Identifying the feasibility of establishing a Passive House School in central Europe: an energy performance and carbon emissions monitoring study in Germany

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Abstract

The development of the Passive House (PH) Standard has provided an important opportunity to minimize the energy consumption of buildings in accordance with global targets for climate change and energy savings. This article presents a 3-year monitoring study (operation and optimization) of energy performance and CO_2 emissions in a newly built Passive House school building in southern Germany. Monthly, annual and specific energy demands (including heating, cooling and electricity) were analyzed and evaluated using three energy- benchmarking systems: EnEV, LEE and PHPP. Sorted load duration profiles for heating and electricity from 2012 to 2014 have also been presented and assessed. In addition, the CO_2 equivalent emission resulting from the total energy consumption of the building was calculated. The results illustrate that the newly built Passive House school building could meet the requirements of the three energy-benchmarking systems and would reduce the total annual CO_2 emissions of a standard school building in Germany by up to two-thirds.

Keywords

Passive House School Building; Energy Consumption; Heating and Cooling; Electricity Use; CO_2 Equivalent Emission; Germany

1. Introduction

As defined in the Energy Performance of Buildings Directive (EPBD) 2002/91/EC [1] and its update 2010/31/EC [2], the 'Nearly Zero-Energy Building (NZEB)' designation in Europe indicates a building with a very low energy consumption. The energy can be explained as 'the actual energy that is consumed in order to meet the different needs associated with its typical use and shall reflect the heating energy needs and cooling energy needs (energy to avoid overheating) to maintain the envisaged temperature conditions of the building; and domestic hot water needs' [2]. In addition, the 'very low amount of energy demand' in NZEBs should be mainly supplied through renewable sources, including both on-site and nearby renewable solutions [2]. For applications and investigations of NZEBs, residential buildings were the first target and still are a research focus in Europe (e.g. Passive Houses [3]), especially in the EU countries with cold climates [3, 4]. Recently, school buildings in Europe have received increasing attention from researchers, building designers and engineers [5, 6, 7], because of the strict requirement of the new European directive 2010/31/EC [2]. More importantly, the application of Passive House standards in school buildings has been recognized as one of the critical solutions for achieving the NZEB standard and meeting the directive requirements in educational buildings [4, 8].

Thus this article presented a 3-year monitoring study of energy performance in a newly built school building in southern Germany, which was designed based on Passive House Standard [3]. Monthly, annual and specific energy demands (including heating, cooling and electricity) and relevant CO_2 equivalent emissions have been comprehensively evaluated using three key energy-benchmarking systems, aiming to verify the feasibility of establishing a Passive House School Building in central Europe. This article is structured as follows. In Section 2, a literature review of passive houses and low- energy school buildings is first presented, and the research question is achieved from the discussions. The research methods (Section 3) include descriptions of the school building, the energy performance monitoring procedures, and three benchmarking systems. Section 4 presents an analysis of the monitored data of energy consumption of the heating, cooling and electrical systems and their equivalent CO_2 emissions and is followed by a discussion (Section 5). Finally, conclusions and future work are given in Section 6.

2. Literature review

This literature review includes the Passive House Standard and its applications in residential buildings, and the low-energy solutions in school buildings. A research question is presented in the last part.

2.1 Passive House residential buildings

As one type of low-energy building, the Passive House was first introduced and developed in northern Europe [3, 9]. The aim of the Passive House is to explore the best possibility for applying passive technologies, such as passive solar, internal gain, night ventilation, in buildings. [3, 10-11]. The main energy standards for a Passive House in central Europe are defined as follows: annual heating/cooling demand ≤ 15 kWh/m^2; total primary energy consumption (including electrical applications, heating/cooling, and hot water) ≤ 120 kWh/m^2; and air infiltration rate ≤ 0.6 h^{-1} at 50 Pa (N/m^2) [9, 11-

13].

Most of the available studies of Passive Houses have been implemented in residential buildings [13]. Figueiredo et al. [14] and Fokaides et al. [15] presented optimization studies of two passive houses based on thermal performance and overheating problems in two Mediterranean regions. The analysis of Mihai et al. [16] showed that one passive house using a ground-air heat exchanger and that PV can achieve proper thermal comfort with a minimum energy consumption of approximately 13 kWh/m^2 per year. In a cold climate, Shan et al. [17] tested and analysed the thermal performance of a combined solar heating system integrated with an air source heat pump (ASHP) in a Chinese passive house. The electricity consumption of ASHP accounted for approximately one-third of the total heating energy consumption during the coldest period. Dan et al. [18] introduced a way to reduce energy consumption by implementing the Passive House concept in Eastern Europe. Using data collected over two years, Ridley et al. [19] tested the thermal performance of two adjacent passive house buildings in Wales, and some useful design strategies have thus been achieved. The extra cost of low-energy houses and passive houses was 4% and 16% respectively, in comparison to the standard house [20]. In addition, in a life-cycle assessment, Dodoo et al. [21] investigated the effect of the Passive House Standard and Swedish building codes on the primary energy use of residential buildings. More recently, more comprehensive investigations of passive house performance have been initiated in Europe. Mahdavi et al. [22] studied and compared one passive-house apartment with another low-energy apartment in Vienna in terms of monitored indoor conditions (indoor temperature, relative humidity and CO_2 level), metered energy use, CO_2 emissions, embodied energy, user evaluation, and construction cost data over 5 months.

2.2 Low-energy school buildings

It has been noted that the standards of the Passive House or low-energy building have been successfully applied in educational buildings [5]. Normally, unlike residential buildings, educational buildings have very densely occupied classrooms and meeting rooms [5]. Thus, the level of environmental requirements for educational buildings is relatively high [5]. As mentioned in a study [23], the improvement of learning and teaching performance in schools requires a higher level of thermal comfort and indoor air quality, which can significantly affect the health and well-being of students and teachers. However, the operational energy cost in educational buildings must be very high level in order to achieve proper comfort and indoor air quality in classrooms and meeting rooms [6]. Therefore, it is a big challenge to balance the increasing requirements of environmental performance standards and the pressure to reduce energy costs. Based on the assessment of energy and thermal comfort in a French university building, Allab et al. [24] produced a building energy model, which can be used to predict building operating strategies for energy savings, in particular for pre-heating solutions unoccupied periods (e.g. holidays and weekends). Barbhuiya and Barbhuiya [25] investigated how the ventilation strategy for a typical educational building in the UK can influence energy consumption and how exactly it affected the thermal comfort of occupants. Indoor air temperature and lighting levels in the building have been monitored. In a Finnish study, the monitored energy consumption indicated that electricity is the dominant energy type in new educational buildings [26]. Natural ventilation could be an optimal passive strategy to achieve thermal comfort and save energy in schools in warm climates [27]. Huang et al. [28] proposed passive strategies for how to design naturally ventilated solutions in a school building that was, certified as a higher-level green building in a sub-tropical climate. A tailored approach for energy diagnosis for building refurbishment was proposed in a project of an Italian educational building [29]. The evaluation of the energy, environmental and economic impacts of each retrofit action was carried out. An energy audit study in a school [30] found that an annual building energy reduction of approximately 6.5% could be expected, while the payback time was less than half year. More importantly, it was possible to reduce carbon emissions by up to 648 tons per year [30]. In an educational building in Saudi Arabia, a study found that energy auditing would play a powerful role in helping save energy by up to 35.3% and that the payback period is approximately 2.7 years [31]. Raatikainen et al. [32] compared electricity and heating energy consumptions in six school buildings in Finland. However, the variation in electricity consumption was very low between these buildings. Deshko et al. [33] developed a methodology for energy - efficiency assessment in university campuses in Ukraine. The factors affecting energy consumption in university buildings were comprehensively investigated, while the possibilities and problems of applying certification to limit energy use were also identified.

2.3 Research question

Given the discussion above, energy performance and relevant low-energy solutions in educational buildings have been broadly investigated at various locations across the world. Most studies have just emphasized the necessity and importance of passive solutions to achieve energy efficiency and indoor comfort and health, e.g., natural ventilation [27-28]. In comparison to passive solutions, there is a clear lack of research on the improvement of active solutions, especially for renewable/low-carbon systems [8]. On the other hand, studies of energy retrofitting and auditing methods in schools have demonstrated that it is a big challenge to balance the increasing requirements of indoor thermal comfort and air quality (mainly relying on active systems) and the target to reduce the cost of operational energy systems [29-31]. In addition, the trend of the 'Nearly Zero-Energy Building' and relevant energy policies (e.g., 2010/31/EC) [2] will continuously encourage more investigations into low-carbon technologies in educational buildings, especially for non-passive solutions.

In fact, it could be very hard to deny that few studies in educational buildings have been conducted with the stricter Passive House Standard [5], which were recommended as an effective solution to the NZEB goal [4]. In addition, one literature review [8] noted that before designers and engineers can apply practical design guidelines and strategies to fully meet current and/or future requirements (e.g., NZEB), it is still necessary to monitor the long-term performance of new Passive House buildings integrated with renewable/low-carbon systems. Thus, in this article, a 3-year monitoring study in a newly built school building was conducted to answer one critical research question: is it feasible or practical to design and build a low-energy school building using the Passive House Standards in central Europe?

3. Research methods

3.1 Location, climate conditions, and school building

This article studied a newly built school building in Erding, Germany (Latitude: 48°18’40”, Longitude: 11° 53’ 49”). This location has a temperate continental climate, which is the dominant climate type in central Europe (https://www.climatestotravel.com). The coldest month in Erding is January, and its average temperature is 0 °C; while the warmest month is July, and its average temperature is 18.5 °C. The sunshine time from November to February is generally lower than 3 hours per day. However, there are an average of 7-8 hours of sunshine per day from May to August.

This new school building, named the FOS/BOS (Figure 1), has three blocks, including the North Building, South Building and a fully glazed atrium in the middle to connect the two building blocks. The main building façade faces southeast. As shown in Figure 2, with four stories, North Building has a dimension of 81 × 17.78 × 14.53 m, while the South Building has three stories and a dimension of 71 × 12.78 × 11.32 m. The glazed atrium has a sloped roof and a dimension of 5.8 × 40.20 × 12.03 m. FOS/BOS has various spaces including a lecture room, offices, IT room, laboratory, storeroom, toilet, common room, kitchen, etc. Opened in March 2011, this school building was designed to be used by 750 students and staff.

This building was designed based on Passive House standards [5]. Materials, configurations and thermal properties, solar energy transmittance properties and typical building service systems of the building can be found in Table 1. The heat transfer coefficients (U-values) of the building envelopes are set with very low values, i.e., 0.128 W/m^2K (external wall), 0.095 W/m^2K (roof), 0.176 W/m^2K (ground floor), and 0.87 W/m^2K (glazing surface). The ventilation rate of the mechanical ventilation system and the average infiltration of the building envelope are 660 m^3/h and 0.01 h^{-1}, respectively, and they were designed based on the human health and comfort issues mentioned in the Passive House Standards [5]. In addition, a groundwater cooling system was planned to provide cooling in the summer for 750 persons with a volume of 22400 m^3/a.

3.2 Prediction of energy demand: heating, cooling and electricity

At the planning stage, as shown in Figure 3, three energy balance boundaries [34] were applied in predicting and analyzing the energy demand in the FOS/BOS building, including Q_c, Q_f, *and* Q_b. The energy Q_f represents the actual energy consumed by the FOS/BOS building. Q_c includes the thermal losses of heat supply pipelines when compared with Q_f. Since the kitchen has been classified as a special use in the planning phase, the balanced energy Q_b is determined by excluding the heating, cooling and electrical power supply of the kitchen. In general, two energy sources were used: one is the geothermal district heating system, providing heating energy from the secondary-network of the adjacent building [i.e., the catering centre, see Figure 1 (c)], while the other is the public power grid, which provides. In addition to the electricity used by the night ventilation system for cooling the building in summer, the thermal groundwater cooling system will also contribute to the cooling energy consumption.

Three building energy-benchmarking systems were applied to predict energy demand based on the three energy balance models above: the Energy Saving Ordinance (EnEV) [35], the Passive House Planning Package (PHPP) [12] and the electrical energy in building construction (LEE) [36]. The EnEV standard (version 2007) was adopted to estimate the energy-savings of thermal insulation and plant technologies [35]. The heating demand was calculated by the PHPP from the Passive House Institute of Darmstadt [12]. For a further estimation of overall balance, the guidelines of LEE from the Institute of Housing and Environment [36] was employed. The three systems have different algorithms for determining energy requirements. For example, for the PHPP, a larger range of internal heat gains in buildings are taken into account, whereas the EnEV 2007 does not include some techniques (e.g., heat recovery) [35]. As mentioned above, for the three benchmarking systems, different boundary conditions have been considered in the calculations. Typical differences can be found in the energy reference area (ERA). Table 2 shows that ERA varies by calculation method. The kitchen is included in the calculation using EnEV, while it is not considered by PHPP and LEE. In addition, stairways and circulation areas in the PHPP are included in calculations through the weighting factors.

Table 3 gives the predicted specific heating energy demand using different methods. There are two types of values according to PHPP; monthly and annual specific heating energy demands are 10.4 kWh/m^{2}a and 10.9 kWh/m^{2}a, respectively. Both demands have the same units in order to conduct a practical comparison between them. Table 1 gives the input data used for the PHPP calculations, including the thermal envelope of the building, ventilation system and weather data file. LEE and EnEV showvalues of

12.4 kWh/m^{2}a and 31.3 kWh/m^{2}a respectively, which are higher than the targets of PHPP.

Table 4 shows the predicted specific final electrical energy according to the energy reference area (ERA) calculated in the planning phase. Since PHPP is only used to determine the thermal energy demand, the comparison was based on EnEV and LEE. Their electricity consumptions are 19.6 kWh/m^{2}a (EnEV) and 21.45 kWh/m^{2}a (LEE), respectively. Both systems only focused on the electricity demands of the building services but not the total electricity consumption.

3.3 Monitoring of energy performance

3.3.1 Introduction of on-site monitoring

Monitoring was conducted by the Bavarian Centre for Applied Energy Research (ZAE Bayern) to understand if the design targets for energy performance were achieved. The monitoring project consisted of operational optimization and evaluation phases. The project objectives of operational optimization and evaluation phases involved several goals: to conduct the detailed performance monitoring via the building management system (BMS); to achieve a proper level of energy efficiency and indoor comfort through operational optimization; to lower operational and maintenance costs; and to identify performance relevant to comfort and energy consumption. In this article, the evaluation of energy performance will be mainly investigated based on heating, cooling and electrical systems.

