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Simultaneity in Renewable Building Energy Supply—A Case Study on a Lecturing and Exhibition Building on a University Campus Located in the Cfb Climate Zone

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Abstract: A major issue in the renewable energy supply of buildings is to establish a simultaneity of the fluctuating renewable energy generation and the energy consumption in buildings. This work provides a new case for a better understanding of how to establish this simultaneity. Future solutions are being explored in practice on the campus of the FH Westküste University of Applied Sciences in the Lecturing and Exhibition Building (LEB). The motivation was to design and operate a case building for research in energy science for teaching the bachelor's program Green Building Systems as well as for demonstration purposes for the general public. With a floor space of 207 m, the LEB is supplied with renewable energy from the adjacent energy park consisting of a 10 kW wind turbine and photovoltaic modules with 10 kWp. The heat and cold generation system consists of two reversible heat pumps: one is an air–water heat pump with approx. 7 kW heating and 6 kW cooling power, and the second is a brine–water heat pump with approx. 8 kW heating power and a depth of the two boreholes of 80 m. To match the energy generation and the energy consumption, different kinds of storage units, i.e., batteries with 3 × 8 kWh and storage tanks with 1000 L heat storage and 600 L cold storage, were installed as well as a smart automation system with a database. This paper evaluates measurement data from 2021. It is demonstrated that a fully renewable energy supply of the building is possible for most of the time from spring to autumn. In winter, an additional long-term energy storage, e.g., hydrogen, is necessary for certain days.

Keywords: renewable energies; sustainable energy; energy efficiency; zero energy buildings; building operation; energy management; smart energy system; research infrastructure; green campus; hydrogen storage

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1. Introduction

The existence and the operation of research infrastructure is a prerequisite, a conditio sine qua non, to assure scientific advance and innovation. At the same time, research infrastructures exert negative impacts to the environment, e.g., by emitting greenhouse gases. In the overall ecological footprint of research infrastructures, the operation of buildings plays an important role, which is reflected in the sustainable universities discourse [1]. Sustainability on the campus itself is proposed as one of the four key managerial strategies (besides education, research and Outreach and Partnership) to become a sustainable university [2]. There are several campus projects with a focus on energy use and green buildings [1,3–6], Table 1. To highlight just a few, White et al. operated a Research House on the University Park campus at the University of Nottingham [6]. They found that a combined system with an air source heat pump and a solar thermal collector and an immersion heater as a back-up is a suitable installation for providing hot water and space heating for a home in the UK climate [6]. In another case study, photovoltaic power plants were integrated and monitored on a university campus in Brazil [5].

Table 1. Literature review table with similar case studies.

Authors	Year	Content
Opel et al. [1]	2017	Project on a climate neutral university campus
Dyussembekova et al. [3]	2022	Case study on an educational building of the Kazakh-German University in Almaty
Yoshida/Shimoda/Ohashi [4]	2017	Sustainable campus at Osaka University, Japan using photovoltaic and energy-saving technologies
de Souza et al. [5]	2022	Sustainable campus at University of Campinas in Brazil using photovoltaic
White et al. [6]	2014	Operation of a Research House on the University Park campus at the University of Nottingham with an air source heat pump and a solar thermal collector for providing hot water and space heating
Gehlert et al. [7]	2018	Sustainable operation of a non-university research institution. Energy savings by a change from a static operation of the facility ventilation to a dynamic operation using smart automation
Amaral et al. [8]	2021	Overview over several campus projects and their pitfall

To obtain an overview over campus projects and their pitfalls, Amaral et al. give a comprehensive review [8]. As causes of unsuccess, they name (1) inappropriate planning or design of systems, (2) a lack of proper maintenance, (3) a low return on investment, (4) a mismatch between the actions and the local climate, and (5) uncertainty of long-term commitment to a sustainable behavior [8]. They find that PV needs to be combined with other sources such as wind, fuel cell, geothermal and storage systems or integrated micro grids to be cost-effective. As knowledge gaps, they identified the mismatch between demand and supply in renewable energy systems. They also found that there may be a gap between the estimated goals and the real performance in the use phase [8], which means that there should be energy monitoring to assess the real performance in practice.

Generally, there is a growing expectation that universities contribute to sustainability [9]. The higher educational sector is considered to play a critical role in the promotion of sustainable development [10] and in the search for a sustainable environment [5]. Several universities have sustainability centers or institutes [9]. By means of their research approaches and activities, these sustainability centers or institutes can be divided into four main types [9] of which we briefly sum up the characteristics of Type II: Innovating technologically for sustainability [9]. These centers focus on technological innovations and practical solutions to promote environmental sustainability, often in an urban environment, i.e., sustainable buildings and architecture, energy solutions, engineering and waste. Sustainability is perceived as an environmental problem linked to global warming that can be mitigated with a new technology or approach. In the background, there is an idea of transition and of improving current technologies, buildings, products and materials for the future [9].

Sustainability in the operation of buildings is based on the integration of renewable energies [11] as well as passive and low energy resources, e.g., solar gains, daylight, natural ventilation or geothermal heat exchange [12]. To distinguish sustainable energy from renewable energy, it is suggested that renewable energy means collecting energy from natural resources, whereas sustainable energy requires that (a) the rate of energy consumed is insignificant compared to the supply capacity (b) that environmental effects are manageable and (c) that serving the existing needs does not compromise the needs of future generations [13]. Thus, sustainable energy can come from natural resources but also includes improved energy conservation and efficiency [13]. A heat pump is a technology which uses a renewable energy source such as air, water, ground source, etc. and also generates sustainable energy (since, compared to, e.g., a gas boiler, much more useful energy is generated from the input power) [13].

Recent studies and projects in the building sector explore various options for integrating renewable energies (e.g., photovoltaic/building integrated photovoltaic [11], wind turbines [11], solar thermal (solar water heaters) [11], geothermal heat pumps [11,14–16], air source heat pumps [6,11,16], and district cooling and heating with combined heat and power (CHP) [11,16,17]. For a comprehensive review on zero-energy buildings, see [11]). Deep insights into the trends of system supportive heating and cooling as well as the simultaneity between renewable energy production and consumption in buildings are given, e.g., in [16]. The seasonal fluctuation in the demand for cooling and heating is an issue to which (air-to-water) heat pumps can be part of the solution, as they can generate chilled water in summer and hot water in winter [13]. Other issues linked to renewable energies are how to flatten the energy consumption during peak demand (also referred to as peak shaving) by the use of storage, e.g., batteries [18]. Batteries allow reducing the grid-observed peak demand without the need to change the consumption patterns [18]. To realize peak shaving, some researchers use deep learning approaches to forecast the loads [18].

