Conference Proceedings

EuroSun 2014

Aix-les-Bains (France), 16 - 19 September 2014

Concept and first Energy-Balance Results of an Energy-Autonomous House

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Abstract

One new concept for single-family buildings is the Energy-Autonomous House which is presented in this study. The concept is an advancement of solar houses and efficiency houses with fully self-sufficiency in electrical (100 %) and thermal energy. Therefore a reduction of the energy consumption (electrical and thermal) by increase of building efficiency is necessary. The house includes utilization of solar energy with photovoltaic panels and solar thermal collectors coupled with storages (battery, electro mobil and thermal storage tank). Further a water cooled fireplace is integrated for the supply of thermal heat during winter month. To proof the self-sufficiency under realistic user behavior two occupied houses are built in Freiberg / Germany and which are now under an extensive monitoring. First energy-balance results show good correlations among planned and measured consumptions for Jan. - July 2014.

Keywords: autonomous house, energy storage, solar thermal energy, energy efficiency in buildings

1. Introduction

In 2011 the needs in heating and cooling in the EU was about > 40 % of the total energy supply, but only 14 % was contributed by the renewables (Musiol et al. 2013). Thereby the usage of renewables in new buildings and reconstructions for a self-provision with heat and electrical energy becomes more and more important. One new concept for low-energy buildings with solar thermal collectors in central Europe is the energy-autonomous house as an advancement of the concepts of solar houses and efficiency houses (see Fig. 1). This concept is based on a low annual primary energy consumption (planned with < 7 kWh/m² a) and a fully self-sufficiency in electrical (100 %) and thermal energy (partly provided by a fireplace).

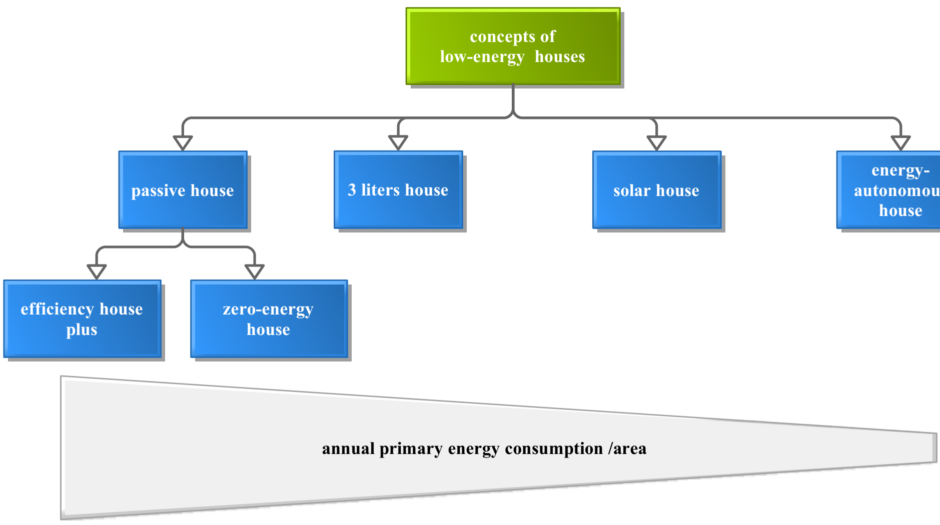

Fig. 1: Classification of the different and most common concepts of low-energy houses

doi:10.18086/eurosun.2014.20.06 Available at http://proceedings.ises.org

So the name “energy-autonomous house” refers to the house operating without fossil fuels and without purchase of electricity from the grid.

For this task the temporal offset between energy generation and consumption is solved by integration of a storage battery and an established thermal water storage tank. Another part of the concept is the integration of electric powered vehicles as a further flexible storage battery.

To reach this goal of autonomy first the annual primary energy consumption had to be reduced by using low-energy-consumption techniques as well as to reduce their needed number for the house technique.

