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Field Monitoring of a Nearly Zero Energy Building

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Abstract

In Switzerland a current definition of nearly Zero Energy Buildings (nZEB) is the MINERGIE-A® label, which also includes non-residential buildings since 2014. A two-year field monitoring has been conducted in the first nZEB with office use in canton Zurich to gather experience with labelling of office buildings, approve the system design/nZEB-balance, investigate demand response options and identify optimisation potentials.
The core components of the "all electric building" are the PV-system and the ground-source heat pump. The floor heating is also used for ground-coupled free-cooling in summer. A direct electric heating is installed for legionella protection and an accompanying pipe heating for DHW comfort. Extensive monitoring equipment enables to evaluate key characteristics of the system performance.
The nZEB-balance has been reached in the first year from May 2014 to April 2015 with a surplus of 8.6 kWh/(m^2·a), which has been increased to 15.0 kWh/(m^2·a) in the second year by reduction of the direct electric heating consumption by 58%. The overall seasonal performance factor of the heat pump was increased from 4.2 to 4.5. Regarding demand response capabilities, the self-consumption of the on-site PV-electricity is around 40%, which is higher than in residential buildings with 15-25% due to better load match with office use.
Detailed monitoring results of two entire years confirm that nZEB can also be reached in office buildings by state-of-the-art highly efficient heat pump and building envelope technologies in Switzerland. Moreover, good demand response can be further increased by load shifting with heat pumps.

Keywords: nearly Zero Energy Buildings; field monitoring; demand response; operational optimisation

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1. Introduction

As one of the first buildings in Switzerland with mixed residential and office use the newly constructed building located in the centre of the Swiss town Uster in Eastern Switzerland complies to the MINERGIE-A® label. The building has been commissioned in February 2014 and has an energy reference area of 1206 m^2 divided into 367 m^2 office and 839 m^2 living space. The office part provides space for 20 workplaces. The calculated specific heating demand of the building is 33.8 kWh/(m^2·a) and thereby less than the limit of 43.9 kWh/(m^2·a). The design value for the MINERGIE-A® index of weighted energy consumption yields with -5.0 kWh/(m^2·a) a slight surplus. Table 1 summarizes the building envelope characteristics, which approaches values of ultra-low energy house constructions.

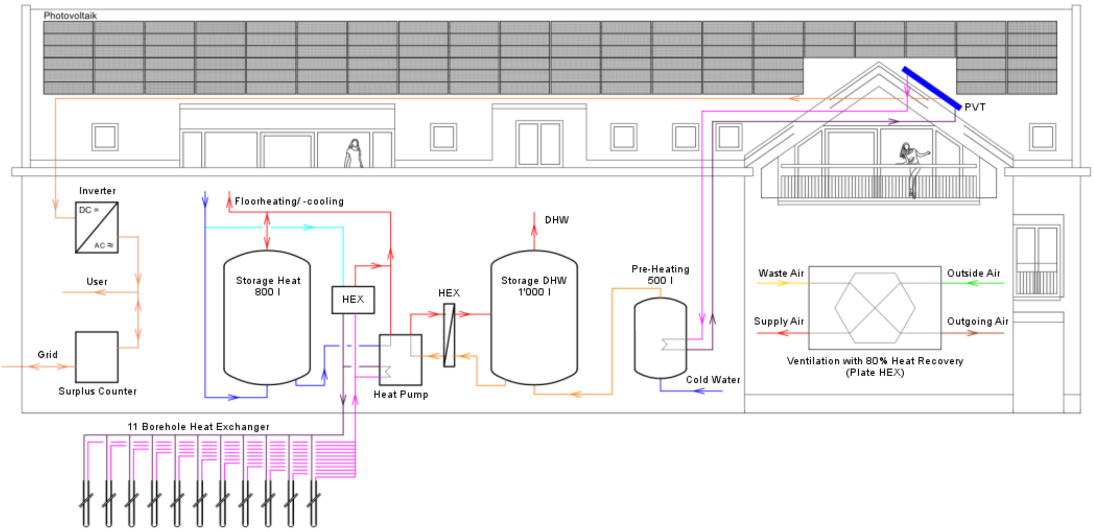
Table 1. Envelope characteristics of the monitored building in the Swiss town Uster

Living space	**U-Value** *(W/m²K)*
Floor	0.18
Roof	0.18
Outside Walls	0.15
Windows (ø of all)	1.00
Office space	
Basement	0.13
Walls, cellar	0.16
Outside walls	0.15
Windows (ø of all)	0.97