Building modernization projects in general often certify a zero emission energy supply based on the annual energy balance (e.g., as in the calculations in [19] or for Osaka University Hall [4]). This annual energy balance for zero emission buildings omits that the excess energy generated by usually photovoltaic installations in summer is balanced with energy shortages for heating in the winter season. Thus, certified zero emission buildings cause additional electric loads for the electrical grid in the summer and, moreover, consume fossil fuels and emit CO_2 in the winter. Thus, in the field of sustainable building operation, there are still white spots concerning the simultaneity of the fluctuating renewable energy generation and the consumption in buildings.

In contrast to the mentioned zero emission buildings, the lecturing and exhibition building (LEB) of FH Westküste aims not only at a computational net zero emission balance per year but focuses on the simultaneity of energy generation, storage and consumption. This constitutes the novelty of this work compared to other works. To obtain strong research and demonstration data, the LEB has the following properties:

- Its own electricity generation by photovoltaic modules and a small wind turbine;
- Different energy storage units:
  - Lithium-ion batteries;
  - Thermal storage vessels;
- Fully electric heating and cooling units, i.e., reversible heat pumps; and
- A comprehensive data acquisition and processing system enabling different kinds of operation strategies.

Research is carried out in the areas of sustainable energy supply for buildings, sustainable heating and cooling, and grid-supportive heating and cooling, i.e., simultaneity between renewable energy production and consumption (in buildings).

The central questions of this publication are:

- Which different (storage) technologies can be easily applied for renewable and grid-supportive building energy supply;
- How it is possible to achieve simultaneity; and
- How to increase efficiency.

2. Research Scheme and Data Acquisition

The general purpose of this study is to set a benchmark of how to achieve simultaneity of the generation of renewable energy and the consumption of energy in a building which is designed for education, research and technology exhibition. We study long-term data on the electricity generation, energy demand, demand for heating and cooling and storage and simultaneity. The data cover a full year. The geographical location is Heide, in Germany. In this section, we present information on the climate conditions (Section 2.1), give an overview over the building (Section 2.2), and show on which assumptions the building technology was designed (Section 2.3) and which experimental program was conducted (Section 2.4).

2.1. Climate Conditions

The building is located in the "temperate, no dry season, warm summer" climate zone (Cbf) according to the Koppen–Geiger classification [20] (Figure 1). The height above mean sea level is 12.8 m [21]. The solar radiation is around 1026.5 kWh/m (yearly sum, global horizontal irradiation, period 1994–2018 [22]). The main wind power density is 150 W/m with a wind speed of 4.85 m/s at the height of 10 m and 372 W/m with a wind speed of 7.01 m/s at the height of 50 m [23].

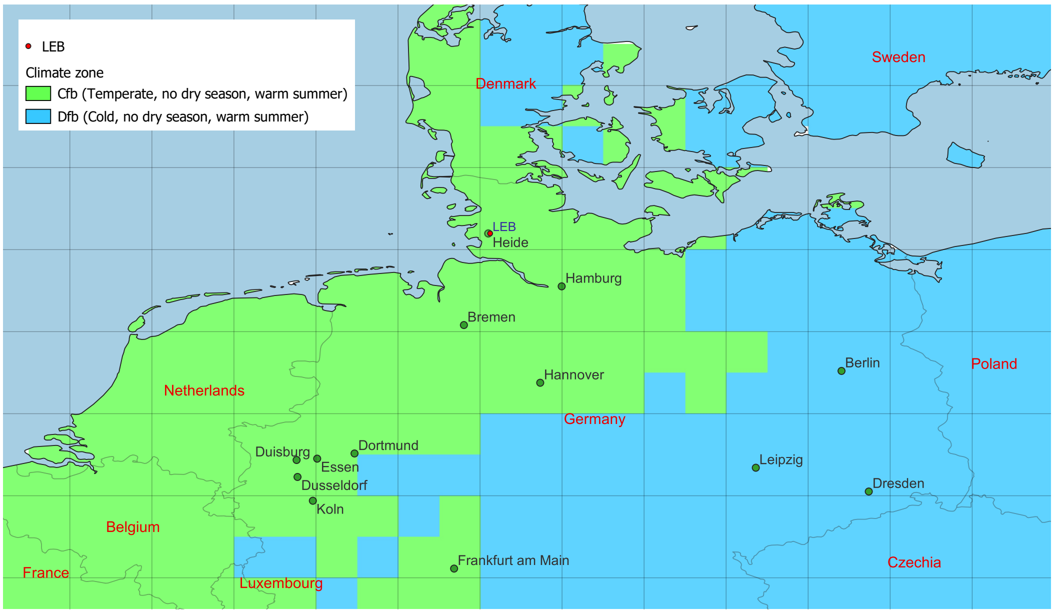

Figure 1. Geographical location of the city Heide within the climate zone Cbf. Map created using QGIS, Version 3.26.2-Buenos Aires and data from [20].

2.2. Building Properties and Technology

The building of this study serves multiple purposes, as can be seen from the layout (Figure 2). The main types of use are seminars, office work and the demonstration of the building services for students in the bachelor's program Green Building Systems and in the master's program Green Energy as well as for external visitors. The total floor space is 207 m^2. The construction type is wood framework with walls made of heat insulating sandwich panels. The building envelope complies with the requirements of the Energy Saving Ordinance (EnEV) 2016 [24].

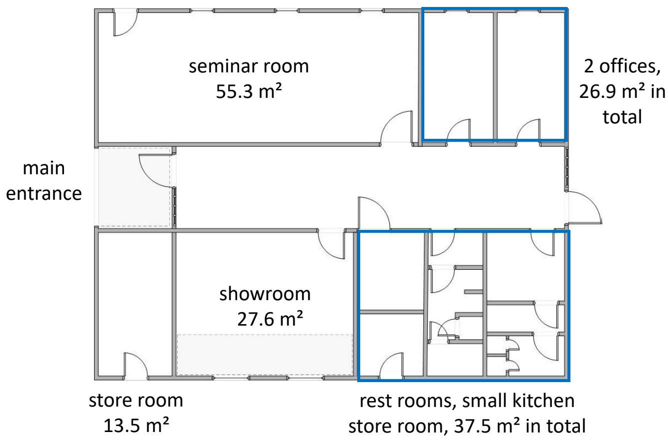

Figure 2. Grand view of the LEB with a total floor space of 207 m.

In the seminar room, classes and seminars for small groups take place. The offices are dedicated to the project staff. In the showroom, major elements of the energy supply system and of the automation are installed. The installation is made in a way that everything is visible (see Section 4). Thus, visitor groups experience the complexity of a modern heating and cooling system as well as the automation.

The overall energetic system of the LEB can be subdivided into the following three sections:

- Electric energy generation and storage (EEGS);
- Heat and cold generation (HCG);
- Heat and cold distribution system (HCDS).

Figure 3 gives an overview.

