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Smart Building as Power Plant – EnergyPLUS House with Energy Charge Management

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Summary

The energyPLUS building is a role model example of integral planning and allows researching future orientated technology- and energy strategies today. It demonstrates an integral solution of appealing architecture, energy efficiency and optimal usage of solar power through photovoltaic. The goal is to achieve an intelligent power load management with an intrinsic power-usage share of 50% for the building's internal power consumers. To achieve this goal several measures were realized. By a backup-system of two batteries, the small-scale appliances get supplied in times at which the PV-System provides no power. Further surplus is fed into the public grid and drawn from it at times when the energy demand exceeds the PV energy yield. The plus-energy building is one answer to the challenge of increasing the share of renewable energies in the future energy supply.

key-words: EnergyPLUS, PV-self-supply, energy storage, smart grid, sustainable architecture and design

1. Introduction

The goal of this project was to create a building that would meet the future demands on energy-efficiency and living comfort as well as eco-friendly mobility. It combines these energetic goals with an ambitious architecture. In the future it will be not only important to reduce the heating energy demand but to have an integral overview on the entire electricity demand and the utilization of energy for private mobility. Important parts of this concept are the interfaces between building and building power grid (smart metering).

Previous research projects and demonstration building relate to the planning and execution of "Net zero energy buildings" or "Nearly zero energy buildings". With the demonstration building Berghalde, for the first time it will be shown that energy plus buildings – so called "small power plants" - can be implemented easily and operated successfully. The building is designed according to the German EnEV standard and is equipped with equivalent building services. The house neither is a passive house nor a self-sufficient house. Berghalde is integrated in the EffizienzhausPlus network from the BBSR and serves as reference project for the other buildings. Apart from the development of concepts for climate neutral buildings, the network promotes the possibility to combine highly energy-efficient buildings with electric mobility. With the results of the project, the energy management of modern buildings should be improved and the required components for an energy efficient building envelope and the use of renewable energy will be developed further.

The applied definition and calculation method for the energy-plus standard is based on the specification and the definition of the BMVBS [2]. For the calculation of the energy-plus standard, either the building or the plot is defined as a balance limit. The balance includes all energy needed for conditioning and operating the building as well as the equipment. It includes the demand for heating and cooling, ventilation, lighting, auxiliary energy sources as well as household appliances and the e-mobility. The energy consumption is compared to the renewable energy production on an annual balance. The difference (consumption minus production) must be less than zero on both levels, final energy and primary energy. Besides the definition of the BMVBS two more criteria were defined, namely that more than 30% of the annual generated PV electricity must be used in the building, and that more than 30% of total annual electricity consumption must

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be met by the PV production (see chapter 3).

2. Method and energy concept

The existing net-plus-building is one of the first buildings of this kind in Germany and demonstrates an integral solution of appealing architecture, high energy efficiency and optimal usage of solar power through photovoltaic. The “only-electricity-building” has an annual demand of approx. 9,500 kWh for space heating, domestic hot water, white goods and user equipment. The PV-system delivers approx. 14,500 kWh/a.

Due to the active solar energy use the annual regenerative energy output is higher than the whole power demand. This was only achievable through the high energy efficiency of the building, which is based on its orientation, the shape of the building, high quality air-tight building envelope with low heat transfer coefficients (Table 1) and the innovative building technology.

Tab. 1: Overview of the heat transfer coefficient of building envelope

	U-Value [W/m²K]
Exterior wall	0,15
Roof	0,12
Base plate	0,3
Glazing	0,9
n50	0,6 1/h

The single family house near Stuttgart has been completed at the end of 2010. The building’s floor area is approx. 260 m². The northern part of the basement is embedded into the hill slope, while the southern part opens up to the valley with a large window front (Figure 1). Due to the slope, all living spaces are oriented to the south. The children's and guest rooms are located in the ground floor with a room-high window front. On the 1st floor is the large contiguous kitchen, dining and living area. A structural sun protection for the ground floor is given by the cantilever of the top floor. The secondary rooms, such as bathrooms, utility room and building equipment are located on the north side.

Fig. 1: South side with cantilever as structural sun protection (left), north-west side (right)

On site neither natural gas nor district heating are available, electricity is selected as energy source. The use of renewable energies is carried out by a roof-integrated photovoltaic system (15 kWp, 120 m², polycrystalline photovoltaic). Additional connection to the public power grid ensures a safe energy supply. Heating energy is generated by the heat pump, which is coupled with three borehole heat exchanger (each with 100 m depth). It is possible to ventilate the entire building by natural ventilation opening the windows. Additionally, to reduce the ventilation heat losses during the wintertime, a controlled mechanical ventilation system with heat recovery is available. An earth-air heat exchanger preconditions the outdoor air. In winter, the outside air is preheated. Beyond heating season, the mechanical ventilation is turned off and the use of natural ventilation has priority. During times with extreme high ambient temperatures the earth-air heat exchanger in conjunction with the mechanical ventilation can be used for cooling and to avoid overheating. (Figure 2)

The electricity from the PV system is fed into two batteries with a capacity of 7 and 20 kWh. The implementation of the batteries increased the share of intrinsic power-usage in comparison to electricity fed into the grid.