1.1. Technical concept of the building

The technical concept of the building technology as shown in Fig. 1 [1]. The building is designed as an “all-electric building” with a heat pump and a PV-system as core components, i.e. only electricity is used as delivered energy. The ground source brine-to-water heat pump covers the space heating and domestic hot water (DHW) energy needs. A ground heat exchanger of 11 boreholes with a length of about 80 m each are used as a source for the heat pump. The heating capacity/Coefficient of Performance (COP) of the heat pump are 33.1 kW/4.6 at B0/W35 and 30.5 kW/3.0 at B0/W50, respectively. The heat emission to the room is accomplished with a floor heating, which is also used for ground-coupled free-cooling in summer operation. For the space heating operation, an 800 l buffer storage is integrated in parallel to the floor heating system. By the heating buffer storage, cyclic operation of the heat pump can be avoided in situations with low space heating loads, since the heat pump does not have a variable speed control, but is on-off controlled. An accompanying electrical tube heating (heat tape) is installed to fulfil the Swiss SIA-standard 385/1 [2] for DHW comfort. The system has a power of 1 kW and allows supplying tab water at 40 °C in 10 s at any time of the day. A DHW preheating of a 500 l DHW tank is realized by an innovative photovoltaic-thermal (PV/T)-collector (5 modules with a total area of 7.1 m², an electrical peak power of 1 kW_p and a thermal peak power of 2.3 kW_p), which also contributes to the electric generation. The PV/T-collectors are installed on the roof oriented to the south. The DHW is reheated by the heat pump and a heat exchanger in a 1000 l storage to a temperature of about 53 °C. For legionella protection a direct heating element is installed in the DHW storage to reach temperatures of 60 °C, since the heat pump only covers the DHW energy up to a 53 °C water temperature due to the upper operation limit of the heat pump.

Fig. 1. Overview of the building technology of the nZEB [3]



The 23.7 kW peak (kW_p) PV-system installed on the roof covers an area of 128 m^2 and consists of 103 modules. It is installed on the SSW oriented roof with an inclination of 35°.

The calculated electrical energy generation for the PV-system is 1,007 kWh/kW_p or about 24,000 kWh/a. The building is equipped with a mechanical ventilation system with heat recovery.

Moreover, in order to enhance the local use of PV electricity and reduce grid interaction a publicly rentable electric car is used as local electricity storage of PV electricity.

2. Approach

During a two year energy measuring the energy flows of the building were logged on the one hand to evaluate relevant key metrics like the MINERGIE-A® index, the seasonal performance factor (SPF) of the heat pump or the supply cover factor (SCF), and on the other hand to optimize the current operation and increase the efficiency of the installed building technologies.

2.1. Measurement concept

A detailed measurement concept has been realized to monitor the building. The monitoring system records relevant data of the major components of the building technology, detailed electrical energy consumption of the space as well as metrics related to comfort conditions. The main objective of the field monitoring was the evaluation of the net zero energy balance according to the requirements of the MINERGIE-A® label. The monitoring of the PV/T-collector, the PV-generator, the heat pump and electrical energy comprises around 70 measuring points. The building has been commissioned in February 2014 and has been measured during a two year period. The first measuring period covers the period of May 2014 till April 2015 and characterises the first year of operation. The second measuring period consists of the period of May 2015 till April 2016 and enables the assessment of the second year of operation.

2.2. MINERGIE-A® label

In Switzerland the most common definition of nZEB is the MINERGIE-A® label [4]. The MINERGIE-A® index for the measured building includes the relevant building technologies (heat pump, mechanical ventilation system and additional heating systems) on the consumption side and the PV- and PV/T-collectors on the production side. Household electricity (plug loads), mobility and embodied energy are not considered for the yearly based balancing. MINERGIE-A® uses so-called national weighting factors for the conversion to primary energy. Due to the all-electric building concept, only electricity has to be weighted which is done with the factor 2 according to the label requirements. The MINERGIE-A® index is thus calculated using the following formula:

$$Minergie-A^{®}-index=\frac{2}{1206\,m^2}\left(E_{Ven}+E_{HP}+E_{HR}+E_{Sol}-E_{PVT}-E_{PV}\right) \quad (1)$$

E_{Ven}:	Energy consumption ventilation	E_{Sol}:	Energy consumption circulation pump
E_{HP}:	Energy consumption heat pump	E_{PVT}:	Energy production PV/T-generator
E_{HR}:	Energy consumption heating element	E_{PV}:	Energy production PV-generator

3. Results

3.1. Energy flow

Fig. 2 shows the energy flow of the MINERGIE-A® relevant consuming and producing building technologies for the second year of operation.