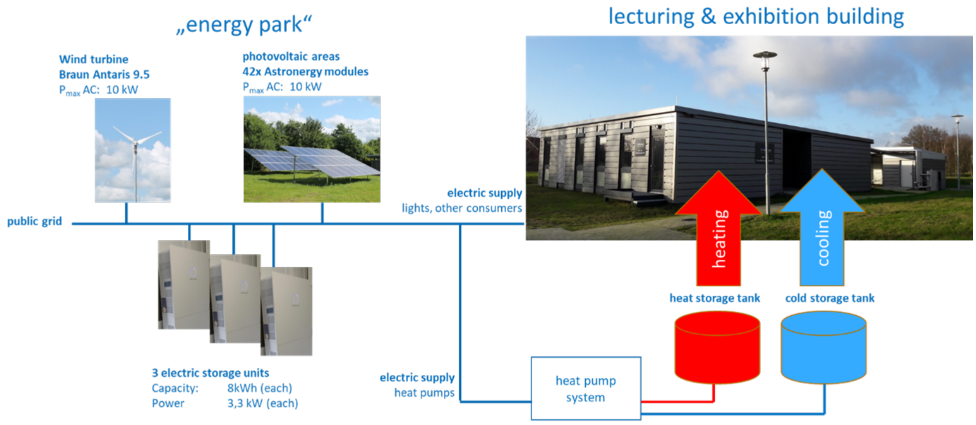

Figure 3. Scheme of the energy supply to the LEB. Renewable electricity is generated by (**1**) a wind turbine (WT) with a nominal power of 10 kW and (**2**) a photovoltaic (PV) system with a nominal power of 10 kW. For periods of shortages in renewable energy from the energy park, the system has a connection to the public grid. Furthermore, three energy storage units by sonnen GmbH are connected in parallel. Each storage unit has a capacity of 8 kWh and a maximum load/unload power of 3.3 kW.

The electricity is used for (1) operating the heat pump system and (2) for illumination and other end-use devices such as the hot water boiler, the coffee machine, the smart board, etc. The heat pump system is connected to a heat and a cold storage tank, which enables a temporary decoupling of the heat pump operation and the heat or cold consumption.

2.2.1. Electric Energy Generation and Storage

The WT and the PV system are connected to the AC grid, which consists of three phases resulting in a voltage of 400 V and a frequency of 50 Hz (Figure 3). The conversion from the generated electricity to grid compatibility is completed by inverters. The three storage units are connected to each of the three phases. The automation interfaces enable an external control of the three stages of the storage units: (1) load, (2) storage and (3) unload. Hence, it is possible to establish a temporary decoupling of the electricity generation and the consumption controlled by the central automation system.

2.2.2. Heat and Cold Generation

The key elements of the complex heat and cold generation system are (a) an air–water heat pump from Alpha Innotec with approx. 7 kW heating and 6 kW cooling power, (b) a brine–water heat pump by Alpha Innotec with approx. 8 kW heating power and a depth of the two boreholes of 80 m, (c) a heat storage tank with a volume of 1,000 L, (d) a cold storage tank with a volume of 600 L and (e) a brine/water plate heat exchanger (Figure 4).

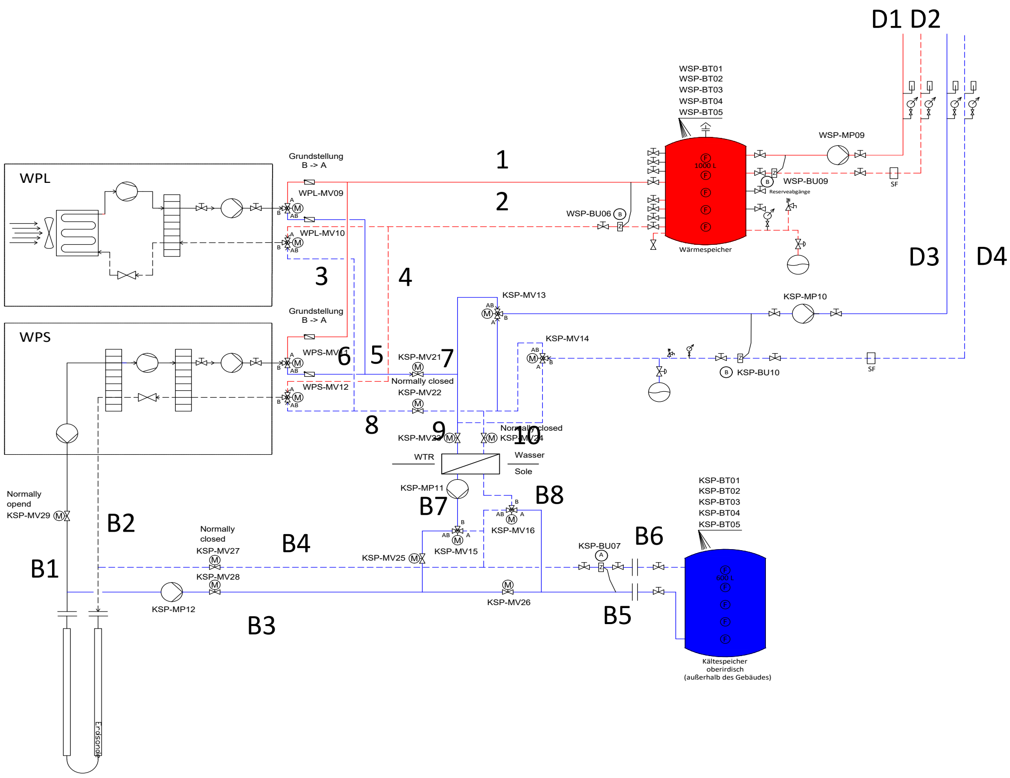

Figure 4. Scheme of the heat and cold generation system. Three sections have to be differentiated: generation system (no leading letter), distribution system (leading letter D) and brine system (leading letter B). For better understanding of the operation modes, the piping system is numbered.

The high complexity enables many different operation modes (Table 2). Note that different operation modes can be combined; e.g., in spring or autumn, a situation of simultaneous heating of the offices and cooling of the seminar room may occur.

Table 2. A selection of operating modes.