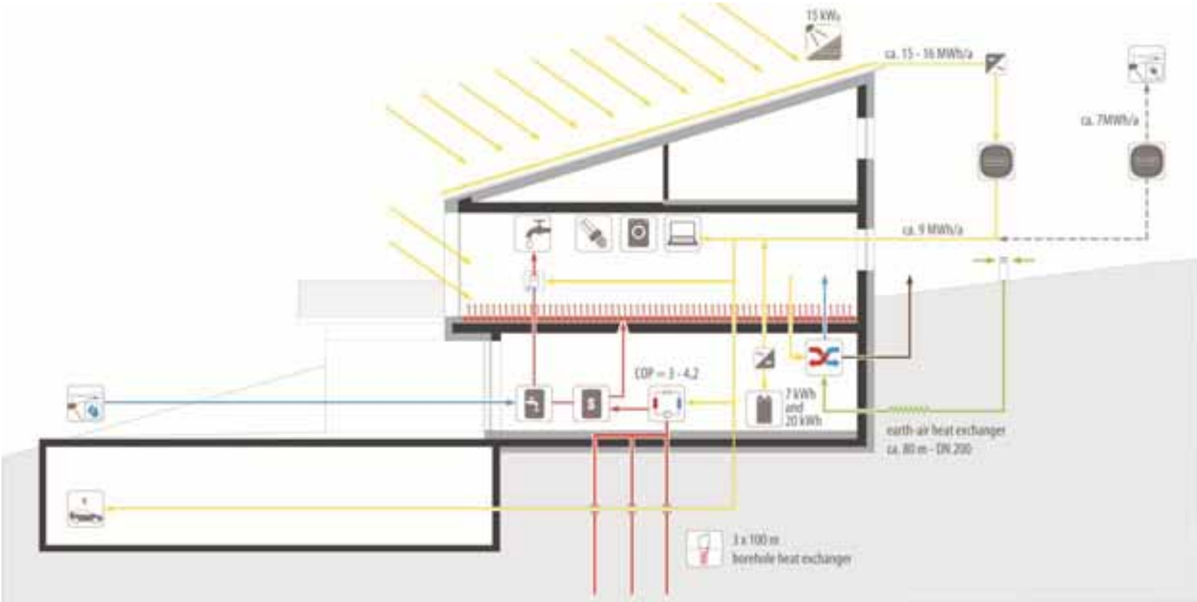

Fig. 2: Energy concept

Detailed monitoring enables the supervision of particular systems, the overall performance of the building and the validation as well as optimization of the target values.

Furthermore the significant loads of heat and electricity, temperatures, humidity levels and local weather data are collected.

3. Results

Based on the intense and broad-based measurement and monitoring concept, results for plant and building performance and energy balances are now available for three full years (2011 to 2013). The primary goals of achieving net-plus energy standard and high user satisfaction have been achieved.

In the first two years of operation (2011/2012) the energy balance already surpassed expectations. In comparison to the calculated annual PV energy yield of 14,500 kWh/a, 16,000 kWh/a were collected per year, which is about 12% more than predicted (Figure 4). This numbers correspond to a specific annual yield of 1,085 kWh/kWp (forecast: 967 kWh/kW$_p$). Compared to DIN 4108-6, the annual global radiation (horizontal) is specified by 1,074 kWh/m² for the city of Stuttgart. The PV energy yield within the first year of operation was approximately 80% higher than the annual electricity consumption. For each year more than approx. 4,000 kWh/a (2011: 2,857 kWh/a; 2012: 5,262 kWh/a; 2013: 4,113kWh/a) was used directly in the building and consequently less than approx. 11,300 kWh/a (2011: 13,417kWh/a; 2012: 10,661 kWh/a; 2013: 9,781kWh/a) was fed into the grid. Approximately 38% of the electrical energy consumption was covered directly by the PV system. The direct usage reached 18% in the first year of operation and increased to 33% and 30% in the following years considering the total PV yield. The balance shows a surplus of about 7,250 kWh/a in 2011, which would be sufficient to cover the electrical demand of a building hosting five to six persons (Figure 3).

