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Climate-neutral and sustainable campus Leuphana University of Lueneburg

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ABSTRACT

The Leuphana University of Lueneburg changed to renewable energy supply with the first climate-neutral energy balance for heat, electricity, cars and business trips in 2014. The heating network is based on two biomethane-powered combined-heat-and-power (CHP) units of 525 $kW_{el.}$ each. A total of 720 kW_p photovoltaics with 95% self-consumption covers > 20% of the electrical demand. We present the campus development and transformation to provide a best-practice example for conversion to exergy-efficient renewable energy systems.

The new central building provides a large auditorium, seminar rooms, offices, a cafeteria, machine hall and space for exhibitions and events. It uses low-grade heat at 58 °C for optimized integration of short and long term heat storage installations. The architecture and façade design significantly lower cooling demand (≈ 2.5 kWh/m^2a), modern lighting systems and user integration allow for superior overall energy efficiency. Exergy efficiency, storage options and emissions of the campus system as well as energy efficiency of the buildings were analysed. A high-temperature aquifer thermal energy storage (HT-ATES) installation perfectly matches the low-exergy heating demands and increases the share of CHP-heat, resulting in an additional surplus of 2.3 GWh/a of renewable electricity and additional savings of 2.424 t CO_2-eq./a.

1. Introduction

1.1. Sustainable universities

Indeed, sustainability is elusive [1]. There are manifold perspectives towards the definition of sustainability. For instance, the term is adapted in different contexts and social spheres such as civil society, business and higher education [2,3].

Sustainability assessment in universities is more concise and can be measured with a number of important indicators such as decreased consumption, centrality of sustainability education, cross-functional integration or cross-institutional integration [4].

In this context, sustainable university can be defined as a higher educational institution that involves and promotes the minimization of adverse environmental, economic and societal effects generated by use of their resources [5]. Related to this, universities can be seen as key-players to fulfil a central role in sustainable development processes on a regional level [6].

With respect to size, population and the various complex activities, universities have serious impacts on the environment as they can be regarded as “small cities” [3] and “living labs” for sustainability. There is a substantial environmental footprint of universities in context with material and energy consumption. The key concerns have been identified as waste generation, energy consumption and mobility [7]. Although there are plenty organizational and technical measures to reduce the magnitude of the negative environmental impact of universities, a systematic and sustainable approach is generally lacking [3,8,9]. The concept of sustainability may contrast with the existing concepts and teaching methods in universities, which are mainly focused on resource depletion [10]. However, many universities have installed Environmental Management Systems (EMS) to operationalize responsibility and to manage their environmental performance. These endeavours are not limited to a single country or region, but have been particularly prominent in Europe, USA, Canada, Australia, Asia, South America and Africa [11,12]. To mitigate negative environmental effects emanated by universities, three widely spread approaches are used – green building initiative, ISO 14001 and EMAS [3,12,13]. According to Savely et al. [14], two EMS

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Nomenclature

ATES	Aquifer thermal energy storage
CHP	Combined heat-and-power cogeneration
CO_2-eq	Carbon dioxide-equivalent emissions
DHS	District heating system
EE	End energy
EMAS	EU Eco-Management and Audit Scheme
EMS	Environmental management systems
EU	European Union
f_{EM}	Specific emission factor
GHG	Greenhouse-gas emissions
HRF	Heat recovery factor
HT-ATES	High-temperature aquifer thermal energy storage
ISO	International standardization organization
kWel	Kilowatts electric
kWp	Kilowatts peak
kWth	Kilowatts thermal
LED	Light-emitting diode
PE	Primary energy
PV	Photovoltaic
Q	Heat energy
T_{sup}	Superior temperature of the carnot cycle
T_{inf}	Inferior temperature of the carnot cycle
UNESCO	United Nations educational, scientific and cultural organization
ε	Exergy
η	Energy efficiency
η_c	Carnot factor
η_ε	Exergy efficiency

models have been proposed specifically for colleges and universities – the Osnabruck model [9] and the university of South Carolina sustainability initiative [3], the latter additionally involving cross-institutional audits. Both highlight institutional learning, participation and public relations, since organizational structures and decision-making processes, just like outside the “living lab university”, often limit the pace-setting progress.

1.2. Renewable energy systems

Strategic environmental planning and goal-setting is a key part of environmental and sustainability management. Since climate change and energy-related greenhouse-gas emissions are major topics in this field, renewable energy systems and efficient buildings are a focal point within the sustainable universities discourse. Kılkış provides a comprehensive up-to-date overview [15]. As Li points out, zero energy buildings are designed to be very energy efficient, but the use of renewable energy sources is at least equally important [16]. The shift towards renewable energy involves the integration of fluctuating sources like wind and solar, therefore using decentralized smart grids and storage (both for power and heat), energy-efficient heat pumps as well as low-temperature 4th generation heating networks to meet the needs of energy-efficient buildings and to minimize losses [17–19].

Tuning energy efficiency of existing buildings and infrastructure is an even more complex multi-disciplinary mission dealing with economic, legal and social constraints. Often, technically achievable energy standards cannot be fully realized. Limiting factors are cost-efficiency and sometimes urban heritage conservation as well as more or less fixed temperature levels of the heat supply, especially in case of rather heterogeneous demand-sided structures. A methodology related to exergy, which takes into account the relative quality of the energy source and fluxes, can help in efficiently meeting the needs, avoiding unnecessary losses at the system scale [15,20–23] as well as improving the integration of thermal storage [20] and environmental heat. Besides cost-efficiency, reduction of carbon dioxide emissions at the system scale is of highest importance practically and should be compared to more theoretically derived exergy efficiencies [15,21]. This paper analyzes the campus development of the University of Lueneburg as a case study regarding the conversion to renewable energy systems.

1.3. Background: The Leuphana, university policy and the campus

The existing campus was constructed in 1936. It served as a Wehrmacht casern during the 2nd world war. The casern was converted in the early 90'ies, when the barracks of the southern part were broken off. This part was reconstructed to a residential and mixed use area whilst the massive buildings in the northern part gave home to the expanding University of Lueneburg. Already during the reconstruction, combined heat and power (CHP) cogeneration systems were installed, burning natural gas. In the newly constructed residential and commercial areas of the “Bockelsberg” district south of the university campus, new district heating pipes were used whereas for the old massive buildings the existing steam network was kept in place for hot water distribution. The Campus consists of 14 old casern buildings with double-box windows used by the university and 2 buildings used as dormitories, which were already equipped with double glazing, all of them constructed with up to 1 m thick solid brick masonry resulting in high thermal mass.