Operation Mode	Flow Directions
Heat storage tank loading by the air–water heat pump	1 → 2
Heat storage tank loading by the brine–water heat pump	3 → 1 → 2 → 4
Heat storage tank unloading	D1 → D2
Cold generation and distribution by the air–water heat pump (reversible operation)	5 → 7 → D3 → D4 → 8 → 6
Cold storage tank loading by the air–water heat pump (reversible operation)	Generation side: 5 → 7 → 9 → 10 → 8 → 6 Brine side: B7 → B5 → B6 → B8
Cooling by unloading the cold storage tank	Generation side: 10 → D3 → D4 → 9 Brine side: B5 → B8 → B7 → B6
Passive cooling by the earth heat source	Generation side: 10 → D3 → D4 → 9 Brine side: B3 → B8 → B7 → B4
Simultaneous loading of the heat and cold storage tank by the brine–water heat pump	Generation side: 3 → 1 → 2 → 4 Brine side: B1 → B3 → B5 → B6 → B4 → B2

The heating may be performed by loading the heat tank with the air–water heat pump. The heat storage tank may be unloaded simultaneously. The cooling may be performed passively or by unloading the cold storage tank. Another option for cooling is the active cooling mode by the reversible operation of the air/water heat pump and heating by the brine–water heat pump. This versatility enables an optimal efficiency of the heat pumps. In spring, the coefficient of performance (COP) of the air–water heat pump may be higher compared to the brine–water heat pump, depending on the weather conditions.

2.2.3. Heat and Cold Distribution System

The HCDS is realized as a four-pipe system (Figure 5). A four-pipe system offers the possibility of simultaneously heating and cooling different zones in the building.

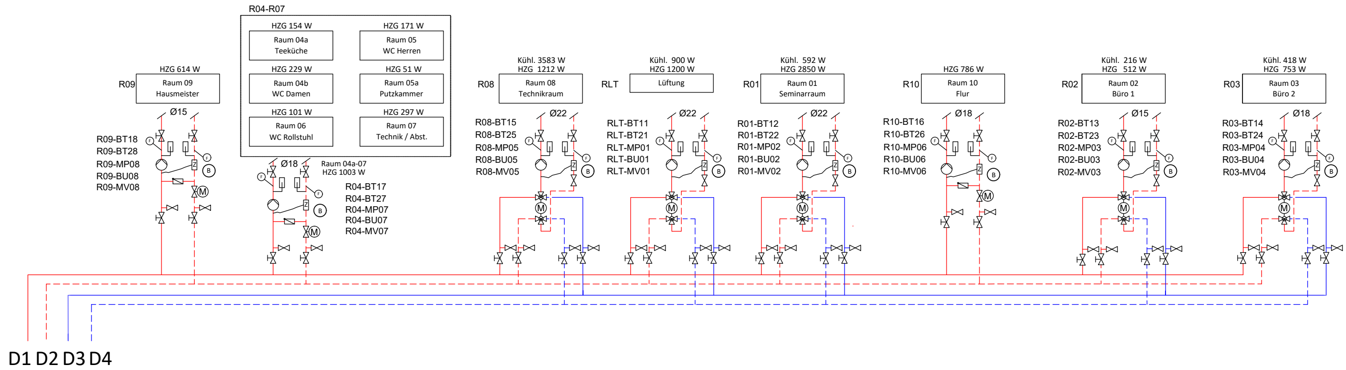

Figure 5. Four-pipe heat and cold distribution system of the case building on campus.

The two offices, the seminar room, the corridor and the show room have separate connections to the distribution pipes (D1D4). The storeroom has a connection to the heating pipes (D1, D2) only. The section of restrooms and the small kitchen is supplied together. Additionally, the air ventilation system of the seminar room has separate connections.

2.2.4. Automation System

The automation is realised by a PC from Beckhoff Automation GmbH & Co. KG. First, the operating modes (Table 2) were implemented to enable the basic heating and cooling functions. Second, a data acquisition and storage system was set up. Thus, the complete data from weather conditions measured on site (temperature, wind speed and direction, precipitation), energy park and LEB are stored in short time intervals. Data acquisition and operating modes have to be combined to meet certain operation objectives (Table 3).

Table 3. Operation objectives and possible drawbacks.

Main Objective	Drawbacks
Maximize autarky	Reduced comfort
Minimize peak power (peak shaving)	Reduced autarky, reduced efficiency
Maximize grid supportiveness	Reduced autarky, reduced efficiency
Minimize greenhouse gas emissions	Reduced comfort, reduced autarky
Minimize energy cost	Reduced autarky, reduced efficiency
Maximize energy for battery charging point	Reduced autarky, reduced efficiency
Optimize room climate	Reduced autarky, reduced efficiency

The main objectives underlie the following constraints:

- Sufficient electricity generation by the wind turbine and PV; and/or
- Sufficient storage capacity in the heat/cold storage tanks and the Li-ion battery units;
- Sufficient room climate in accordance with the existing regulations.

2.3. Design Phase and Simulation of the Heat and Cold Demand

In the design phase, heating and cooling loads were calculated. Heating load calculations were completed according to the DIN EN 12831 standard [25] using the software tool ZUB-Helena by ZUB Systems GmbH. The cooling load was calculated according to the German engineering standards VDI 6007 [26–28] and VDI 2078 [29] using ZUB-Helena. The simulation of the expected energy demand for a year predicts the highest heating demand to occur in January with approx. 3200 kWh/month (Figure 6). The highest heat flow demand is 9.3 kW for an ambient design temperature of −10 °C. The simulation also predicts a certain cold demand. This demand plays a minor role because it occurs during the semester break in summer.

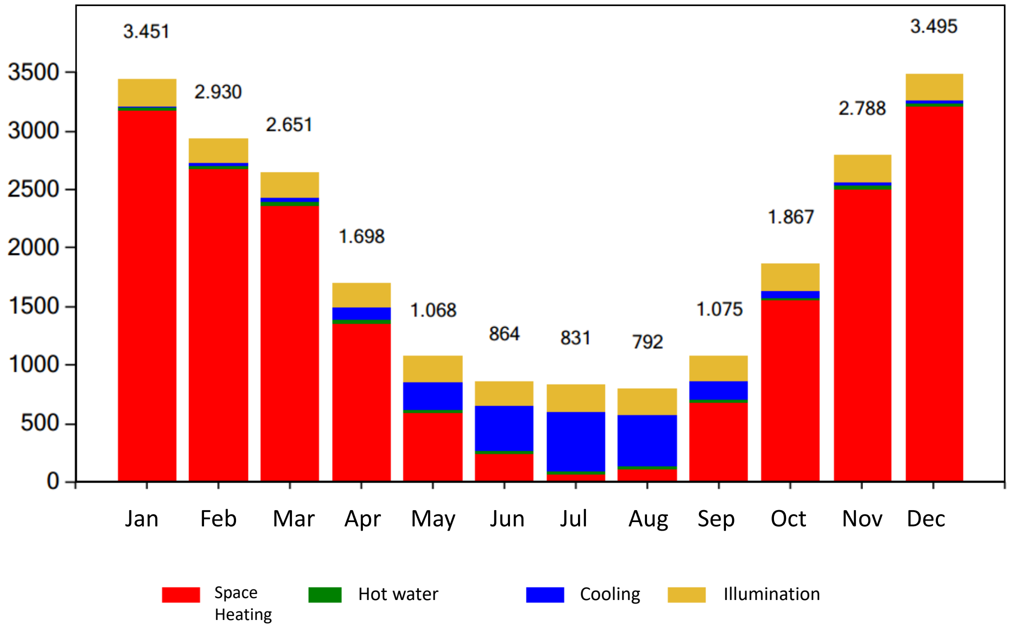

Figure 6. Simulation results according to technical guidelines for the net energy demand of the building in kWh. In kWh/m, the values range from 3.8 in August to 16.9 in December. The months February, July and August are influenced by the breaks between the summer semester and the winter semesters.

