New town hall in Freiburg (D): concept, performance and energy balance after the first year of monitoring of a large net plus-energy building

Nicolas Réhault, Peter Engelmann, Manuel Lämmle, Leo Munzinger
Fraunhofer Institute for Solar Energy Systems, Heidenhofstr. 2, 79110 Freiburg, Germany
E-mail: nicolas.rehault@ise.fraunhofer.de

Abstract. The town-hall building (Rathaus im Stühlinger: RIS) of the city of Freiburg (D) has been designed and built with the objective of a plus-energy balance and has been handed over to the city in November 2017. With a net floor area (NFA) of 22,650 m², it is to date one of the largest designed and built plus-energy building in Europe. The boundaries considered in the annual energy balance are limited to the loads of the heating, ventilation and cooling systems (HVAC), of the domestic hot water (DHW) and of the lighting; user-dependent energy demands are not considered. To achieve a positive primary energy balance, the building envelope is highly insulated, the energy supply is based on a low-exergy concept and onsite energy is generated by a large Building Integrated Photovoltaic (BIPV) plant combined with photovoltaic-thermal combined collectors (PVT). The central component of the heat generation is a ground-water coupled heat pump system supplying thermal activated concrete slabs, heating ceilings and air handling units (AHUs). Cooling is ensured over the geothermal well. To the date of this publication, the building has been intensively monitored for one-and-a-half year. Here, we present the energy concept as well as the results of the first monitoring period and provide an assessment of the energy balance in comparison to the plus-energy objective as well as an initial analysis of the load curves and of the heating and cooling systems.

1. Introduction
The German government has recently recognized that the greenhouse gas emissions have hardly been reduced in Germany between 2009 and 2017 and that the objective of 40% CO₂ emissions reduction for 2020 based on the reference year 1990 will not be met. Whereas the share of renewable energies in the fuel mix has continuously increased during the same period, up to 36% in 2017, the success of the German energy transition is almost concentrated on the power system. In general, the carbon footprint of the heat consumed in the household, services and industry sectors and corresponding to about half of the delivered energy consumption of Germany, has not been reduced [5]. Nevertheless, studies have shown that the sector coupling between power and heat by the use of heat pumps, besides the increase of the energy efficiency and of the local production of energy by means of renewable energy systems, can play an important role to reach the goal of the German government to achieve an ”almost climate neutral” building sector by 2050 [4, 6, 7]. Furthermore, about 300,000 of the approx. 1.7 million non-residential buildings in Germany are municipal property and are thus subject to special attention by the German government.
In this context, the city of Freiburg (D), already known for the pioneering and sustainable character of the Vauban and Rieselfeld neighborhoods, voted climate protection targets in 2014 consisting of CO₂ emissions reduction of at least 50% compared to 1992. Moreover, the municipality is striving to reach climate neutrality by 2050. Especially municipal buildings are in the focus of energy saving measures, aiming among others at building up renewable energy systems and increasing the energy efficiency of buildings by implementing ultra-low-energy concepts. With the design, construction and monitoring of its new administrative center, the city of Freiburg wanted to implement a new concept for large net plus-energy buildings based on the combination of a highly isolated building envelope, of Building Integrated Photovoltaics (BIPV) and on a heat pump system. Furthermore, the objective of the City was to collect experience on the design, the commissioning and the exploitation phase of this type of buildings before replication to further buildings on a whole new administrative campus.

The design phase of the building started in 2012 and the research project, whose initial results are presented here, focusses on the operation phase with a scientific monitoring running until the end of 2019. In this paper, we present the building concept and the targeted energy performance indicators as well as the methodology applied to assess the plus-energy objective. We then provide the results of the first monitoring period and provide an assessment of the energy balance in comparison to the plus-energy objective as well as an initial analysis of the load curves and of the heating and cooling systems.