During the conversion into a university campus, several new buildings were constructed: A dining hall (Mensa), 5 small-to-medium-sized lecture halls, 4 of them connected to each other and to the library by a glazed gear. These, and 2 old barracks that now provide space for a fitness center and shops, where also equipped with double glazing and – at that time – up-to-date insulation. In 2003 the university became a foundation under public law gaining more freedom in decision making and in 2005 merged with the University of Applied Sciences of Northern-East Lower Saxony. Framed by its role as a model university for the Bologna Process, in 2006 the implementation of a new profile based on three pillars – humanity, sustainability and action orientation was started. The new university was renamed “Leuphana”, taken from an ancient map made by Ptolemäus. To accompany this leap forward, a campus development program was introduced, involving refurbishment and extension of the existing campus buildings and the construction of a new central building. Fig. 1 shows the campus as the northern part of the conversion area. To strengthen the focus on sustainability it was decided to become climate-neutral by 2012 in 2007.

2. Materials and methods

2.1. The process - striving for climate-neutrality

Climate-neutrality, explicitly including other greenhouse-gas emissions besides carbon dioxide, is hardly achievable by efficiency measures alone [16]. Moreover, environmental issues are becoming more complex, multidimensional and interconnected

Fig. 1. Site plan of the Leuphana University campus Scharnhorststraße.

between direct and indirect effects [24], such as greenhouse-gas emissions due to energy consumption and induced traffic. Therefore, the Leuphana University of Lueneburg decided to follow an integral approach and framework in order to achieve a sustainable and climate-neutral university [25].

The Leuphana, pioneer in inter- and transdisciplinary sustainability research since the 90'ies and home of the UNESCO Chair for higher education for sustainable development, looks back on 20 years of implementing sustainability guidelines in research, education as well as campus facilities and operation. In 2000, it was the first university to be certified by the EMAS EU Eco-Management and Audit Scheme (based on but far beyond ISO 14001 [26]), a valuable tool to help implement environmental and sustainability guidelines in campus operation involving annual reports, management and goal-setting.

Triggered by the EMAS procedure, but also as an outcome of the set goal to become a climate-neutral and sustainable university, several small-scale, user-oriented measures have been taken to reduce the overall energy demand and promote the awareness of sustainability and environmental issues. Over all, technical measures including two small-scale PV installations ($\approx$ 70 kWp) and the refurbishment of the heating network resulted in savings of around 125 t/a CO_2-emissions. User-oriented campaigns almost doubled this value. However, after the campaign had ended, the user-centered savings were lost again within 2–3 months. In any case, compared to a total of $\approx$ 8,400 t/a CO_2-equivalent, 2/3 of which from traffic (Fig. 2), these are insufficient.

Based on this experience, and due to further plans of the campus development, several large-scale measures have been planned.

To reduce inter-campus traffic (the Leuphana University used 2 more locations in the city of Lueneburg) and to provide space for further growth, the decision had been made to extend the existing buildings and at the same time promote the quality of the buildings in terms of energy efficiency.

As a pre-study for energy-saving potentials in the existing buildings, mostly to reduce heat losses, several steps have been evaluated, for example insulation of the roofs and cellar ceilings, new windows, inner and outer insulation and optimizations of the heating systems.

However due to the high costs of most of these measures and long amortization times, whilst available funds were needed for the construction of the new building and attic conversions, it was decided to announce the future heat supply as well as the refurbishment of the existing buildings, as two independent lots, in an EU-wide tender following an energy-contracting model. The tendering process therefore had to deal with the cross-links between the future energy supply and future demands, both influenced by savings in the existing buildings and the newly constructed building – not all tenderers were able to deal with this task, although a 2-staged negotiation process was undertaken to link both aspects.

For the future heat supply, a benchmark system was used to integrate sustainability measures in the tendering process (with distinct levels for the shares of energy from renewable sources and certain characteristics for exergy efficiency, both aspects scoring 30% each making a total of 60% compared to the price scoring 40%). The conditions were evaluated in terms of percentages compared to the current prices (for energy and power) in order to prevent distinct thresholds that just could have been undershot. For the energy system, renewal of the CHP station and switching to biomethane proved to be the best option, allowing carbon-neutrality and a significant cost reduction due to corresponding feed-in tariffs. As the existing DHS covered the heating demand not only of the campus system but also of a mixed residential district Bockelsberg it was possible to optionally include this system with a heating demand of $\approx$ 5.8 GWh/a compared to estimated $\approx$ 5.2 GWh/a of the campus system (including optimizations and the new building, the total future demand of the DHS including losses was assumed to equal 11.1 GWh/a).

The benchmark system for energy savings in the existing buildings was planned to compare calculated marginal costs for CO_2-equivalent and primary energy savings per measure, respectively, however this did not work out due to cross-influences between certain measures. Therefore the system was changed to providing a baseline calculated with estimated prices for the future energy supply, with which the tenderers were able to make offers for different sets of measures.

The process involved a provisional exergy analysis, integral modelling and planning of the existing campus and the assessment of primary energy consumption and GHG emissions. An energy efficient new central building aiming at low electricity demand and user-friendliness was planned. It was designed to use low-exergy heat from the return line of the campus energy system to lower overall return line temperatures and improve the efficiency of heat storage. The feasibility of a large high-temperature aquifer thermal energy storage (HT-ATES) installation to integrate heating networks of the city of Lueneburg and the low-exergy heat using new central building has been investigated in detail, with very promising results. The transformation towards a 4th generation system [17] that relates to smart energy and smart thermal grids as part of the design of future sustainable energy systems [18] enhances the storage efficiency and promotes usage of the stored heat. Its realization will allow to offset indirect emissions from commuter traffic, enabling a climate-neutral balance including beyond-scope 3-induced emissions (external effects).

For this concept, the Leuphana University was awarded by EUROSOLAR with the German Solar Prize in the category of solar architecture and urban development in 2015 [27].