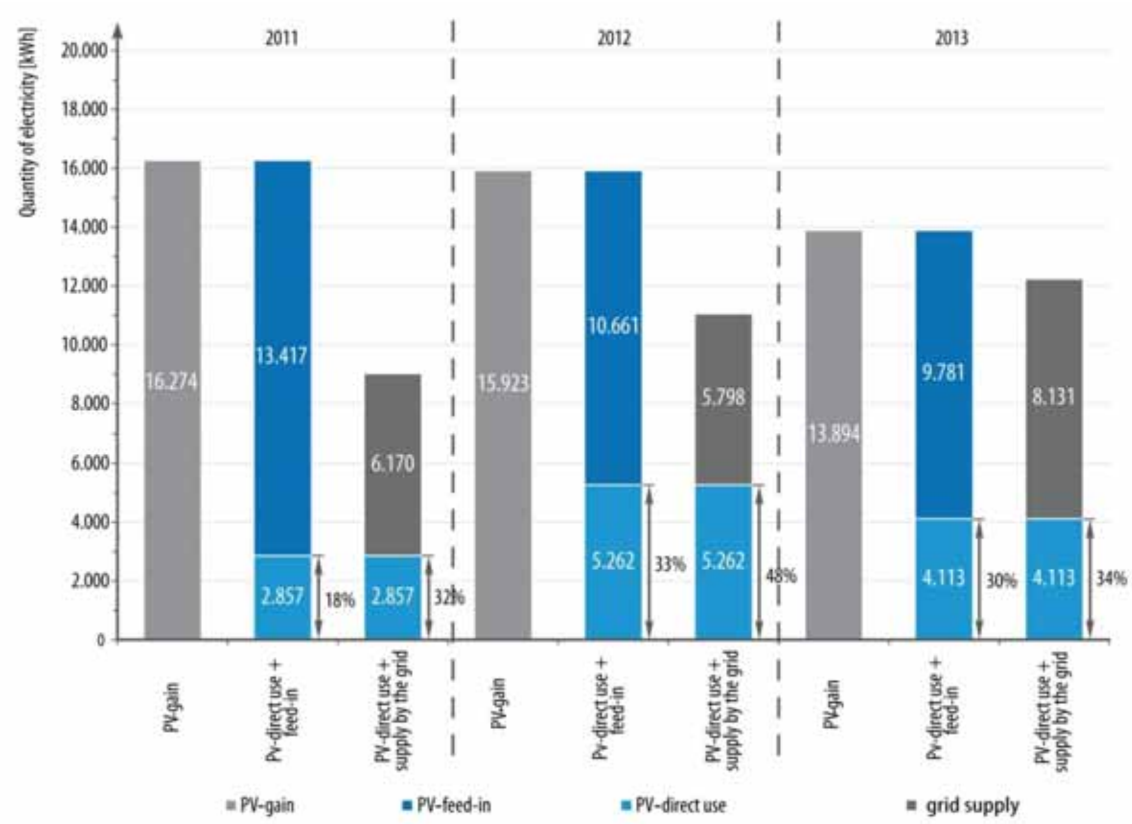

Fig. 3: Annual balance of total electricity of house (2011 - 2013)

Figure 4 shows the shares of heat supply and heat consumption in the building, broken down to heat source, heat distribution (buffer storage/distribution) and heat transfer (heating and domestic hot water). The total heating consumption was amounted to 11,202 kWh/a in 2011 and up to 17,073 kWh/a in 2013. The corresponding specific heating energy consumption was 43.1 kWh/m^{2}a, respectively up to 65.7 kWh/m^{2}a. In 2011, 75% of the heat demand was covered by the heat pump and to 25% by solar thermal collectors. In 2012 the solar collectors were taken down and the thermal energy was covered only by the heat pump. The fraction of heat used for domestic hot water is approx. 10% (1,089 kWh/a in 2011, 8% - 1,024 kWh/a in 2012 and 7% - 1,096 kWh/a in 2013) of total consumed heat energy; whereas approx. 80% were used for heating (78% - 8,753 kWh/a in 2011; 80% - 11,167 kWh/a in 2012 and 81% - 13,834 kWh/a in 2013). This corresponds to specific values of 4.2 kWh/m^{2}a for domestic hot water and 43.0 kWh/m^{2}a for heating. The energy heat losses caused by storage and distribution amounted to around 12% for each of the three years of operation.

According to EnEV 2007, a net energy demand of 40.5 kWh/m^{2}a (referred to floor space area of 423 m^2) was determined, with respect to the floor area (260 m^2) there is a specific value for net energy demand of 65.9 kWh/m^{2}a. The net energy consumption goes below this value during the three years of operation.

The power consumption of the heat pump for space heating and domestic hot water represents approx. 1/3 of the total electricity consumption. The small scale electric consumers have similar fractions of demand.

Space heating, domestic hot water, ventilation and lighting represent 44% of the total power consumption in all three monitoring years. Electricity consumption for lighting and mechanical ventilation accounts around 9%. The high power consumption for the control technology (11%) comes along with the extensive research equipment and is not representative for a residential buildings. 820 - 1,480 kWh/a were consumed for e-mobility. The category "Other" includes all small scale consumers, "standby consumption" (e.g. vacuum cleaner, coffee machine, computer, printer, etc.) as well as outdoor lighting. It should be noted that the storage losses and the standby operation of the inverter to charge the batteries accounts around 7% of power consumption. (Figure 5)