2. Building concept

2.1. Architectural concept

The initial motivation of the City of Freiburg was to centralize several departments that were scattered over 16 sites in the city to a new location organized as a campus and thus to streamline its organization and services offer for the citizens. In 2013, a European architecture competition led to the selection of a designer team led by ingenhoven architects. The RIS building, which represents the first element of the new administrative campus, has been handed over to the City of Freiburg in summer 2017. A total of 840 employees are working in the building, which contains mainly offices but also a canteen and server rooms. The architectural design is characterized by an oval shape and a wooden facade with vertical overhanging BIPV elements that serve as fixed exterior shading devices (see figure 1). The total NFA is distributed over six floors above ground and one basement floor. The thermal performance of the building envelope is high with a specific heat loss by transmission H ’T of 0.45 W/m²°K, thermal transmittance values of 0.1 W/m²°K for the opaque surface and of 0.8 W/m²°K for the triple-glazed windows. Air permeability limit values have been defined for each component of the building envelope. The specific primary energy demand within the boundary defined in the German Energy Saving Ordinance (EnEV: Energieeinsparverordnung) amounts to 61.1 kWh/m²NFA·y (see also Table 1).

2.2. Technical boundaries for the energy supply concept and PV plant

Large buildings in dense urban zones require compact building shapes that enable optimizing the land area use. However, large compact buildings have limited possibility to achieve a positive energy balance with the use of on-site photovoltaic power generation as the roof area to envelope area and the envelope area to netto ground floor area ratios are low and lead to a restricted area for PV installations and thus to low specific photovoltaic yields [4]. The figures 2, 3 and 4 show the different characteristics for the RIS building compared to benchmark data from the tabula building typology [8]. These technical boundaries involve very high requirements with regard to the performance of the HVAC and lighting systems. Onsite power is generated here by a photovoltaic plant composed of monocrystalline solar panels with a total peak power of 682
installed on the roof ($461 \, kW_p$) and in the facade ($221 \, kW_p$). The specific installed PV power amounts thus to approx. $30 \, W_p/m^2_NFA$. Each solar module is equipped with a Maximum Power Point tracker, which continuously controls the point of the current-voltage characteristic curve at which the solar module provides the highest performance. A compound of 22 inverters converts the direct current of the solar modules into alternating current and feeds it into the building or in the public electricity grid accordingly to the current load of the building.

![Figure 1: External view of the new City Hall building. Copyright: Stadt Freiburg, Y. Zerdoun](image1)

![Figure 2: Building envelope area/NFA characteristic](image2)

![Figure 3: Roof area to building envelope area ratio/NFA characteristic](image3)

![Figure 4: Specific PV gain/NFA characteristic](image4)

2.3. Hybrid photovoltaic thermal solar collectors

The heat demand for domestic hot water is mainly required for the canteen. Glazed hybrid photovoltaic-thermal solar collectors (PVT) provide low-temperature heat to cover 15% of the domestic hot water demand. PVT collectors potentially resolve the conflict between the application of photovoltaic or solar thermal systems on limited roof areas. While PVT collectors have a slightly lower electrical yield per square meter than PV modules, they simultaneously generate heat on the same surface area and thus achieve higher specific primary energy yields. Originally, conventional solar thermal collectors with an area of $29 \, m^2$ were planned with a designed solar fraction of 15% or an annual thermal output of $22 \, MWh/a$. The PVT collector array was designed to achieve the same solar fraction. System simulations were conducted with TRNSYS to assess the annual electrical and thermal yields of the PVT collectors. To compensate for their lower thermal efficiency, the area of the PVT collector array amounts to $43 \, m^2$. Thus, the substitution of the solar thermal collectors with glazed PVT collectors is planned to increase
the electrical output of 180% on the given area, while maintaining the same thermal output [11]. The PVT system is subject to a detailed monitoring to assess the thermal and electrical energy output and to identify optimization potentials. The detailed analysis is however beyond the scope of this paper and will be featured in a future publication.

2.4. Building services concept

The heat generation is realized by a combination of two ground-water coupled heat pumps with a total thermal power of 400 kW that supply thermal activated concrete slabs (TACS) and radiant ceilings with 28°C hot water, radiators in the offices with 60°C hot water, as well as five air-handling units (AHU) with 35°C hot water. Each AHU has a heat recovery system as well as heating and cooling coils. A gas boiler with a thermal power of 100 kW operates as back-up to cover peak loads in periods of high heat demand. The specific installed thermal power amounts to 22 W/m²NFA. The cooling of the building is realized by a free-cooling system using the ground-water brine and providing the TACS with 18°C chilled water and AHUs with 15°C chilled water. The TACS are controlled on the basis of weather forecast data to guarantee indoor air temperatures of 20°C in Winter and 26°C in summer. The artificial lighting is realized with LED lights. An automated sunshade system completes the vertical BIPV overhangs and controls the daylight and solar radiation gains in the different building zones accordingly to the azimuth angle of the sun.