2.2. Exergy analysis

Exergy analysis was done during the concept stage to form a basis for decisions regarding the heat supply of the DHS during the tendering process following the general methodology [15,20–23]. Accordingly, the exergy efficiency η_c is given by the maximum efficiency of the corresponding carnot process (equation (1)), calculated from the temperatures on the warm end T_{sup} and the cold end T_{inf}:

$$\eta_c = 1 - \frac{T_{\inf}}{T_{sup}} \tag{1}$$

Exergy flows (ε) were calculated from end energy (EE) units by multiplication with the carnot factor (η_c) as given in equation (2):

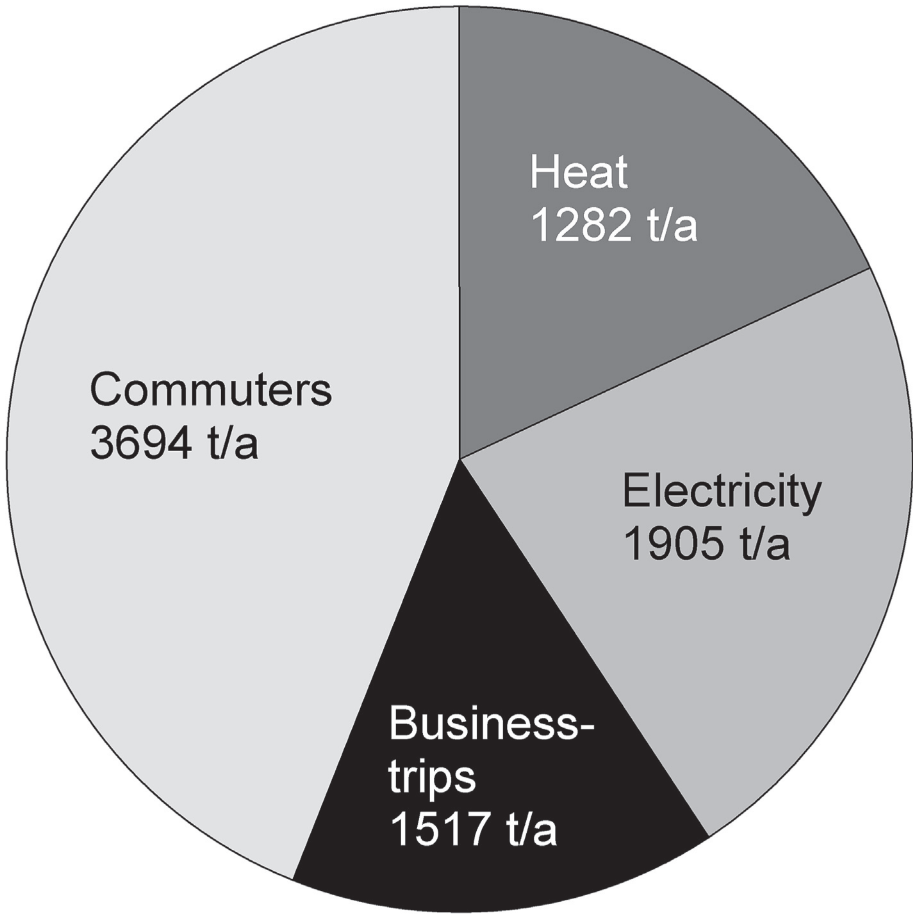

Fig. 2. Average operational CO_2-emissions of the Leuphana University (2007–2011) in t/a CO_2-equivalent. Data on mobility emissions only exist for 2007 (business trips and commuter traffic) and 2015 (only business trips). Electricity was supplied from near carbon-neutral renewable sources since 2012.

$$\varepsilon = \eta_c \cdot EE \quad (2)$$

For useful heat (space heating and dhw), T_{inf} is the outdoor (ambient) temperature, for space heating T_{sup} is the indoor (dry-bulb or setpoint) temperature [15], for DHS the average between supply and return line can be used [23]. Since both temperatures may vary, exact values for η_c can only be obtained using measurements or modelled temperatures. For a provisional analysis, assumptions based on plausible values can be taken. Often, the median ambient temperatures are used for T_{inf}, in this case study 283 K. For T_{sup}, 348,15 K presents an appropriate value for a 3rd generation DHS, leading to $\eta_c = 0.16$ for heat supplied to the DHS (cf [23]).

Carnot factors for different fuels differ in the literature. In theory, as chemically bound energy, they are near or even above a factor of 1 [22,23]. Most authors use equation (1), assuming typical combustion temperatures [cf 15,21]. Similar to the common carnot cycle analogy, that is mandatory for defined temperature levels, a technical best-case scenario could alternatively be used for evaluation of the exergy content of fuels (cf [28]). Natural gas or biomethane, for example, are most efficiently used in combined gas and steam-CHP units (and fuel cells). They reach electrical efficiencies of $\eta_{el} = 0.58$ [28,29]. The thermal efficiency of a high-efficiency unit for example is $\eta_{th} = 0.35$ with $\eta_{c(th)} = 0.16$. The carnot efficiency η_c of a CHP unit can be calculated as given in equation (3),

$$\eta_c = \eta_{el} \cdot \eta_{c(el)} + \eta_{th} \cdot \eta_{c(th)} \quad (3)$$

resulting in a value for $\eta_{c(gas)} = 0.64$, lower but comparable to values derived from eq. 1 [cf 15,21], essentially leading to similar conclusions and reflecting the relative quality in comparison to electricity regarded as “pure exergy” $\eta_{c(el)} = 1$.

Exergy efficiencies (η_ε) are calculated as the relation of ε_{out} (i.e. the heat used in the system (substracting losses) and electricity) calculated from end energy streams $(\eta_c \cdot EE_{out})_i$ and the inflow of exergy ε_{in} from different fuels or other sources $(\eta_c \cdot EE_{in})_i$ as given in equation (4):

$$\eta_\varepsilon = \frac{\varepsilon_{out}}{\varepsilon_{in}} = \frac{\sum_{i=1}^{i} (\eta_c \cdot EE_{out})_i}{\sum_{i=1}^{i} (\eta_c \cdot EE_{in})_i} \quad (4)$$

Four variants were compared to cover the heating demand of the existing DHS (11.1 GWh/a): Oil or gas boilers ($\eta_{th.} = 0.9$), baseload-CHP ($\eta_{el.} = 0.39$ and $\eta_{th.} = 0.49$) with 75% share of CHP heat and 25% boiler, 50 m^3 storage and 2.5% losses, power-operated CHP with 200 m^3 storage (80% cogeneration share, 5% losses) and CHP with aquifer storage (90% cogeneration share and 15% losses).