An essential question during the design phase was whether the electricity from the energy park would be sufficient for meeting the building energy demand, especially the heating demand. The simulated heating demand shown in Figure 6 neglects that heat pumps have a higher heat output compared to their electricity consumption.

Since the aim was to perform heating by heat pumps, the expected heating demand is smaller than in the simulation by Zub-Helena. This depends on the respective COP of the heat pump. Long-term measurements show that the average daily electricity production is approx. 46 kWh/day. Table 4 shows the comparison of energy demand and supply (1) for the heating design day with a temperature of -10C and (2) for an average day in January. For the heating design day, a daily heat demand was calculated to be 223 kWh. Assuming a COP of 4, the heating demand could be satisfied by an electricity demand of 56 kWh going into the heat pump. Thus, the energy of 46 kWh from the energy park would be insufficient.

Table 4. Predicted values from the design phase for power and daily energy.

	Electrical/Heat Power	Daily Energy
Design heat demand without heating-up	9.3 kW heat	223 kWh heat
Design input heat pump (COP = 4)	3.25 kW el.	56 kWh el.
Production Energy Park	Up to 10 kW el. each	46 kWh el.
Prognosis January (heat demand)	4.3 kW heat	104 kWh heat
Input heat pump January (COP = 4)	1.1 kW el.	26 kWh el.

By definition, the ambient temperature of the design day occurs 10 times in 20 years for two days in a row. Therefore, a situation according to the design day is unlikely in a winter period with average temperature values. Thus, a realistic average temperature in January was used to perform a realistic prognosis for the heating situation. As can be seen in Table 4, a realistic heat demand for an average day in January is 104 kWh/day for the LEB. This results in an electricity demand of 26 kWh/day. From this calculation, it can be concluded that the electricity produced would be sufficient in most cases.

2.4. Experimental Program

The experimental data have been being acquired from each component from the commissioning up to the present day. Most data are related to a regular daily operation (long-term data). However, several special experiments were conducted to pursue specific objectives (special data). The process is visualized in Figure 7 and Table 5.

As often in a long-term operation, data gaps occur for certain time periods due to external disturbances. One example is the shutdown of the PV in spring, summer and autumn in 2018 due to a cable cut caused by road works.

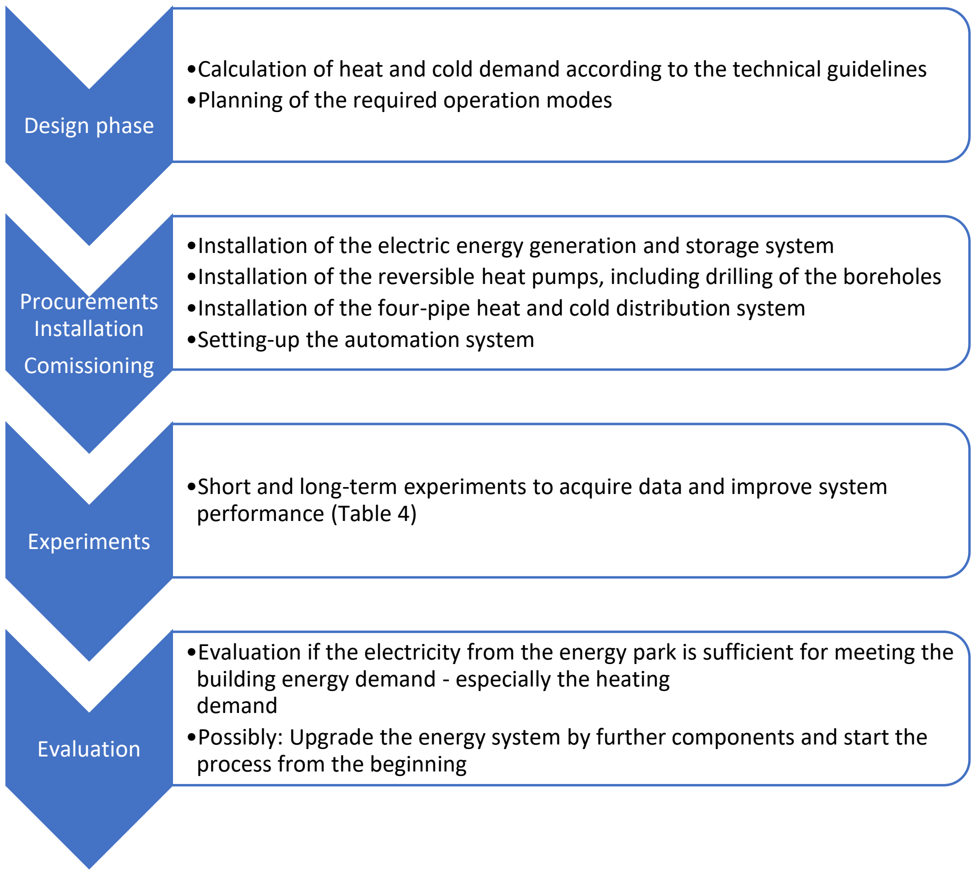

Figure 7. Research scheme as a conceptual framework.

Table 5. Experimental program as a pictorial framework.

		2016	2017	2018	2019	2020	2021	2022
Special experiments	Noise emission optimization of the WT by adjustments to the load curve	Summer						
	Experimental operation of the battery units		Mar.-Nov.					
	System checks of heat pumps, heat storage tanks and heat distribution system			Summer				
	Long-term COP measurements of the air heat pump					Feb.-Apr.		
	Measurement of heat losses of the heat storage tank					Feb.-Apr.		
	System check of the brine heat pump and the geothermal heat sources						June	
	Short-term COP measurements of the air heat pump						December	
Long-term experiments	Data from the WT and the PV system (regular operation)	Since May						
	Sample Data from the LEB			Since June				
	Automatic data from the LEB					Since May		

3. Results

In this section, some of the measured data for the electricity generation and the energy demand are shown exemplarily. The focus lies on the analysis of the simultaneity of the energy production and the consumption. The results are mainly generated at a regular building and energy system operation.

3.1. Electricity Generation

For the year 2021, the energy generation by the WT and by PV was approx. 12 MWh in total (Figure 8) with 3 MWh generated by the WT and 9 MWh generated by PV. The generation by the WT is significantly less because the location is non-ideal and due to the low height of the turbine (18 m). Furthermore, the WT was out of operation in June 2021 due to a cable defect. This was the first and only interruption of the operation since the commissioning in early 2015.