3. Quality insurance and energy balance methodology

3.1. Energy balance methodology

At the publication date of this paper, the German government has still not approved a normative methodology for balancing the energy of net zero-energy and net energy-plus buildings. Here, the applied methodology follows a net-zero energy balance over one whole year [2, 3]. The reasons for this approach is first that local power generation through the PV-plant and power demand of the building do not match most of the time and secondly because seasonal energy storage was not relevant on an economical and technical point of view for a building of that type. The boundary for the assessment of the plus-energy balance used in our calculations accounts for the final and primary energy consumption for HVACs, domestic hot water and lighting accordingly to the EnEv rules. Usage-specific consumptions, such as those of plug-loads, employees personal computers, the restaurant and the IT-servers, as well as their corresponding floor areas are not taken into account. The reference NFA used in our calculations amounts to NFA\textsubscript{En_EV} = 21.819 m². For the calculation of the primary energy consumption, we have considered the primary energy factors used in the design phase of 2.5 for the electricity from the public and into the grid, of 1.1 for fossil gas and of 0.1 for biogas. The results of the monitoring are provided as total and specific final and primary energy consumptions in Table 1 and compared against the target values of the design phase for information. We deliberately did not carry out a climate adjustment that takes into account the climate data used in the model of the design phase and the measured climate data. Reason for this choice is that the adjustment would have only considered temperature variations and neglected other sensitive variables like sun radiation and user behaviour. Focus here is on the verification of the plus-energy target. We plan to conduct a climate adjustment between the first and the second monitoring period on the basis of measured data after the second year of operation.

3.2. Energy performance specifications and monitoring concept

The design and commissioning engineers defined a list of Key Performance Indicators (KPI) in the owner specifications that have been checked systematically through simulations during the design phase and measurements after the commissioning [4]. In the design phase, a detailed monitoring concept aiming at measuring, reporting and analysing the performance of the
building and of its building services has been developed. On this basis, heat and power meters and submeters have been installed to measure and quantify the energy flows into and out of the building and for each main system like the heat pumps, the AHUs and the hydronic loops. In total, over 9,000 data points are measured with a 5 min resolution and stored in a monitoring database. A major drawback remains that, for technical reasons, no submeters could be installed to measure the electrical consumption of the lighting system separately from the plug-loads of the office storeys. Also the power consumption of the building automation systems (BAS) has been accounted as a fixed value as it has not been measured separately. Thus, the reference values from the design phase have been used to take account for the energy consumption of these systems in the real energy balance. For the considered balance boundary and under consideration of a test reference year for the region of Freiburg, the objective was to obtain a specific primary energy surplus of $0.2 \text{ kWh/m}^2_{NFA_{EnEV}.y}$.

![Primary Energy Balance](image1)

**Figure 5:** Yearly primary energy balance within the EnEV-boundary.

![Monthly Primary Energy Balance, Self-Sufficiency and Self-Consumption](image2)

