RENOVATION TOWARDS NZEB WITH PV

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Abstract

A typical residential building from 1937 located near Wuerzburg, Germany undergone deep energy renovation in 2013. A balanced ventilation system with integrated air-to-water heat pump was installed together with an 8 kW PV system (roof-integrated). The key performance indicators were measured over a period of seven years (2014-2020). Energy production, energy use, self-consumption and exported electricity to the grid were monitored. The results show variations in performance indicators. The self-consumption varied between 16.9% and 25% while the level of autarchy varies between 34.1% (2014) and 45.4% (2020). The robustness of the key performance indicators is discussed and recommendations for designers and planners as well as prosumers are given.

Keywords: Solar PV, heat pump, envelope renovation, ventilation

1. Introduction

Residential use of energy is responsible for 28% of EU energy consumption (EC 2012). The barriers to consumer-related energy saving have been known for more than 30 years but are still present, in particular split incentives (e.g. tenants vs. landlords), lack of information, high initial investment in energy-efficient measures and equipment and energy users behaviors (BPIE 2012). Likewise, while awareness of the existence of renewable energies has improved considerably in the last years, there is still a lack of understanding of how to use and optimize them in practice. As of 2021, all new buildings have to be Nearly-Zero Energy Buildings (NZEBs) as required by the EPBD (EPBD 2010). There are many approaches to this goal and several pilot buildings have been built and extensively measured. The theoretical approach in the NZEB concept is typically based on three pillars. The first one refers to energy saving measures to reduce the heating energy needs. The second pillar is focusing on using energy efficient equipment and appliances. The third pillar is represented by the consumption of renewable energy produced on-site (Satori et al. 2012; Voss and Musall 2011). All measures have been applied in this case study. A residential building from 1937 located near Wuerzburg in Germany was deep retrofitted in 2013 (Haase, 2016). Roof, façade and basement ceiling were highly insulated and thermal bridges were minimized. Existing windows were replaced with triple glazing and wood-aluminium framed windows. A balanced ventilation system with integrated air-to-water heat pump was installed together with an 8 kW PV system (roof-integrated). The ventilation ducts were integrated into the existing chimneys. The residential appliances (white goods) (refrigerator, washing machine, dishwasher) were installed or replaced by A+++ equipment. The cooking equipment was replaced by induction device. The existing lighting fittings were replaced with LED lighting products. The project received funding from the German Bank for Rebuilding (KfW) in the class kfW55 which uses 55% of the energy budget defined in the existing German building code EneV. (KfW 2014; EneV 2014). More ambitious levels (e.g. KfW40 or any type of zero energy buildings) did not exist for refurbishments, only for new constructions. However, there were additional funding schemes for heating systems and FIT for photovoltaics (PV) (EEG 2014). Today, the funding schemes as well as FIT are under revision (Bergner and Quaschning 2021).

A 7.95 kW roof-integrated PV system with a south-west orientation and 50°angle was installed. The PV system consists of 30 modules with 265 W each (see Figure 1).

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274.75 Wh 1.1.1	268 Wh 1.1.2	277.5 Wh 1.1.3	272.75 Wh 1.1.4	288 Wh 1.1.5	280.75 Wh 1.1.6	278 Wh 1.1.7	281.5 Wh 1.1.8	273.75 Wh 1.1.9	284.75 Wh 1.1.10
262.75 Wh 1.1.11	271.5 Wh 1.1.12	250 Wh 1.1.13	277 Wh 1.1.14	265 Wh 1.1.15	279 Wh 1.1.16	273.25 Wh 1.1.17	279.5 Wh 1.1.18	276.5 Wh 1.1.19	283 Wh 1.1.20
249 Wh 1.1.21	242.5 Wh 1.1.22	186.75 Wh 1.1.23						269.25 Wh 1.1.24	272 Wh 1.1.25
234 Wh 1.1.26	233.75 Wh 1.1.27	189.75 Wh 1.1.28						266.75 Wh 1.1.29	272.5 Wh 1.1.30

Fig. 1: PV system and layout. south-west orientation (top: photo of the south-west facade; bottom: module layout with monitoring figures for each module (average annual data))

The inverter controls each module separately, ensuring minimized shading effects from the roof obstruction ('Gaube'). The electricity produced by the PV system is primarily used to cover the energy needs of the household and the surplus is exported to the grid. The system was installed in October 2013, thus a rate of 0.1454 €/kWh was given by the local energy provider ('Stadtwerke') for buying (FIT). Although this approach of prosumer is widely used and there exist some experience with new constructions, there is still a lack of knowledge on the long-term performance of buildings based on prosumer models under real conditions. At least the energy produced, purchased from and sold to the grid provide additional performance parameters that define energy performance and related energy costs. Thus, data from seven years of measurements was collected and different performance indicators were calculated in order to analyze how robust these are in practice.