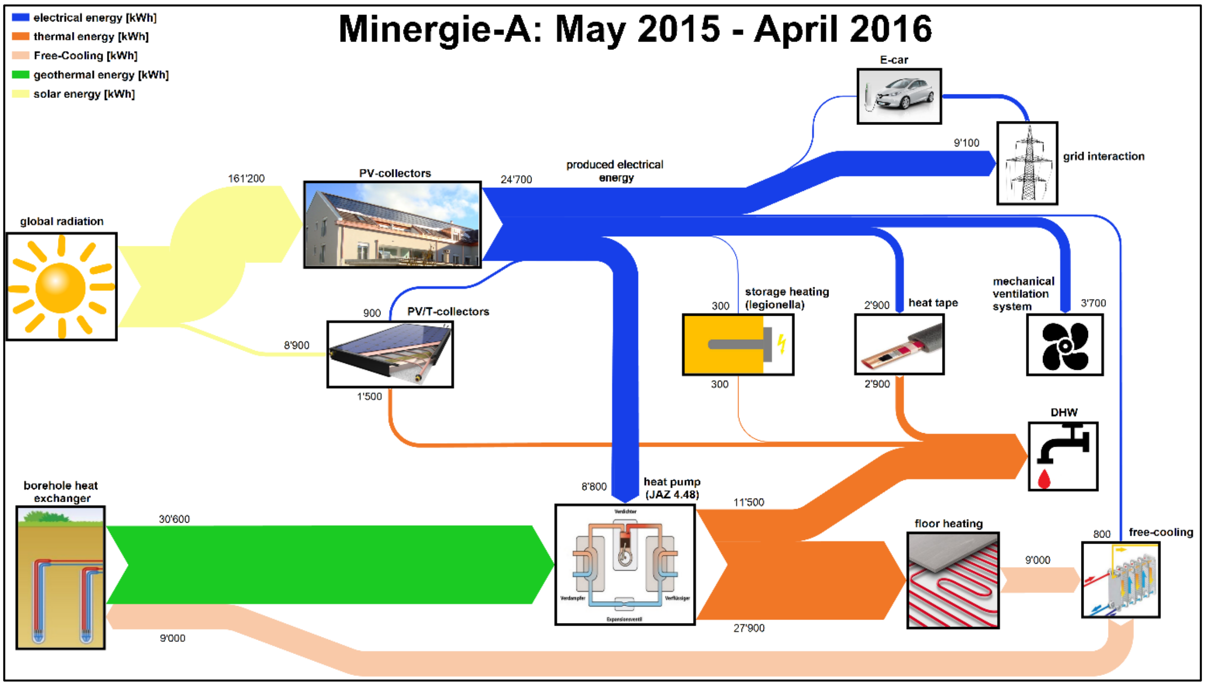


Fig. 2. Energy flow diagram of the building for the period May 2015 – April 2016

Furthermore, the energy flow diagram shows the renewably supplied energy (geothermal and solar energy) to the building. According to the MINERGIE-A® guideline, geothermal and solar energy is weighted with a factor of 0, which means no compensation is required for this energy. Moreover, the ground-coupled free-cooling operation of the office space is illustrated.

3.2. MINERGIE-A® Index

Fig. 3 shows the electrical consumption of the installed building technologies and the on-site production of electrical energy through the PV and PV/T-collectors for both years of operation. Compared to the first year of operation, the consumption of the additional heating systems (heat tape and DHW storage legionella protection) is significantly reduced due to the implemented optimization in the second year as described in chapter 3.5. The electrical production by the PV and PV/T-collectors are similar in both years of operation. The seasonal fluctuations are shown on the right side of Fig. 3. During the summer months the production is 3-4 times higher than in the winter months. The PV-system reaches a specific yield of 1,030 kWh/kW$_p$ in the first and 1,040 kWh/kW$_p$ in the second year of operation. Additionally, the PV/T-collectors generate an electrical energy amount of about 900 kWh in each year. Considering only the building technology, the heat pump is with 45% responsible for the largest share of the electrical consumption in the first year of operation. Due to the performed optimization regarding the additional heating systems the proportion of the heat pump increases in the second year of operation to about 60%. At the same time, the total consumption has decreased by 15%.

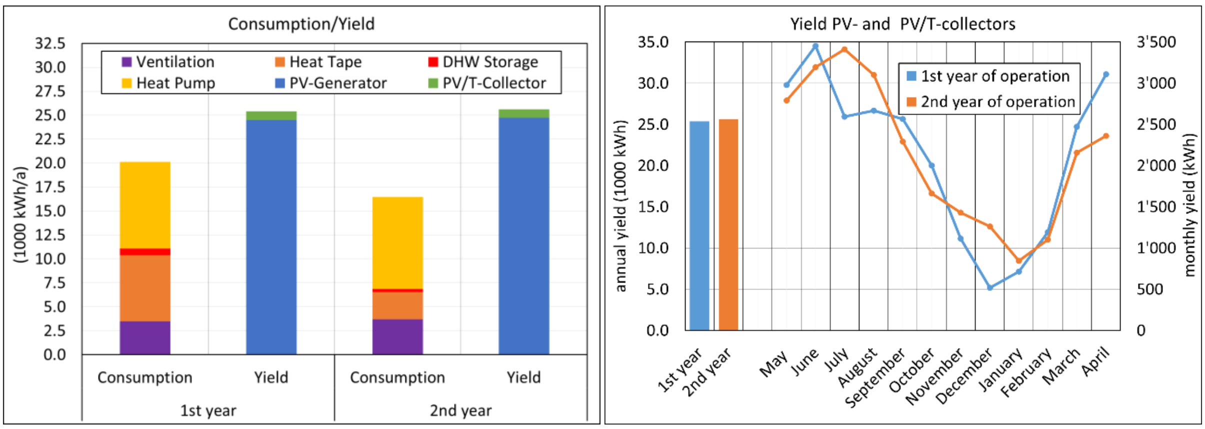


Fig. 3. Production and consumption of the MINERGIE-A® relevant building technologies (left)
and electricity production of the PV- and PV/T-collectors (right)

Fig. 4 shows the MINERGIE-A® index on monthly and annual basis for both years of operation. For the first year of operation, the MINERGIE-A® index has reached -8.6 kWh/(m^2·a) which fulfils the requirements and lies considerably below the design value of -5.0 kWh/(m^2·a). With the implemented optimizations the MINERGIE-A® index decreases in the second year to -15.0 kWh/(m^2·a). During the winter months the limit value of 0 kWh/(m^2·a) is exceeded, because of the high energy use of the heat pump and the low energy production by the PV and PV/T-collectors.