The evaluation phase began in April 2013. Due to the continued optimization of building operation, the energy evaluation was carried out until the end of December

2014. Based on the monitored data, a comprehensive energy performance evaluation has been performed with several critical aspects:

- Energy balance and the annual energy consumption of heating, cooling and electricity have been presented.
- The climate-adjusted energy requirements for a reference year have been identified, and a comparison with the specifications/standards has been conducted.
- Annual CO_2 equivalent emissions have been assessed.

The recording and evaluation of the measurements have been initiated within the optimization phase to identify faults and optimization potential. This phase included the improvement of ventilation capacity, the optimization of heating control (e.g., the set-point of the heating system and the ventilation supply temperature were changed from 20 ºC to 19 ºC), and the optimization of mechanical ventilation control (e.g., the operational mode and ventilation rates can be adjusted based on occupancy, indoor CO_2 concentration level, and seasonal variations). The evaluation of the operational energy consumption and the comparison with targets set during the planning phase were also performed.

3.3.2 Heating system monitoring

The FOS/BOS building is indirectly heated using a district heating system. In this study, a secondary-side return pipe with a temperature of 50 ºC from the adjacent catering centre [Figure 1 (c)] is to supply the heating. For the district heating network, a pipe temperature of approximately 60 ºC is supplied by the underground geothermal system. Table 5 lists the heat meters used for monitoring the heating energy, while Figure 4(a) gives their distributions in the two buildings of the catering centre (primary side) and the FOS/BOS (secondary side). Figure 4(a) includes four WMZ/KMZ-combination meters for the RLT North, RLT South, RLT Event and RLT Kitchen ventilation systems, which can also be used for the cooling system [Figure 4(b)]. In addition, as shown in Figure 4(a), there are five meters for the heating system, including the wall heating UG west, wall heating UG east, wall heating north, wall heating south and floor heating meters. The main heat meter $(WMZ)_c$ was installed on the primary side on 10 January 2012, and can monitor the total energy consumption of the FOS/BOS school building, including the thermal losses of the pipeline between two buildings. In addition, three heat meters (WMZ) were installed on the secondary-side heating circuit bar distributor in the FOS/BOS plant room and included the meter for the wall heating of the North Building $(WMZ)_1$, the meter for the wall heating of the South Building $(WMZ)_2$ and the meter for the floor heating $(WMZ)_3$. There are also four WMZ/KMZ-combination meters, each of which corresponds to their own heating and cooling registers for four large RLT systems. Their hydraulic connecting pipelines are operated as combined heating and cooling circuits.

At the end of September 2013, another main heat meter $(WMZ)_f$ was applied on the secondary side of the FOS/BOS heating circuit distribution bar, because the primary-side heat meter $(WMZ)_c$ failed to provide sufficiently accurate energy data during the project. In addition, the new meter was used based on some operating problems found at the 85 m underground connecting pipeline between the heating centres of the two buildings, i.e., significant heat losses and a large temporal dynamic. The temporal dynamic indicates that a distance of 85 m could cause the time delay observed during heat transfer.

3.3.3 Cooling system monitoring

Modern low-energy buildings are generally equipped with thermal insulation and an airtight building envelope. This is very common for buildings built using the Passive House Standard. However, solar gains and internal heat gains (e.g., occupants and electrical equipment) in summer would cause overheating. Therefore, it is essential to use cooling systems to provide proper indoor thermal comfort.

In the FOS/BOS building, night ventilation was used as a cooling strategy as mentioned in the Passive House Standard [37]. The electricity consumption used for the ventilation systems was monitored (see Section 4.3). In addition, the cooling demand from daytime ventilation systems, IT rooms and the server room are supplied by the thermal groundwater system. Table 6 lists cooling meters used for monitoring and calculating the cooling energy consumption in the study. In addition to the four WMZ/KMZ-combination meters for the ventilation systems (RLT North, RLT South, RLT Event and RLT Kitchen), Figure 4(b) indicates the meters used for the cooling system including the $(KMZ)_1$ for the cooling ceiling in the IT rooms, the $(KMZ)_2$ for the server room cooling, and the (KMZ)g for all of the underground water cooling.

4. Results

This section includes the analysis of the monitored energy data and equivalent CO_2 emissions in the FOS/BOS building.

4.1 Heating energy consumption

4.1.1 Heating energy consumption: primary side

Based on the main heat meter WMZ_c (Figure 4), the total heating energy consumption $Q_{t,c}$ from the heating centre in the catering centre can be determined. In addition, the recorded heating load $P_{t,c}$ can help create the load profile and sorted load duration curves. Figure 5 illustrates the monthly variations of total heating energy consumption $Q_{t,c}$ of the FOS/BOS building (including thermal losses from the pipeline between the two buildings). There was a six-day data gap in the data logger from late May to early June. This is the reason why no accurate monitored data were available for those two months. However, the lack of data did not have any impact on the heating energy consumption since this period is typically not a heating season. The two heating periods in 2011-2012 and 2012-2013 ended in April (i.e. 26 April 2012 and 25 April 2013), while the 2013-2014 heating season ended one month earlier (i.e., 22 March 2014). The date to switch on heating by the BMS was in October for all three years (i.e. 29 October 2012, 11 October 2013, 22 October 2014). The highest monthly heating-related energy consumption was 32240 kWh, and it happened in February 2012.

In Figure 5, it can be observed that nearly all monthly heating energy consumptions notably decreased during the heating season from 2012 to 2014, which was achieved via the improvement of ventilation capacity and heating control, e.g., changing the set-point of the heating system and ventilation supply temperature from 20 ºC to 19 ºC. In February 2012, the energy consumption decreased by approximately 64% ((32240 kWh – 11620 kWh)/32240 kWh) in comparison to the same period in 2014. This finding could indicate that the optimization solution was effective. However, due to the colder weather in March, April and October of 2013, the heating consumption was higher than that in 2012.

Figure 6 illustrates the annual heating energy consumption $Q_{t,c}$ when using the catering center as the balance boundary. The annual balance of the period from 1 February 2012 to 31 January 2013 reached a maximum value of 105520 kWh/a. For the period from 1 January 2014 to 31 December 2014 (the optimization phase was completed), the heating energy consumption was 61730 kWh/a. The optimization caused a significant energy reduction of 41.5%. This reduction could be explained by the fact that this period was generally warmer than the reference year, while an increased number of building occupants from 750 to approximately 900 would increase the internal heat gains.

In addition to the heating energy $Q_{t,c}$, the heating load $P_{t,c}$ has also been monitored. Figure 7 demonstrates the thermal load profile and sorted annual load (each load value is in hours per year) duration in 2014 and the sorted annual load duration in 2013 and 2012. The sorted load duration curve of 2014 shows significantly lower values compared with 2013 and 2012. However, the heating load was found to be significantly higher at the beginning of operation after the Christmas and New Year holidays (e.g., its peak is above 140 kW). When the optimization phase was started, the heating load of 100 kW could not meet the demand, even though the catering centre could still supply the pipe water temperature of approximately 60 °C.

4.1.2 Heating energy consumption: secondary side

The heating energy consumption across a certain period could be calculated based on the primary-side heat meter $(WMZ)_c$ or via the sum of the heating energy consumption of the individual secondary-side heating circuits. The building heating consumption $Q_{t,f}$ is the sum of the three heat meters $(WMZ)_n$ plus the sum of the four combination-meters $(W/KMZ)_n$ and is described as follows:

$$Q_{t,f} = \sum_{n=1}^{3} Q_{t,(WMZ)_n} + \sum_{n=1}^{4} Q_{t,(W/KMZ)_n} \quad (1)$$

Figure 8 illustrates the monthly heating energy consumption in a stacked bar chart broken down by heating circuit. These results were compared with the secondary-side main heat meter $(WMZ)_f$, which measures the total heating consumption of the building. Only small deviations within the measurement tolerance can be found. Compared with February 2012, energy savings due to control system improvement and optimization in the RLT North and RLT Kitchen are significant (from 28806 kWh to 6047 kWh). This result corresponds to the variation of primary-side heating energy consumption (section 4.1.1, Figure 5). However, the data from 2014 are only partially comparable because of the warmer winter and the higher occupancy rates.

Figure 9 shows the annual heating energy consumption in the FOS/BOS building. The largest energy consumption was found in the space heating systems, including wall heating North, wall heating South, and floor heating in the atrium. The numerical values on the top of the bars indicate the total energy consumption $Q_{t,f}$ based on the balance boundary of FOS/BOS building. Meanwhile, the numerical values on the bottom of the bars indicate the energy consumption $Q_{t,b}$ excludes the heating energy consumption of kitchen. In 2012, the heating consumption of the RLT North was significantly reduced after optimizing the control technologies, including user-oriented mechanical ventilation control, and the occupant and air quality- based ventilation operating mode and ventilation rates. From winter 2012-2013, the energy consumption of the main ventilation systems increased because of the increased flow volumes.

Moreover, significant reductions in annual energy consumption for space heating could be found in the building, particularly for the wall heating South area. The energy consumption of the RLT Kitchen clearly decreased, although it was only partially in operation in 2012. The heating energy consumption of the building dropped from approximately 89.6 MWh/a in 2012 to 54.2 MWh/a in 2014. Meanwhile, the heating energy consumption without the kitchen area decreased from 81.0 MWh/a in 2012 to 51.0 MWh/a in 2014.

Compared with Figure 6, there was also a reduction of around 53% ((15929 kWh/a – 7557 kWh/a)/15929 kWh/a) in the heat transfer losses between the heating centres of catering centre and FOS/BOS.

4.1.3 Heating energy benchmarking

Figure 10 demonstrates the annual specific heating energy consumption calculated by the monitoring data and by three balancing methods: PHPP, LEE and EnEV (using three different energy balance boundaries). The specific heating energy $Q'_{t,c}$ (balance boundary is the catering centre) and $Q'_{t,f}$ (balance boundary is the FOS/BOS) are calculated in terms of the energy reference area (ERA) of the benchmark systems (including kitchen). The specific heating energy $Q'_{t,b}$ is achieved using the energy reference area (ERA) of benchmark systems without considering the kitchen (see Table

2). The predicted values using the three benchmarking systems (Table 3) are also given in this figure (dashed line) for comparison.

As for Figure 10, the heating energy obtained by the EnEV calculation (red bar) is much lower than the predicted t value 31.3 kWh/m^{2}a since 2012 (just around 12 kWh/m^2). Meanwhile, all heating energy consumption analyzed by LEE was found below the predicted value (12.4 kWh/m^2). The requirement from the PHPP method (10.9 kWh/m^2) could have been achieved by implementing the optimization measures during 2013. However, if the predicted value of 15 kWh/m^{2}a was applied (the limit for issuing the Passive House certificate), all heating energy consumption would fall into the proper range.

Overall, the results discussed above have proven as positive. The heating energy consumption of the building in 2014 was below 8 kWh/m^{2}a (EnEV 7.1 kWh/m^{2}a; LEE without kitchen 6.7 kWh/m^{2}a, PHPP without kitchen 7.7 kWh/m^{2}a) due to a warmer climate period. The electrical consumption for the heat supply will be introduced in Section 4.3. Since the year 2014 had a relatively warmer winter, its heating energy consumption does not correspond to the long-term variation. A climate correction will have to be carried out to correct for the variation in heating demand.

4.1.4 Climate-adjusted heating demand

To effectively analyze the heating energy demand, a standardization was used. A climate adjustment model was applied to mitigate the impact of climate change. In this study, the degree days (D) and heating days (H_d) were employed [38] to adjust the heating energy demands.

Figure 11 shows a comparison of different evaluations based on the method recommended by the German Weather Service (DWD) [39] and the Climate Adjustment Method produced by the Institute for Housing and the Environment (IWU) [40]. Defined by the IWU, the heating days H_{d10} indicate that the heating system will be operated during the days when the outside temperature drops below 10 °C, while degree days D20/10 include the days that the indoor average temperature is heated to 20 °C when the average outside temperature is 10 °C. They were proposed as an environmental condition for assessing Passive House and low-energy buildings. Both the DWD and IWU also adopted a climate factor f_c for energy evaluations according to the EnEV standards [35]. From the EnEV 2013, the reference location was set as Potsdam (P) instead of Wuerzburg (WUE).

A summary of climate-adjusted heating energy demands of the FOS/BOS building (located in Erding) is given in Table 7. In 2014, the long-term average values of heating energy are approximately 8.0 kWh/m^{2}a by the EnEV method and 9.1 kWh/m^{2}a by the PHPP method (for the energy to be balanced without the kitchen; degree day D20/10). If the standardization for the building with high heat capacity is carried out based on the heating-days (H_{d10}), 7.2 kWh/m^{2}a and 8.2 kWh/m^{2}a can be achieved using the EnEV and PHPP methods respectively. In general, the climate-adjusted heating demands in 2014 are still lower than the predicted values (Table 3), even though a climate factor (> 1) was used in the calculation to correct the lower monitored heating energy due to a warm winter. In addition, the value in Table 7 is significantly lower than the target value (31.3 kWh/m^{2}a, EnEV) in Table 3, because no heat recovery was included in the EnEV standard.

4.2 Cooling energy consumption

4.2.1 Cooling energy consumption: primary side

A cooling meter $(KMZ)_g$ was installed in the primary groundwater circuit to monitor thermal groundwater use. The volume $V_{c,g}$ of groundwater was also monitored. At the beginning of the project, the annual groundwater consumption of around 74689 m^3/a was more than triple that of the quota of 22400 m^3/a approved in the planning phase. This is mainly because the server room was cooled continuously. There are three levels of regulated volume for the primary circuit pump, designed for the maximum load of the entire building. In winter, the unit volume is 11 m^3/h, which is the lowest level. An extremely low temperature difference of less than 0.1 K was then achieved between supply and return flow. The groundwater cooling system was designed to allow a maximum difference of 5 K at the proposed flow rate. Due to the high rate of water flow, the electricity consumption of the server cooling was higher than that for cooling computer equipment. The initial parameter optimization in the control system has resulted in some improvements. Some supplementary optimization solutions were also applied, such as the use of waste heat from the server room in winter and the plate heat exchanger for the primary circuit.