2.3. Modelling and planning tools

Different planning and modelling tools have been used as a basis for integral planning and optimization and to investigate future energy demand and storage options. The existing campus buildings as well as the new building have been modelled with the transient system modelling tool DOE 2.1E [30] and ZUB Helena, a tool for the assessment of building energy performance based on the German standard DIN 18599 [31]. The DOE 2.1E campus model was validated against measurements. The building models showed differences of 25% for heating and cooling demands in the new building, highly dependent on user scenarios. The energy system and ATES has been modelled in TRNSYS [32] using TRNAST [33], a TRNSYS-derived system model for two-well storage systems. The TRNAST model was validated against a site-specific numerical hydrogeological FeFlow model [34] and in earlier studies [35–37]. For the TRNSYS simulations, measured (campus and Bockelsberg district) and modelled (new building) energy demands and supply temperatures were used.

From an energetic point of view, the buffer storage is a crucial component. The heat sources are controlled sequentially by checking the charging level in the storage, which is why the stratification within the tank is affecting the line control. Therefore a simulation model in TRNSYS was developed in order to get estimations about how the low-exergy building and the long term storage is probably influencing the overall system behavior. The method of system comparison and a detailed performance of the CHP's behavior in combination with the ATES system is given in Ref. [38].

A key performance indicator for ATES is the Heat Recovery Factor (HRF), which is defined as the quotient of the heat output and the heat input [39] as can be seen in equation (5):

$$HRF = \frac{\int_{October}^{March} \dot{Q}_{Discharge}(t)}{\int_{April}^{September} \dot{Q}_{Charge}(t)} \tag{5}$$

The energy system model has been refined to improve the representation of the stratification of the short-term heat storage tanks by using the Multiport Store Model [40]. Moreover, a realistic control strategy for CHP and vessel usage dependent on storage temperatures and demand was implemented. Geological and waterchemical investigations as well as a cost analysis were also carried out as part of the feasibility study and showed favorable results.

2.4. Calculation of primary energy values and carbon balancing

To reach the goal of climate-neutrality, the ongoing assessment of primary energy consumption and GHG emissions is a necessary part of the integral planning process but also needed for sustainability controlling and reporting. Primary energy (PE) was calculated using primary energy factors (equation (6)):

$$PE = f_{PE} \cdot EE \tag{6}$$

CO_2-eq. was calculated using end energy units and specific emission factors (equation (7)):

$$CO_2eq = f_{EM} \cdot EE \tag{7}$$

For carbon balancing, external effects on the regional (heat supply of the Bockelsberg district) and system scale, i.e. credits for fed-in electricity, were included as well as emissions from commuters traffic. The overall CO_2 balance is calculated as given in equation (8):

$$CO_2eq_{total} = \sum_{i=1}^{i} (f_{EM} \cdot EE)_i \tag{8}$$

with $(f_{EM} \cdot EE)_i$ representing contributing end energy flows and their respective emission factors.

3. Results and discussion

The CHP-powered DHS proved to be a good exergy efficient basis for a climate-neutral energy system. It was refurbished and switched to biomethane, resulting in a far negative GHG-balance that allows compensation of unavoidable emissions. Optimization of the old buildings and the efficient new building resulted in significantly lowered energy demand per square meter. The new building serves as a low-exergy heat sink that improves the integration of storage options. The integration of an ATES would further increase exergy efficiency of the system and result in additional savings of 2.424 t CO_2-eq./a that would allow to further offset emissions from commuter traffic due to an increased share of cogeneration and increased surplus renewable electricity production.

3.1. District heating system

The results of the provisional exergy analysis is given in Table 1 according to equation (4).

Table 1 shows that exergy efficiency is lowest in the case of oil and gas boilers. They merely convert high quality fuels to comparably low quality heat. In contrast, CHP units produce high quality electricity, heat can be used additionally. Thus, the exergy efficiency of CHP units is significantly higher. Consequently, all CHP-based concepts provide similar exergy efficiencies. However, higher heat losses due to the seasonal ATES and thus higher values for ε_{in} are compensated by higher electricity production and thus ε_{out}, resulting in the highest exergy efficiency for the CHP combined with ATES, which is why it was decided to further investigate this option.

The existing DHS was refurbished in 2010, when the old steam network was exchanged by modern highly insulated pipes. In 2013, new CHP units were installed with a nominal power of 670 kW_{th} and 525 kW_{el} and fuel changed to bio-methane. The CHP units which show efficiencies of $\eta_{el.} = 0.39$ and $\eta_{th.} = 0.49$, two peak load boilers and a 50 ^{3} buffer storage cover the heating demands of the university campus and the mixed residential and commercial area Bockelsberg ($\approx$ 0.25 km^2 in total) nearby. The f_{PE} of the system is 0.37, as currently the f_{PE} of biomethane equals the f_{PE} of natural gas ($f_{PE} = 1.1$).

The concept for the new building involves a gradual thermal use at different temperature levels. Two cascaded temperature levels (55 °C/35 °C and 35 °C/25 °C) enable the exploitation of temperatures down to 25 °C on the primary supply side. This low-exergy approach is realized by using the return flow of the DHS for the mid- and low-temperature-level of the new building (Fig. 3). Different temperature levels in the energy system allow for optimal

Table 1
Exergy flows and efficiencies associated with different concepts.

	ε_{in}	ε_{out}	η_ε
Oil & gas boilers	8.05	1.81	0.22
Baseload-CHP	13.1	8.60	0.65
Power-operated CHP	13.8	9.23	0.67
CHP with ATES	15.9	10.9	0.69