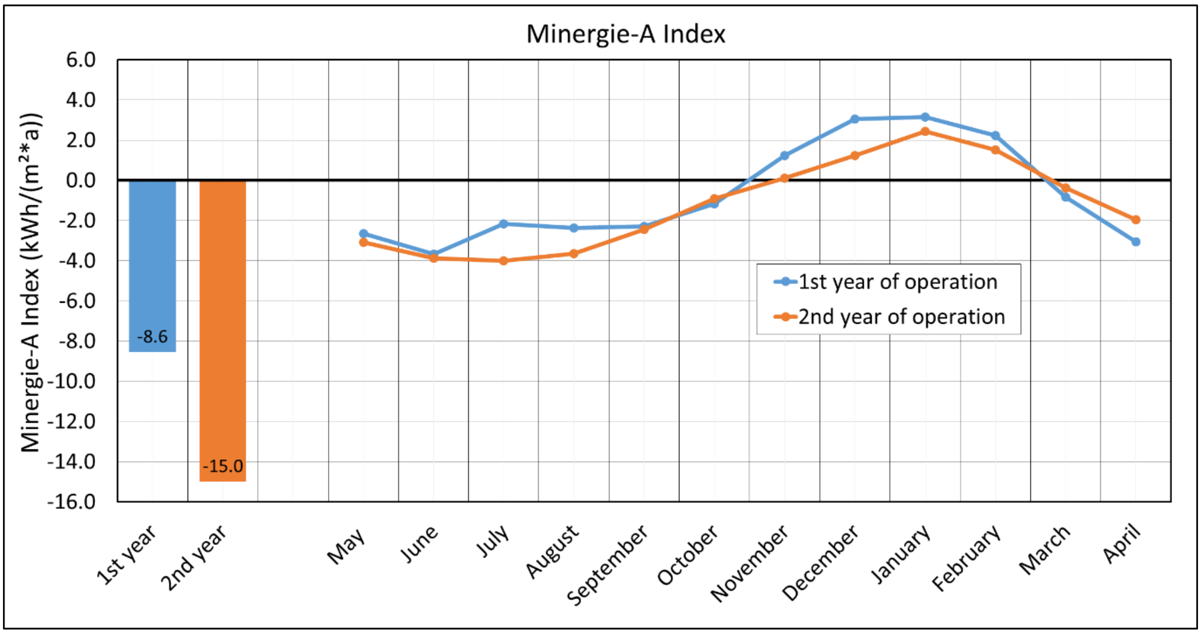


Fig. 4. MINERGIE-A®-index for both years of operation

3.3. Heat pump

For both years of operation, the seasonal performance factor (SPF) for heating and DHW operation as well the overall seasonal performance factor including the entire source pumping energy have been determined. The SPF_H in space heating mode reaches with 4.6 in the first and 4.9 in the second year of operation a high value, and also the SPF_{DHW} in DHW mode is high for the evaluated period with a value around 3.5 for both years of operation. This leads with a DHW fraction of about 30% and 70% space heating fraction to an overall SPF of 4.24 and 4.48, respectively. The increase of the SPF can be explained by the following reasons:

- A longer running time for the heat pump was implemented through a wider temperature range in the controller setting of the DHW storage
- The heat pump operation time throughout the working days was slightly switched from 00:00 to 05:00 in order to reduce the storage losses
- The operation time for the legionella protection (electrical heating element in the DHW storage) takes place directly after the DHW operation of the heat pump
- The temperature difference of the buffer storage has increased from ± 2 to ± 3 °C
- The minimal operation time for the space heating has increased from 30 to 60 min

Another factor for the high SPF in the monitored period is the source temperature for the heat pump, which allows the heat pump to operate at low temperature lifts and thereby high performance level. Fig. 5 right shows the return flow temperature of the boreholes (2 min before stopping the circulation pump). The source temperatures are constantly high. Especially in the late summer months the heat pump source temperatures reaches high values of 12-16 °C. An explanation for the high source temperatures is the ground-coupled free-cooling operation which takes place in the summer month and regenerates the borehole field.

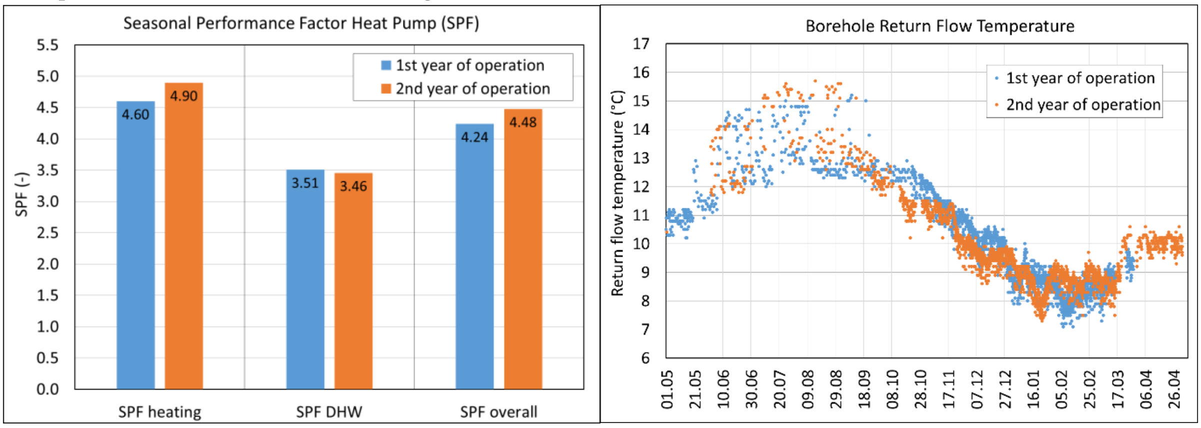


Fig. 5. Seasonal performance factor of the heat pump for DHW and space heating mode and overall (left) and heat pump source temperature for both years of operation (right)