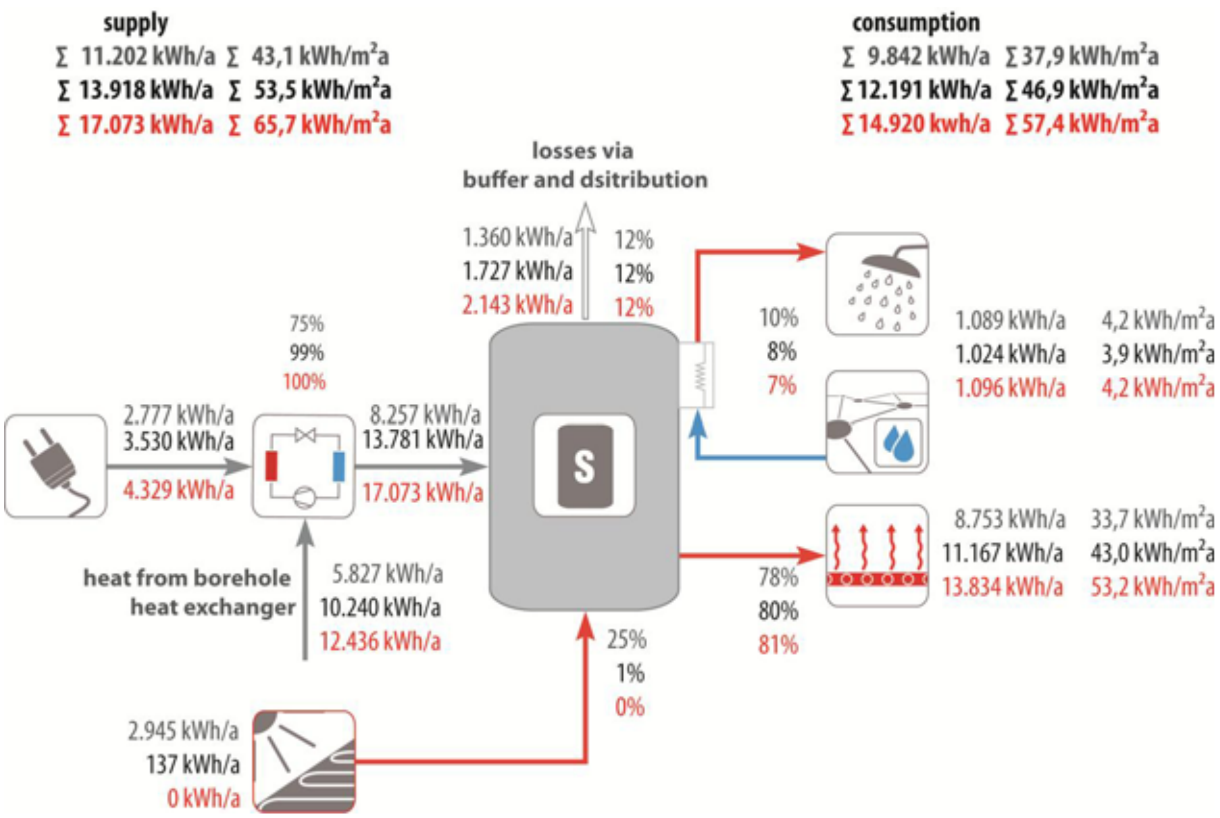

Fig. 4: Annual thermal energy balance (2011 - 2013)

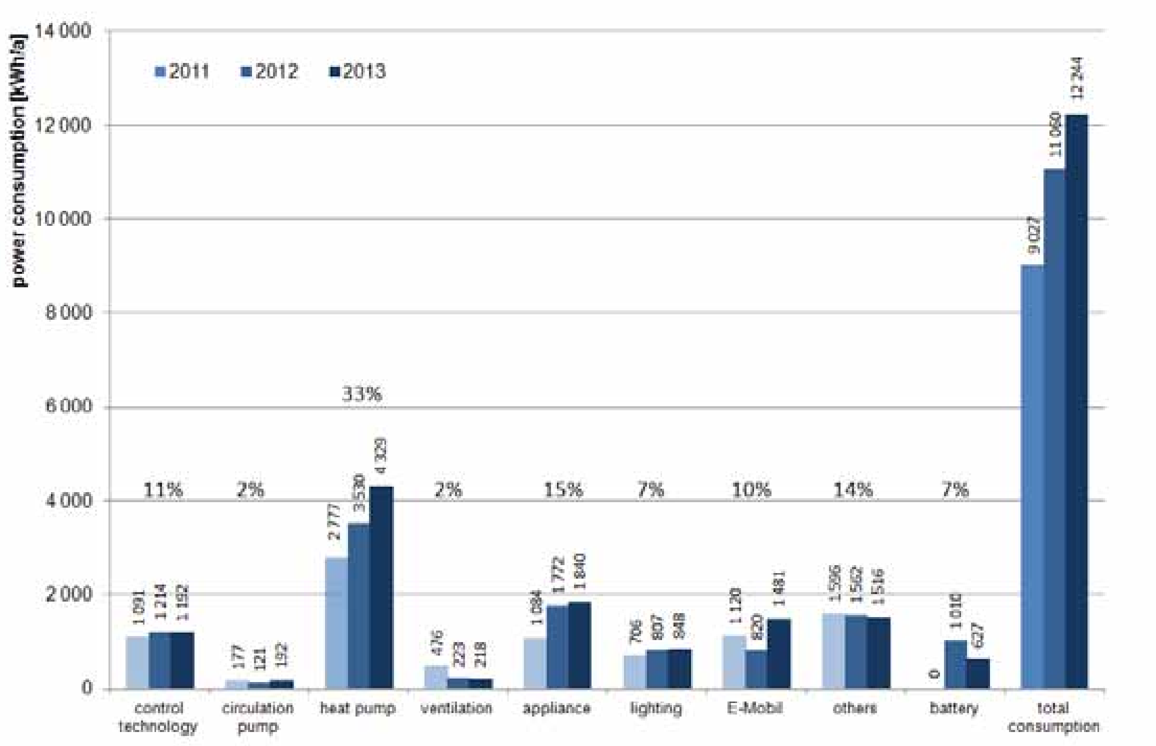

Fig. 5: Annual electrical energy consumption (2011 – 2013)

The monthly balance between PV generated and demanded power shows large surpluses during the summer and a lack during the winter months (Figure 6). The PV power and thus the solar yield were designed to cover the roof area in an optimal way.