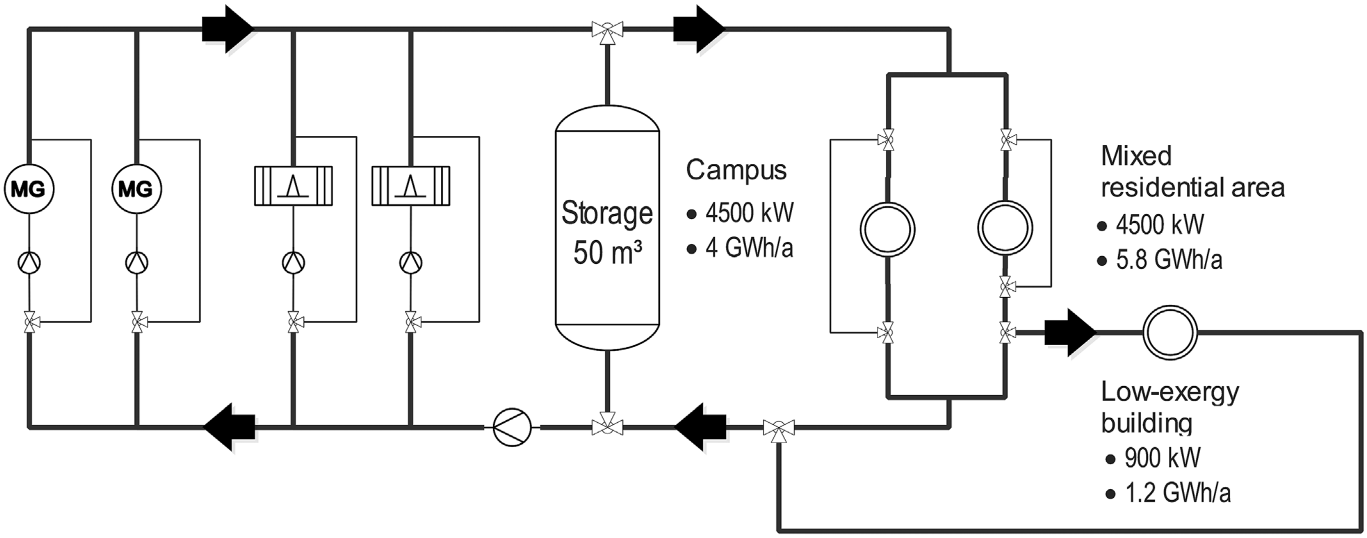

Fig. 3. Sketch of the District Heating System and hydraulic integration of the new low-exergy building.

heat use and increase thermal storage efficiency [41]. The highest temperature level is found in the Bockelsberg strand with up to 90 °C depending on the ambient temperature and heat demand. Here, compact heat exchangers are used to supply secondary systems. In the campus buildings, the hot water (up to 70 °C) is used directly in radiators and ventilation systems. To be able to decouple the system during summer to minimize losses, domestic hot water is supplied by electrical heaters only for the laboratories and cleaning storerooms.

With the new low-exergy building, positive and negative effects arise. Investigations were carried out particularly with regard to the interaction of cogeneration and heat storage options to increase system flexibility and reduce CO_2 emissions (see section 3.4 and 3.5).

3.2. The new building

The architecture of the new building designed by Daniel Libeskind is characterized by non-orthogonal walls. It disrupts the “chessboard” structure of the old casern. The aim is to contradict the rigid regime of the 3rd Reich and promote open-mindedness, creativity and free thinking in contrast to obedience and dogmatism. Inevitably, such architecture poses a challenge in terms of building construction but also in terms of energy efficiency, as naturally an extravagant design normally means a less optimized A/V ratio and higher cooling demand due to excessive glazing. Indeed the design of the new building had to undergo several steps, with inspiration from student seminars and a summer school, in order to form a good basis for an efficient building (Fig. 4).

Besides the low-exergy heating system, the cooling demand was targeted as a key issue in modern, highly insulated buildings. Internal loads and solar gains tend to heat up the building especially in summer, resulting in high cooling loads. The façade design therefore avoids a southern faced façade (instead the middle part of the building forms an arrow towards the south, compare also Fig. 1) and the south-eastern and south-western faced parts, in contrast to older solar façade designs, are shifted to the south, resulting in a self-shadowing façade that significantly reduces irradiation during summer, whilst still allowing high solar gains in winter. Additionally, switchable glazing is used that is adjustable in five shades from lighter to darker blue (and only using 1 W/m^2 during switching), allowing for 50% higher solar gains in winter and 50% lower cooling

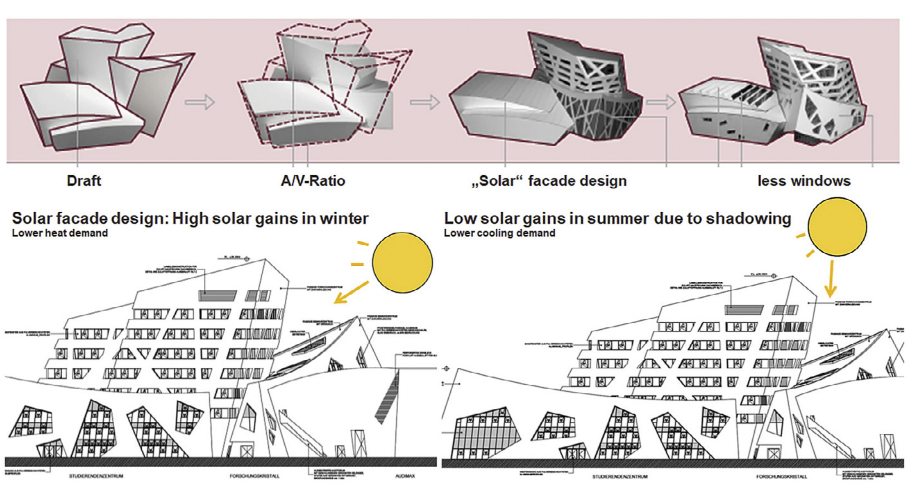

Fig. 4. Design optimization steps and solar façade design.

Fig. 5. Switchable glazing is used in south-eastern and south-western parts of the façade, resulting in 50% higher solar gains in winter and 50% reduced solar irradiation in summer compared to sunshade glazing.

demand in summer compared to sunshade glazing (Fig. 5).

The glazing combined with back-ventilation in the opaque parts of the façade, 250 mm insulation, robust titan-zinc-panels and openable windows make active cooling and mechanical ventilation redundant in these parts of the building. The overall savings add up to ≈ 160 MWh/a end energy or 10% of the end energy use of the building. The overall cooling demand for the building is as low as 2.5 kWh/m^{2}a or 56 MWh/a in total. Another advantage is the lower dew point compared to actively cooled rooms, resulting in a more comfortable indoor climate. CO_2-traffic lights as well as an experimental ambient-computing system for active user integration [42] aid in correct and efficient use of the openable windows and temperature control/optimization of heating and cooling demands. Moreover, the system is developed to gain prolonged savings from continuous user-system interaction in contrast to half-lived campaigns. Fitting the adjustable windows and skylights in the other parts of the building perfectly, daylight and presence-controlled LED lighting is used. As a consequence, the electricity demand for lighting (4 kWh/m^{2}a) and cooling (<1 kWh/m^{2}a) is negligible, making ventilation (13.5 kWh/m^{2}a) the highest primary energy consumer (32.4 kWh/m^{2}a PE) in the building besides user-specific appliances (23.2 kWh/m^{2}a or 55.7 kWh/m^{2}a PE). However, these are to be optimized during operation, since the large auditorium, due to a movable tribune, was designed with a constant volume flow ventilation system. In practice, adjustable swirl diffusers will allow for substantial savings and CO_2-controlled ventilation like in the other parts of the building. Many other high-tech components like phase-change materials in the cooling ceilings and vacuum insulation in sensible areas, however sparingly used and intelligently combined to form a rather robust system that excels by the very good passive characteristics, aid to achieve the low energy demand of the very versatile building. It holds space for up to 1,200 people in the large lecture hall, up to 2,500 people for concerts and exhibitions (also as town hall for the city of Lueneburg), a cafeteria, seminar rooms, working space for 300 people and a machine hall in the basement on 17,400 m^2 net floor area. End energy and primary energy demands are given in Fig. 6.