Figure 12 and Figure 13 illustrate the annual and monthly groundwater consumptions respectively. The optimization solutions implemented in autumn 2013 met the requirements (target: 22400 m^3/a). Groundwater consumption has been significantly reduced from around 75000 m^3/a to around 7500 m^3/a, which is lower than the proposed quota (22400 m^3/a) as expected. To ensure that the annual groundwater consumption can meet the requirements, monitoring was continued after the end of this project on 31 December 2014.

4.2.2 Cooling energy consumption: secondary side

Figure 14 and Figure 15 show the monthly and annual cooling energy consumption in terms of the cold-water circuits. As shown in Figure 15, the largest cooling energy consumption of approximately 6.3 MWh/a was in 2014 and was for the server room. However, only around 0.27 kWh/m^2a was used for the ventilation system of the entire building (RLT North and South) and IT rooms. The total cooling energy consumption without the kitchen in 2014 was approximately 8.3 MWh/a. The specific cooling energy was consequently around 1.1 kWh/m^2a.

Furthermore, despite the increased number of students and flow volume of the fresh air supply, the cooling consumption of the air-conditioning systems could be obviously reduced. However, since autumn 2013, a moderate increase was observed.

4.3 Electrical energy consumption

4.3.1 Evaluation of electricity consumption

The electrical systems in the FOS/BOS building include the building service systems (heating, cooling, ventilation and lighting) and IT equipment.

Figure 16 illustrates the electricity load profile in 2014 and the sorted load duration curves from 2011 to 2014. The peak load occurred within the normal occupancy time. However, low electricity consumption can be found on weekends and school holidays in July, August and September (ranging from 5000 h to 6120 h). Although electrical services (IT, fans and HVAC systems) were increased in the FOS/BOS building, the base load dropped from around 13 kW_{el} in 2011 to a value lower than 10 kW_{el} in 2014 after implementing the optimization solutions. It can also be found that optimization via optimizing the control systems and operation strategies of the HVAC obviously reduced the base load compared to the previous load from 2011 to 2013.

Given Figure 16, the upper medium load range obviously increased compared to the base load. This is mainly due to the improvement in RLT flow volume and the increased student numbers every year. To meet the requirements of thermal comfort, the operation of the larger ventilation facilities in the two main RLT systems and a pre-ventilation application in the morning began at the end of the summer holidays in 2012, which contributed to the significant increase in the medium load. The peak loads of electricity consumption are listed in Table 8. The table shows that there is a slight increase of approximately 8.5 kW_{el} in 2014 (104.55 kW) compared to the consumption in 2011 (96.06 kW), based on the abovementioned reason.

For detailed electricity consumption in individual zones (e.g. kitchen, RLT), integrated electricity meters have been used to record consumption via the control system. Figures 17 and 18 illustrate the monthly and annual electricity consumptions, respectively. Both figures present the total electricity consumption of the building without considering the kitchen. For Figure 18, the electricity consumption (excluding the kitchen) slightly decreased by 3.2% ((150352 kWh/a - 145578 kWh/a)/(150352 kWh/a)) over the course of the project, although the total electricity consumption increased from 168635 kWh/a to 176566 kWh/a with the kitchen. The increased consumption when the kitchen was included occurred because it was temporarily not used at the beginning of 2012.

4.3.2 Electricity energy benchmarking

Figure 19 illustrates the evolution of the continuously monitored specific electricity consumption and the predicted values using two benchmarking systems (as shown in Table 4). The total electricity consumption in 2014 (excluding the kitchen) was below 18.25 kWh/m^{2}a, which is obviously much lower than the predicted value of 21.45 kWh/m^{2}a according to the LEE. For the EnEV, the total electricity consumption in 2014 (including the kitchen) was 23.11 kWh/m^{2}a, which was higher than the predicted value of 19.6 kWh/m^{2}a. The annual electricity consumption in 2014 (excluding the kitchen) is 145578 kWh/a. Thus, the specific electricity consumption is 19.48 kWh/m^{2}a (excluding the kitchen) [41], which is lower than the EnEV predicted value of 19.6 kWh/m^{2}a. Except for the building services, this calculation included other special applications in the FOS/BOS building, e.g. outdoor parking lighting, regular testing and maintenance systems during school holidays, etc. Therefore, the FOS/BOS building could meet the requirements for electricity consumption based on the LEE and EnEV after the optimization phase.

4.4 CO_2 equivalent emission

This section gives the calculations of the CO_2 equivalent emissions relating to the energy consumption in the FOS/BOS building.

The CO_2 equivalent emission was estimated for the energy consumption of the heating system and the electricity use, which can be calculated by the following algorithm: Estimated annual electricity usage × electricity $f_{CO2,e}$ (0.628 kg/kWh) + Estimated annual heating demand × district heating $f_{CO2,dh}$ (0.177 kg/kWh) [42]. This methodology is applied based on two conditions: 1) the emission factor for each type of energy resource and 2) the adjustment factor as a function of time [34]. Thus, the calculated CO_2 equivalent emission is 119 t/a. Similar to the energy balance calculation (section 3.2), the kitchen was not considered in the emission calculation, which was based on the energy consumption model of Q_b. Table 9 illustrates the factors for calculating CO_2 equivalent emissions for electricity and district heating (DH) [34]. Another algorithm can also be used for the calculation of CO_2 equivalent emission, i.e., coal usage weight (t) * CO_2 emission factor of coal + natural gas usage weight (t) * CO_2 emission factor of natural gas + nuclear usage weight (t) * CO_2 emission factor of nuclear + renewables usage weight (t) * CO_2 emission factor of renewables + other fuels usage weight (t) * CO_2 emission factor of other fuels [34].

For the heating system of the catering centre, the factors of CO_2 equivalent emission for the supply flow and return flow of the DH (district heating) were calculated as 201 g/kWh and 22 g/kWh, respectively, (see Table 10) and took taking into account the costs and losses of the upstream chain. Table 10 demonstrates the CO_2 equivalent emission for various energy boundaries. For the case of the normalized DH return flow without the kitchen, the CO_2 equivalent emission is 88.1 t/a. However, for the case of the normalized DH supply flow, it can increase up to 99.0 t/a. Both values are obviously lower than the target value of 119 t/a. The budget figure of 2010, 97.6 t/a, was also regarded as a reference for cases using the DH system. Compared with a standard school building with a CO_2 equivalent emission of 281 t/a (building services) [34, 42], the new school building FOS/BOS produces only one-third of the value.

5. Discussions

Based on the results above, several key findings are discussed as follows.

1. The measured specific heating energy consumption in 2014 was around 7.09 kWh/(m²a), which was obviously lower than the Passive House standards of 15 kWh/(m²a) and 10.9 kWh/(m²a), the LEE standard of 12.4 kWh/(m²a), and the EnEV standard of 31.3 kWh/(m²a). These results demonstrated that a combined passive and active design solution (see sections 3.1 and 3.2) has led to high energy-efficiency performance in this school. Clearly, the cool climates in central Europe could make the passive solutions work well. Similar results have been observed in a previous simulation of this building [43]. Based on six design solutions of building service systems, nearly all specific heating energy consumptions were less than 15 kWh/(m²a). The average specific heating energy consumption of these solutions was 7.83 kWh/(m²a). Apparently, monitored and simulated data of heating energy consumption can achieve agreement. Thus, using passive solutions combined with proper active optimization approaches, a school building in central Europe can meet the requirement of the Passive House Standard from the point of view of specific heating energy consumption.

2. A climate adjustment of the monitored heating energy consumption in 2014 was conducted due to the risk of climate change. Based on the IWU method of Degree Days (D20/10) [40], the long-term average heating energy consumption can be adjusted as

8.0 kWh/m^{2}a (EnEV) and 9.1 kWh/m^{2}a (PHPP). Another method using the heating-days method (H_{d10}) [40] yields values of 7.2 kWh/m^{2}a (EnEV) and 8.2 kWh/m^{2}a (PHPP). Although different models can have some variations all calculations are still less than 15 kWh/(m^{2}a) (Passive House Standard). These again highlighted that the design solutions used in this school have proven very effective, even with possible negative impacts due to climate change (e.g., very cold winter that was never expected).

3. The cooling performance showed that groundwater consumption was greatly reduced from around 75000 m^3/a in 2012 to 7500 m^3/a in 2014 through the optimization phase and is lower than the planned quota of 22400 m^3/a. This finding could be explained by the optimization of the design of the cooling and mechanical ventilation systems. The key optimization solutions include the adjustment of the inlet ventilation set-point temperature from 17 °C to 19 °C and the application of passive night ventilation. The combined passive and active solutions have proven not only to be energy efficient but also to be effective in providing occupants with a proper level of thermal comfort.

4. The total specific electricity consumption in 2014 was found to be below 18.25 kWh/m^{2}a (section 4.3.2), which was obviously lower than the planned value of 21.45 kWh/m^{2}a using the calculation method of the LEE [37]. This result was mainly due to some of the optimization solutions including optimizing the control systems and operation strategies of the HVAC. In this school, these modifications can effectively help to reduce electricity consumption from IT, fans, HVAC systems and lighting. In addition, the kitchen was not included in the evaluation of electricity consumption (as

mentioned in the Passive House Standard [5, 12]), which could be another reason to explain the lower electricity consumption. This could be the specific aspect that made this study different from other studies of low-energy schools. [27-28].

5. The CO_2 equivalent emission relating to total energy consumption in the FOS/BOS was calculated as 88.1 t/a, which was only one-third of that value for a standard school building (281 t/a; from building services) [34, 42]. This finding clearly indicates that a significant reduction of CO_2 emission can be achieved through the passive solutions and active system optimizations of this new school. However, the estimations of the CO_2 emissions of various buildings could be completely different, depending on the assessment models of the life cycle of the building systems [44] and the fuel types [45].

This study has some limitations in terms of energy performance and CO_2 emission. First, because all current design methods and benchmark systems have no specific requirements for kitchen areas, all monitored data and analyses of relevant energy performance and CO_2 emissions could overestimate the actual building performance. The school is generally used by around 750 persons (staff and students), who might spend non-negligible energy during the normal school days. Second, local microclimates due to the vegetation and town topology were not included in the discussion. When considering the regional climate condition (temperate continental climate) and the size of the location studied (as a small town, Erding has a population of 34,122), this effect may not be critical.

6. Conclusions, design implications and future work

As found from the discussion, under central European climate conditions, a school building with a medium size could be practically designed and built in accordance with the Passive House Standards. However, it could be necessary to integrate renewable/low-carbon systems (i.e., active systems) into the passive solutions if a very low energy target is expected to be achieved (e.g. Nearly Zero-Energy Building). In addition, this study has shown that the Passive House method could be improved by adding amendments for specific spaces (e.g., kitchen or non-regular working spaces) to reflect real energy consumption.

Some design implications are also produced to help establish new low-energy school buildings in central Europe as follows: 1) The design of a heating system could directly refer to Passive House methods and relevant standards, which could yield an energy-efficient design based on heating energy consumption. 2) It is necessary to include a factor for climate change in the design of heating and cooling systems and in the calculation of energy performance to achieve realistic long-term energy performance. 3) Post-project monitoring could be necessary for the optimization of building system operations, especially for active systems, including renewables and low-carbon technologies.

In the future, this research would also benefit the early-stage design and optimization of other building types and their building service systems. More environmental factors, including indoor air quality, thermal comfort, acoustics and visual performance, will be conducted in the next stage of this project.

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Nomenclature

f_c climate factor (dimensionless)

$f_{CO2,dh}$ factor for calculating CO_2 equivalent emission based on district heating (g/kWh)

$f_{CO2,e}$ factor for calculating CO_2 equivalent emission based on electricity (g/kWh)

$P_{el,max}$ annual electricity peak load (kW)

$P_{t,c}$ sorted load of heating (kW)

P_{th} heating power (kW)

Q_b heating energy for energy balance boundary of the FOS/BOS without the kitchen (kWh)

Q_c heating energy for the energy balance boundary including the catering centre (kWh)

$Q_{c,f}$ cooling energy for the energy balance boundary of the FOS/BOS (kWh)

Q'_e specific electrical energy demand (kWh/m^{2}a)

$Q_{e,b}$ electrical energy for the energy balance boundary of the FOS/BOS without the kitchen (kWh)

$Q_{e,f}$ electrical energy for the energy balance boundary of the FOS/BOS (kWh)

Q_f heating energy for the energy balance boundary of the FOS/BOS (kWh)

Q'_h specific heating energy demand (kWh/m^2a)

$Q_{t,b}$ heating consumption for the energy balance boundary of the FOS/BOS without the kitchen (kWh)

$Q'_{t,b}$ specific heating demand for the energy balance boundary of the FOS/BOS without the kitchen (kWh/m^2a)

$Q_{t,c}$ heating consumption for the energy balance boundary considering the catering centre (kWh/m^2a)

$Q'_{t,c}$ specific heating demand for the energy balance boundary considering the catering centre (kWh/m^2a)

$Q_{t,f}$ heating consumption for the energy balance boundary of the FOS/BOS (kWh)

$Q'_{t,f}$ specific heating demand for the energy balance boundary of the FOS/BOS (kWh/m^2a)

$V_{c,g}$ consumed groundwater volume (m^3/a)

Abbreviations

ASHP air source heat pump

BMS building management system

CEPHEUS cost efficient Passive Houses as European standards

Ca climate-adjusted

COP coefficient of performance

DBU Deutsche Bundesstiftung Umwelt (German Federal Foundation for the Environment)

DH district heating

DWD Deutscher Wetterdienst (German Weather Service)

EnEV Energieeinsparverordnung (energy saving regulation)

ERA energy reference area

FOS/BOS Fachoberschule/Berufsoberschule (professional secondary school or vocational high school)

HVAC heating, ventilation and air-conditioning

IWU Institut Wohnen und Umwelt (Institute for Housing and the Environment)

LEE Leitfaden Elektrische Energie im Hochbau (electricity in buildings)

NZEB Nearly Zero-Energy Building

PCM Phase Change Materials

PH Passive House

PHPP Passive House planning package

PV photovoltaic

RLT Raum Luft Technik (room ventilation technique)

WMZ Waermemengenzaehler (heat meter)

WMZ/KMZ Waermemengen or Kaeltemengen-Kombizaehler (heat or cooling-combination meter)

ZAE Bayern Bavarian Centre for Applied Energy Research

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Tables

Table 1: Materials, configurations and thermal properties and solar energy transmittance properties, and ventilation and cooling systems in FOS/BOS school building.