2. Methodology

The monitored key performance indicators (KPI) are:

- Electricity produced by PV
- Electricity exported to the grid
- Electricity purchased from the grid

The electricity exported to the grid is monitored (for obvious tariffs reasons). Based on these measurements measured from 2014 to 2021 energy production, energy use, energy costs, self-consumption and exported electricity to the grid which were monitored it was possible to calculate key performance indicators (KPIs): self-consumption [10], level of autarchy, load matching and grid integration. The following definitions were used:

- Self-consumption: $SC = E_{OC} / E_{PV}$ (eq. 1)
- Level of autarchy: $LA = E_{OC} / E_{total}$ (eq. 2)
- Load matching: $f_{load} = \frac{1}{N} \cdot \sum_{year} \min\left[1, \frac{g(t)}{l(t)}\right]$ (eq. 3)
- Grid interaction: $f_{grid} = STD\left(\frac{ne(t)}{max(|ne(t)|)}\right)$ (eq. 4)

where

E_{CO} is own consumption (household)

E_{PV} is the electricity produced by PV system

E_{total} is the total energy use of household

g(t) is the energy generation at each time step

l(t) is the energy load at each time step

N is the number of samples in the evaluation period

ne(t) is the net export at each time step

3. Results

The difference between the energy produced and the exported energy gives an indication of the renewable energy consumed by the household (self-consumption). When adding the self-consumed component of the PV electricity production, the household energy use was calculated. The monitored key performance indicators (KPI) are:

- Electricity produced by PV (as shown inf Figure 1-3)
- Electricity exported to the grid (shown in Figure 4)
- Electricity purchased from the grid (shown inf Figure 4)

In addition, the KPIs were calculated and are shown inf Figure 5 to 7.

3.1. Electricity produced by PV

Electricity production from PV was monitored. Figure 2 shows the electricity production of each module (P1.1.1 to P1.1.30 according to the layout shown in Fig. 1) for the 1. July 2020 as an example. It can be seen that some modules are producing more and some considerably less (e.g. P1.1.22 P1.1.23, P1.1.27 and P1.1.28). These are left from the obstruction and more shaded than the rest (on that day).

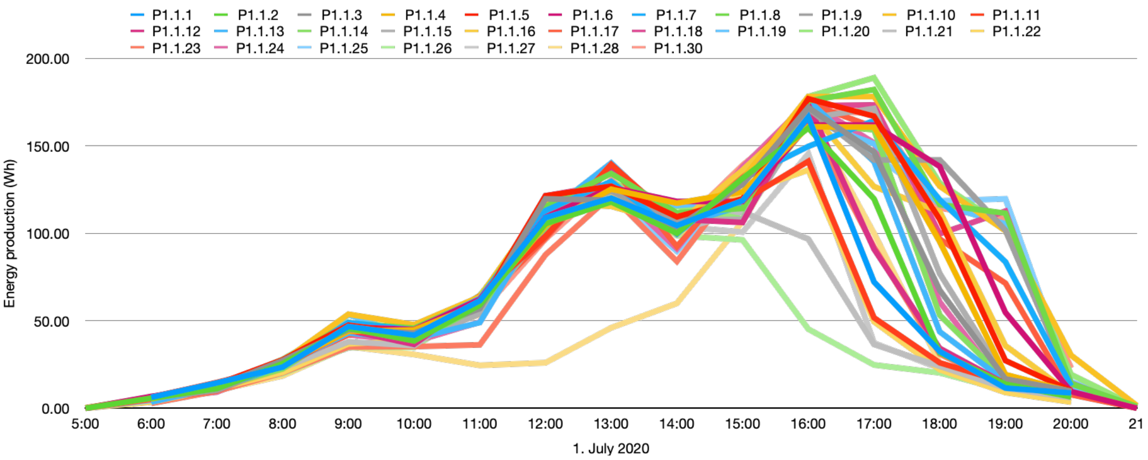

Fig. 2: Electricity produced by PV panels 1-30 on 1. July 2020 at inverter

Fig. 3 gives values of the electricity production of each module (P1.1.1 to P1.1.30 according to the layout shown in Fig. 1) for the 1. January 2020 as another example. Here, it can be seen that modules P1.1.22 P1.1.23, P1.1.27 and P1.1.28 produce considerably less than the rest. This is due to the shading from the obstruction is even more prominent during the winter months with its azimuth angles.