As shown in Fig. 6, heat for space heating and domestic hot water (DHW) has the highest share in end energy use (57.5 kWh/m^{2}a corresponding to 21.3 kWh/m^{2}a PE). Both systems are supplied on low-exergy level with 58 °C supply line temperature. The DHW for use in the kitchen is generated by freshwater heating modules placed in direct vicinity to the tapping points. In kitchenettes, DHW is supplied by electrical heaters. The respective hot water piping has less than 3 L volume and no buffer vessels as to prevent growth of *Legionella* bacteria. As in most other parts of the campus, no warm water is provided in washrooms.

The comparably high heating demand is due to the openable windows, which propose high heat losses in winter compared to mechanical ventilation with heat recovery. However, the active user integration, window contacts and CO_2-traffic lights aim to reduce heat losses through open windows. The high share of CHP heat leads to the low primary energy factor for heat $f_{PE} = 0.37$ (projected $f_{PE} = 0.11$ with ATES), making it a favorable trade-off to save valuable electricity (f_{PE} of 1.8 since 2016) at the expense of low-exergy waste heat from CHP units. Furthermore in terms of sustainability, the building comprises green roofs and rain water usage. Emissions during construction (only about 12,500 t CO_2-eq.) are reduced due to the use of a “cobiax” construction: Polyethylene balls of 250 mm diameter are used to reduce concrete and steel masses. The maintenance-free titan-zinc panels promote a long life-cycle (weathering protection). A wide range of re-use opportunities for the building is given due to the “cobiax”-system and double floors.

3.3. Refurbishment and optimization of the old buildings

Energy efficiency optimization in the old buildings focused on technical measures like optimization of the heating system (new pumps and valves), automation, LED lighting and optimization of ventilation systems besides a large installation of photovoltaics on eastern, western and southern faced roofs. The estimated savings were calculated to reduce 30% of the heating demand and 40% of electricity consumption, including the shut-down of the heating system in summer (and domestic hot water production from electricity during these times) and the self-produced electricity from an additional 650 kWp PV (70 kWp that existed before in 2 separate installations that are connected to the public grid) providing 550 MWh/a of electricity (compared to 2.5 GWh/a total consumption). Fig. 7 shows specific primary energy demands in the existing buildings before and after (including optimizations of the heat supply and network) compared to the new energy-efficient building (simulations). The primary energy production of the PV installations are shown as negative demands in Fig. 7.

Electricity, also for the new building based on DOE 2.1E simulations, is including lighting, ventilation, cooling, DHW in cleaning storerooms and laboratories (no warm water is provided in washrooms. The DHW of the canteen is heated using steam from natural gas) as well as all user-specific demands like mobile devices, research appliances etc. The attic conversions (Fig. 8) in the existing buildings resulted in 6,713 m^2 space under the roofs (compared to 56,148 m^2 before) and, due to double and triple glazing, up-to-date insulation, automation and efficient lighting, lower energy demand per square meter.

Over-all reduction of end energy heating demand per square meter was 107 kWh/m^{2}a (before) to 74.5 kWh/m^{2}a (after). Electricity consumption was 41 kWh/m^{2}a compared to 39 kWh/m^{2}a and primary energy demand was reduced from 152 kWh/m^{2}a to 120 kWh/m^{2}a (excluding self-produced electricity), also due to better primary energy factors for the heating supply (f_{PE} of 0.42 before and 0.37 after, respectively) and electricity (f_{PE} of 2.4 compared to 2.6). The specific primary energy consumption