External walls	
U-value in W/(m^{2}K)	0.128
Concrete thickness (mm)	260
Insulation thickness (mm)	240
Internal walls	
U-value in W/(m^{2}K)	4.357
Concrete thickness (mm)	125
Floor	
U-value in W/(m^{2}K)	3.587
Estrich thickness (mm)	65
Ceiling/Roof	
U-value in W/(m^{2}K)	0.094
Concrete thickness (mm)	300
Insulation thickness (mm)	360
Windows and glazing surfaces	
U-value in W/(m^{2}K)	0.87
g-value	0.501
Ventilation and Cooling	
Ventilation rate (m^3/h)	660
Infiltration rate (h^{-1})	0.01
Groundwater cooling (m^3/a)	22400
NOTE: *Weather data used in this study comes from the weather station at the FOS/BOS school building.*	

Table 2: Energy reference area (ERA) of various calculating methods. In the planning phase, the kitchen was considered as a special application and excluded in the regular building operation according to PHPP and LEE [34, 36].

	PHPP	**LEE**	**EnEV**
ERA, m^2	6663	7574	7640

Table 3: Predicted values of the specific heating energy demand based on three benchmarking systems EnEV, PHPP and LEE at the planning phase. #

	$PHPP_m$	**$PHPP_y$**	**LEE**	**EnEV**
Q'_h kWh/m²a	10.4	10.9	12.4	31.3

Table 4: Predicted values of the final specific electrical energy demand at the planning phase.

	EnEV	**PHPP**	**LEE**
Q'_e kWh/m²a	19.6	n/a	21.45

Table 5: Heat meters used for the monitoring and calculation of the heating energy.

Meter	**Boundary**	**Location**
$(WMZ)_g$	Catering centre	Primary side
$(WMZ)_f$	FOS/BOS	Secondary side
$(W/KMZ)_1$	RLT North	Secondary side
$(W/KMZ)_2$	RLT South	Secondary side
$(W/KMZ)_3$	RLT Event	Secondary side
$(W/KMZ)_4$	RLT Kitchen	Secondary side
$(WMZ)_1$	Wall heating North	Secondary side
$(WMZ)_2$	Wall heating South	Secondary side
$(WMZ)_3$	Floor heating	Secondary side

Table 6: Cooling meters used for the monitoring and calculation of the cooling energy.

Meter	Boundary	Location
$(KMZ)_g$	Thermal groundwater use	Primary side
$(W/KMZ)_1$	RLT North	Secondary side
$(W/KMZ)_2$	RLT South	Secondary side
$(W/KMZ)_3$	RLT Event	Secondary side
$(W/KMZ)_4$	RLT Kitchen	Secondary side
$(KMZ)_1$	Cooling ceilings of IT rooms	Secondary side
$(KMZ)_2$	Cooling in Server room	Secondary side

Table 7: Climate-adjusted (Ca) heating demand in 2014. Overview of the determination of the climate-adjusted heating energy demand with the described balance boundary and correction method. The predicted values are given in Table 3.

Balance boundary	**Without Kitchen**	**Without Kitchen**	**Without Kitchen**	**With Kitchen**
Real Heating consumption 2014 (kWh/a)	51043	51043	51043	54173
Method	Degree day 20/10	Heating day 20/10	Degree day 20/15	Degree day 20/15
Reference location	Erding	Erding	Potsdam	Potsdam
Climate factor 2014	0.84	0.93	0.917	0.917
EnEV floor space (m^2)	7574.5	7574.5	7574.5	7640.4
PHPP floor space (m^2)	6663.1	6663.1	6663.1	n/a
Ca heating consumption 2014 (kWh/a)	60765	54885	55663	59076
Specific heating demand 2014 (EnEV) kWh/(m^2a)	8.02	7.25	7.35	7.73
Specific heating demand 2014 (PHPP) (kWh/m^2a)	9.12	8.24	8.35	n/a

Table 8: Annual electricity peak load based on the data from power supply company.

	2011	**2012**	**2013**	**2014**
$P_{el,max}$ kW	96.06	96.97	104.84	104.55

Table 9: Factors for calculating CO_2 equivalent emission. These values are used as a reference at the planning phase [34].

CO_2 equivalent for	**Factor g/kWh**
Electricity $f_{CO2,e}$	628
District heating $f_{CO2,dh}$	177

Table 10: CO_2 equivalent emissions [34]. Total consumption with kitchen in 2014 and normalized demand without kitchen were calculated using the district heating (DH) return flow. For the reason of comparison, budget figures of 2010 were also as a reference of evaluation using the DH supply flow performed.

Balance boundary	Total turnover with kitchen	Normalized DH return flow without kitchen	Normalized DH supply flow without kitchen	Reference 2010 without kitchen
Electricity consumption 2014, kWh/a	176566			
Heating consumption 2014, kWh/a	54173			
Final electricity energy consumption 2014, kWh/a		138235	138235	138235
Final heating energy consumption 2014, kWh/a		60765	60765	60765
EnEV ERA, m^2	7640.4	7574.5	7574.5	7574.5
CO_2 equivalent for electricity, kg/kWh	0.628	0.628	0.628	0.628
CO_2 equivalent for DH, kg/kWh	0.022	0.022	0.201	0.177
CO_2 equivalent emission, t/a	**112.1**	**88.1**	**99.0**	**97.6**
Specific CO_2 equivalent emission, kg/m^2a	14.67	11.64	13.07	12.88

Figures

Figure 1

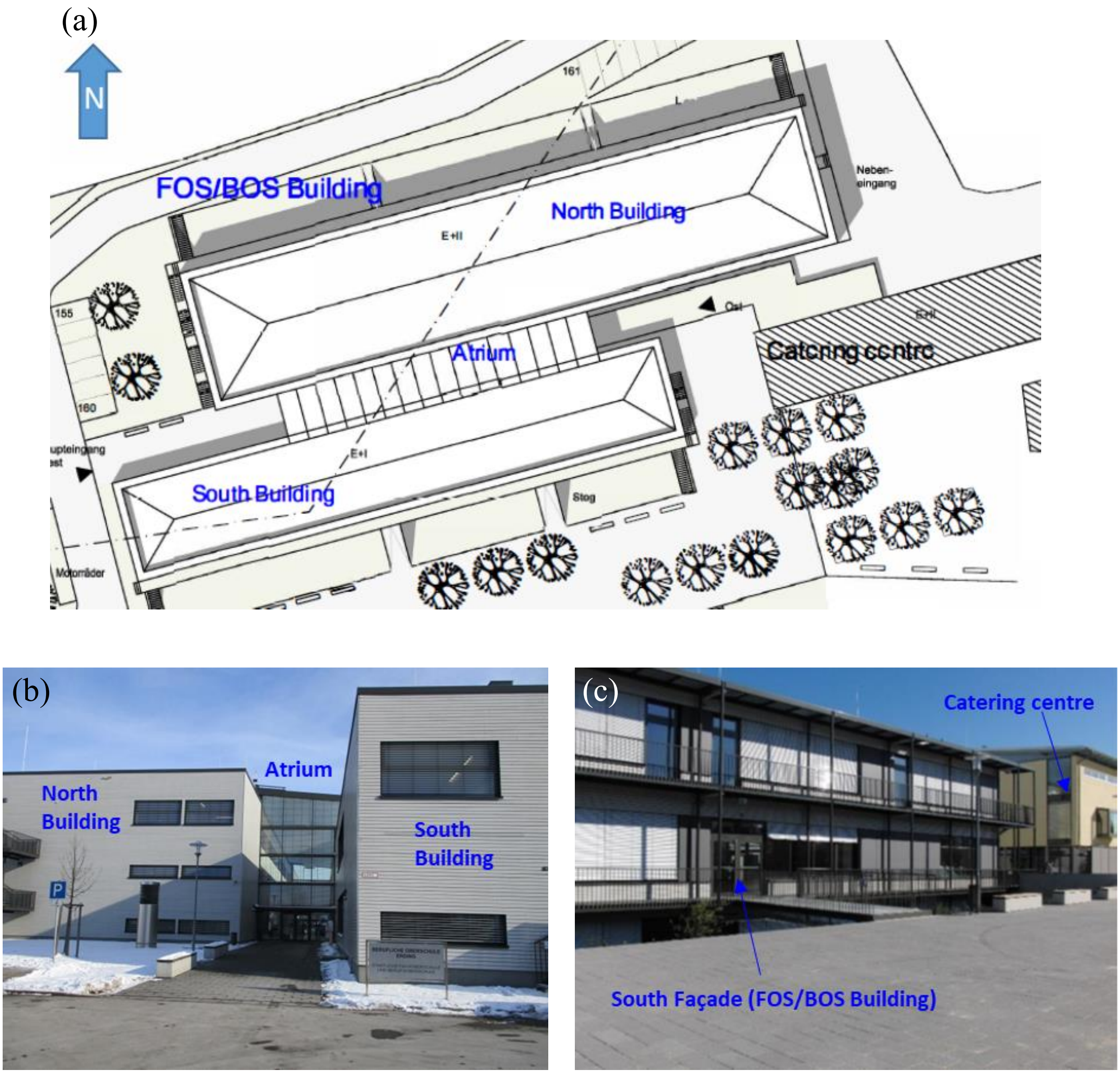
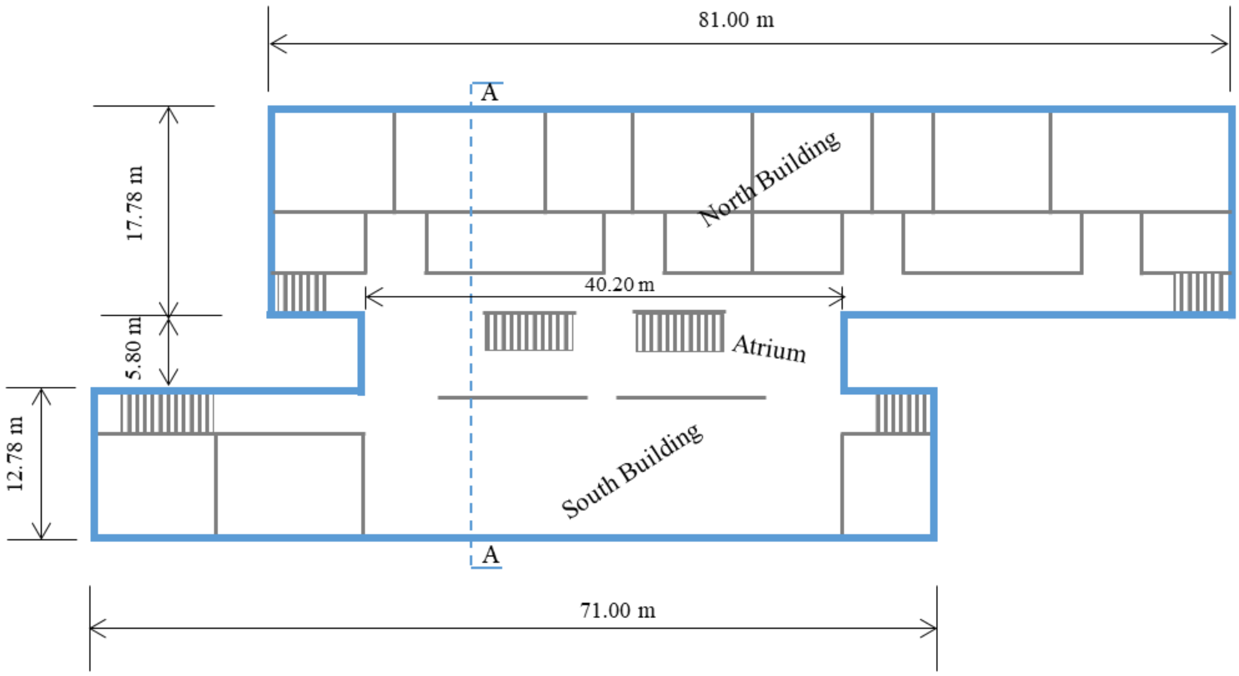


Figure 1: Pictures of FOS/BOS building, the low-energy school building studied in this article, including (a) site plan of the building; (b) north and south buildings and atrium; (c) south facade (FOS/BOS) and the catering centre nearby.

Figure 2

(a)



(b)

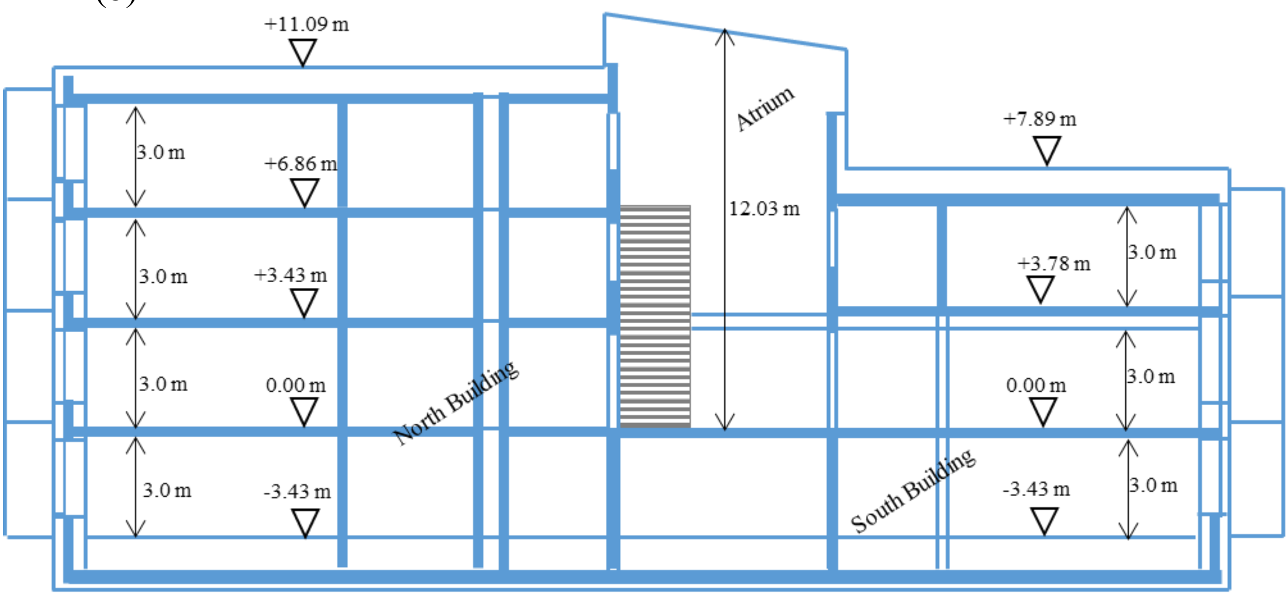


Figure 2: Dimensions of FOS/BOS building, including (a) Plan of ground floor; (b) Section (A-A) of the building.