2. Details of the “Energy-Autonomous House” Concept

Actually three Energy-Autonomous Houses (EAH) of HELMA have been built: one as a prototype and two for scientific investigations with real user behavior (one of them is shown in Fig. 2). The summary of the main construction details of the equal houses is shown in Tab.1, for more details see also Corradini et al. (2014). The houses are made of monolithic bricks without any further insulation at the outside wall. The building structure is similar to solar houses, whereby the house orientation is north-south with big windows in the ground-floor in direction to the south. As already mentioned the house concept is based on a fully self-sufficiency in electrical energy without energy purchase from the electricity supplier. This shall be ensured by a combination of roof integrated photovoltaic-panels of 8.4 kWp (Fig. 2, (b)) and a 58 kWh storage lead battery which is situated outside the house in a weatherproof box, see Fig. 2, pos. (c). The planed overall electrical energy consumption (including consumers, e. g. pumps, controllers) shall be less than 2000 kWh/a.

Fig.2: Occupied energy-autonomous house with roof integrated solar collectors (a), pv panels (b), storage battery (c) and charging column for electro mobility (d)

The thermal energy concept is based on a combination of a roof integrated solar thermal collector (46 m²) (Fig. 2, (a)), a house integrated thermal storage tank (V = 9.12 m³) and a water cooled fireplace (natural draft wood gasifier). Further to avoid an overheating of the houses by the sun during summer month the windows are equipped with electrical shutters.

An overview of the planned energy consumption and the yield of the EAH is given in Tab.2. Thereby the annual demand in thermal heat was calculated for 185 days of heating (degree day ~ 2915 Kd, see VDI Gesellschaft (2013)). It has to be mentioned that the planned primary energy consumption is about 80 % lower than the standard of passive houses (primary energy coefficients of Germany, see Normenausschuss Bauwesen im DIN (2011)).

Tab. 1: Building construction properties of the realized energy-autonomous house concept (* … new calculated)

Building properties	Energy-autonomous house (EAH)
Living area / effective area* / heated house-, air volume*	162 m² / 206 m² / 644 m³, 489 m³
Windows (triple glazed): area / U-Value	~ 49 m² / ~ 0.6 - 0.8 W/m²K
Walls (monolithic bricks with plaster): area / U-Value	~ 169 m² / 0.18 W/m²K
Area of solar thermal- / PV-collector / slope of the roof	46 m² / 58 m² / 45° (south)
Volume of heat storage tank/ capacity of storage battery	9.12 m³ / 58 kWh
Fireplace (water cooled)	25 kW

In sunny and warm months (March –October) the photovoltaic panels will deliver more energy than needed for the house supply. This excess capacity will either be stored in the battery, active feed into the electricity grid or used for electro mobility (charging column, Fig.2 (d)). The integration of electro mobility will be at the end of 2014.

Tab. 2: Planned energy consumption and yield of the energy-autonomous house in Freiberg / Germany

Planned consumption	**EAH** (location: N 13,34271° E 50,90166°)
Annual demand in thermal energy (*heating; tap water*)	~ 40.2 kWh/m²a (*8300 kWh/a; 2600 kWh/a*)
Annual electrical energy consumption	≤ 2000 kWh/a
Annual primary energy consumption	≤ 7 kWh/m²a
Planned yield	
Annual solar thermal energy yield	~ 12000 kWh/a
Annual electrical energy yield	~ 8000 kWh/a

2.1. Use of "Energy-Autonomous House" and measurement equipment

To investigate several user behaviors the two houses are in different use. In the first **single family house** two children and three adults are living. Therein a part of the attic is in use as an additional bureau (~ 6 m²) which is not included in the effective area in Tab. 1 and will not be considered, further. The second house has the same equipment but it is used as an **office house** with 2-4 working people from Monday to Friday.

For monitoring both houses are equipped with a high amount of measuring techniques to enable detailed balances of electrical and thermal energy as well as the thermal comfort of all rooms. The measuring system consists of about 190 measurement sensors / devices in each house (heat and electric meter, humidity, temperatures, solar radiation, air pressure, etc.) which are interconnected via M-BUS. The data is stored by several multi-utility communication controllers. The own consumption of the electric meters was measured before installation and is subtracted from the total house energy consumption in all presented figures.