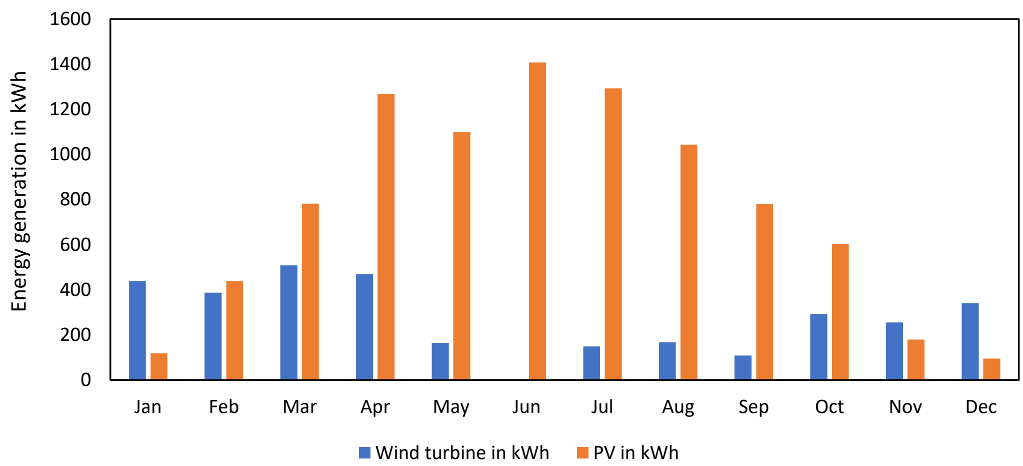

Figure 8. Electricity generation by the WT and by PV in 2021. Note that in June, the WT was out of operation due to a cable defect.

PV and the WT complement each other: in winter when sunshine is rare, the WT generates a significant amount of electricity. In spring, summer and autumn, the PV system dominates the electricity generation. The daily mean electricity generation calculated for each month varies from 14 to 15 kWh/d for November and December 2021 up to approx. 58 kWh/d in April 2021. The comparison of the value for January (18 kWh/d) to the prognosis (Table 4, last line: 26 kWh el.), indicates that energy shortages occur so that energy purchases are necessary.

3.2. Energy Demand

The average energy demands of the LEB for the test period from 5 February to 19 October 2020 (Table 6) are of limited significance, because (1) the average values over a long period miss the details about the real heating and cooling situations and (2) the test period does not cover a complete year. More recent data are still unavailable due to data gaps and inconsistencies because of several database updates.

Note the two interesting results:

- The electric consumption of the heat pump is rather low in comparison to the total electric consumption;
- The cooling demand is rather low compared to the heating demand.

To overcome the limited informative value of the average data, representative results for winter, the transitional period and summer are presented. We chose 6 May, 27 August, 2 November and 25 December from 2021 as representative dates. For selection, the criterion was to include a day which is (1) winterly, with ambient temperatures <3 C and (2) to include days where the electricity generation was lower than the demand in the building. Out of these, 25 December was the coldest day of the year based on the temperature measured on site.

Table 6. Electricity demand of the LEB for the test period from 5 February to 19 October 2020.

Nature of Demand	Energy in kWh/Day
Total daily energy demand (average)	12.35
Average electric energy demand of the air heat pump (brine heat pump not yet in operation)	4.84
Average heat demand of the LEB	14.19
Average cooling demand of the LEB	2.52

3.3. Heating and Cooling

Table 7 shows results for situations in winter, in the transitional period and in summer. Note that 25 December represents a rather cold winter situation in northern Germany. The ambient temperatures range from −1 to −12 °C. The data of 6 May and 2 November represent situations typical for the transitional periods in spring and autumn. Here, the ambient temperatures differ strongly between the day- and the nighttime, ranging from 4 to 11 °C and 2 to 12 °C. The date 27 August represents a typical summer situation, where the temperature exceeded 20 °C, whereas the night temperature stayed at moderate values (12.5 °C).

The two dates of 2 November and 25 December represent periods of dark doldrums: the electric energy generation falls far below the daily average (Table 7). The electric demand of the heat pump and the total electrical demand (see Nov 2) were above the daily electricity generation. These example data clearly show that the simultaneity of the production and the demand is a major challenge, which has to be addressed by installing more storage capacity.

The data from May and August show that the renewable energy supply in the transitional and in the summer period is no real problem, normally. The renewable energy production in these months is always sufficient.

Table 7. Specific results for the generation, heating and cooling (2021).

	25 December	6 May	2 November	27 August
Average ambient temperature in °C	−7.4	6.9	6.6	15.4
Electric energy production in kWh	7.2	77.9	25	40.6
Heat demand of the LEB in kWh	87	43	28	0
Cooling demand of the LEB in kWh	0	0	0	6
COP of the air heat pump (daily average)	3.2	n/a	n/a	n/a
COP of the brine heat pump (daily average)	4.5	3.27	4.5	4.3 (EER)
Electric input of the air heat pump in kWh	3.5	0	0	0
Electric input of the brine heat pump in kWh	17	13.1	6.2	1.4
Total electric demand of the LEB in kWh	n/a	n/a	35.5	19.8

3.4. Storage and Simultaneity

In Figure 9, electricity data (generation and demand) are plotted over 24 h for 25 December 2021.

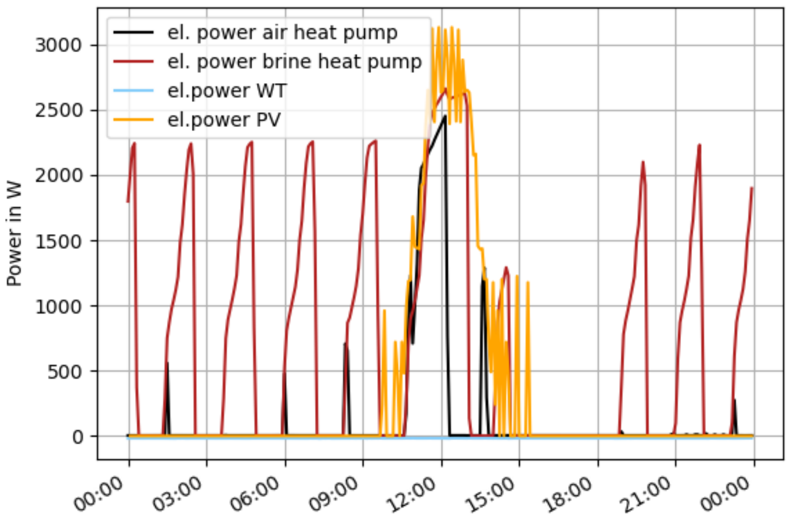

Figure 9. Electricity generation and demand in W on 25 December 2021.

