²$_{ST}$ a) if all storage losses are accounted to the ST. The specific yield of PV is $q_{PV(COPav)}$ = 484.5 kWh/(m²$_{ST}$ a) based on the average COP of 2.9 and is $q_{PV(COPM)}$ = 428.5 kWh/(m²$_{ST}$ a) based on the monthly measured COPs (from 2016). With improved system design and control, a COP of the GW_HP of at least 3.2 should be possible (see section above) which would give PV a slight advantage over ST on annual basis, but ST would still perform slightly better in winter.

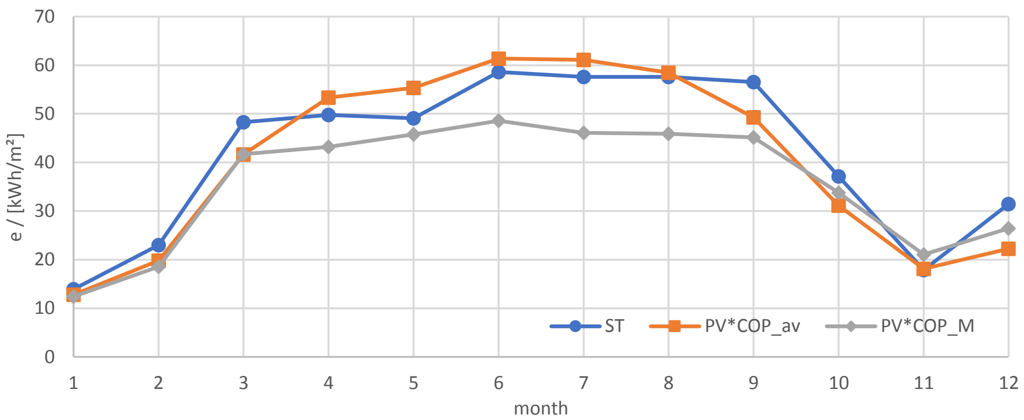

Fig. 9: Specific thermal energy (related to 1 sqm. of ST or PV, respectively) delivered by ST and by PV (with HP, with average and monthly COP of 2.9) (year 2016), storage losses are excluded

3.6 Electricity Consumption and Auxiliary Energies

The electricity consumed by the HP for heating and DHW is shown in Fig. 10. Aux. energies (pumps, MVHR, control, monitoring, etc.) are relative high. Electricity consumption is 15.3 kWh/(m² a) or 33 MWh w\o aux. and 22.9 kWh/(m²) or 49 MWh w\ aux. energy.

It can be seen in Fig. 10 that the first optimization measures proposed after the first winter already led to significantly reduced energy demand for heating and DHW and also to reduced auxiliary energy demand (5.6 MWh in December compared to 9.7 MWh in January, but still further optimization is required. The ambient temperature (and thus the heating degree days) and the global solar radiation were comparable in January 2016 and December 2016, see section 3.1, above.

PV yield is 167.6 kWh/(m²$_{PV}$ a) or 27 MWh or 12.6 kWh/(m²$_{AT}$ a) and is not even sufficient to cover the electricity for the heat pump. For heat pump and the auxiliary energies almost double the PV field size would be required. In December (where the el. consumption could already be significantly reduced with respect to January), on monthly basis, PV can cover 30 % of the electricity consumed by the heat pump and only 22 % if aux. energies are included. The remaining electricity has to be purchased from the grid.

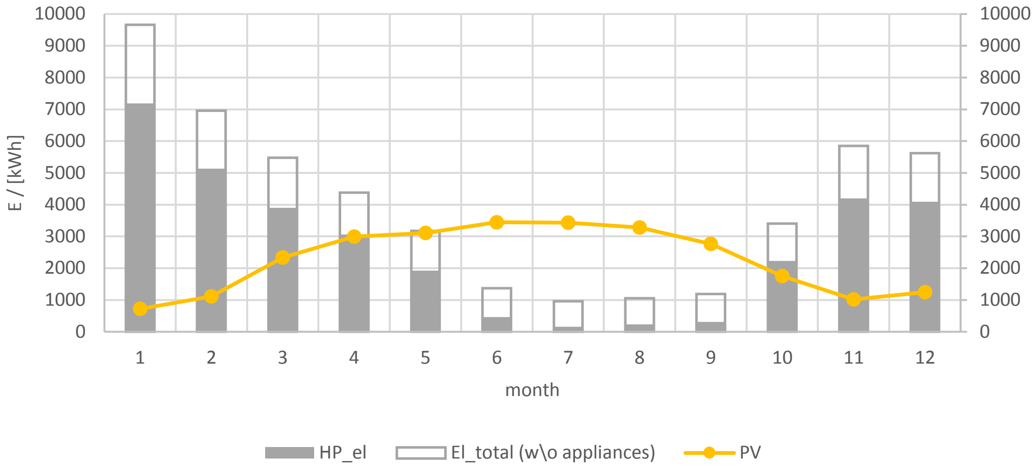

Fig. 10: Electric energy consumed by HP (grey bars), with auxiliary energies (white bars, appliances not included), and monthly electric energy produced by PV, monitoring results from 2016