2.2. Hydraulic system of the "Energy-Autonomous House"

Fig. 3 shows a simplified hydraulic flow chart of the single family EAH with one heat storage tank (9.12 m³) in the center. Further the main several metering points for the heating control unit (yellow) and the integrated

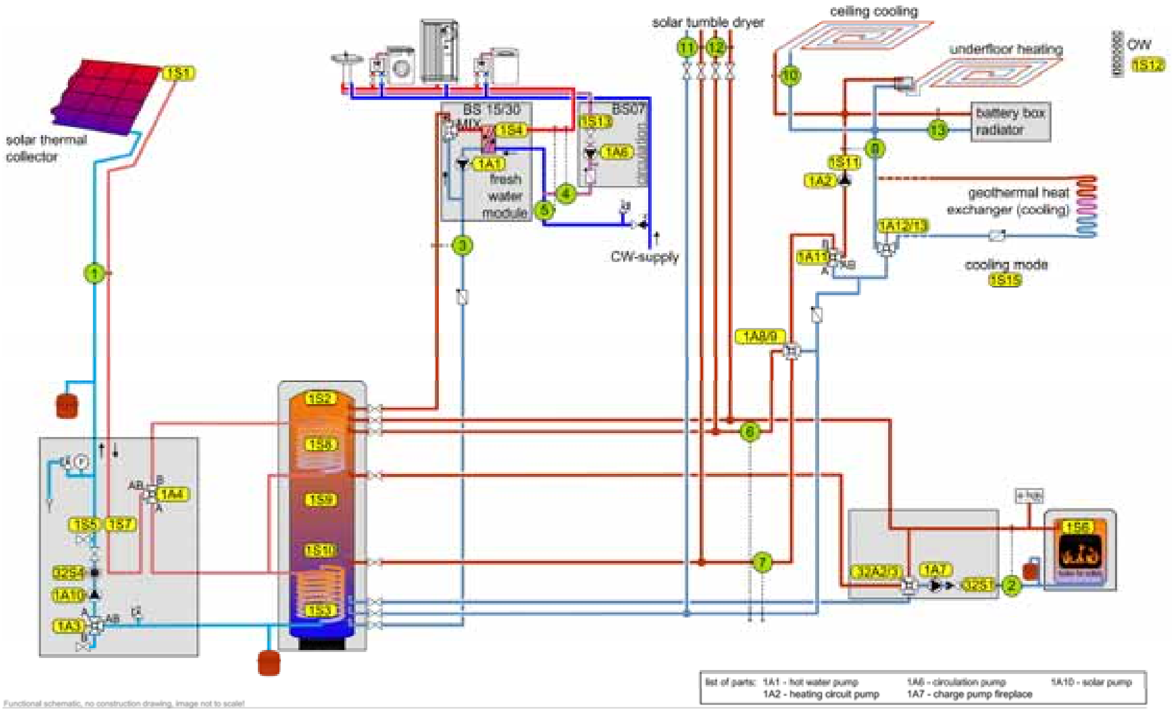

Fig.3: Hydraulic flow chart of the single family Energy-Autonomous House with metering points for the heating control unit (yellow) and heat meter (green)

heat meters (green cycles) are shown. The heating system consists of underfloor heating cycles and one wall heating cycle (not shown in Fig. 3). One specialty of the single family EAH is an integrated ceiling cooling system to avoid overheating of the house during warm periods in summer. A geothermal borehole heat exchanger (double-U-tube) is used as heat sink.

In the **office EAH** neither a ceiling cooling nor a geothermal borehole heat exchanger is integrated. However a standard air ventilation system with heat recovery is installed but wasn't enabled before March 2014.

For balancing the fireplace actually only the mass and humidity of the wood which is used and the thermal heat output to the heat storage (by a heat meter) are measured. Nevertheless it can be assumed that the fireplace has a thermal efficiency of about 75 % to 85 %, which will be checked with emission measurements in future. So in this paper the thermal storage tank is considered wherefore only the thermal heat provided by the fireplace to the tank is presented. The heat losses through the chimney and the real efficiency of the fireplace will be added in the future publication.