The brine heat pump is operating periodically throughout the whole day (Figure 9). Additionally, the air heat pump runs in some situations. At daytime, from 9 am to 3 pm, the PV system generated some electricity. There was no wind on that day. The energy gap between the generation and the demand exceeds 13 kWh. These data clearly highlight the necessity of storage units.

An example of the transitional period is 6 May 2021 (Figure 10). Here, more than sufficient electrical generation was measured, with a significant share from the wind turbine. The brine heat pump was in operation periodically during night and early morning and in the late evening. Later (11 pm), stored energy was necessary. Due to the oversupply before, sufficient electrical and thermal energy was available.

The date of 2 November 2021 can also be assigned to the transitional period (Figure 11). Here, the brine heat pump was operating only in two periods: in the early and the later morning. The integrals show that the second operation period is fully covered by the PV generation at the same time. However, in the early morning, external or stored electricity was necessary. By comparing the total electricity generation with the demand, the supply was insufficient: 25 kWh was generated, 35.5 kWh was consumed.

Figure 12 depicts a summer situation in northern Germany with the cooling demand. During the regular working hours, the electric demand for cooling was overcompensated by the wind and PV supply. The area between the orange line and the red line gives an idea of the surplus energy generation, which is partly stored in the battery units. Therefore, the additional electric demand for cooling in the evening could be satisfied by the battery storage units. Unfortunately, automatic data for the battery charge state are still not available due to network issues (safety concerns by the university administration).

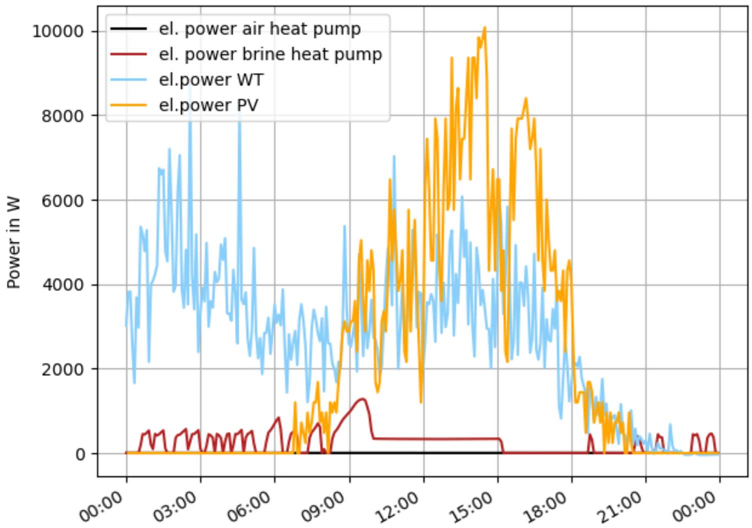

Figure 10. Electricity generation and electricity demand in W on 6 May 2021.

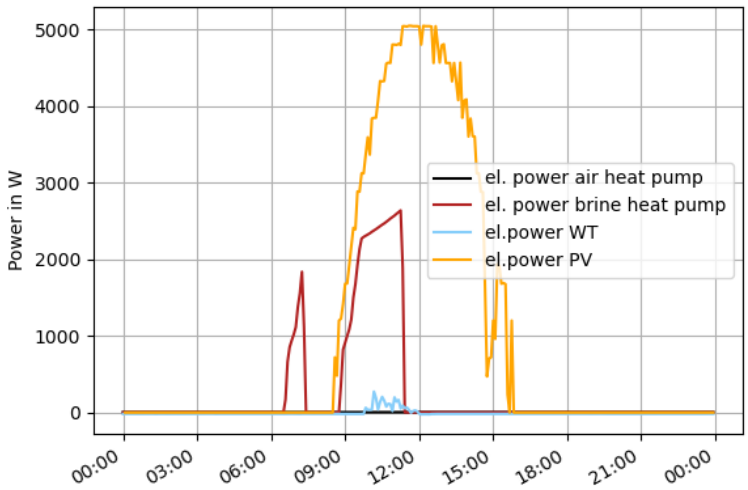

Figure 11. Electricity generation and electricity demand in W on 2 November 2021.

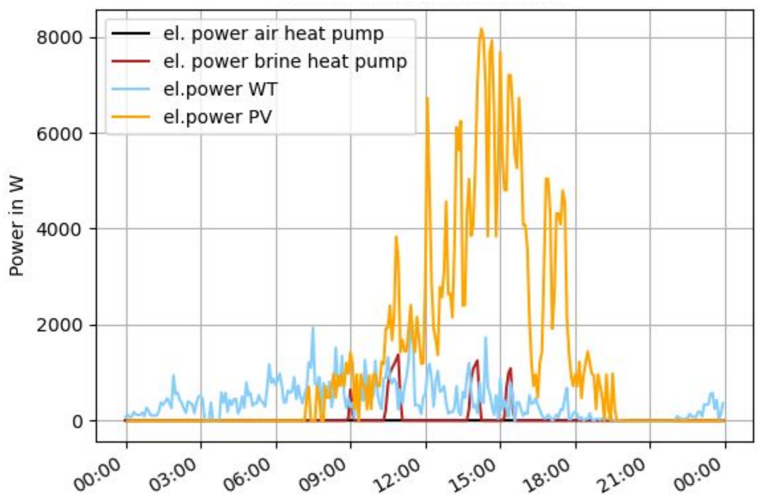

Figure 12. Electricity generation and electricity demand in W on 27 August 2021.

4. Discussion

4.1. Main Findings

In the previous section, we analyzed the long-term data from the operation of a case building. In the following, we discuss the results from the electricity generation, the energy demand, the heat and cold demand and the question of whether supply and storage capacity are sufficient. Furthermore, we discuss the limitations and the scientific value added as well as the applicability of the findings. We also give an outlook on future works.

Concerning the electricity generation, it is unlikely that a single renewable technology source can provide the required energy throughout an entire year. It is common that different renewable energy systems are used in conjunction. White/Gillott/Gough, for example, use an air source heat pump and a solar thermal collector to deliver heating and hot water requirements [6]. In the case of the LEB, two electricity generators, PV and WT, were combined and backed up with storage options and with the connection to the public grid. The evaluation of the measurement data from 2021 shows that the two complement each other well. Wind power generation was higher in the months when photovoltaic power generation was low.

With respect to the total energy demand, automatically logged data are available for the test period from 5 February to 19 October 2020. For the recent historical data, editing is still in process. There are data gaps and inconsistencies because of software updates. In this work, the details about the real heating and cooling situations are of higher interest than an average total energy demand. Therefore, we focused on the daily demands of the heat pumps.