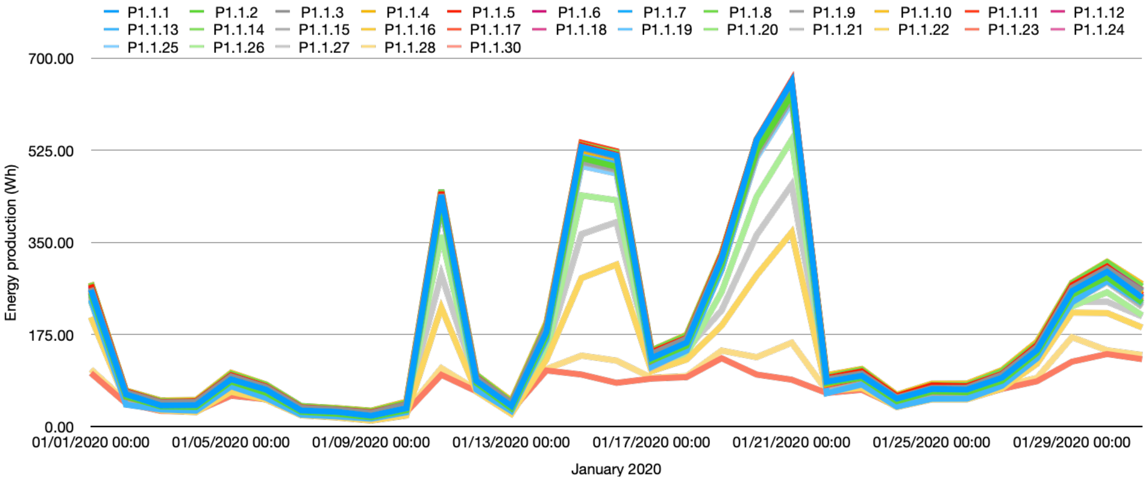

Fig. 3: Electricity produced by PV panels 1-30 on January 2020 at inverter

The electricity production values were monitored for the monitoring period and summarized in daily, weekly and monthly values.

Fig. 4 shows the monthly electricity production which varies over the year with maximum yields in summer months and minimal yields in winter months. The largest (median) values were monitored in July (851 kWh/month), followed by May (802 kWh/month). The lowest (median) values were monitored in December (82 kWh/month), followed by January (136 kWh/month). Figure 4 shows the predicted electricity production (sim_min and sim_max) form the planning phase. Sim_min was based on PVGIS, while sim_max was based on the simulation tool of the PV planner. Both value sets were estimated based on local weather data and not taking into consideration any shading effects of surrounding vegetation. It can be seen that the measurements mostly fall within the bandwidth (sim_min and sim_max) with some months higher (Jan 2017, March 2015, April 2015, April 2020; Sep 2020, Nov 2020, Oct 2018) and some moths with lower values (Jan 2015, Jan 2016, Jan 2018, Jan 2019, Jan 2019, Feb 2014, Feb 2016, Feb 2020, Mar 2018, Apr 207, May 2019, Jun 2014, Jun 2016, Jun 2020, Jul 2017, Aug 2014, Sep 2014, Sep 2017, Oct 2014, Oct 2015, Oct 2016, Nov 2014, Nov 2017, Dec 2014-2020).