3. Results and Discussion

The monitoring of the two EAH began with moving in of the users at the end of 2013. The heat storage tank started at a low temperature level, wherefore a high amount of wood was needed for heating. Further the building structures (walls) were not dried out completely after built up, which could result as well in a higher heating demand. In the first month after occupation of the houses several adaptations in the heating control (e.g. runtime of pumps, supply temperature, etc.) and measurement equipment were done. Therefore only measurement data from 2014 is presented in the following.

3.1. Weather conditions in Freiberg/Saxony

It has to be mentioned that in Germany the winter in 2013/2014 was very warm and dry. For the location Freiberg there are monthly averaged temperature data available from 1961- 1990 which are presented in Fig. 4 compared to the actually measured ones. So the mean temperature in Saxony was about +2.9°C higher and the cumulative sunshine duration was about + 34 % higher (216 h instead of 161 h) than the average (1981-2010) for December until February (Deutscher Wetterdienst (27.02.2014)). This resulted in higher production rates of solar thermal and electrical energy as well as a lower heating demand in the winter.

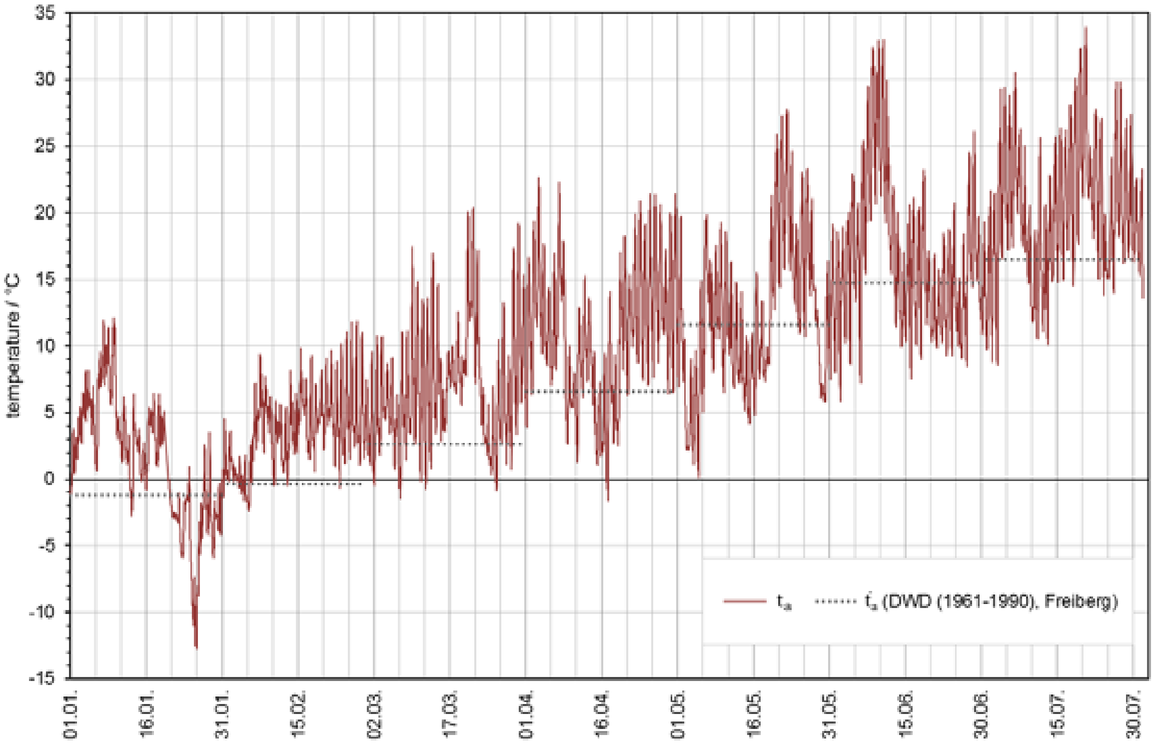

Fig.4: Comparison of measured outside temperature (2014) and average temperature for Freiberg (1961-1990, Deutscher Wetterdienst (DWD 04.2014))