An interesting finding from the test period was that the electric consumption of the heat pump is rather low in comparison to the total electricity consumption. This speaks for the good efficiency of the heat pump under real-world conditions. The air–water heat pump with approx. 7 kW heating power had a COP of 3.2 on the coldest day with an average ambient temperature of −7.4 °C . In another study in a similar climate (UK), a 100 m Research House was supplied with an air source heat pump of 9 kW for space heating and hot water. The COP fell below the value 3 for a significant number of individual days even though the winter was mild. However, in this work, the heat pumps only serve the space heating demand and do not deliver hot water.

The cooling demand was found to be rather low compared to the heating demand. This shows that cold demand was marginal in 2021. This is partly because of the semester break, as simulated with the planning software. In addition, opening the windows appears to be sufficient to satisfy the cold demand by users for most of the warmer season. However, climate projections for the region and the period 2036–2065 expect six more days per year with temperatures over 25 °C in the scenario with low climate mitigation action [30]. Thus, the cold demand is expected to rise.

The focus of this study is how to establish the simultaneity of the renewable energy generation and the energy consumption. The approach differs from other undertakings, which aim at an annual "net-zero" balance. Apart from the maximization of autarky, other operation objectives, namely:

- Peak shaving;
- Maximizing grid support;
- Maximizing energy for battery charging point;
- Minimizing greenhouse gas emissions;
- Minimizing energy costs.

Their trade-offs and possible drawbacks were presented. For other buildings, the prioritization of the objectives might be different. For instance, the operators of the central building at the Leuphana University prioritize a low electricity demand and user-friendliness over the autarky of the single building [1]. At the University of Nottingham, it was also intended to reduce the occupants' energy bills as compared to traditional heating systems and to contribute to affordable housing [6].

The electrical generation and the consumption, including the demand for heat and cold, often occur at different times. Hence, storage capacities are necessary. An exemplary day for the cold period shows an energy gap between the production and the consumption of more than 13 kWh, revealing that the existing storage capacity is insufficient.

The limitations of this paper are that the short-term experiments are excluded (such as noise emission optimization, COP measurements, heat loss measurements, etc.). Furthermore, within the scope of this paper, it cannot be assessed how much the LEB contributes to a sustainable development in terms of education and outreach [2]. On the one hand, experiencing the building and its technology was meant to be easily understandable for a broad audience (see Supplementary Materials Figures S1–S4). On the other hand, interested experts request in-depth insights. The staff intended to find a compromise in the exhibition. It is unclear if and how the LEB motivated actors to take climate change mitigation action on their own.

Further limitations are linked to the purpose of the LEB: as the building is used for demonstration purposes and research and teaching, more technical infrastructure and equipment was installed than what would have been economical in the private sector. In the private sector, technically achievable energy standards are often limited by cost-efficiency [1]. Normally, in the search for the optimal building design, both performance and costs are calculated ([16] p. 780). Yet, there is a tendency to minimize initial cost rather than life cycle cost, especially if the builder and the occupant are different actors. In the future energy system, it is unlikely that every building will have its own energy park, especially not a wind turbine.

In general, the LEB offers a template for future supply strategies in terms of heating and storage units. The data from the energy park of the FH Westküste University of Applied Sciences contribute to understanding the challenges of fluctuating energy supply. For the FH Westküste, the building may contribute to the institutionalization of the sustainability research agenda [9]. The LEB is a Type II (cf. the introductory section) sustainability center on the campus where learning, teaching and researching are combined. As Luederitz et al. state, sustainability research and education are often considered to be independent activities within universities [31]. Here, students are writing degree theses which bring forward the ongoing research project (e.g., Tunable White, an innovative light concept for the new Lecturing and Exhibition Building of FH Westküste, Fachhochschule Westküste (FHW), Heide, 2019; Assessment of the indoor air parameters for the thermal conditioning of the new Lecturing and Exhibition Building of FH Westküste, Fachhochschule Westküste (FHW), Heide, 2019). The collaborative publishing of research findings in peer-reviewed journals (as suggested by [31]) is planned.

4.2. Future Work

For the building discussed in this paper, the development of a comprehensive automation system is under continued development. Integration of the battery data is one of the next steps. Moreover, the implementation of the operation objectives (Table 3) is the second focus of the ongoing work. For seasonal storage and for bridging the periods of dark doldrums, an investment in a combined unit with an electrolyzer to produce hydrogen, a hydrogen storage and a fuel cell and the integration into the existing infrastructure is planned. This unit is supposed to maximize autarky. Furthermore, the unit is meant to serve research and teaching purposes (i.e., bachelor theses and master theses) as well as demonstration purposes (addressing the general public and small craft businesses with apprentices). Technical data for the unit are estimated to give an electrolyzer capacity of 2×500 NL/h, water preparation of 0.8 L/h, purification module with Lm^3/h, compressor unit with 3 kW, hydrogen storage (pressure change operation) with 600 kWh, fuel cell (1.5–2 kW$_{el}$), gas drying module (2 m^3/h) and a heat exchanger (with 93% heat recovery).

5. Conclusions

Universities are expected to contribute to sustainable development, by their research, through education and also by actions on the campus itself. This case study on a research building provided valuable research by investigating solutions how to establish the simultaneity of renewable energy generation and energy consumption. The different energy generation and storage technologies of the Lecturing and Exhibition Building (LEB) on the campus of the FH Westküste (Germany) have proved reliable and efficient in practice. The energy park provides an energy surplus, most of the time. The energy system with heat and cold generation by two different heat pumps enables a high flexibility through the different operation modes. Cold demand was overestimated, and opening the windows was sufficient for most of the warmer season. On the coldest day of the year, we determined COP values of the heat pumps of 3.2 for the air–water heat pump and 4.5 for the brine–water heat pump. It is possible to switch between the air–water heat pump and the brine–water heat pump depending on the higher COP. The LEB intended to achieve an effective 100% renewable energy supply per each day instead of a mere computational net balance per year. The question was if the installed technology is sufficient for this purpose in practice. We picked representative days of the year 2021 for the cold season, summer and for the transitional periods. These example data show that it is possible to achieve an effective 100% renewable energy supply for most of the year. In this case building, more storage capacity is required to bridge certain days with a high heat demand and low electricity generation.

Future research should perform more case studies in research institutions, but there should also be works addressing the question of how to implement simultaneity beyond small-scale sand boxes.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su141912538/s1, Figure S1: Thermal concept of the LEB with ventilation system for seminar room (1), radiant ceiling panels for heating and cooling (2), heat storage inside building (3), outside cold storage (4), air heat pump (5), brine heat pump (6) and geothermal probes (7); Figure S2: Exterior view with cold storage (1) and air heat pump (2); Figure S3: Seminar room with radiant ceiling panels for heating and cooling (1) and ventilation system (2); Figure S4: LEB showroom with heating and cooling distribution (1), circuit cabinet (2), brine heat pump (3) and heat storage (4).

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