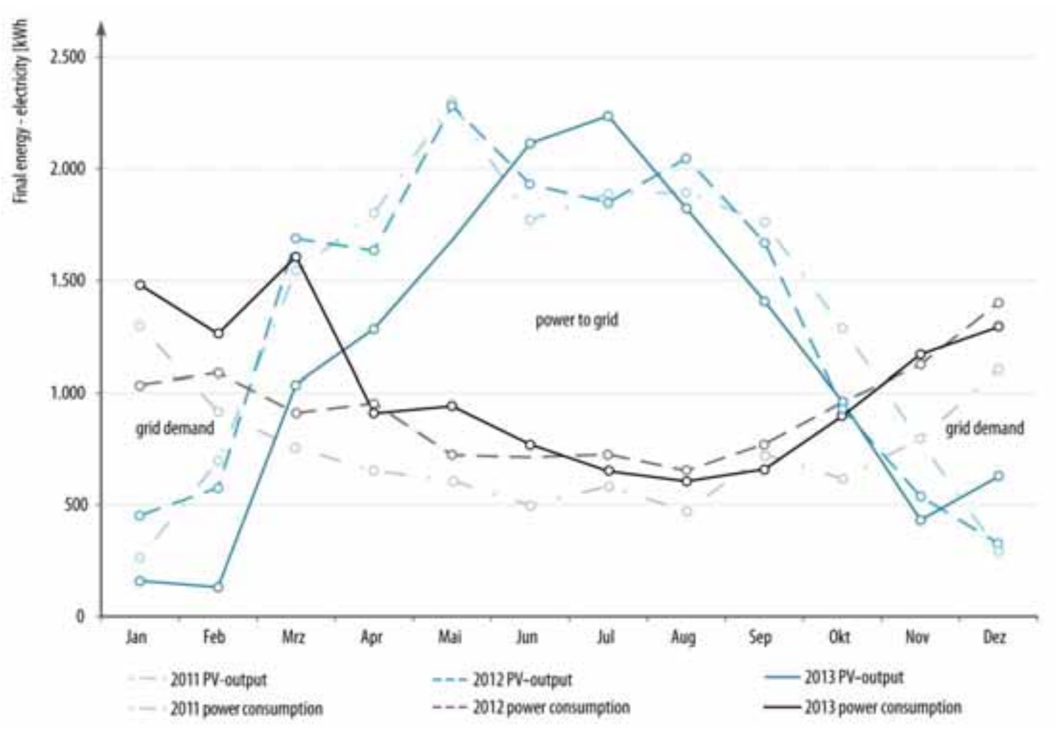

Fig. 6: PV power output and total power consumption (2011 – 2013)

4. Optimization of operation

A seasonal heat pump performance factor below 3.0 is determined within the first operation time. Various optimizations and adaptations have been made in collaboration with the manufacturer. In addition to that the heat pump was changed in summer 2013. Table 2 and Figure 7 shows the change in the measured weekly / annual performance factor of the heat pump from below 3.0 in 2011 up to 6.0 / 3,95 in 2013. During the summer months, the heat pump is mainly used for domestic water heating. The heat pump is running only a short operating time and at a high temperature level on the building side. These operating conditions are not very efficient and lead to performance factors below 3.0.

Tab. 2: Seasonal Performance Factor 2011 - 2013

	2011	2012	2013
SPF	2.97	3.90	3.95

The focus of the second operation year (2012) was to improve self-consumption of PV-output and to lower power consumption. Taking down the solar thermal system, the self consumption increased from 18 % to around 30%. With a combination of PV and electrical heat pump a solar thermal system is not economically sensible.

In order to increase the direct use of electricity on site, the following measures have been implemented:

- Operation of all electricity-intensive appliances (e.g. dryer, washing machine, dishwasher) and units such as the heat pump at the same time using the regenerative power output from the PV and the maximize possible charging of e- mobile.
- Use of all available thermal storage such as floor heating and the buffer.
- Targeted operation of the heat pump (possible only during the day), only in exceptional cases at night or with grid power, for example, at very low outdoor temperatures during the heating season or during lack of solar yield.