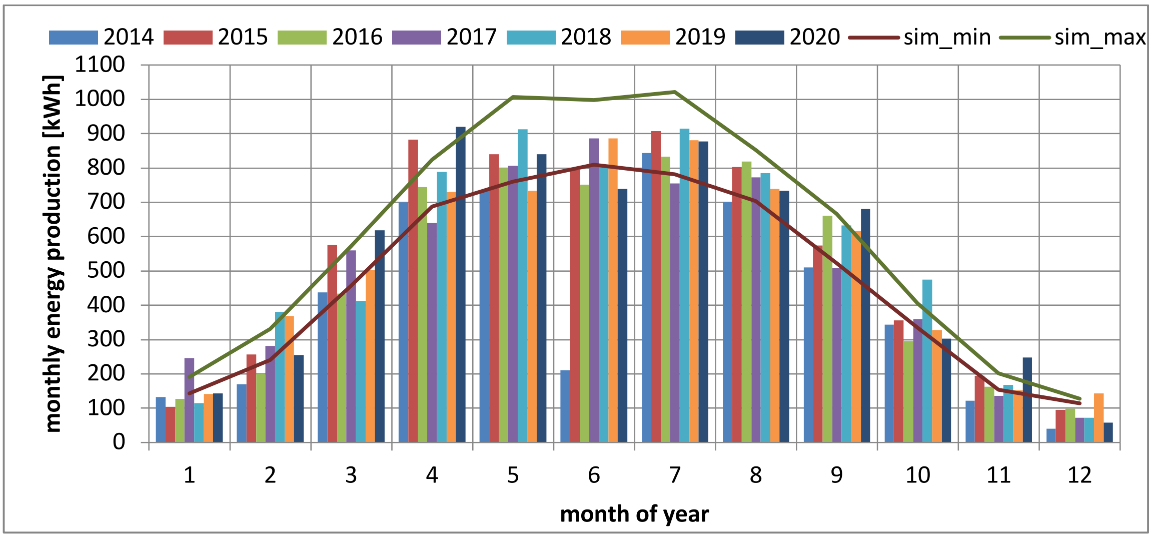

Fig. 4: Electricity produced at inverter for 2014 to 2020

3.3 Electricity purchased from and sold to the grid

Fig. 5 shows annual electricity purchased from and sold to the energy provider (grid). Electricity was purchased for the heat pump and the household (appliances and lighting). It can be seen that electricity purchased as well as electricity sold are varying over the seven years measurement period. The highest amount of electricity sold was in 2018 (5470 kWh) and the lowest amount in 2014 (4198 kWh). The highest amount of electricity purchased was in 2020 (7500 kWh) and the lowest amount in 2014 (5975 kWh).

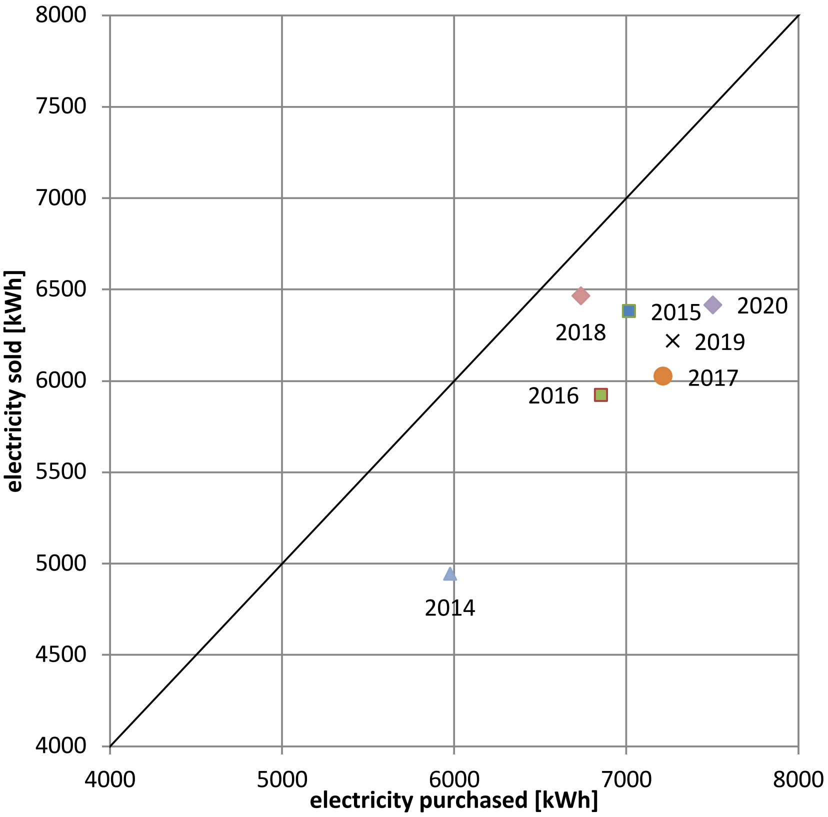

Fig. 5: Electricity sold and purchased, monitored for the period from 2014 to 2020

3.2. Key performance indicators

The purchased electricity was monitored separately for the heat pump and the household. The difference between electricity production from PV and electricity sold was calculated to self-consumption of household energy. Figure 6 illustrates the annual energy balance with electricity purchased (negative values) and electricity sold and self-consumed (positive values). While the balance between PV and household energy is always positive it becomes always negative if the electricity consumption of the heat pump is included. The average mismatch is -883 kWh for the period 2014 until 2020.