3.2. Energy balances of EAH – Electrical Energy

In Fig.5 an example of the electricity yield and the consumption of the two EAH during a sunny day in winter (21.02.2014) are shown for a small metering time period (average of 5 min value). Overnight both houses show a nearly equal consumption by the house equipments (e.g. pumps, etc.). The consumption level

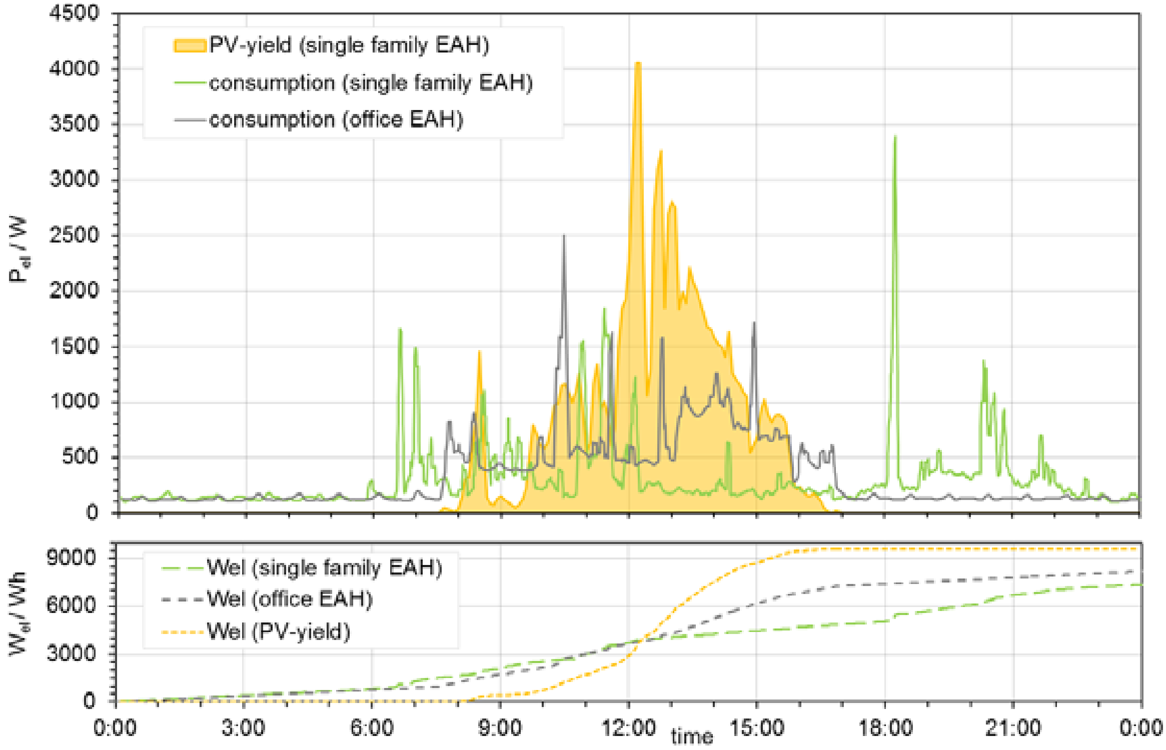

Fig.5: Comparison of electrical energy yield (photovoltaics, PV) and consumption (21.02.2014 – Friday), up: daily variations (average of 5 min value), down: cumulative consumption and yield over one sunny day in winter

of the single family EAH (green line) starts to rise earlier in the morning than the office EAH (grey line), due to the normal daily routine of the home residents. Without a storage battery this electricity demand could not be covered.

In the single family house a fluctuating consumption at 12:30 was measured, which is explainable with home office work of one person. Nevertheless the consumptions trend is similar to Samweber et al. (2014), where a higher energy consumption is measured in the evening. Between 07:30 and 17:00 the office building has a higher demand in electricity than the single family house due to the technical office equipment (e.g. printer, etc.). This leads to a higher cumulative daily consumption of the office building. Though for 21.02.2014 the daily electricity yield by the photovoltaic panels (PV) was even higher than the house consumptions (single family and office) at this sunny day in February (see Fig.5).