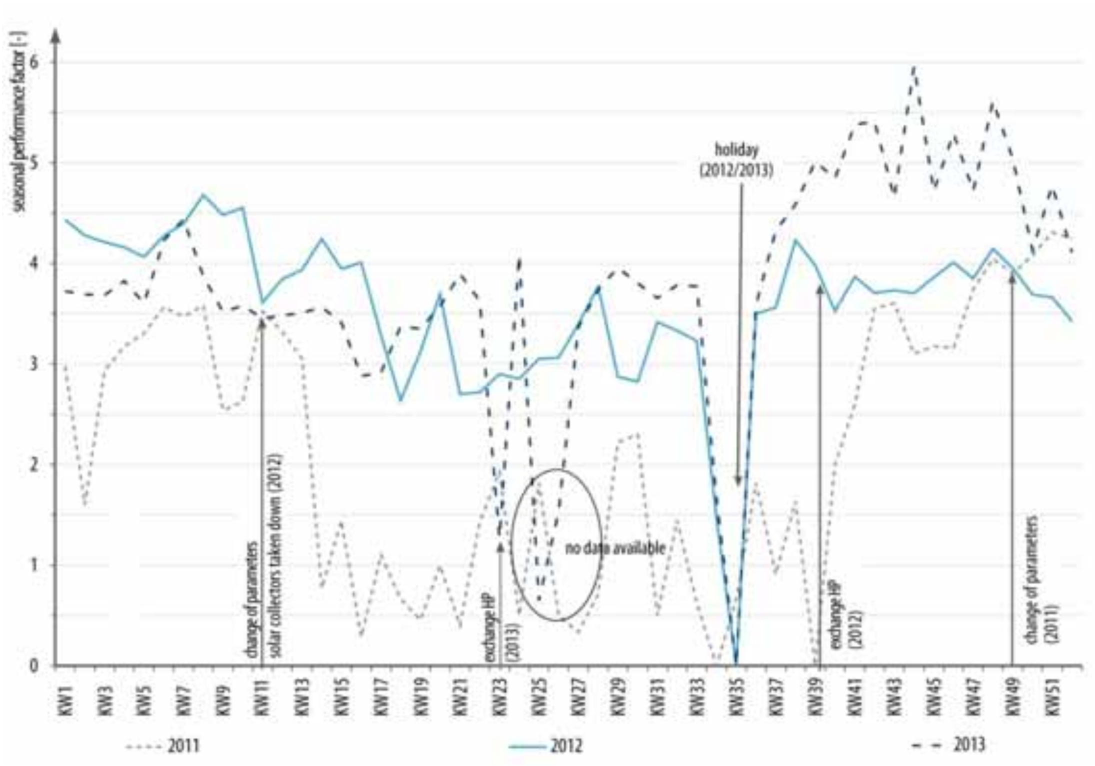

Fig. 7: Weekly Seasonal Performance Factor (2011 – 2013)

- Changes in the control strategy of the heat pump: increasing the use of power from the PV system and the fraction of self use by implementing enhanced control strategies to increase the running time of the heat pump.
- As long as there is sufficient solar energy available, heat pump operation strategy is changed in the following way:
    - Increasing the temperature in the buffer to more than 60 °C to increase the storage capacity, and thus to generate sufficient heat storage for time without power output.
    - Increase the reference value of surface and supply temperature of the floor heating by up to 2 Kelvin and thus to increase the operation time of the heat pump. The heat is stored in the space-surrounding solid components, thus counteracting a decrease in temperature in the evening and night hours under the comfort limit. The user comfort is not to be limited by the proposed measures.

The comparison of the measurements between the operation years 2011 and 2012 shows an increase in self-consumption (Figure 3). The target share of over 30 % self use was reached in the context of the defined energy plus standard.

Figure 8 shows the heat pump operation for 2012 as carpet plot. Green inked areas mean operation of the heat pump and red-inked the change of operation strategy by sufficient solar energy. It becomes clear that the heat pump was not in operation during the period 22 - 5 o´clock. In addition, the change of operation strategy at midday can be seen. In fall 2012, the heat pump was replaced and the operation strategies could not be implemented properly. This led in disadvantages and losses in the PV use. The heat pump is running at night time again.

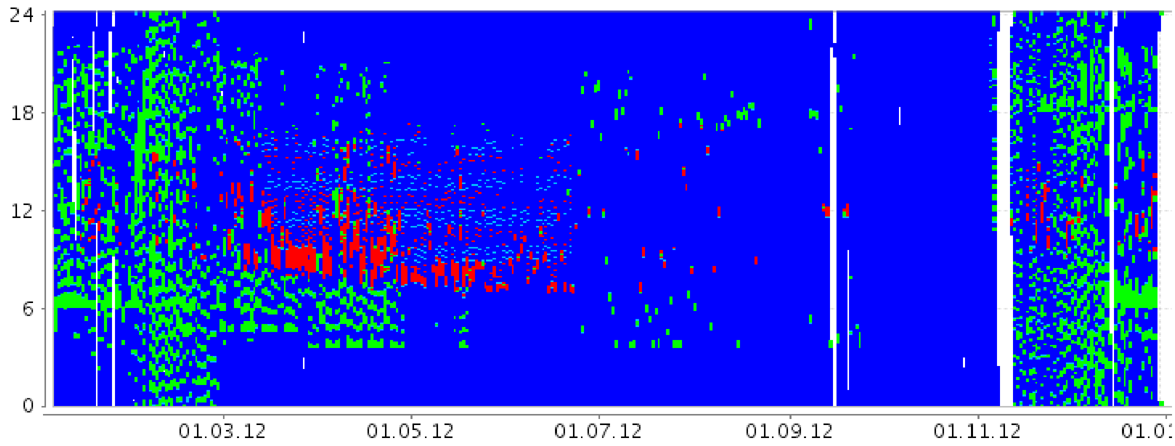

Fig. 8: Operation of heat pump (green) with overheating mode (red) (2012)

During winter season with low PV production and high heating demand the power demand of the heat pump could be covered up to 15% by PV production. Therefore three conditions needed to be satisfied. A decent implementation and integration of the heat pump to the load management was implemented. Furthermore the implementation of changing strategies by PV production was also implemented. During the summer months, no change in strategies occurs. Throughout this time, the heat pump only runs to provide domestic hot water. This leads to a solar fraction up to 93%. 2013, due to the low PV yield at the beginning of the year only a share of the power consumption of 4% was covered. In the summer months, the proportion increased up to 78%. (Figure 9)