4. Discussion

4.1 NZEB for heating, DHW (without appliances)

The goal of achieving a net zero energy balance (NZEB) for heating and DHW was not reached in the first monitoring period (2016) for several reasons: The higher HD in the first year (mainly because of construction moisture) and the relative high thermal losses of the storage led to a higher load. Furthermore, control settings were not optimal (e.g. not enabling good stratification) resulting in rel. poor performance of the heat pump. During the first year of monitoring some improvements were implemented and an increased performance of the HP can be expected. By avoiding thermal bridges of pipes and valves and convection (by heat traps) and by reducing storage set pint temperature, storage losses can be reduced.

If the heating demand can be reduced to PH-level (i.e. 15 kWh/(m² a)) and if further storage losses can be limited, higher solar fraction can be expected and the load for the heat pump can be reduced. If moreover, because of reduced set points and improved stratification, better performance of the HP can be achieved and finally aux. energies can be reduced, the electricity consumption could be reduced from ca. 22.8 kWh/(m² a) to the design level of ca. 11.8 kWh/(m² a). With all these possible improvements and optimization measures, the goal of NZEB could be achieved, as is shown in the prediction in Fig. 11. The annual yield of PV (167.6 kWh/(m^2_{PV} a) or 12.6 kWh/(m^2_{AT} a)) is enough to cover the consumed electricity on annual basis. However, the remaining purchased electricity in December would still be 3.1 MWh or 71 % (compared to 4.4 MWh or 78 % from the measurements).

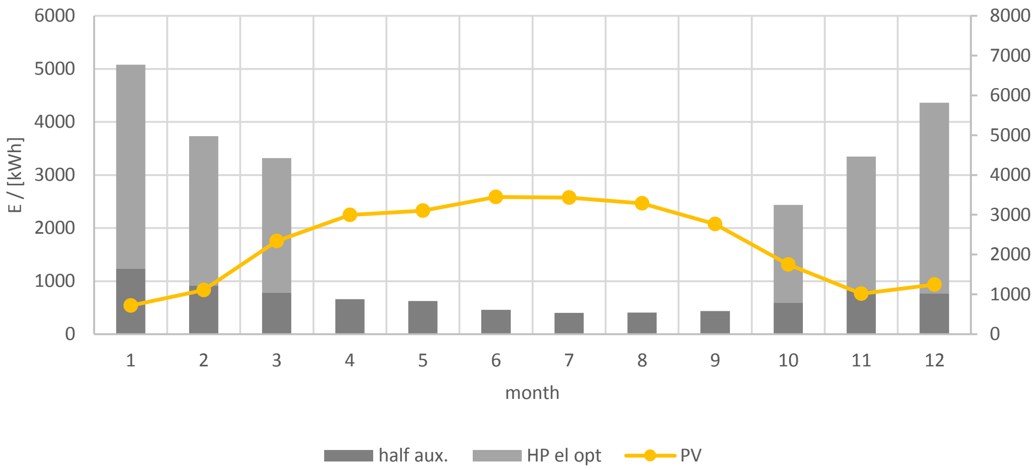

Fig. 11: Net-zero energy balance; prediction after optimization (50 % of auxiliary energies with respect to measurements, HD acc. to PH standard and improved HP performance (sCOP = 3.7)) Load is 25.2 MWh or 11.8 kWh/(m² a); PV yield is 167.6 kWh/(m²PV a) or 12.7 kWh/(m^2_{AT} a), respectively

4.2 NZEB for heating, DHW and appliances

Annual PV yield is not enough to cover appliances, even if only 1500 kWh/a are assumed per household (appliances are not measured, but European average is about 1500 kWh/person/year, see above in section 1.2). The monthly balance after optimization (prediction) but including appliances is shown in Fig. 12. If appliances are included, the net balance cannot be fulfilled. It is obvious, that in the winter months there is no PV electricity left for HP and auxiliary energies. Instead, 100 % has to be purchased from the grid. Only in summer, there is slight PV excess electricity which can be used to cover auxiliary energies and a small amount of PV has to be sold to the grid (again on basis of monthly balance). If higher consumption of appliances are assumed (e.g. 2500 kWh), on monthly basis, there would be no excess PV at all.