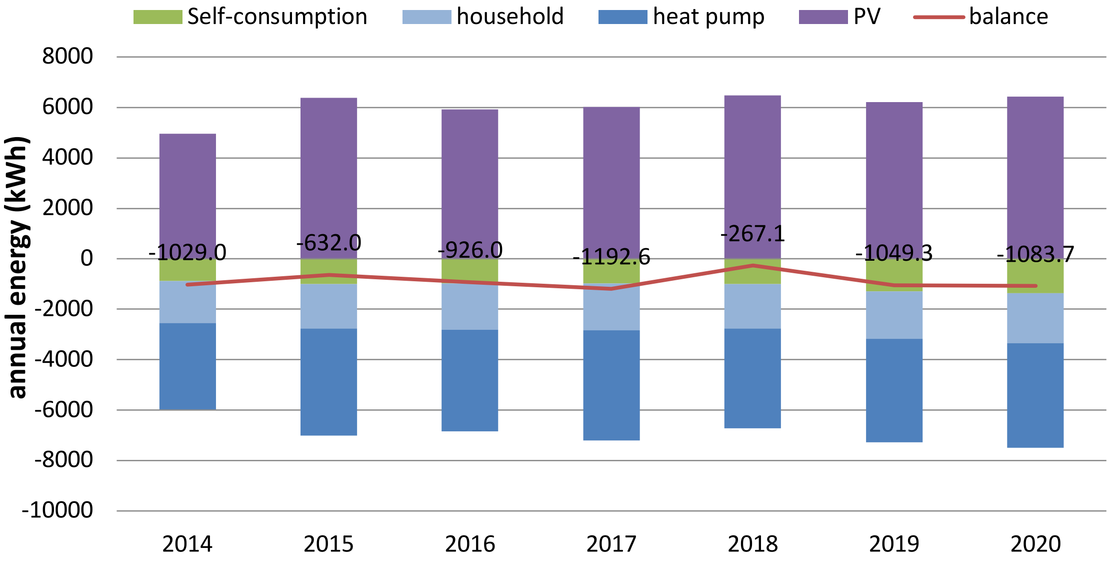

Fig. 6: PV (FIT), Self-consumption and electricity purchased (household and heat pump)

Table 1 shows the figures in specific values (divided by the area of heated floor space). It can be seen that self-consumption increases from 5.45 kWh/(m² a) in 2014 to 8.53 kWh/(m² a) in 2020. Household electricity use increased from 10.53 kWh/(m² a) (2014) to 12.31 kWh/(m² a) in the same period. This is due to an increase in appliances (an additional dryer was installed in 2015 and more communication equipment and computers were installed). PV production increased in the same period from 30.91 kWh/(m² a) (2014) to 40.11 kWh/(m² a) (2020). However, the lower electricity production from PV in 2014 is due to a failure of an inverter part which lead to a maintenance in June without electricity production. The electricity balance varies between 1.67 kWh/(m² a) in 2018 and 7.45 kWh/(m² a) in 2017.

Tab. 1: Specific electricity use (negative values) for self-consumption (household), household, heat pump, and production (positive values) from PV

(kWh/(m² a)	2014	2015	2016	2017	2018	2019	2020
Self-consumption	-5.45	-6.31	-6.15	-6.19	-6.24	-8.13	-8.53
household	-10.53	-11.04	-11.38	-11.55	-11.00	-11.74	-12.31
heat pump	-21.37	-26.49	-25.29	-27.36	-24.85	-25.56	-26.03
PV	30.91	39.89	37.03	37.64	40.42	38.87	40.11
balance	-6.43	-3.95	-5.79	-7.45	-1.67	-6.56	-6.77

The level of autarchy (LA) is shown in Fig. 7. LA was calculated with weekly values and for household energy (in blue) as well as theoretically values including the electricity used for the heat pump. It should be noted that these are not measured values as the heat pump is connected in a separate circuit and does not get electricity from the PV system. It was included here to illustrate the potential for connecting the heat pump and the PV. As shown, the level of autarchy (LA) varies over the year. Obviously, the LA is higher during summer months than during winter months. LA reaches 100% in 23 weeks of 2020 (week 9, 13, 14, 16, 17, 18, 19, 20, 22, 23, 24, 26, 27, 28, 29, 30, 31, 32, 34, 36, 37, 38, and 45). In three weeks, LA reaches 200% (week 17, 22, and 45). The largest LA is observed in week 45 (340%) which is due to a combination of high PV production and very low household energy use (due to absence).

During the winter months, in 21 weeks, LA is below 50% and below 20% in 12 weeks (week 3, 6, 10, 38, 42, 46, 48, 49, 50, 51, 52, and 53). This illustrates that the PV system can deliver only a small fraction of the household electricity use during these weeks. The figures for LA including the electricity use of the heat pump are much lower and do not show potential for an increase of LA by additional batteries.