3.4. Free-cooling

During the summer months the office spaces in the basement are cooled with a ground-coupled free-cooling. In cooling operation, the system efficiency can be described as the ratio of the heat removed from the building and the electricity consumed by the borehole- and the floor-heating circuit auxiliary pumps. The system performance factor for cooling operation (SPF_C) reaches in the monitored summer months a value of 17, which is comparable with other cooling systems, which reached values in the range of 10 to 30. A positive side effect of the ground-coupled cooling mode is the regeneration effect of the boreholes. Fig. 5 shows the return flow temperature of the boreholes for both years (2 min before stopping the circulation pump). The higher source temperatures of the heat pump leads to an increase of 5% for the SPF_{DHW}. The minimum temperature of the borehole return flow never falls below 7 °C, which is also a reason for the high overall SPF of the heat pump described in chapter 3.3.

3.5. Heat tape and legionella protection

The two additional DHW heating systems – heat tape for DHW comfort and direct electric heating element for legionella protection in the DHW storage – are responsible for 38% of the entire energy consumption in the first year of operation according to the MINERGIE-A® label. Through stepwise improvements, the electricity consumption could be reduced by 60%, which leads to reduction of 4,450 kWh each year, as shown in Fig. 6. Effectively, this means a decrease of the MINERGIE-A® index of about -6.4 kWh/(m^2·a) for the second year of operation. The improvement steps, indicated in Fig. 7, are the following:

1. Permanent operation of the heat tape leads to a temperature in the DHW pipes of 55 °C and a high energy consumption
2. By amendment of a control system, the DHW pipe temperature is reduced from 55 °C to 40 °C
3. The heat tape operation time has been restricted to times with low DHW needs (during high DHW needs, no additional pipe heating is provided to meet the comfort requirements).
   Heat tape operation is restricted to 22:00 – 06:00 and 10:00 – 20:00
4. By simulations the operating time of the heat tape the consumption is investigated and afterwards adapted to the user behaviour. Subsequently, the heat tape operation was reduced to 00:00 – 06:00 and 14:00 – 20:00
5. The operating time of the legionella protection was adapted. Before the adaption, the legionella protection was conducted two times a week on following days. After improvement, the legionella protection is operated just once a week and directly after the preheating of the heat pump.

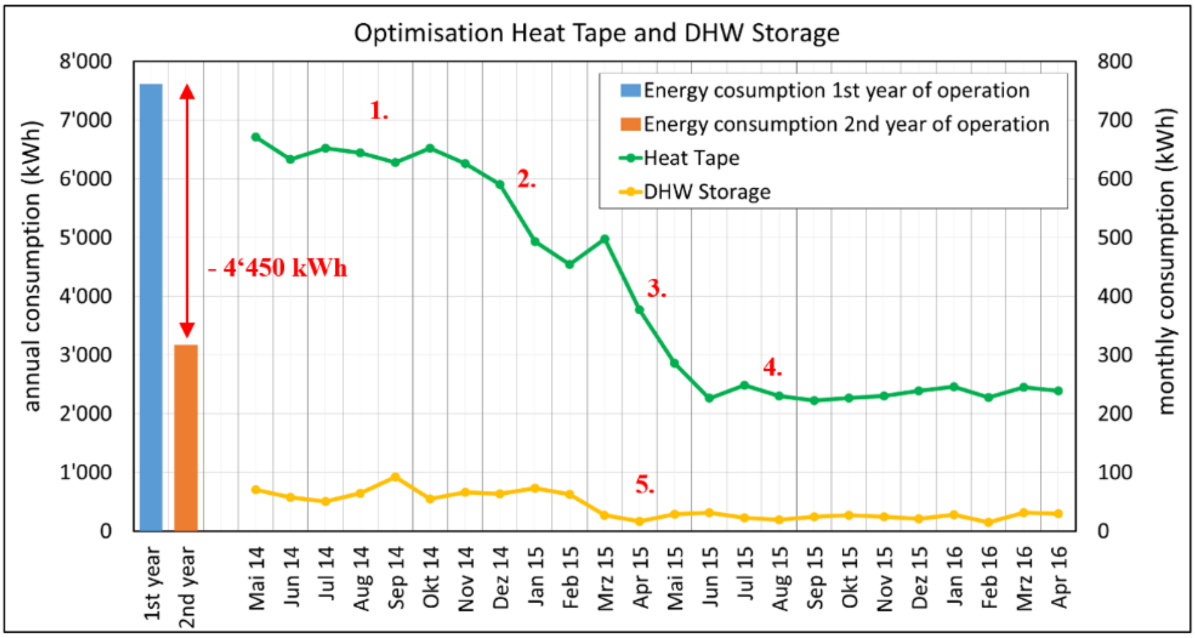


Fig. 6. Optimisation of the heat tape for DHW comfort and the electric heating element for legionella protection

3.6. PV/T-collector

The performance of the PV/T-collectors is in both years similar with a production of 900 kWh_{el} and 1,300-1,400 kWh_{th}. After deducting the energy need for the solar cycle pump of about 100 kWh, a yield of 280 kWh/m^2_{col} is gained.