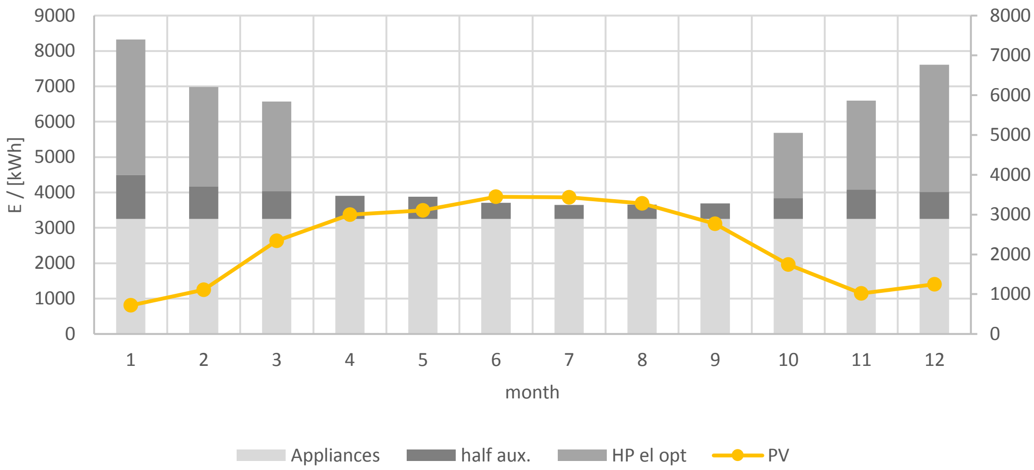

Fig. 12: Prediction of electric energy balance after optimization (as in Fig. 11 but with appliances; 1500 kWh/household; remark: electricity consumption for appliances is not measured (contract between electricity provider and the tenants); 64.3 MWh or 29.9 kWh/(m²$_{AT}$ a), respectively

For a NZEB with appliances, PV must be used in addition in the façades. An additional theoretical area of 300 m² (ca. 45 kW$_{peak}$) would be required in the south facades.

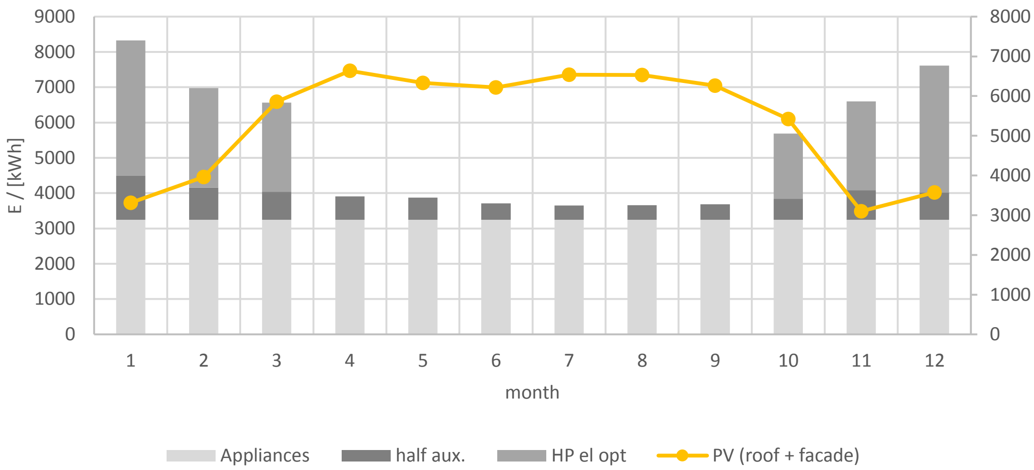

Fig. 13: Prediction of electric energy balance after optimization with appliances (as in Fig. 12) but with additional theoretical 300 m² PV on south facades (ca. 45 kW$_{peak}$)

4.3 PE balance

The specific primary energy (e$_{PE}$) for heating and DHW production with the HP, for the case with the improved system, with appliances without and with 300 m³ of PV in south facades is calculated assuming two scenarios, see section 1.3:

- case A with 10 % hydro, 10 % wind and 10 % PV and
- case B with 10 % hydro, 30 % wind and 30 % PV.