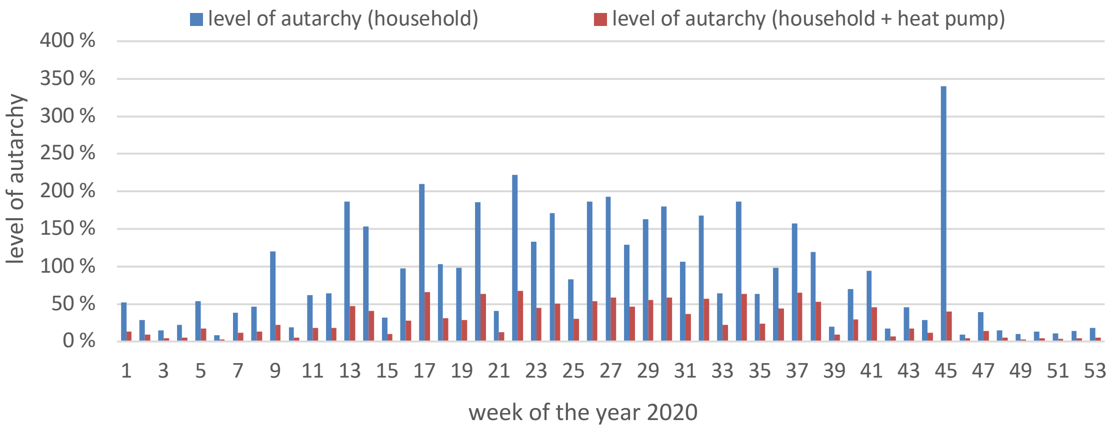

Fig. 7: Weekly level auf autarchy for 2020 (blue: household; red: household + heat pump)

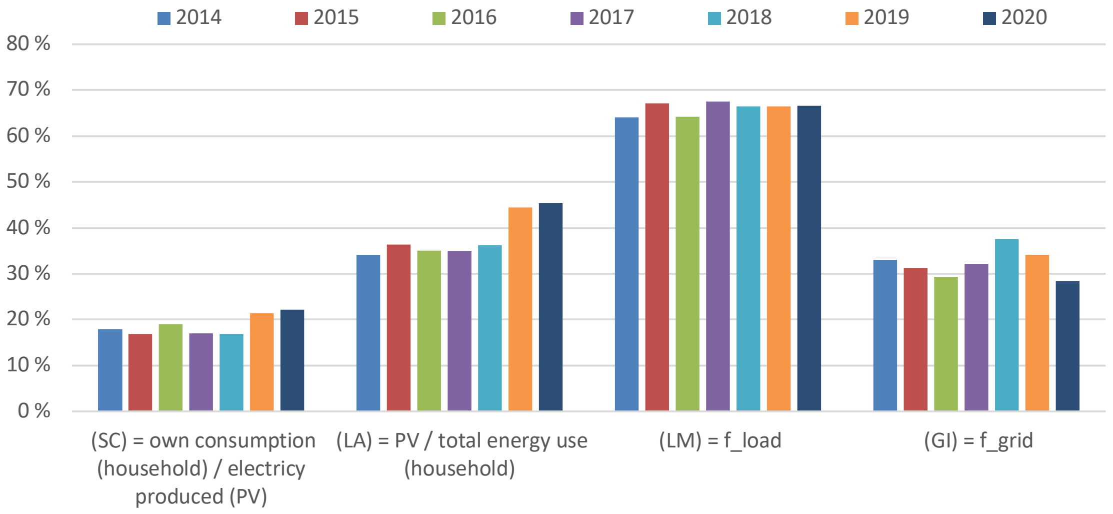

Fig. 8: Key performance indicators SC, LA, LM and GI (eq. 1 – 4)

The other key performance indicators are shown in Fig. 8. Annual self-consumption (SC) varies between 16.9% (2015) and 22% (2020). The level of autarchy (LA) varies between 34.1% (2014) and 45.4% (2020). Load matching (LM) varies between 64.1% (2014) and 67.5% (2017). Grid interaction (GI) varies between 28.4% (2020) and 37.1% (2019).