Figure 3

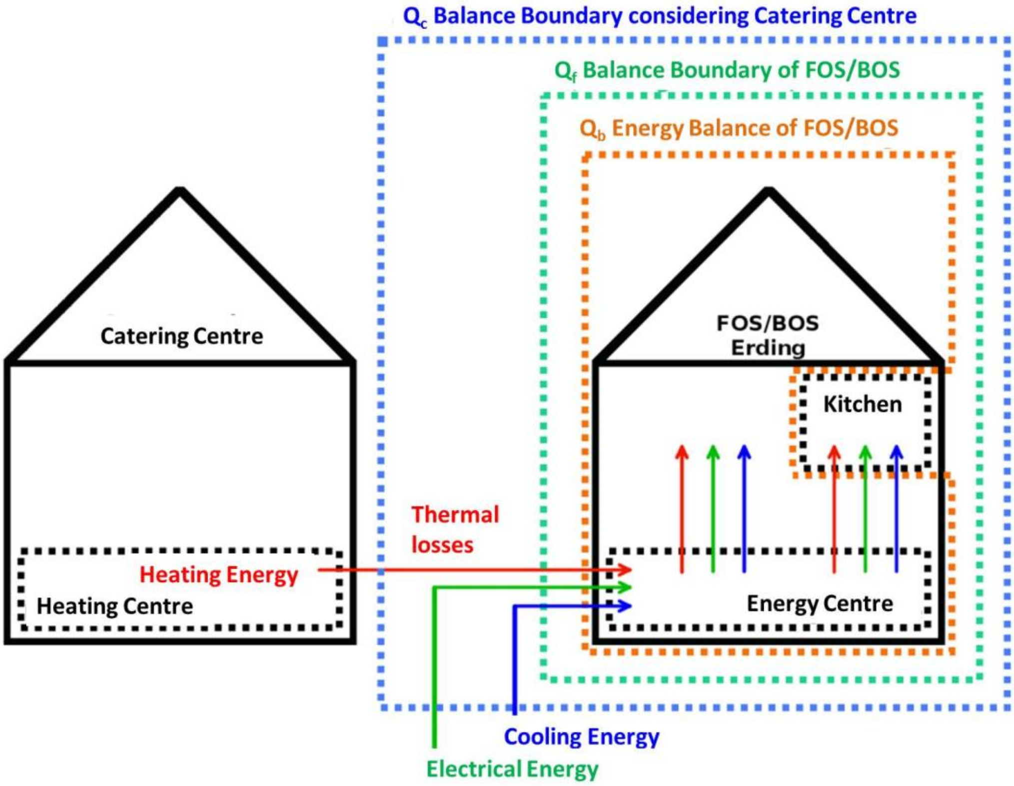
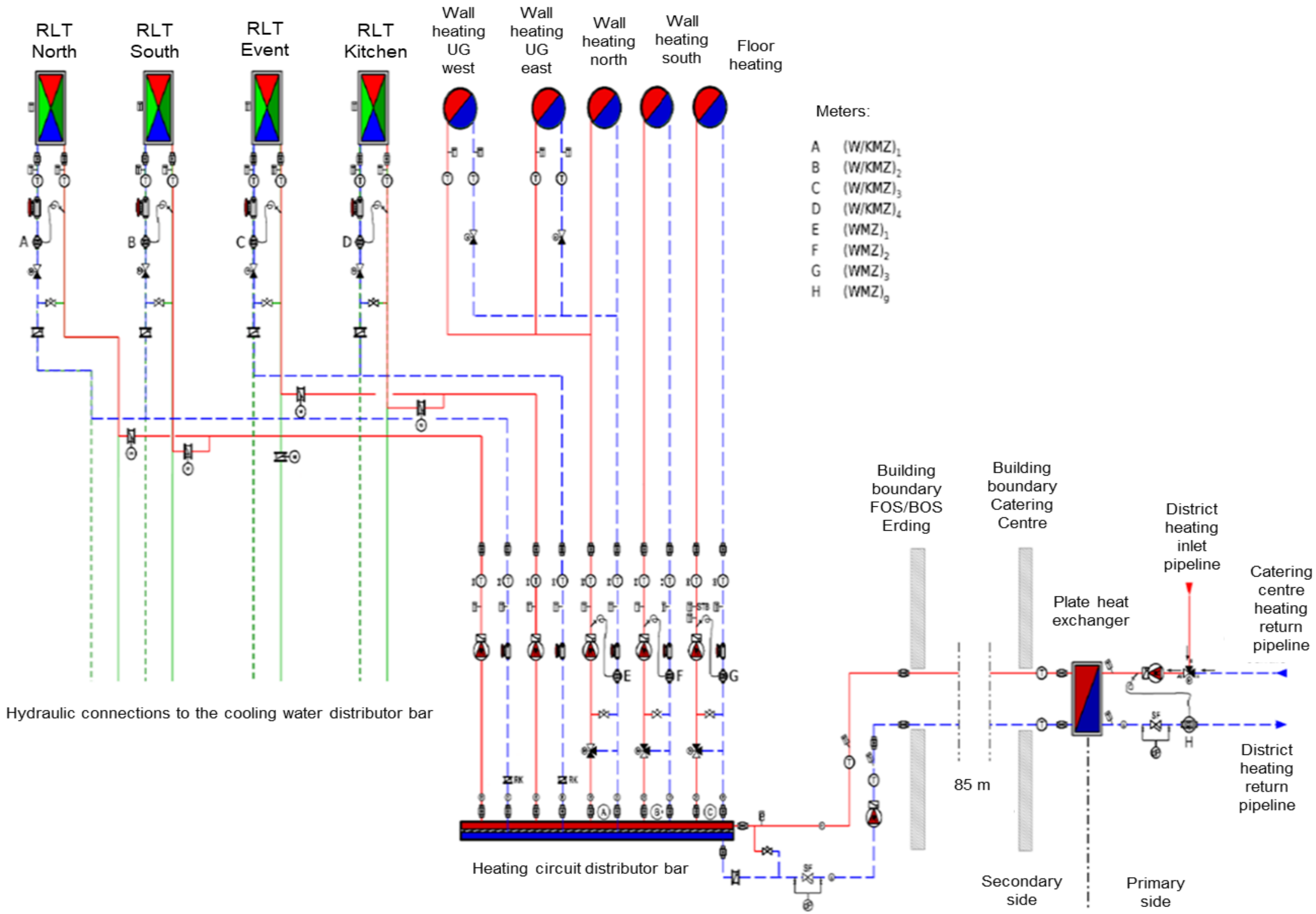


Figure 3: Schematic description of the balance boundaries for FOS/BOS energy evaluation. Three models have been applied for the energy balance: Q_c, Q_f, *and* Q_b. Q_c includes the thermal losses of heat supply pipelines when compared with the energy Q_f; while Q_b represents a system boundary in which the kitchen area is classified as a special use.

Figure 4

(a)



RLT North
RLT South
RLT Event
RLT Kitchen
Wall heating UG west
Wall heating UG east
Wall heating north
Wall heating south
Floor heating
Meters:
A (W/KMZ)1
B (W/KMZ)2
C (W/KMZ)3
D (W/KMZ)4
E (WMZ)1
F (WMZ)2
G (WMZ)3
H (WMZ)9
Hydraulic connections to the cooling water distributor bar
Heating circuit distributor bar
Building boundary FOS/BOS Erding
Building boundary Catering Centre
85 m
Plate heat exchanger
District heating inlet pipeline
Catering centre heating return pipeline
District heating return pipeline
Secondary side
Primary side

(b)

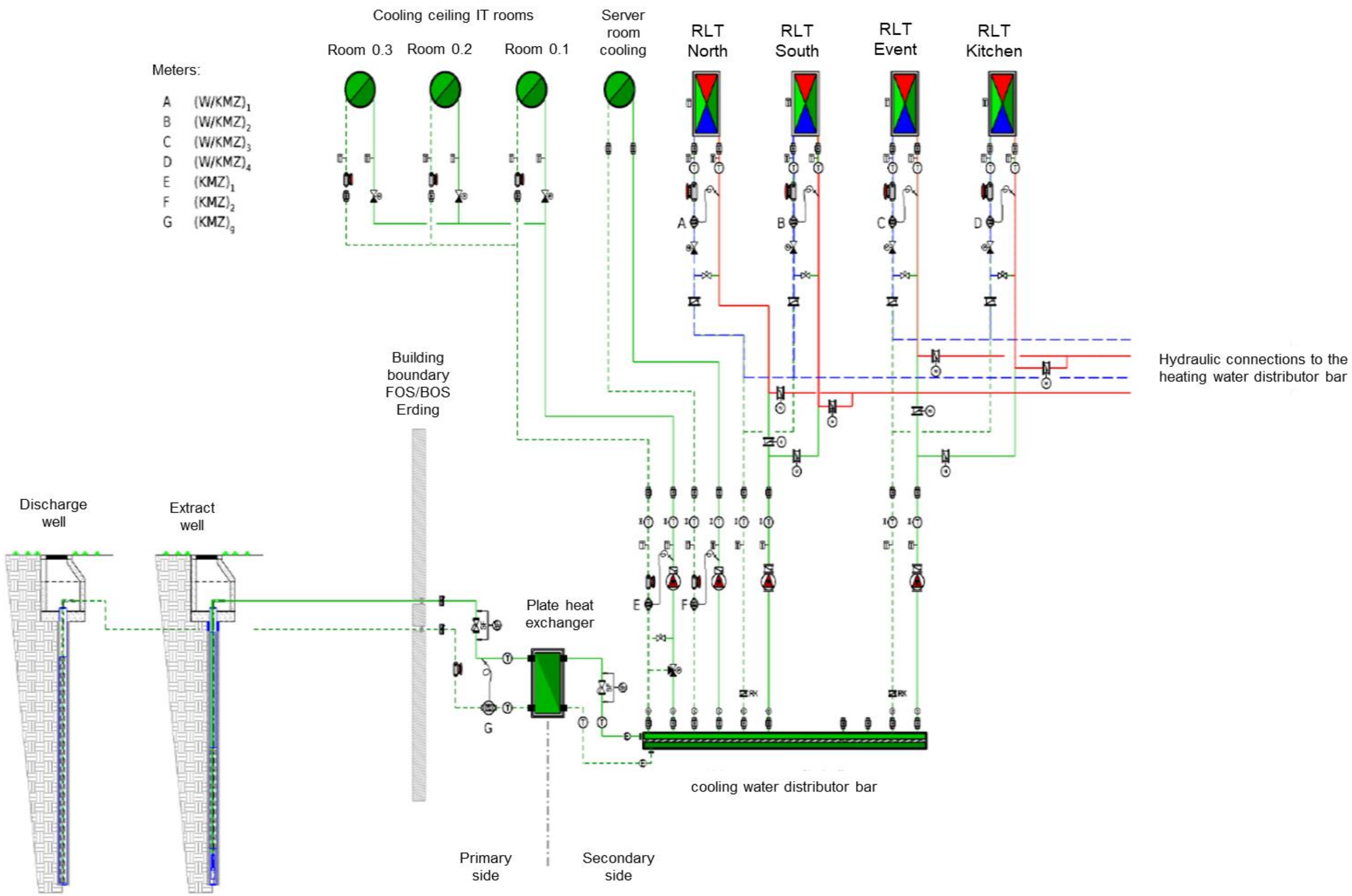


Figure 4: The schematics of heating (a) and cooling (b) installations in primary and secondary sides.

Figure 5

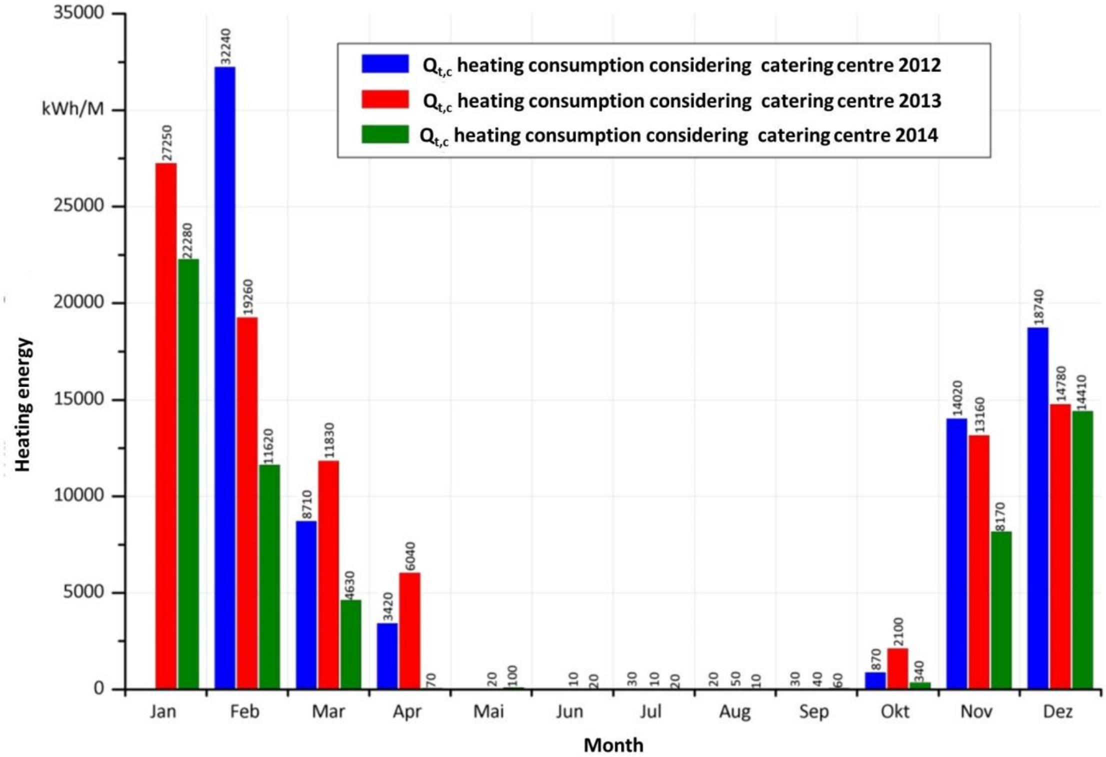


Figure 5: Primary monthly heating energy consumption (considering thermal losses of pipeline between catering centre and FOS/BOS building) during the evaluation period of project from 2012 to 2014. The data monitoring was started in February 2012. All heating seasons start in October. The tiny consumption during the summer months was caused by measurement errors of the heat meters. The months of May and June 2012 could be not exactly monitored because of a six-day data gap.