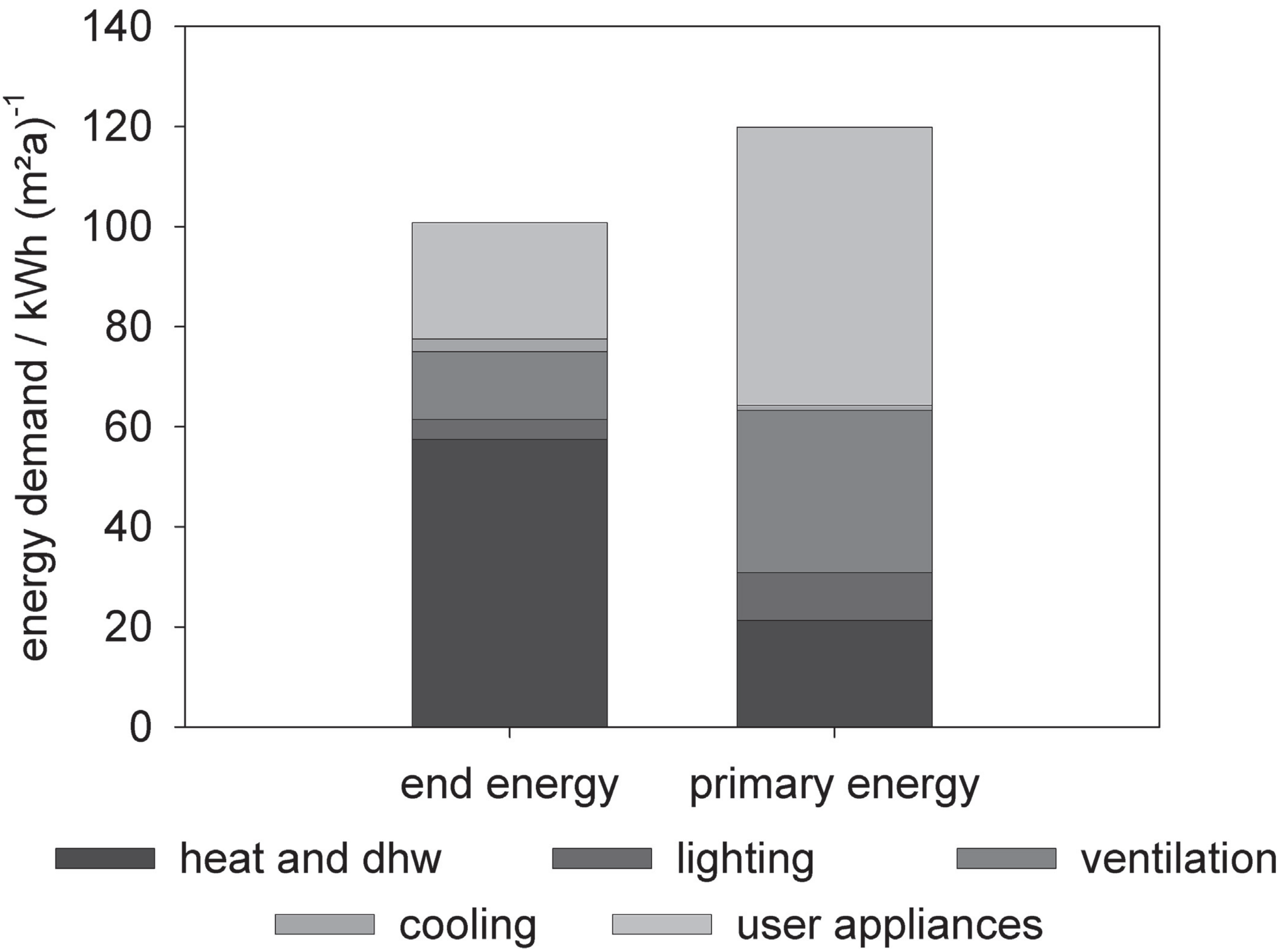

Fig. 6. End energy and primary energy demand of the new building (DOE 2.1E simulation).

including self-produced electricity from PV installations ($f_{PE} = 2.8$) is 77 kWh/m^{2}a.

The performance of the refurbished buildings, in primary energy terms, is comparable to the modelled primary energy demand of the new building. This is due to comparably low heating demands of the old buildings and the comparably low f_{PE} of the existing DHS. The demand for electricity is also comparable as all buildings comprise efficient lighting, mechanical ventilation not in all rooms and a high share of user appliances.

3.4. Considered storage options

Along with the conceptual design of the new building, new concepts of heat storages were evaluated. Short term storage by means of hot water tanks is widespread due to high performance and financial reasons. Although water provides an excellent specific heat capacity, of course, disadvantages are heat losses and, usually, short storage periods. To decouple the heat production and the demand side, additional temporal storage levels are aspired to get involved in the future DHS of the university. As Fig. 9 illustrates, a thermal battery potentially serving as mid-term storage and an ATES for seasonal storage were investigated.

3.4.1. Short-term storage

By lowering the return line temperatures and improving the stratification, the storage capacity is expected to increase by up to 112% whereas the contribution of cogeneration is decreasing by about 5% because of an increased heating demand of 1.2 GWh or ≈ 10%, comparatively.

3.4.2. Mid-term storage

Over recent years researchers at the Leuphana University in Lueneburg are following up with a heat storage system based on reversible thermochemical reactions. For instance, dehydration and hydration of inorganic salts exhibits very high energy density, the operating temperature levels can be adjusted by choosing different salts. Heat energy can be stored with low losses over a long period of time. Therefore, investigations have been performed from the material at micro-scale [43–45] to the system at lab-scale [46–49]. Whilst storage capacity of such options compared to ATES is limited, additional peak load and back-up heat supply could be provided.

3.4.3. Long-term storage

Basically there are several techniques for seasonal storage of thermal energy. A very cost-effective technology associated with heating and cooling of buildings or districts is ATES. Particularly in combination with cogeneration systems and solar energy use the performance of the overall system can be positively affected by storage and recovery of large quantities of thermal energy in the