4. Conclusions

An energy renovated building was equipped with BIPV on the roof. Energy use was monitored over a period of seven years. The first step of the renovation process was successful as purchased energy was reduced to extremely low levels (6937 kWh on average for the period from 2014 to 2020). In addition, PV produced is on average 6055 kWh in the monitoring period. The electricity balance varies between 1.67 kWh/(m^2 a) (2018) and 7.45 kWh/(m^2 a) (2017). Electricity purchased from and sold to the grid are important measurements that provide robust information about the performance of the building. However, electricity use in the building is thus derived from electricity produced by the PV and the electricity self-consumed in the building. This is a standard prosumer model which will become more and more common. The PV system exporting energy into the grid and delivering electricity to the household can be used to introduce new performance indicators of grid interaction, level of autarchy, self-consumption and load matching. Energy storage based on batteries will in these cases have only a limited effect on LA, as the total electricity produced is not sufficient to cover the household electricity. These new key performance indicators are varying over the monitored period of seven years. This provides valuable information to designers and planners of prosumer models. However, they provide relatively robust indicators of the system. Energy balance can vary over time due to variations in household and heat pump electricity use and variations in electricity production from PV. These should be considered when planning a prosumer model, e.g. by sensitivity analysis of the influencing parameters.

The next step will be to analyze the performance of the systems. This includes the performance of the PV system, the heat pump system, the appliances, and lighting.

Another step must include the detailed study of the weather data. Variations in cloud cover and thus solar radiation influences of course the performance of the PV system and the PV modules.

It will also be interesting to analyze associated costs to the building. Electricity tariffs vary for household, heat pump and PV (feed-in tariff). Thus, the economic performance of a prosumer will be interesting to evaluate.

5. Acknowledgments

This work has been conducted within the strategic project DECARB of ZHAW which is highly acknowledged.

6. References

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Appendix: Units and Symbols

This section provides guidance on the use of units and symbols in your paper. Please follow these guidelines.

1. Units

The use of S.I. (Système International d'unités) in papers is mandatory. The following is a discussion of the various S.I. units relevant to solar energy applications.

Energy
The S.I. unit is the joule (J ≡ kg m^2 s^{-2}). The calorie and derivatives, such as the langley (cal cm^{-2}), are not acceptable. No distinction is made between different forms of energy in the S.I. system so that mechanical, electrical and heat energy are all measured in joules. Because the watt-hour is used in many countries for commercial metering of electrical energy, its use is tolerated here as well.

Power
The S.I. unit is the watt (W ≡ kg m^2 s^{-3} ≡ J s^{-1}). The watt will be used to measure power or energy rate for all forms of energy and should be used wherever instantaneous values of energy flow rate are involved. Thus, energy flux density will be expressed as W m^{-2} and heat transfer coefficient as W m^{-2} K^{-1}. Energy rate should not be expressed as J h^{-1}.
When power is integrated for a time period, the result is energy that should be expressed in joules, e.g. an energy rate of 1.2 kW would produce 1.2 kW x 3600 s = 4.3 MJ if maintained for 1 h. It is preferable to say that

Hourly energy = 4.3 MJ

rather than

Energy=4.3 MJ h^{-1}.

Force
The S.I. unit is the Newton (N ≡ kg m s^{-2}). The kilogram weight is not acceptable.

Pressure
The S.I. unit is the Pascal (Pa ≡ N m^{-2} ≡ k^2 m^{-1} s^{-2}). The unit kg cm^{-2} should not be used. It is sometimes practical to use 10^5 Pa = 1 bar = 0.1 MPa. The atmosphere (1 atm = 101.325 kPa) and the bar, if used, should be in parenthesis, after the unit has been first expressed in Pascals. e.g. 1.23 x 10^6 Pa (12.3 atm). Manometric pressures in meters or millimeters are acceptable if one is reporting raw experimental results. Otherwise they should be convened to Pa.

Velocity
Velocity is measured in m s^{-1}. Popular units such as km h^{-1} may be in parentheses afterward.

Volume
Volumes are measured in m^3 or litres (1 litre = 10^{-3} m^3). Abbreviations should not be used for the litre.

2. Flow

In S.I. units, flow should be expressed in kg s^{-1}, m^3 s^{-1}, litre s^{-1}. If non-standard units such as litre min^{-1} or kg h^{-1} must be used, they should be in parentheses afterward.

Temperature
The S.I. unit is the degree Kelvin (K). However, it is also permissible to express temperatures in the degree Celsius (°C). Temperature differences are best expressed in Kelvin (K).
When compound units involving temperature are used, they should be expressed in terms of Kelvin, e.g. specific heat J kg^{-1} K^{-1}.