Figure 6

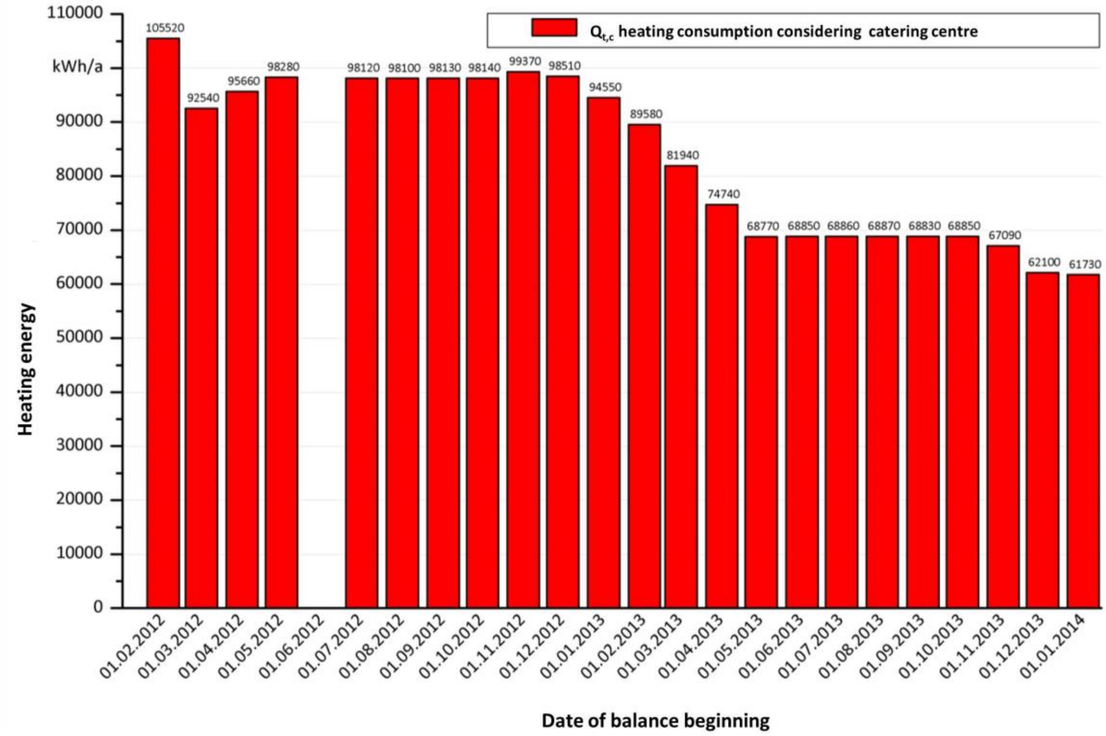


Figure 6: Annual energy consumption (including thermal losses of pipeline between catering centre and FOS/BOS). The annual consumption of heating energy varies in the Date of Balance Beginning; the first date was 1 February 2012. The missing data on 1 June 2012 was caused by a six-day data gap with the month change. The values on the top of the bar means annual heating energy consumption calculated from the Date of Balance Beginning. For example, the first bar value of 105520 kWh/a means the total heating energy consumption from 1 February 2012 to 1 February 2013.

Figure 7

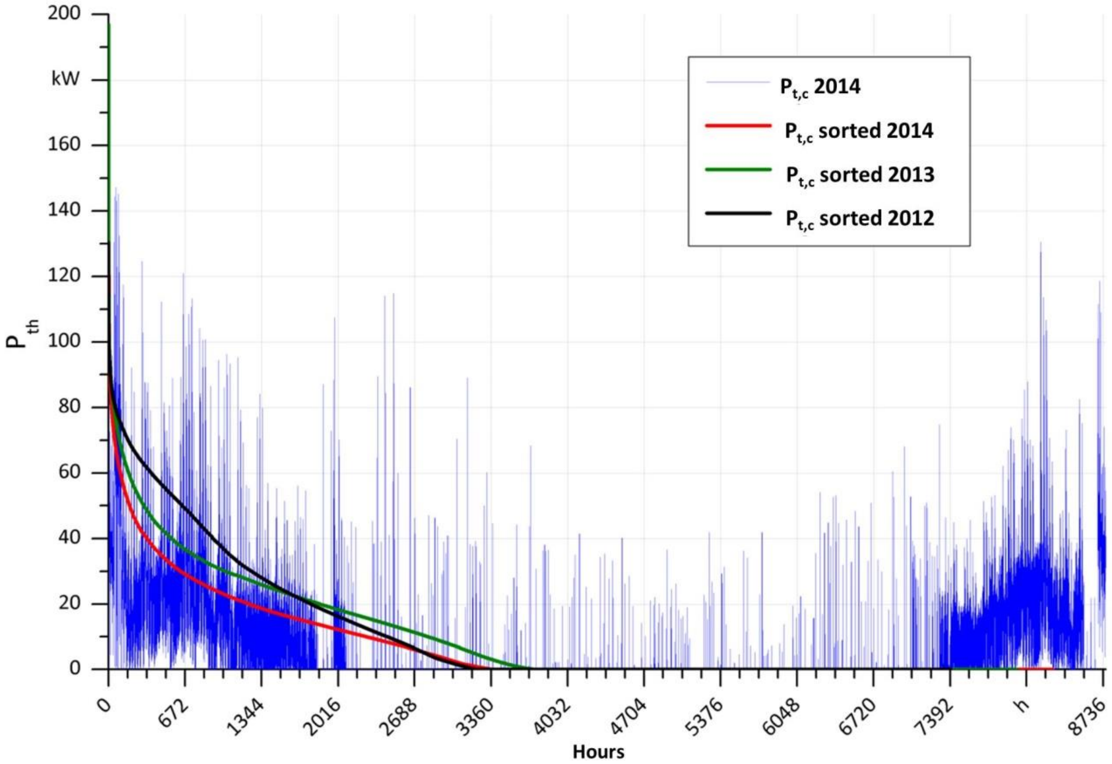


Figure 7: Thermal load P_{th} profile of 2014 and its sorted load $P_{t,c}$ durations of primary heat meter. The sorted load duration curves of 2012 and 2013 are also presented. The very low values appeared in summer were due to the system errors, which could be neglected.

Figure 8

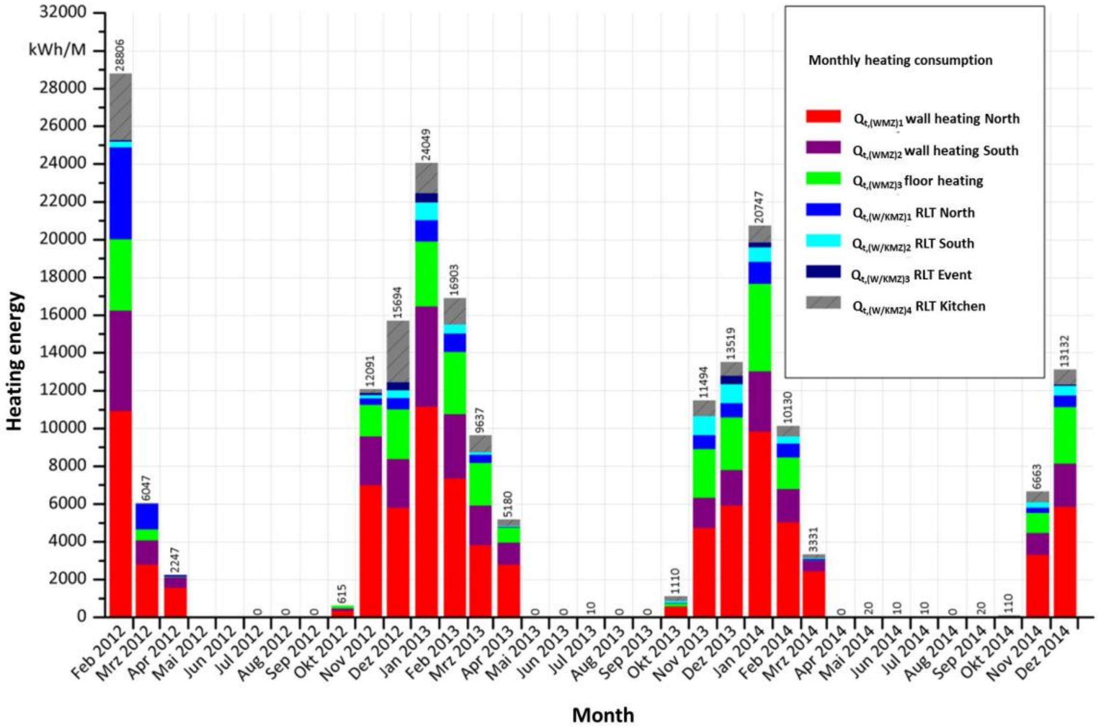


Figure 8: Monthly heating energy consumption. The bars are subdivided according to the consumption of the individual heating circuits. The numerical values above the individual bars indicate the respective monthly consumption $Q_{t,f}$, whose balance boundary is the entire FOS/BOS building. The months of May and June of 2012 cannot be included due to a six-day data gap for monthly-change. For 2012, the kitchen including RLT Kitchen was temporarily out of order.

Figure 9

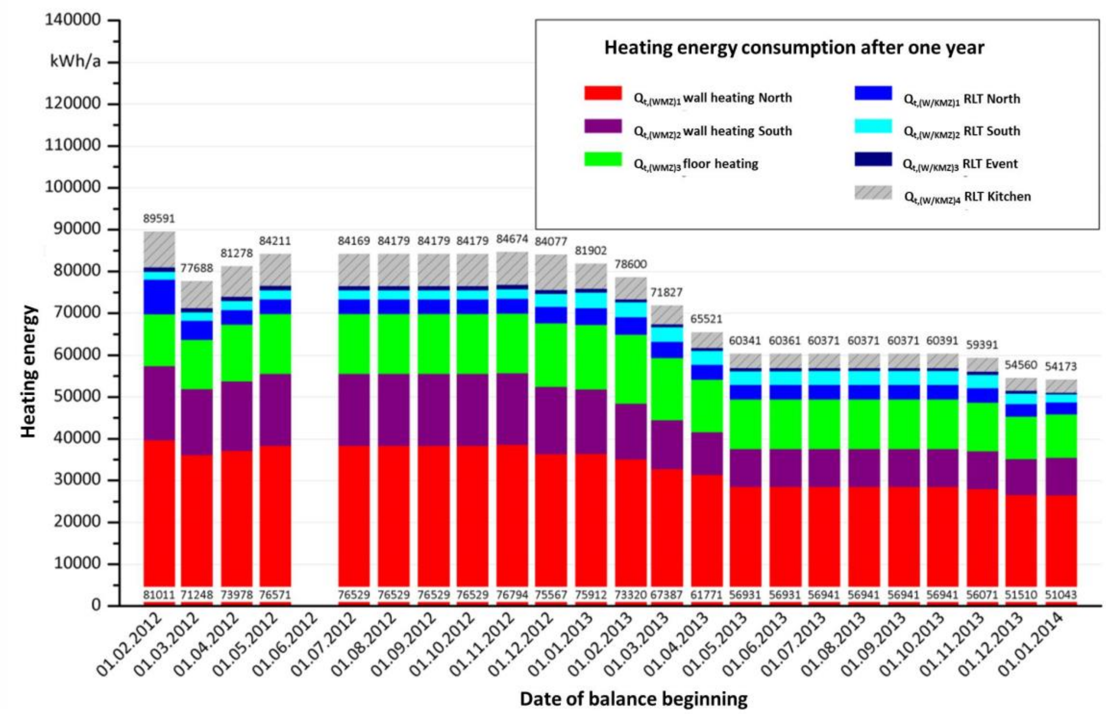


Figure 9: Annual heating energy consumption of the FOS/BOS building. The bars are subdivided according to the individual heating circuits. The number on the top of the bar indicates the total annual energy consumption $Q_{t,f}$ of FOS/BOS building, while the number on the bottom of the bar means the annual consumption $Q_{t,b}$ of FOS/BOS building excluding the kitchen. The data on 1 June 2012 are not available due to a six-day data gap with the monthly change. In 2012, the kitchen including the kitchen RLT was temporarily out of order.

Figure 10

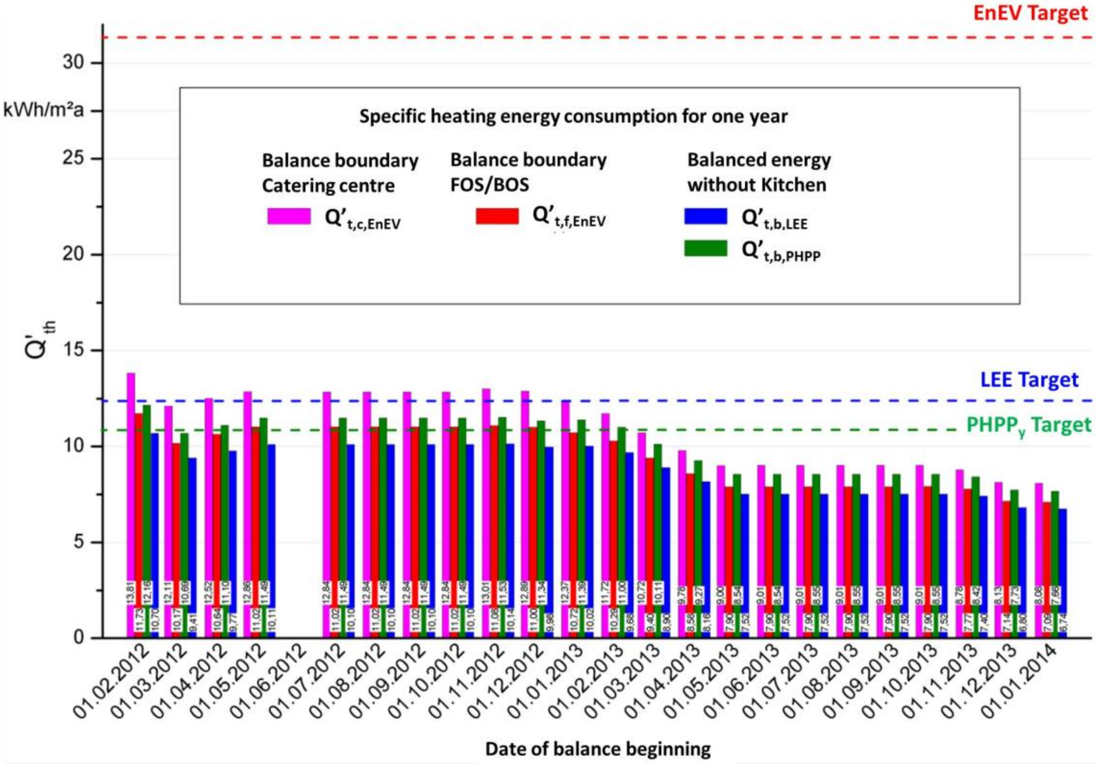


Figure 10: Annual specific heating energy consumption. The bars represent the monitored annual energy consumption according to the three benchmarking systems and separated by the three balance boundaries. The three horizontal dashed lines illustrate the target values (predicted based on PHPP, EnEV, and LEE) according to the requirement calculations in the planning phase.