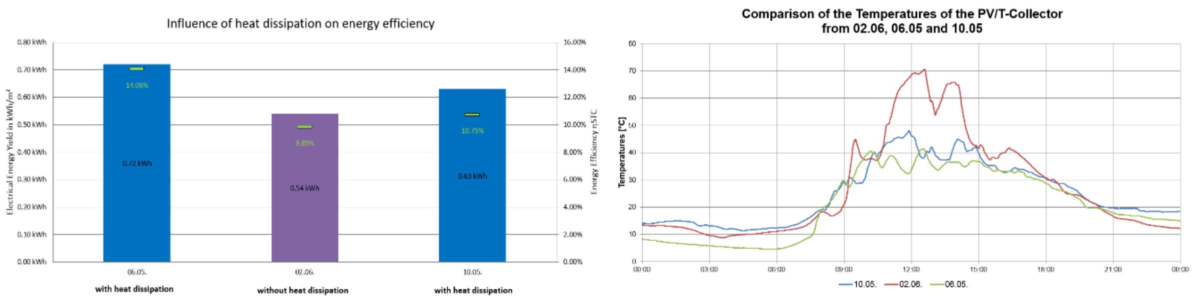


Fig. 7. Effect of higher efficiency due to lower collector temperature

In both years of operation the collector performance factor, which is calculated by the annual yield divided by the solar irradiation, is in the range of 0.27. Based on the monitoring of the PV/T-collectors, the effect of higher efficiency due to lower collector temperatures could be approved, as shown in Fig. 8. For the duration of a day (June 2) the solar cycle pump was switched-off and compared with a day (May 6) when the solar cycle pump was running. Without heat removal, the electrical efficiency of the PV/T-collectors decreases from 14.06% to 9.85%. The right side of Fig. 8 indicates a 30 K higher collector temperature without the heat removal.

The overall seasonal performance factor SPF_{gen} includes the whole source systems, but also the heat and electricity produced by the solar PV/T-collectors and the heating element in the DHW storage. The electrical yield of the PV/T-collectors is subtracted from the electrical energy. Additionally, the heat tape can be included. Fig. 9 shows the SPF_{gen} for both years of operation with and without the heat tape included. Due to a measurement interruption, the results from April 2015 to July 2015 are missing. Without the heat tape a SPF_{gen} of 4.5 for the first and 4.8 for the second year was measured. The SPF_{gen} is significantly less affected by the heat tape in the second year due to the implemented optimization.

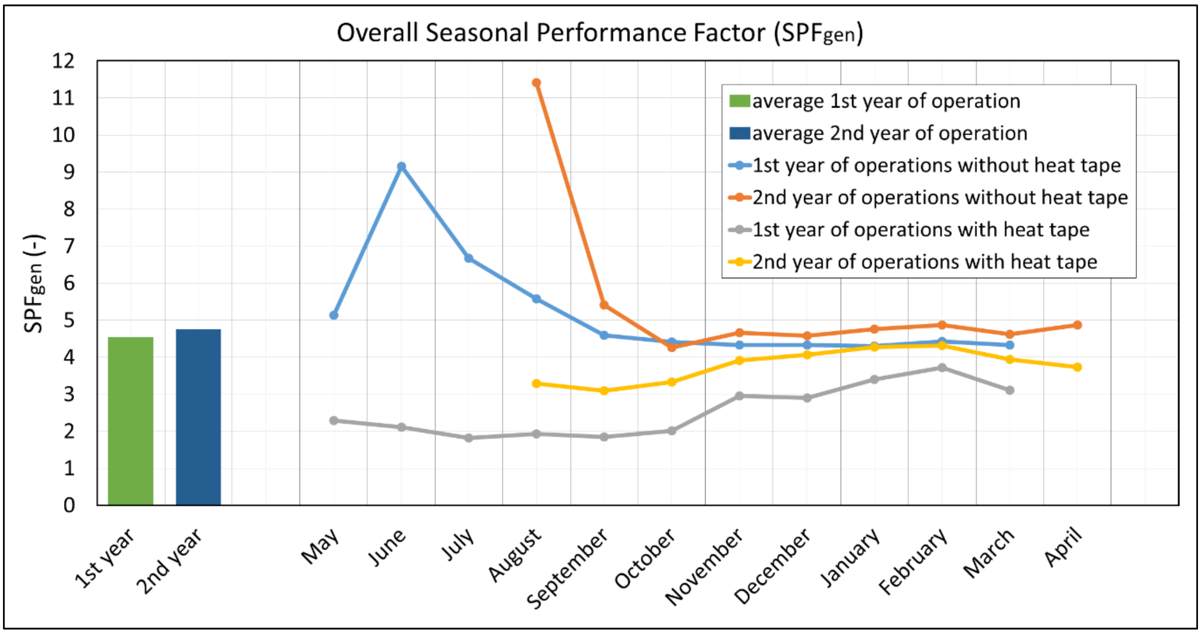


Fig. 8. Overall seasonal performance factor (SPF_{gen})

3.7. Indoor-environment

Temporary measurements of the indoor environment has been performed in the beginning of the measuring period in May 2014. Fig. 9 depicts the room temperature and the respective limits of comfortable room temperature according to the Swiss standard SIA 382/1 [5] and the CO_2-concentration in the offices. Due to good insulation levels and thereby high internal surface temperatures close to the room air temperature, the room air temperature is a good indicator and thereby significant to assess the global thermal comfort. All monitored temperatures are in the comfortable temperature range and to 90% in the range of 23-24 °C. The relative humidity was during the measuring period in about 80% of the time in the comfortable range of 45-50%. The CO_2-concentration in the office is an indicator for the indoor air quality.