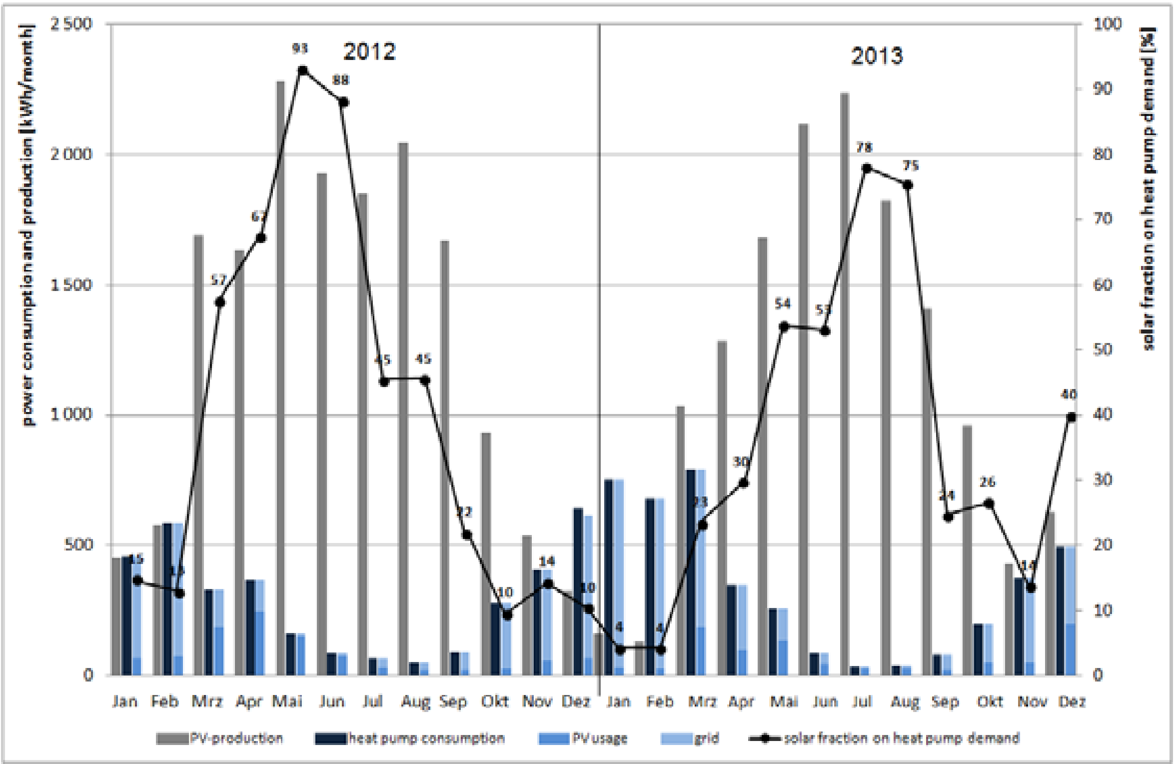

Fig. 9: PV-production, heat pump consumption and solar fraction on heat pump demand (2012 - 2013)

The integration of the battery to the load management is crucial to cover the power demand of the building. Furthermore it helps to optimize the usage of the current self-produced PV energy.

Through the integration of the two batteries, the solar self-consumption could be increased in 2012 (Figure 10 and Figure 11). The monthly solar fraction of the batteries in the total electricity consumption in 2012 ranged from 7% to 44% (Figure 10). 2013, the 20 kWh-battery was no longer running and removed from the system caused by not scheduled operation. The percentage of battery on total power consumption is clearly energized on an average of 6% by eliminating the battery.

Comparing the annual electricity production and self usage of electricity from 2011 to 2013, the increase of self usage of electricity from 2011 to 2012 is caused by the integration of the batteries and therewith the storage capacity (20 kWh + 7 kWh). The share of self usage of electricity on the PV production could be increased from 18% in 2011 to 33% in 2012. The reducing of 2012 to 2013 can be attributed to the elimination of the 20 kWh-battery.