Figure 11

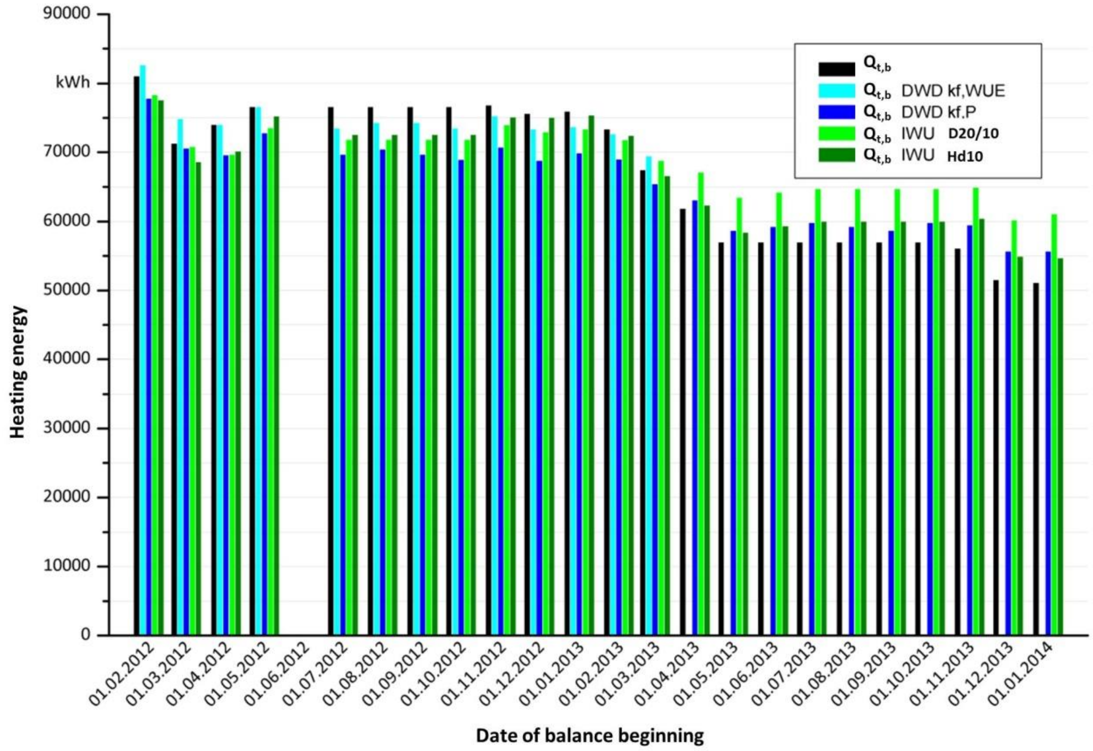


Figure 11: Climate-adjusted annual heating energy demand. The comparison of the method for climate adjustment of heating energy consumption illustrates some variations. It could be found that 2012 and 2013 see slightly colder winters than the reference; while 2014 has a warmer winter. Depending on the different methods, the heating energy demand in 2014 varies from 54.9 MWh/a to 60.8 MWh/a.

Figure 12

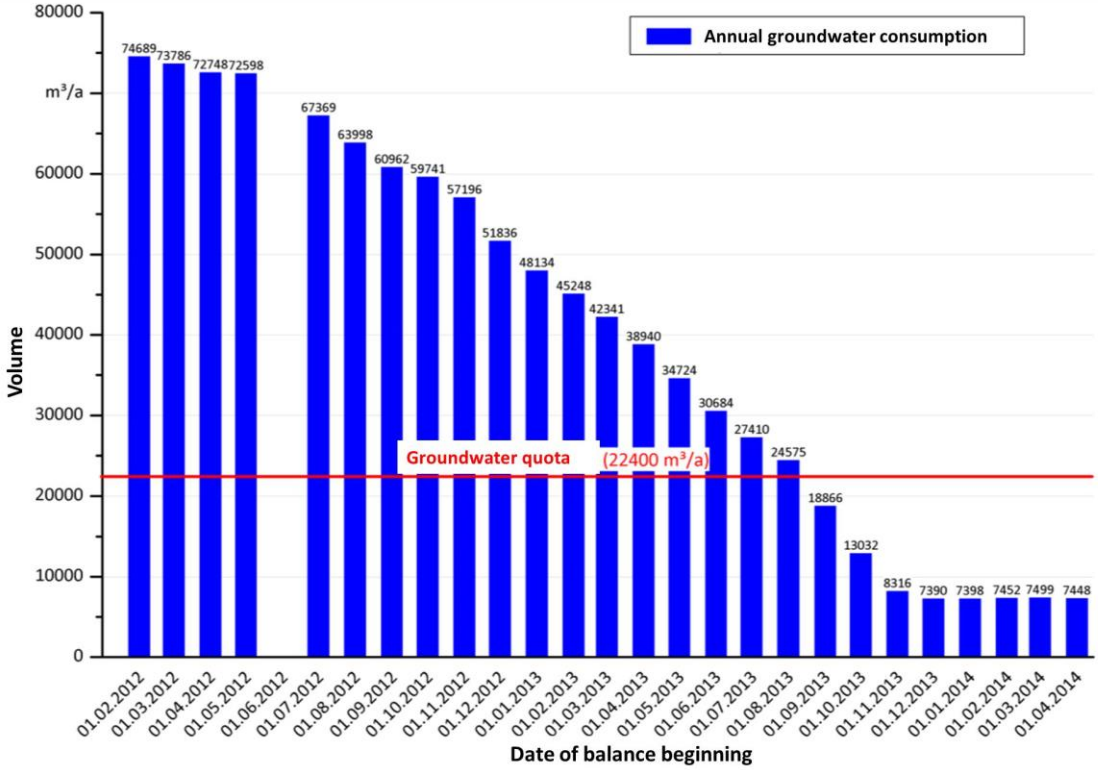


Figure 12: Annual groundwater consumption of the cooling system. The early monitored data showed that the consumptions were significantly beyond the permitted annual groundwater quota (red line). After implementing the optimization solutions, it was possible to meet the requirement despite the increased cooling demand for the supply air. The missing period from 1 June 2012 is due to a six-day data gap at the end of May.

Figure 13

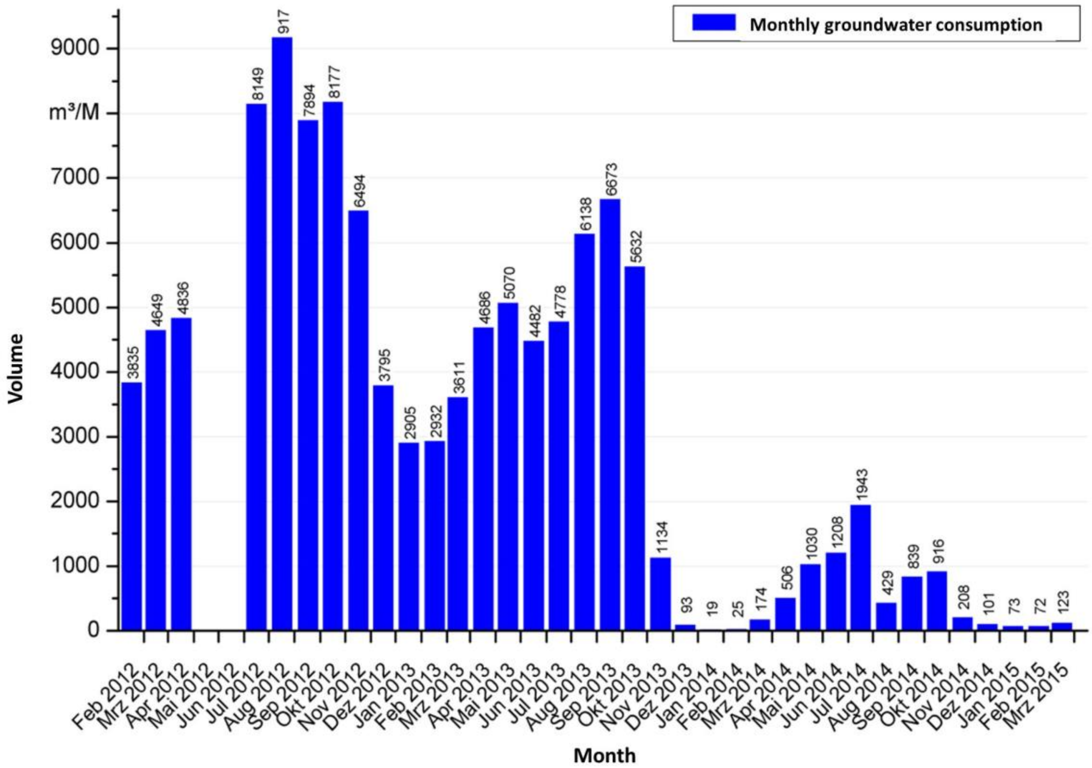


Figure 13: Monthly groundwater consumption of the cooling system. In November 2013, the most effective optimization solutions were implemented. The months of May and June 2012 could not be accounted for due to a six-day data gap at the end of May.

Figure 14

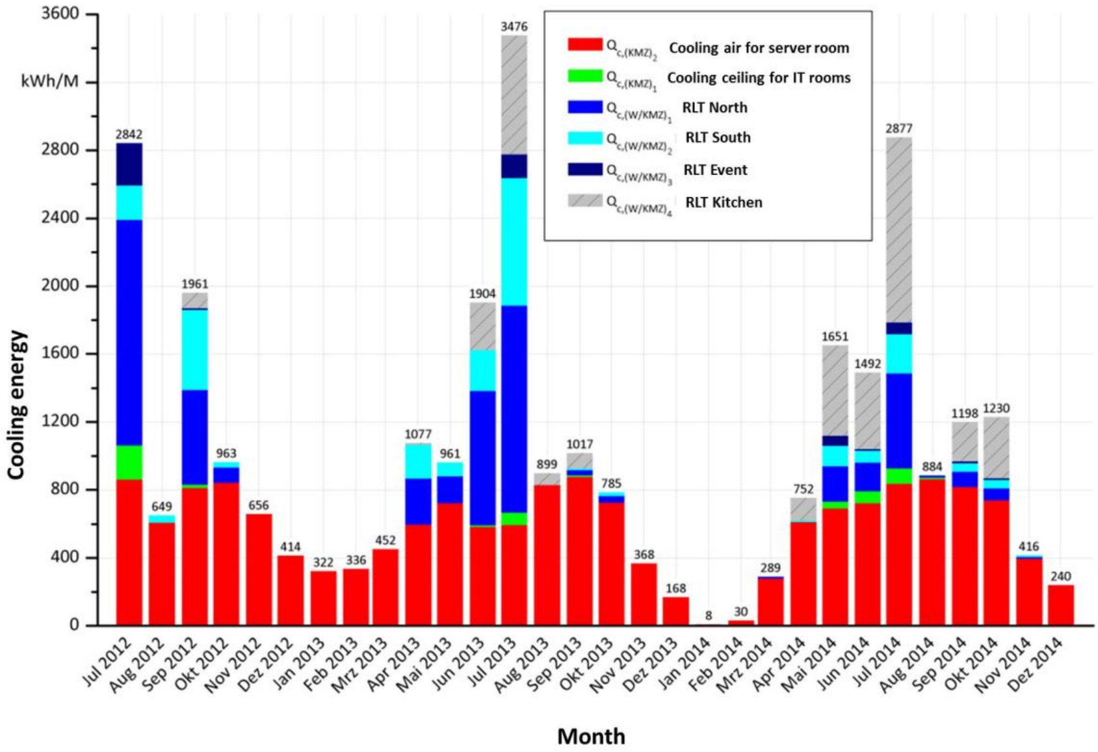


Figure 14: Monthly cooling energy consumption. The distribution is based on the consumption of the individual cooling water circuits. The number on the top of the individual bars indicates the monthly consumption $Q_{c,f}$ (FOS/BOS as its balance boundary) of the sum of all cooling water circuits including the RLT Kitchen.