**Figure 6:** Monthly primary energy balance, self-sufficiency and self-consumption

### 4. Results

#### 4.1. Primary energy balance

For 2018, the results of the energy performance for the main services heating, cooling, lighting, auxiliary energy for pumps, AHUs are presented and compared with planned values in Table [ ] and Figure [ ] which shows the primary energy balance on a yearly basis. The photovoltaic
plant produced $554.1 \text{ MWh}$ of electricity in 2018, which corresponds to a specific gain of $25.4 \text{ kWh/m}^2_N^{\text{NFA EnEV}}$. These results exceed the targeted values for the PV production whereas it is important to mention that the solar radiation was particularly high in Freiburg in 2018 (reference: $1050 \text{ kWh/m}^2.y$, measured: $1243 \text{ kWh/m}^2.y$). The roof PV plant produced the highest share of the electricity production with 81\%, whereas the facade PV plant and the PV-T plant contributed respectively to 18\% and 1\%. On the other side, the main consumers are the respectively the lighting (33\%) of the total consumption), the AHUs (32\%) and the heating system (23\%). The part of the primary energy consumption for cooling is very low with 2\% of the total consumption. The results reveal a slightly negative balance with a gap of about $+16.7 \text{ MWh}$, representing 1.2 \% of the total primary energy consumption, which amounted to $1402.0 \text{ MWh}$ for 2018. In the same time, the photovoltaic plant produced $1385.2 \text{ MWh}$. After one year of operation, this result is encouraging as the net plus-energy objective could have been reached without a failure in a BIPV-inverter and if bio-gas instead of fossil gas would have been purchased by the building owner, leading to a plus-energy balance of about $+30 \text{ MWh}$ or $+1.3 \text{ kWh/m}^2_N^{\text{NFA EnEV}.y}$. Nevertheless, as 2018 was especially sunny and warm in Freiburg, additional measurements are necessary to assess the performance and the robustness of the concept in the long run.

As shown in figure [6] during six months of the year, from April to September, the building produces more energy than it consumes within the balance boundary and feeds surplus energy into the grid. From January to March and from October to December, the building energy provision is strongly dependent of the public grid. As expected under this latitude, July is the month with the highest energy excess (- 135 \text{ MWh}) and January with the largest gap (+ 140 \text{ MWh}).

### Table 1: Planned and measured KPIs in $\text{kWh/m}^2_N^{\text{NFA EnEV}.y}$

| Service          | Delivered energy target | Primary energy target | Delivered energy result | Primary energy result | Deviation |
|------------------|-------------------------|-----------------------|-------------------------|-----------------------|-----------|
| Heating Total    | 4.3                     | 10.7                  | 8.1*                    | 17.1                  | +60\%     |
| Cooling          | 0.9                     | 2.2                   | 0.4                     | 0.9                   | -57\%     |
| AHUs             | 7.0                     | 23.3                  | 8.1.6                   | 20.2                  | -13\%     |
| Aux. Energy      | 1.4                     | 3.5                   | 1.8                     | 4.6                   | +32\%     |
| BAS **           | 0.1                     | 0.2                   | 0.1                     | 0.2                   |           |
| Lighting **      | 8.50                    | 21.3                  | 8.5                     | 21.3                  |           |
| Total Demand     | 61.1                    |                       | 64.3                    |                       | +5\%      |
| Gain PV-Roof     | 20.2                    | 50.6                  | 20.6                    | 51.4                  | +2\%      |
| Gain PV-Facade   | 4.0                     | 10.0                  | 4.5                     | 11.1                  | +11\%     |
| Gain PV-T (electrical) | 0.3             | 0.7                   | 0.3                     | 0.7                   | 2\%       |
| Gain PV-Total    | 24.5                    | 61.3                  | 25.4                    | 63.5                  | +4\%      |
| Energy balance   | +0.2                    |                       | -0.8                    |                       |           |

*: power consumption heat pumps = 5.9, gas consumption: 2.2, **: not measured/design value

4.2. Performance assessment of the photovoltaic plant

The specific PV gain of the roof installation amounted to $981.6 \text{ kWh/kW}_p$, the facade to $447.9 \text{ kWh/kW}_p$ and the PVT to $869.0 \text{ kWh/kW}_p$. The maximum power generated by the whole PV plant amounted to $430.8 \text{ kW}$ on June, 22nd at 2 pm. It is noteworthy to mention here that an inverter controlling one facade BIPV group was defect during summer 2018. This breakdown led to an eletrical gain loss estimated in a range of 5.0 to 10.0 \text{ MWh}, which could not be accounted for in the energy balance [10]. The self-consumption reached values above 90\% from January to April and from October to December as depicted in figure [6]. These results are above typical values for residential buildings equipped with PV-plants. It can be explained by the fact that the offices, the canteen and the servers, whose energy demand is high compared to the PV gain during the winter months, are mostly used during the day and can thus directly benefit from
the solar power production. The mean yearly value of the degree of electrical self-sufficiency for the whole building amounted to 23.7% and was above 30% from April to September 2019.