The weekly electrical energy consumption of the two houses is compared in Fig.6, wherein a fluctuation and resulting standard deviation in weekly consumption was measured about ± 5.6 kWh. This fluctuation is explainable e.g. with business trips, meetings (mainly office EAH) and holidays. Despite of the seven-day use of the single family EAH the average weekly consumption is only about 3.2 kWh higher than the five-day used office EAH. Based on the average daily consumptions (Jan. – July) an extrapolation for one year was done:

- single family EAH: ~ 2150 kWh/a
- office EAH: ~ 1950 kWh/a

Hence a very good correlation among planned (2000 kWh/a) and extrapolated measured consumptions of the houses for one year is visible. Therein all consumers like house equipment (pumps, etc.) and household (cooking, etc.) are contained. It has to be mentioned that in comparison with standard equipped houses in both monitored EAH additional consumers as a water well pump (~ 60 to 140 kWh/a) and a BUS-System (~ 80 to 140 kWh/a) are installed. Thus the planned total consumption in electrical energy of 2000 kWh per year should be reachable wherefore the very low total consumption shows the high potential for single and multi-family houses in future. This low self-consumption is the key for autonomy in electricity.

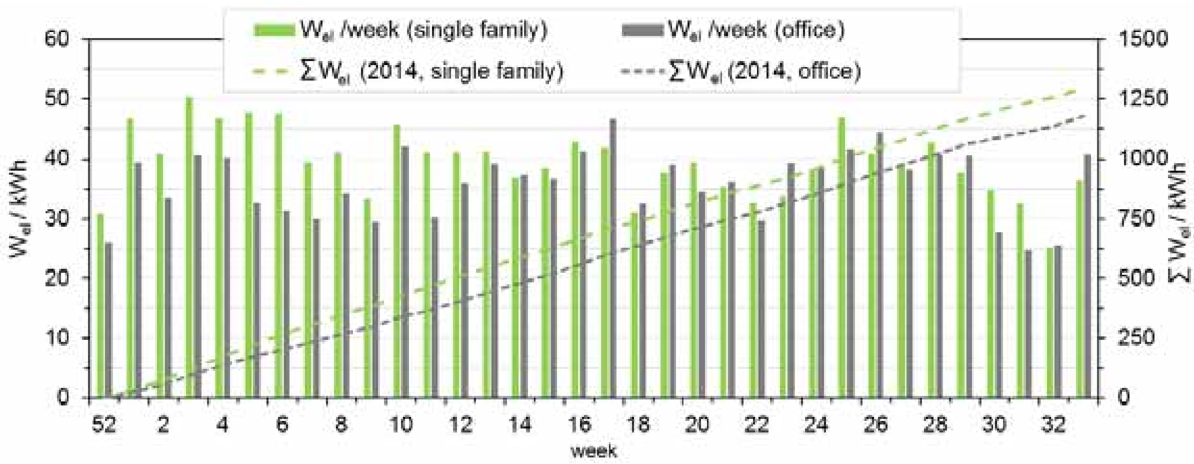

Fig.6: Comparison of weekly and overall electrical energy consumption of the two EAH with different user behavior (2014)

The different user behavior (family / office) leads to differences in height of electrical energy consumption for several consumption groups, see Fig.7. Thereby the single family EAH shows a significant higher consumption of the house equipment (~ 32% of the total consumption), which is explainable by considering the cumulated consumptions of the heating control and pumps. The family uses e.g. water for showering and house heating for seven days a week, which results in a higher electricity consumption. The averaged consumption for illumination is very low with about 4.6 % (4.2 % office EAH) of the total house consumption.

Further the total consumption of the household of the two EAH is approximately the same. Nevertheless by detailed consideration of the subordinate consumers, e.g. the consumption of the appliances for washing, cooking etc. is about two-times higher than the office EAH's appliances. Therefore the sum of all other socket consumers in the office EAH is higher than of the single family due to a higher number of technical office equipment (computers, printers, etc.), see Fig. 7.