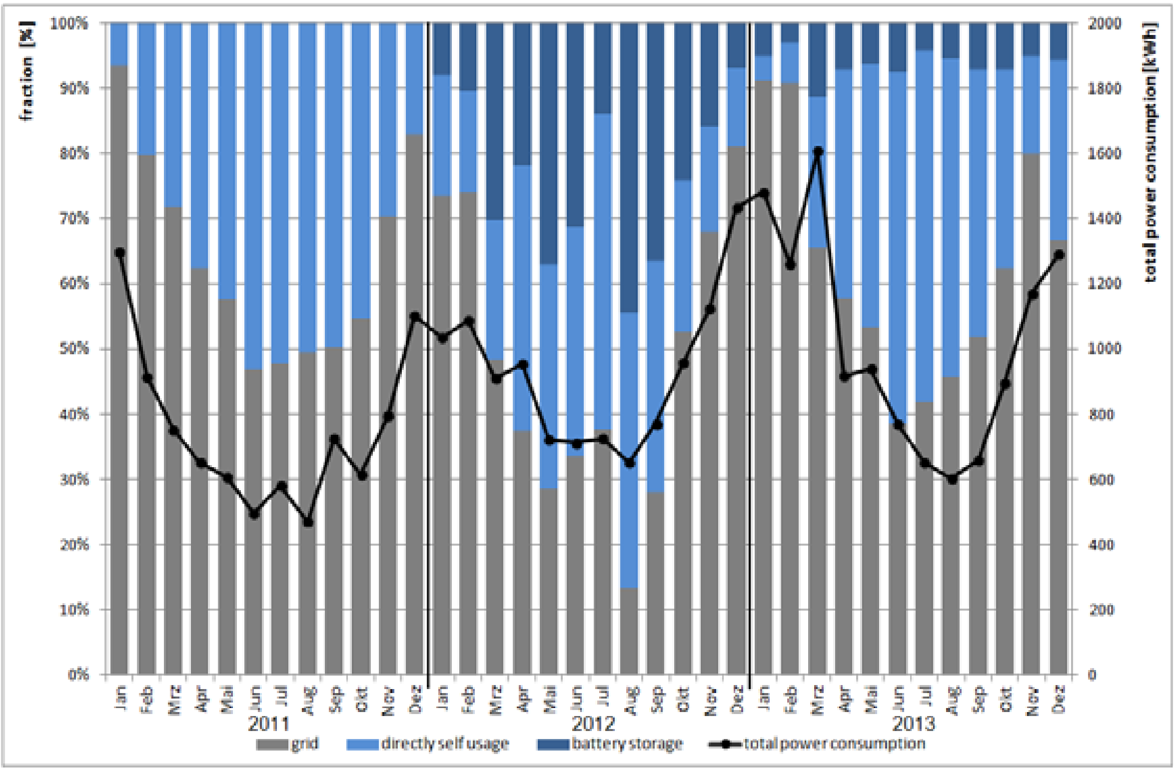

Fig. 10: fraction on total power consumption by PV, battery and grid (2012-2013)

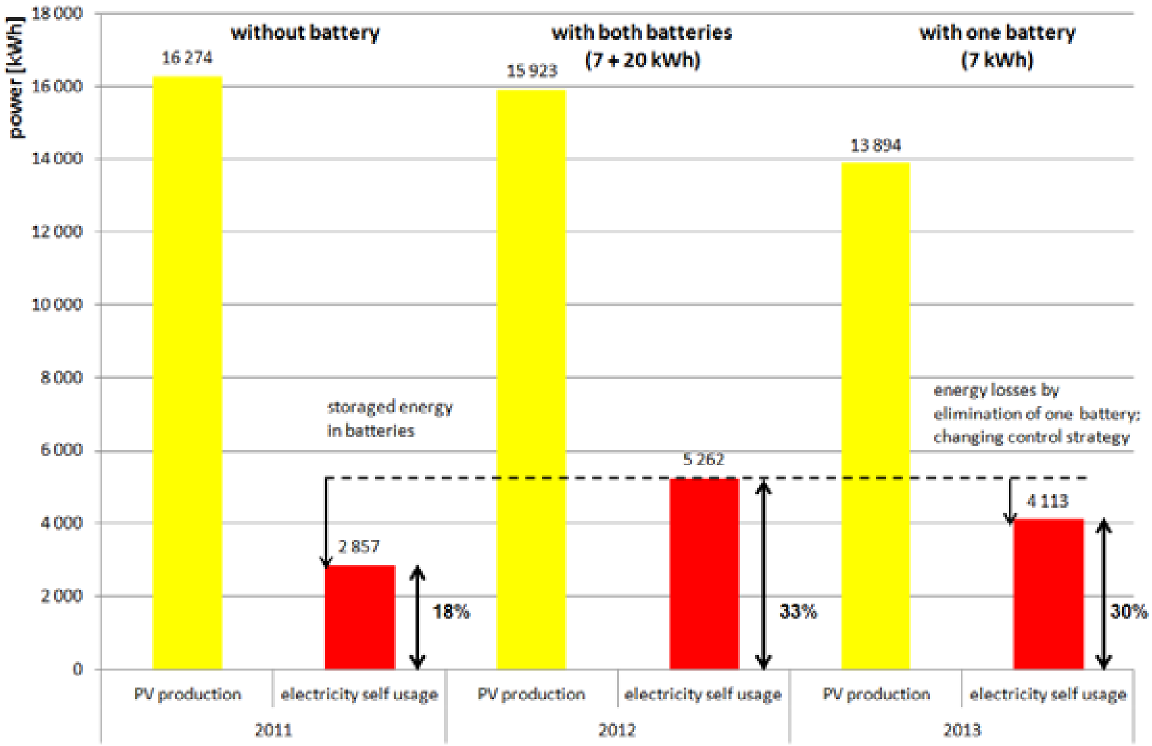

Fig. 11: Influence of battery and increase of self usage, 2011 - 2013

5. Outlook

The results and optimization show that there is still potential to increase the self- use of solar electricity. This will be realized in the ongoing project.

The increase in self-consumption within the building is going to be implemented through the following measures:

- Increasing of thermal storage mass by the buffer volume from 825 l to 825 l + 700 l.
- Improved use of available thermal building mass (active function description and optimized control strategies).
- On-line monitoring to monitor the success and operation optimization.

In addition to energetic issues, comfort measurements will also be analyzed the personal feeling regarding to room temperature, room humidity, etc. These analyses will help to change the installed ventilation equipment and the user-specific heating to increase the comfort of the residents.

6. Conclusion

The primary goal of achieving energy plus standard in terms of an annual balance for final and primary energy coupled with the aim of high user satisfaction has been continuously achieved since three years of operation. The realized energyPLUS building covers 35 - 50% of its total energy consumption by renewable sources. In combination with a solar direct use of electricity over 30%, the energyPLUS concept is an important module for our future energy supply.

Sustainable energy concepts play a major role in energy-efficient construction. Besides the integration of renewable energy sources, integrated design includes a high level of user comfort in conjunction with a healthy indoor environment. The project is a commendable example of integrated design and allows the investigation of future-oriented technology and energy concepts. By the construction of energy plus buildings with high internal electricity consumption future-oriented concepts for future standards are set.

7. Literature

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