4.3. Performance assessment of the heat and cold generation

In 2018, the total heat consumption was higher by +78% than the targeted value. This overshooting is due to a higher consumption of the main heat consumers - the TACS and the AHUs - whose control settings (time-schedules, temperature set points,...) needed being adjusted during the first months of operation. The performance of the heat pumps are below the expectations. The Seasonal Performance Factors (SPF) of the heat pumps 1 and 2, calculated for the system boundary of the heat pump units, reached 4.6 and 4.0 respectively and lie below the targeted SPF of 4.8. The heat pumps contributed to 87% of the total heat production amounting to 579 MWh and heat from the gas boiler has only been consumed to a minor part, corresponding to approx. 44 MWh. A detailed analysis of the heat pump operation revealed that heat pump 1 has run about one and a half times longer than heat pump 2 due to an issue in the alternating operation control, which could lead to earlier wear and efficiency loss of heat pump 1. Furthermore, the mean temperature level of the heat supply for the AHUs lied with 35°C above the design value of 32°C and reached a values above 40°C at some operation points in winter. An optimization of the temperature levels could lead to higher SPF of the heat pump system and thus enhance the total performance. The operation of the cooling system was very high in 2018 with a seasonal energy efficiency ratio (SEER) of 45.0 and a measured specific primary energy that undercut the targeted values by -51%.

Even if optimization potentials are remaining, the monitoring results confirm that this kind of heat and cold generation system based on a low-exergy principle is a cornerstone for the success of the plus-energy concept.

4.4. Load curves analysis

Figure 7 shows a typical profile for a working day in summer. First, the base load of the whole building at night is about 120 kW and the maximum load is about three times larger at 1 pm with a peak at 335 kW. The load profile of the facade shows a local maxima of about 40 kW at 10 am and at 4 pm corresponding respectively to the maximum power of the BIPV groups of the east and of the west oriented facades. This specific construction of the BIPV installation with BIPV groups almost all around the facade (with the exception of the North orientation) contributes to a maximum yield. During that typical working summer day, power from the grid is drawn at night and with a consumption peak at around 6 am with the start of the AHUs and lighting. Power is fed into the grid from 10 am to 5 pm with a peak at 3 pm. The figure also shows clearly that the load curve of the services within the EnEV-boundary is almost constant due to the fact that lighting is not measured but estimated with a constant consumption and that the power consumption of the AHUs is almost steady. Furthermore, one notes that the load curve within the EnEV-boundary is far beneath the total load curve of the building due to the power consumption of the canteen, the plug loads and the servers. For the winter, Figure 8 shows that the power is mainly consumed from the grid as expected. The PV plant alleviates the energy balance to only to a small part. The curve load of the EnEV-boundary is dominated in winter mainly by lighting and the heat pumps.
5. Conclusion and outlook

The results of the first full year of monitoring of the new town-hall of the city of Freiburg, designed as a net plus-energy building, have shown that a plus energy balance has almost been reached within the defined boundary, under the limitation that the electricity consumption of the lighting has been estimated as it could not be measured. The analysis of the energy balance showed that the BIPV system on the facade, even though it only contributed to approx. 18% of the total solar gain in addition to the PV installation of the roof, is indispensable to reach this result for this type of building. Also, the performance of the building services and especially the very low specific energy consumption for cooling contributed significantly to a very high energy efficiency compared to mechanical cooling with classical chillers. The performance of the heat pump system revealed optimization potentials with lower COP as expected. After one year of operation, the presented results are encouraging as the net plus-energy objective could have been reached without a flaw in one BIPV group, if bio-gas instead of fossil gas would have been used and through fine-tuning of the heat and cold generation system. The city of Freiburg is currently implementing corrective measures. Nevertheless, the solar radiation was particularly high and the heating degree days were 5% below the reference in Freiburg in 2018. Additional measurements are thus necessary to assess the robustness of the concept over the years. The design phase of the second net plus-energy building of the future campus with an approx. similar
area will start in 2019 and the results presented here will serve as reference in the design process. Additional analyses on hygrothermal comfort, on the performance of the PVT-collectors and of the building services are currently being conducted and will be published at a later date. A special emphasis will also be set on the interaction of the building with the local power grid, and especially on the role and control strategies of the heat pump system that realizes the desired sector coupling between heat and electricity sectors.

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