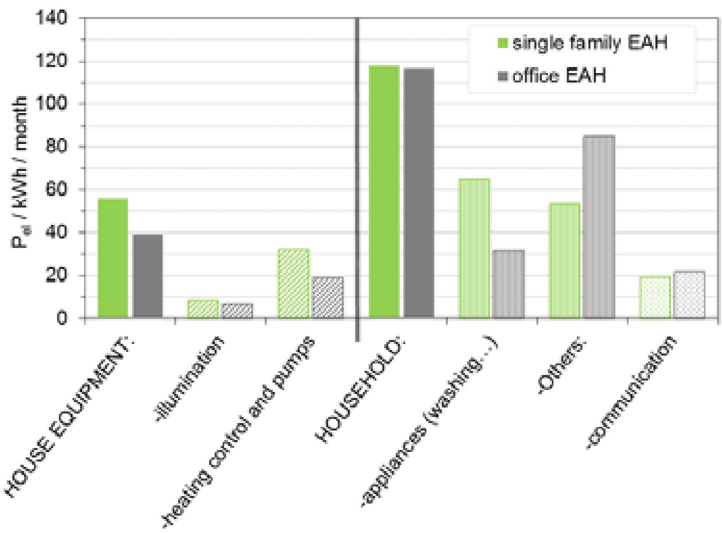

Fig.7: Comparison of the user specific averaged electrical energy consumption of the two EAH (Jan.-July 2014)

A monthly balance of electricity yield, self-consuming as well as the in- and output of electricity of the EAHs is shown in Fig.8. Due to the mentioned high sunshine duration in winter the amount of electricity yield via PV was very high. During January electricity procurement was measured because the electrical inverters were tested and under construction, so the house grid switches on input from the electricity grid.

Further a small amount of one to five KWh was measured every following month. This result from switching action between the house grid of the EAH to electricity grid for power feed-in due to a high yield in electricity by the PV-panels. Since February the electricity yield was higher than needed for the EAH, wherefore power feed-in the grid was detected. Thus the total house consumption was provided by the house electricity grid (battery and PV) for January to July 2014. For this short measuring period an autonomy in electricity was measureable so far. Nevertheless a longer measuring period (2 years) with “normal” weather conditions is needed for reliable and reproducible results. Therein further optimizations of heating and air conditioning techniques in dependence of the real user behavior should be done.

If the amount of power feed-in the electricity grid (feed-in from Jan. to July) would have been used for electro mobility (17 kWh/ 100 km), an average distance of about 21200 km (22750 km office EAH) could have been driven. Even for January to March 2014 a distance of about 4200 km (5500 km) would have been possible. So compared to the planned period (March-October) of e-mobility usage, the period could be much longer. This depends mainly on the weather conditions. For the high yield in electricity and resulting long distances new charging concepts for e-mobility could be developed. First the integration of electro mobility will be the next step during this monitoring project for energy autonomy.

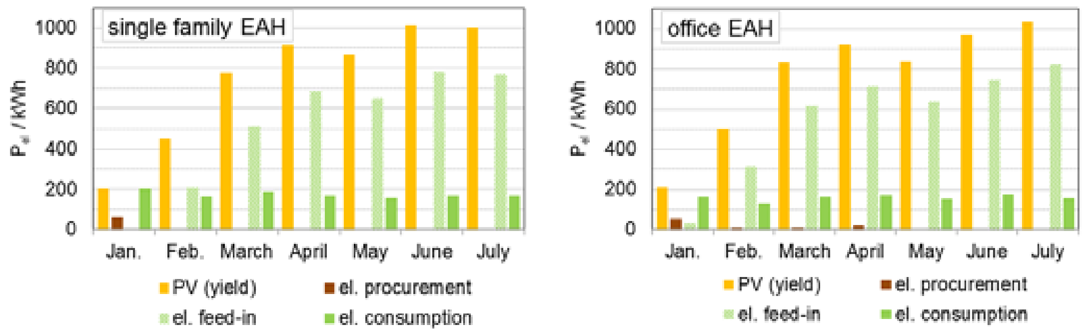

Fig.8: Monthly house balances for electrical energy (yield, procurement, feed-in and consumption), left: single family EAH, right: office EAH

3.3. Energy balances of EAH – Thermal energy (heat)

In Fig.9 the monthly thermal energy loads of in- and output of the thermal storage tank is shown for both EAH. Thereby the thermal losses of the storage tank and the heat losses from the fireplace to the living room are not yet considered.