The limit value of 1,350 ppm (middle air quality) was never exceeded and the value for high air quality of 950 ppm was achieved in most of the time during the measurements. The CO_2 concentration was in 95% of the time in the range of 400 to 900 ppm and in 55% between 400 to 500 ppm, which is comparable with outdoor air. During the summer time in 2015, also a survey was performed with the inhabitants regarding the indoor environment. A positive feedback was given by all inhabitants regarding the room temperature and the indoor air quality by mechanical ventilation.

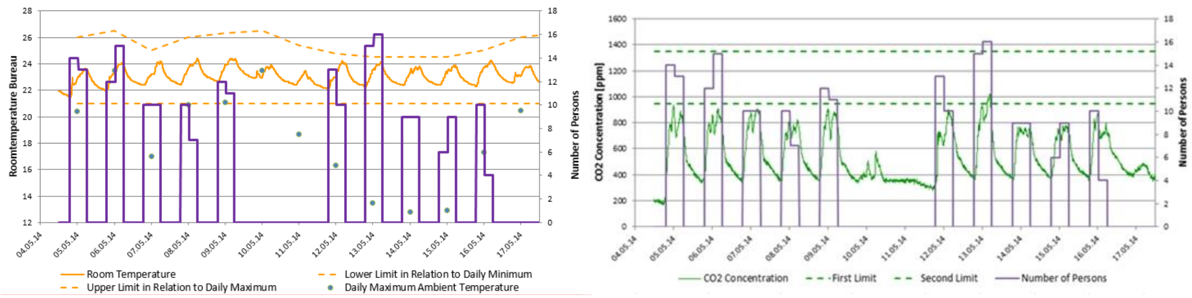


Fig. 9. Room air temperature and CO_2-concentration in the office in May 2014 with limits according to SIA 382/1

3.8. Self-consumption

Due to the growing number of nZEB equipped with solar PV systems the grid interaction gets more important. The on-site produced photovoltaic energy should have as minimal impact on the grid as possible and should work in line with grid needs. Therefore, as a metric for the grid interaction and demand response capability, the self-consumption of the office use has been evaluated. The metrics supply cover factor (SCF) and demand cover factor (DCF) for the measured period from May 2014 to April 2015 are given in Fig. 10 left on the basis of a balancing period of 5 min. The SCF describes how much of the PV yield in the balancing period is consumed on-site. The DCF describes how much of the total energy consumption can be covered by the on-site PV yield. The curves of the two metrics in Fig. 10 are opposite, since for instance in wintertime, the PV electricity production is low and the electricity consumption is high, so most of the PV electricity can be consumed on-site which leads to a high SCF, while the DCF is low, since the PV electricity can only cover a small part of the total energy consumption. Thus, the self-consumption in terms of the DCF decreases due to the lower PV-yield during wintertime. At the same time the SCF increases due to the increasing electricity consumption during wintertime.

The impact of the balancing time on the metrics is depicted in Fig. 10 right exemplary for the SCF. While it is easier to cover the entire demand with on-site production on annual basis, it gets harder with shorter balancing periods, since the compensation possibility is missing and a higher simultaneity is needed for high values. For a balancing period of 5 min the overall SCF is about 40% and the DCF about 30%, which is higher than for residential applications, where typical values are about 15-25%. The office hours have a positive effect for the SCF and DCF.

Also the electric car can have a positive effect to the DCF, when the charging time may be shifted time with high PV production, e.g. during midday. Compared to the heat pump, though, the electric car is with 2,000 kWh per year a rather small consumer during the measurement period.

The charging station has a power of 22 kW, which is in the range of the peak-power (24 kW_p) of the PV-generator and surpasses in combination with other consumers the produced PV-electricity on-site. The presently installed charging station charges the electric car with 100% power, until the electric car is charged to about 80%. Afterwards, the charging power is slowly reduced for the protection and life time of the accumulator.

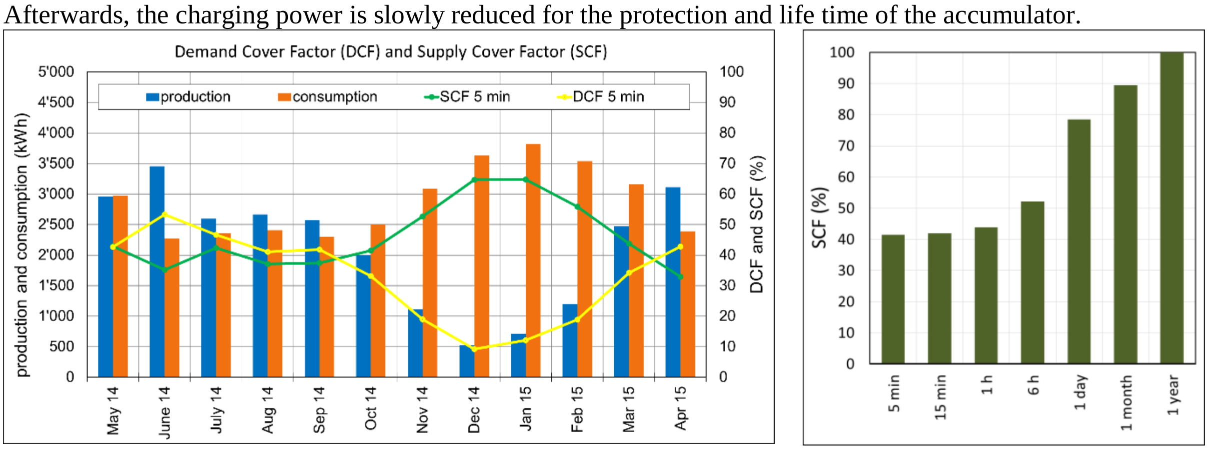


Fig. 10. Monthly on-site electricity production and consumption as well as SCF and DCF (left)
and dependency of the SCF on balancing period (right)