It can be seen in Fig. 14 that in scenario B with higher share of renewables in the grid(all together 70 %), the additional PV in the façade yields less primary energy savings then in the case A with all together 30 % of renewables. In scenario A the additional PV in the façade reduces the annual specific PE demand from 32.7 $kWh_{PE}/(m^2 a)$ to 15.2 $kWh_{PE}/(m^2 a)$, or by 53.5 % while in scenario B, it reduces from 21.9 $kWh_{PE}/(m^2 a)$ to 11.2 $kWh_{PE}/(m^2 a)$ or by 49.2 %. As discussed in section 1.3, the state of the art is using a constant primary energy conversion factor, e.g. 1.91 as in At (OIB). PE savings with a constant PE conversion factor are 58 % (13.8 $kWh_{PE}/(m^2 a)$ with compared to 32.9 $kWh_{PE}/(m^2 a)$ without PV in the facade). With constant primary energy conversion factor, savings are accounted for with the same weighting independent of the season. Therefore, savings in summer are overrated.

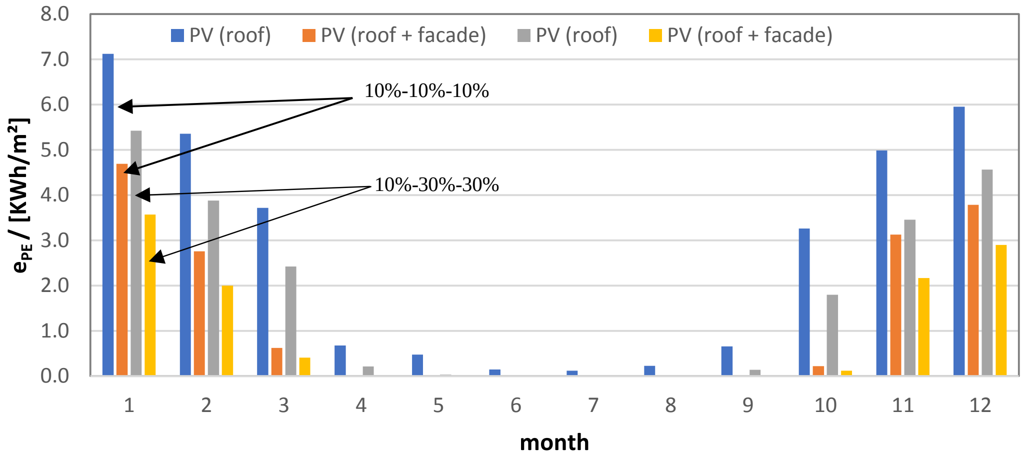

Fig. 14: Specific primary energy (e_{PE}) for heating and DHW production with the HP, improved system, with appliances without and with 300 m³ of PV in south facades for case A with 10 % hydro, 10 % wind and 10 % PV and case B with 10 % hydro, 30 % wind and 30 % PV.

5. Conclusions and Outlook

Two MFHs in PH Standard were implemented with solar thermal and heat pump system and PV to achieve maximum primary energy savings. Thus, the project can represent a best practice example for future nZEBs. PH standard is key for achieving real nZEB/NZEB level. ST has energetic benefits over PV in case of relatively small systems (i.e. f_{sol}(DHW) < 40 %). However, system complexity increases and a well-tuned control strategy is of major importance. Stratification of the buffer storage is crucial for optimal performance of the solar thermal plant and the heat pump. Obviously, storage size (i.e. volume) and connections must be carefully designed in order to avoid excessive storage losses. The reduction of the flow and return temperatures and the minimization of the distribution losses is also very relevant. Finally, also auxiliary energies have to be kept to minimum level.

In the paper monitoring results of the buildings (heating and DHW demand) and of the system (distribution losses, performance factors, solar thermal and PV yield) are reported and improvements after the first year of operation were discussed and design recommendations based on monitoring data and simulation results were given.

Net zero energy balance (for heating and DHW and auxiliary energies) could not be achieved during the first year of monitoring (2016), but predictions based on results after some improvements show that with it could be achieved. However, it is also highlighted in the paper, that electricity of appliances cannot be excluded from the energy balance and that NZEB do not significantly reduce winter grid load.

The mismatch between (electricity) demand and PV yield has to be considered, e.g. by means of different electricity prices for purchase and sell or by seasonal/monthly primary energy conversion factors. A method is discussed allowing to compare different nZEB/NZEB concepts considering the time (season) of the electricity purchase from the grid in order to be able to optimize concepts towards reduced non-renewable primary energy demand or CO_2 emissions in winter when renewable electricity is rare. In this sense, also concept of net zero energy buildings (NZEB, e.g. IEA SHC Task 40) can be critically discussed.

There is a need to develop design guidelines for HP design, HP and system control. Performance monitoring for fault detection and system optimization is strongly recommended.

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