In comparison to the electrical energy consumption the thermal energy balance shows big differences between the two EAH due to the different user behavior. E.g. the single family EAH has a 6 to 16 times higher consumption in hot water than the office EAH. Due to the lower demand in hot water (office EAH), the average storage tank temperature is higher (not shown here). Therefore the heat input by solar energy decreases because the collector temperature must be higher than the storage temperature before the control unit runs the solar pump. So, the time of the solar pump run of the single family EAH is 23 %, 49 %, 31 %, 19 % higher (March, April, Mai, June) than of the office EAH.

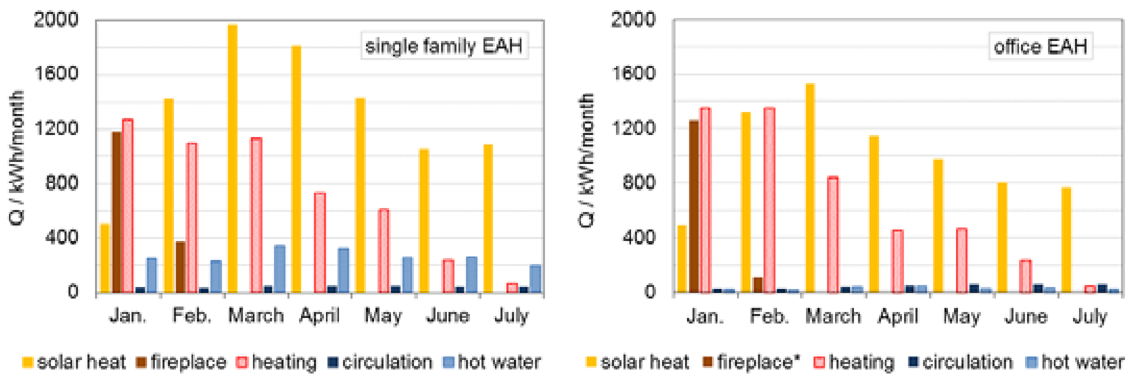

Fig.9: Monthly house balances in thermal energy (yield and consumption), left: single family EAH, right: office EAH

There was a failure in measuring the thermal heat from the fireplace of the office EAH, wherefore the January lasts until 9th of February. This is also the explanation for the lower thermal input in February compared to the single family EAH. The measured consumption in wood of the office EAH is 18 % lower than the single family house.

At the beginning of this measuring period the office EAH has had a higher demand in heating. This can be explained with a different user behavior. The lower consumption in March (compared to single family EAH) is explainable with the additional air ventilation system with heat recovery which was running in the office EAH after first problems.

For January to July (7 months) the total cumulated demand for house heating compared to the heated area was about 25 kWh/m² (single family EAH) and 23 kWh/m² (office EAH) and shows a good correlation with the planned consumption of ~ 40.2 kWh/m²a. For further first conclusions concerning the primary energy consumption a minimum measuring period of one year is needed and will be presented at the Eurosolar 2015.

4. Summary and Outlook

The first results of a fully seven month monitoring period showed a very good correlation between the planned and measured electricity and heat consumption of two "Energy-Autonomous Houses". The planned low consumptions in electrical energy of the EAH's (~ 2000 kWh/a) are realistic and show big advances compared to other house concepts. These presented low consumptions can enable an autonomy in electrical energy, which was detected for the first seven month of monitoring for both houses. During the winter months the weather conditions have been very positive wherefore a longer period of monitoring is needed.

Further the heating demand for house heating showed a good correlation with the planned consumption. Nevertheless the measuring period is not long enough to draw more conclusions.

In the next months the integration of electro mobility is one task. Furthermore measurements and calculations concerning the thermal heat losses of several technical installations and the EAH's itself shall be done to find further parts for optimization.

Acknowledgements

We want to thank the Federal Ministry of Economics and Technology (BMWi) for the financial support for the monitoring project (no. 0325995 A). Further we thank the lead partner Jülich for the good assistance and the house owners, the technicians and all involved companies for the good and productive cooperation.

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