With an adapted charging power, simulations provide a 5% higher SCF and DCF. However, due to the high investment cost related to a rather small financial revenue, this option was not installed for the charging system.

4. Conclusion

As one of the first buildings in Switzerland an nZEB with mixed residential and office use according to the MINERGIE-A® label was monitored. The all electric building is equipped with a large solar PV-system and PV/T-collectors on the roof and a ground-source brine-to-water heat pump as core components of the building technologies. The monitoring has shown that PV/T-collectors and the ground-coupled free-cooling could be well integrated in the building technologies with appropriate planning. Monitoring results of the two years of operation confirm, that the nearly zero energy balance has been reached with a MINERGIE-A® index of -8.6 kWh/(m^2·a) in the first and -15.0 kWh/(m^2·a) in the second year of operation. Regarding these results, the solar PV-system is appears slightly oversized regarding MINERGIE-A® label. However, compared to residential use only, the combined office use leads to a high supply cover factor SCF of 40%. With further adaption of the heat pump running time and the electric car charging operation to the PV generation, also higher values are possible.

Monitoring results of the first year of operation have revealed various optimization potentials in the operation of the building technology, in particular regarding the heat tape and the heat pump standard operation settings. Therefore, the running time of the heat tape was significantly reduced without reducing the comfort of DHW use. Compared with small adjustments of the legionella protection in the DHW storage, the improvements reduce the energy consumption of the additional electric heating elements of about 4,500 kWh, which leads to cost savings of 700 CHF each year. By adjustments of the heat pump standard operation settings, in particular extending the running time, the SPF_H and the overall SPF could be improved from 4.60 to 4.90 and 4.24 to 4.48, respectively. However, a high performance of the ground-coupled heat pump has been achieved due to high source temperatures from the borehole and the low temperature design of the emission system, as well.

Especially during the summer months high source temperatures of about 12-16 °C are measured and therefore a higher performance of the heat pump for DHW operation of 5% was measured.

Based on the monitoring of the PV/T-collectors, the effect of the higher efficiency due to lower collector temperatures could be approved and the thermal and electrical energy production corresponds to the expectations. The preheating of the DHW with the PV/T-collectors from a thermal view is useful as long as the dimension is deliberately kept concise, what is given for the measured system with 1 m^2 collector area for each apartment. Currently, a major drawback of the PV/T-collectors are still the high investments costs with a payback time of more than 20 years and the competition of the system with the heat pump for DHW preheating. PV/T-collectors may get interesting, when they get more cost-effective and the low-temperature heat can be used advantageous, for example to regenerate a ground borehole heat exchanger field or for higher DHW demands. Due to the complexity of the system technology, the additional regeneration of the borehole exchanger field besides the DHW preheating was not considered. However, if the DHW is prepared by a heat pump, the preheating of DHW lead to decreasing performance values of the heat pump, since the heat pump tends to operate longer at higher DHW temperature levels.

From the gained experiences of the monitoring and measurement the following recommendations could be derived for the additional heating systems heat tape and direct electric heating element:

- Beside the heat tape other alternatives to comply with the DHW requirements according to SIA 385/1 should be taken into account during the planning phase
- An efficient operation of the heat tape requires a control, otherwise the heat tape will be activated 24 hours a day. Anyway, the manufacturer of the heat tape should be included in the planning process to ensure an efficient operation and a professional installation
- An adaption of the heat tape control to the user behaviour and the building requirements led to reduced energy use. The control setup should be frequently checked and if necessary be adapted
- In larger scale buildings the energy use of the additional heating systems should be tracked for optimization of the operation and to charge the costs to the tenants of the apartments.

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References

[1] Hässig, W., Wyss, S., Staubli, J. Bericht zum Messprojekt Büro-/Wohngebäude Neuwiesenstrasse 8, Uster Minergie-A® Standard und mit Hybrid-Kollektoren für die solare Warmwassererwärmung, Schlussbericht AWEL Zürich, hässig sustech gmbh, Uster, Oktober 2015

[2] SIA 385/1. Anlagen für Trinkwarmwasser in Gebäude – Grundlagen und Anforderungen, Schweizerischer Ingenieur- und Architektenverband, Zürich, 2011

[3] Hässig W. Publicschema Neuwiesenstrasse 8 in Uster, hässig sustech gmbh, Uster, 2013

[4] MINERGIE association. Reglement zur Nutzung des Produktes Minergie-A nach Norm SIA 380/1:2009, Bern, 2015

[5] SIA 382/1, Ventilation and air conditioning systems – general basics and requirements, Swiss society of engineers and architects, Zuerich, 2007