Figure 15

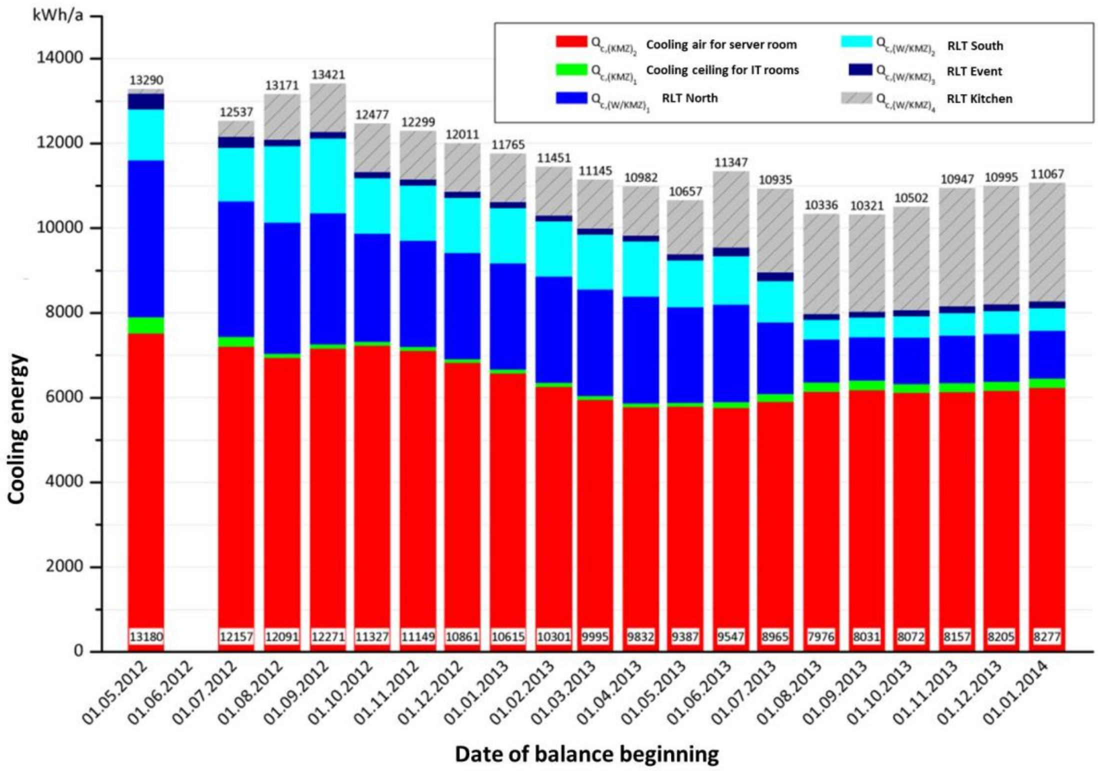


Figure 15: Annual energy consumption of cooling systems. The distribution of annual consumption is based on individual cold water circuits. The number on the top of bars presents the annual consumption $Q_{c,f}$ of the sum of all cold water circuits including RLT Kitchen. The missing period, which could not be exactly calculated from 1 June 2012, is due to a six-day data gap. The total cooling energy consumption with kitchen and without kitchen in 2014 are approximately 11.1 MWh/a and 8.3 MWh/a, respectively. Meanwhile, around 2 MWh/a is for cooling main occupied areas of the building i.e. RLT North and South; while about 6.3 MWh/a was used for cooling server room.

Figure 16

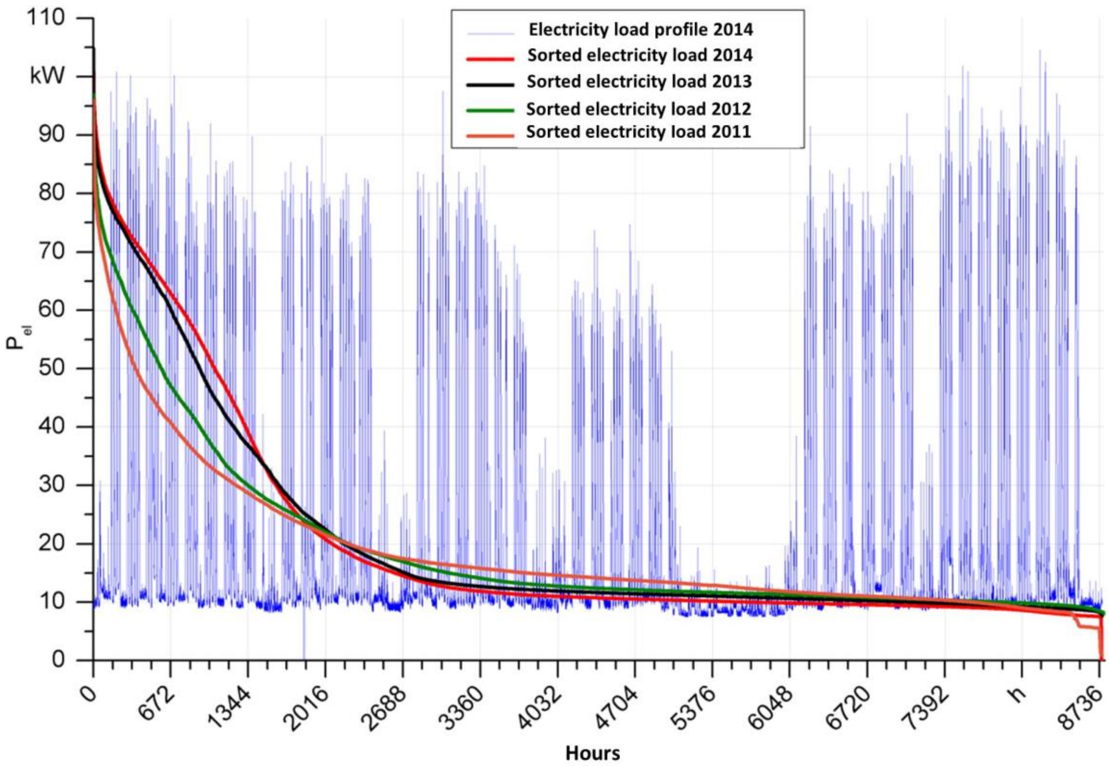


Figure 16: Electricity load profile in 2014 and sorted load duration curves from 2011 to 2014. The optimization phase obviously reduced the base load compared to previous sorted load curves from 2011 to 2013.

Figure 17

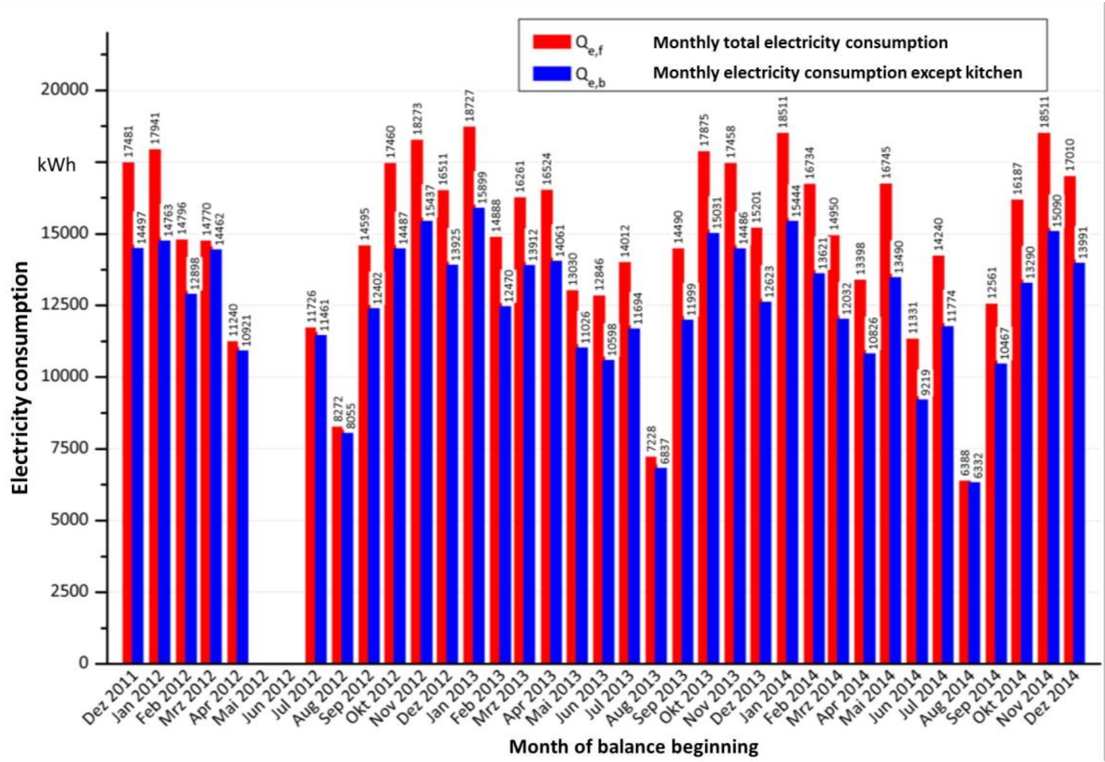


Figure 17: Monthly electricity consumption. It shows the comparison between the monthly electricity consumption of entire building $Q_{e,f}$ and the consumption of entire building $Q_{e,b}$ without considering the kitchen. The missing periods, which could not be exactly amounting from end of May to June 2012, are due to a six-day data gap.

Figure 18

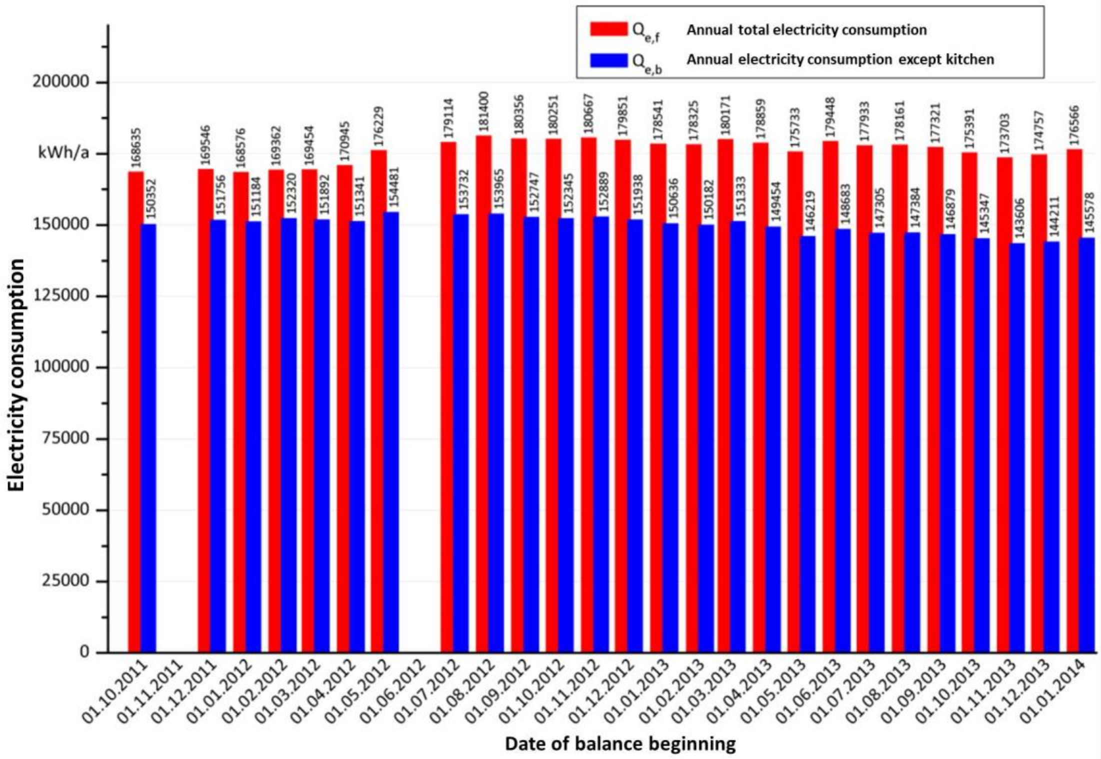


Figure 18: Temporal evolution of annual electricity consumption. It includes the annual electricity consumption of entire building $Q_{e,f}$ and the consumption of entire building $Q_{e,b}$ without considering the kitchen. The missing periods, which could not be exactly amounting for 01.10.2011 and 01.06.2012, are due to the data gap.

Figure 19

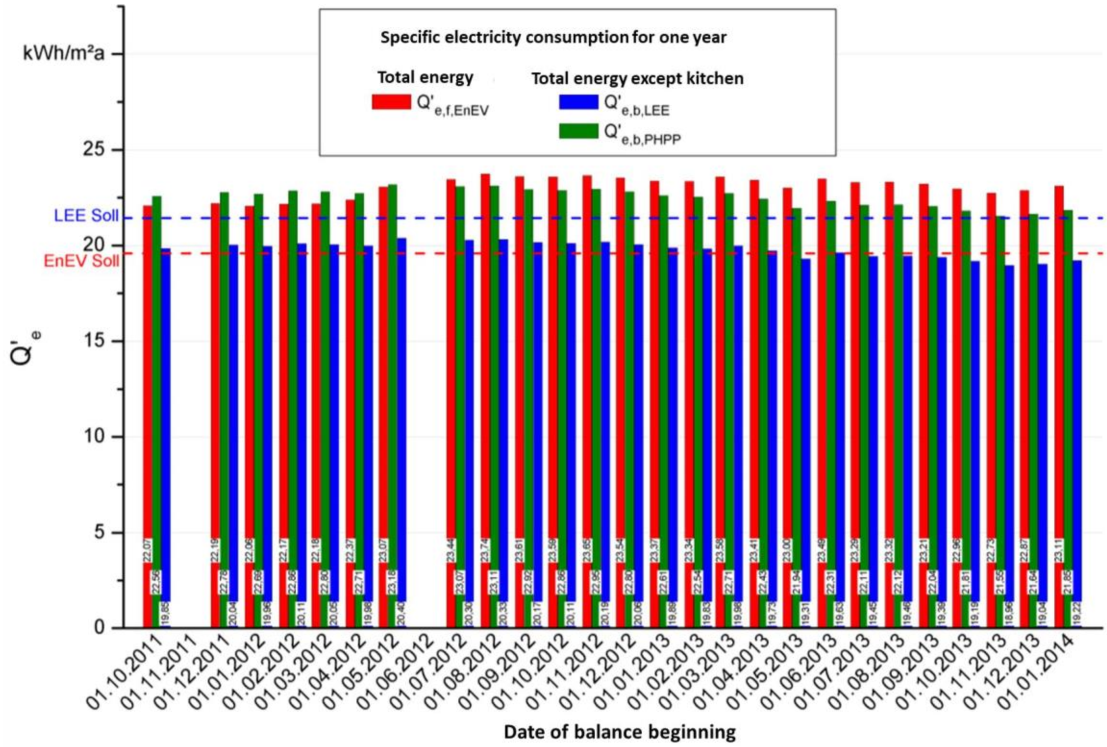


Figure 19: Time evolution of the specific annual electricity consumption. The continuously measured energy consumption is shown according to the three specific benchmarking systems with various balance boundaries and ERA. The two horizontal dashed lines means the predicted values based on the requirements calculated at the planning phase, both of which are applied only for the building services (not the total electricity demand).