3. Nomenclature and Symbols

Tables 1-5 list recommended symbols for physical quantities. Obviously, historical usage is of considerable importance in the choice of names and symbols and attempts have been made to reflect this fact in the tables. But conflicts do arise between lists that are derived from different disciplines. Generally, a firm recommendation has been made for each quantity, except for radiation where two options are given in Table 5.
In the recommendations for *material properties* (see Table 1), the emission, absorption, reflection, and transmission of radiation by materials have been described in terms of quantities with suffixes 'ance' rather than 'ivity', which is also sometimes used, depending on the discipline. It is recommended that the suffix 'ance' be used for the following four quantities:

$$\text{emittance}\,\varepsilon = \frac{E}{E_b}\left(or\,\frac{M_s}{M_{sb}} \right)$$

$$\text{absorptance}\,\alpha = \frac{\Phi}{\Phi_i}$$

$$\text{reflectance}\,\rho = \frac{\Phi}{\Phi_i}$$

$$\text{transmittance}\,\tau = \frac{\Phi}{\Phi_i}$$

where E and ϕ is the radiant flux density that is involved in the particular process. The double use of α for both absorptance and thermal diffusivity is usual, as is the double use of ρ for both reflectance and density. Neither double use should give much concern in practice.

Table 1: Recommended symbols for materials properties

Quantity	Symbol	Unit
Specific heat	c	J kg^{-1} K^{-1}
Thermal conductivity	k	W m^{-1} K^{-1}
Extinction coefficient^{+}	K	m^{-1}
Index of refraction	n	
Absorptance	α	
Thermal diffusivity	α	m^{2} s^{-1}
Specific heat ratio	γ	
Emittance	ε	
Reflectance	ρ	
Density	ρ	kg m^{-3}
Transmittance	τ	

$^{+}$ In meteorology, the *extinction coefficient* is the product of K and the path length and is thus dimensionless.

Table 2: Recommended symbols and sign convention for sun and related angles

Quantity	Symbol	Range and sign convention
Altitude	α	0 to ± 90°
Surface tilt	β	0 to ± 90°; toward the equator is +ive
Azimuth (of surface)	γ	0 to 360°; clockwise from North is +ive
Declination	δ	0 to ± 23.45°
Incidence (on surface)	Θ, i	0 to + 90°
Zenith angle	Θ_z	0 to + 90°
Latitude	Φ	0 to ± 90°; North is +ive
Hour angle	ω	-180° to +180°; solar noon is 0°, afternoon is +ive
Reflection (from surface)	r	0 to + 90°

Table 3: Recommended symbols for miscellaneous quantities

Quantity	Symbol	Unit
Area	A	m^{2}
Heat transfer coefficient	h	W m^{-2} K^{-1}
System mass	m	kg
Air mass (or air mass factor)	M	
Mass flow rate	$\dot{m}$	kg s^{-1}
Heat	Q	J
Heat flow rate	$\dot{Q}$	W
Heat flux	q	W m^{-2}
Temperature	T	K
Overall heat transfer coefficient	U	W m^{-2} K^{-1}
Efficiency	η	
Wavelength	λ	m
Frequency	ν	s^{-1}
Stefan-Boltzmann constant	σ	W m^{-2} K^{-4}
Time	t, τ, Θ	s

Table 4: Recommended subscripts

Quantity	Symbol
Ambient	a
Black-body	b
Beam (direct)	b
Diffuse (scattered)	d
Horizontal	h
Incident	i
Normal	n
Outside atmosphere	o
Reflected	r
Solar	s
Solar constant	sc
Sunrise (sunset)	sr, (ss)
Total of global	t
Thermal	t, th
Useful	u
Spectral	λ

Table 5: Recommended symbols for radiation quantities

	Preferred name	Symbol	Unit
a)	Nonsolar radiation		
	Radiant energy	Q	J
	Radiant flux	Φ	W
	Radiant flux density	Φ	W m^{-2}
	Irradiance	E, H	W m^{-2}
	Radiosity or Radiant exitance	M, J	W m^{-2}
	Radiant emissive power (radiant self-exitance)	Ms, E	W m^{-2}
	Radiant intensity (radiance)	L	W m^{-2} sr^{-1}
	Irradiation or radiant exposure	H	J m^{-2}
b)	Solar radiation		
	Global irradiance or solar flux density	G	W m^{-2}
	Beam irradiance	G_b	W m^{-2}
	Diffuse irradiance	G_d	W m^{-2}
	Global irradiation	H	J m^{-2}
	Beam irradiation	H_b	J m^{-2}
	Diffuse irradiation	H_d	J m^{-2}
c)	Atmospheric radiation		
	Irradiation	$\Phi\downarrow$	W m^{-2}
	Radiosity	$\Phi\uparrow$	W m^{-2}
	Exchange	Φ_N	W m^{-2}