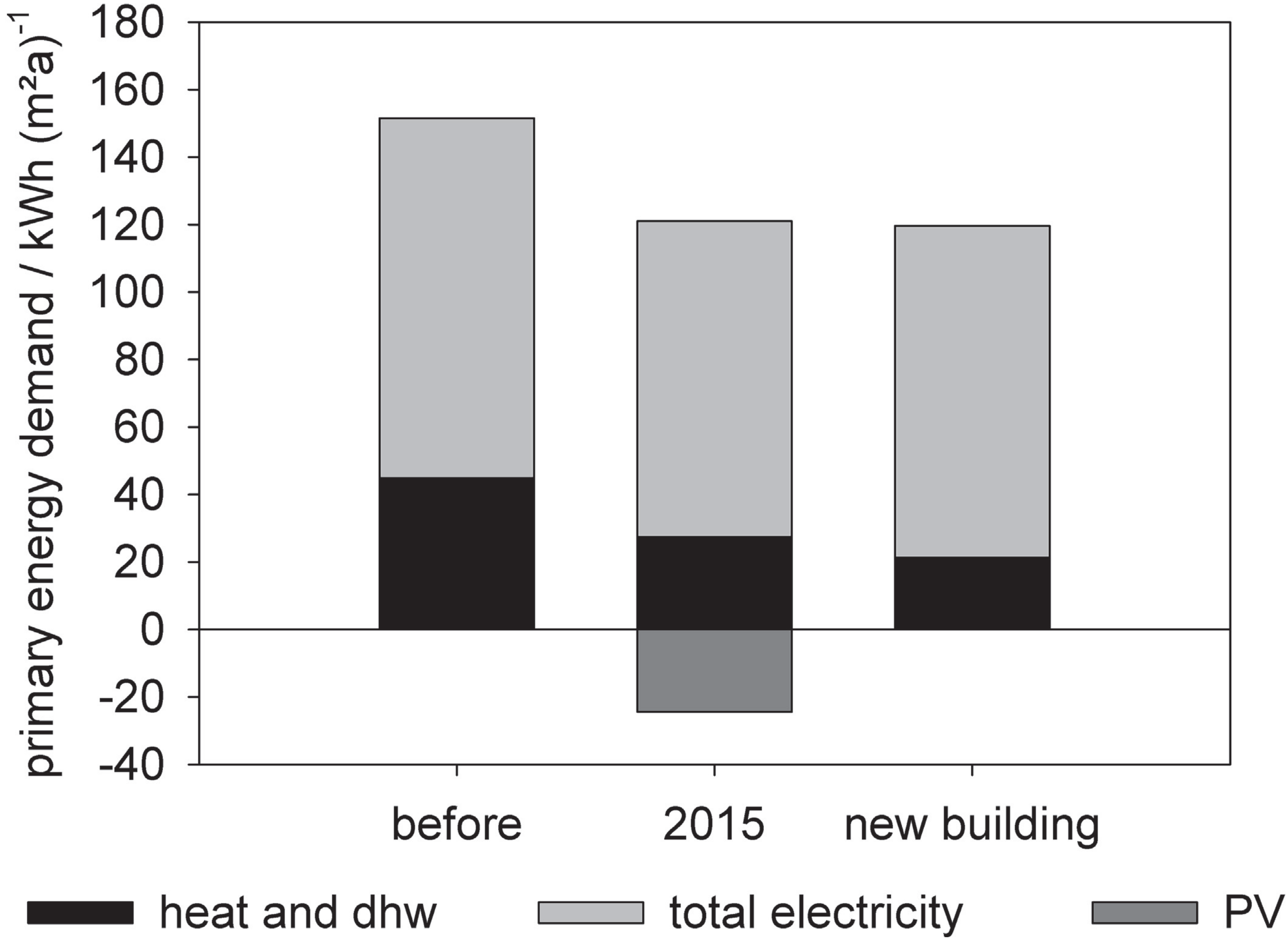

Fig. 7. Specific primary energy demands of the existing buildings before and after optimization and the new building.

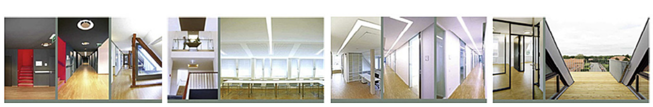

Fig. 8. Attic conversions in the existing buildings.

subsurface. Plans to integrate an ATES into an existing DHS in Lueneburg date back to 2010. The hydro-geological conditions at 450 m depth were investigated. The water chemistry allows high temperatures of up to 90 °C to facilitate direct use of the recovered heat in the campus system combined with the low-exergy systems

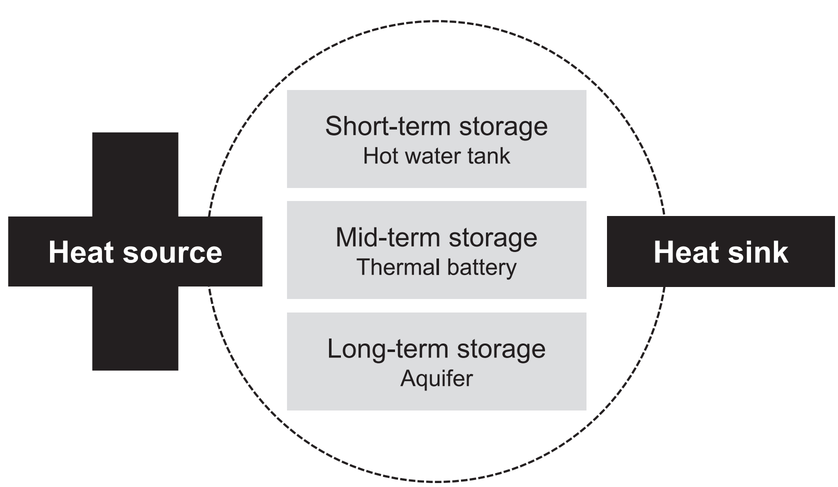

Fig. 9. Temporal storage levels to decouple heat sources and heat sinks.

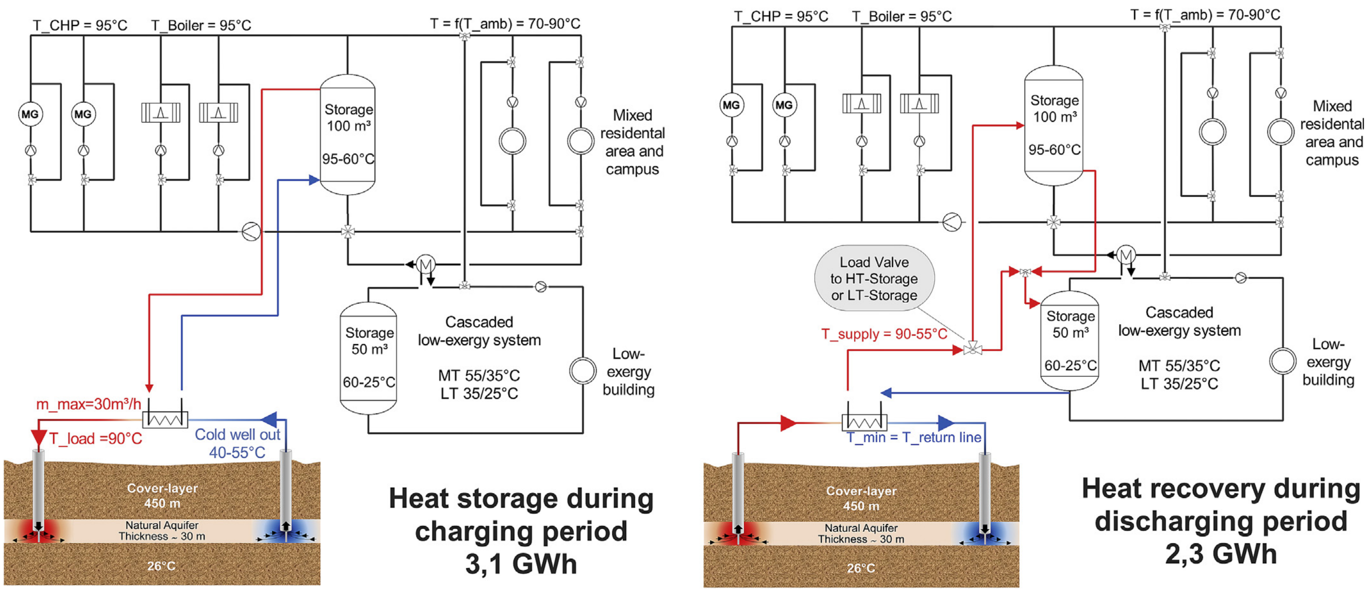

Fig. 10. Charging period (left) and discharging period (right) for the 10th year.

of the new building [50]. A simulation environment in TRNSYS was developed to simulate possible case studies. Considering preliminary results of a specific case study with a maximum charging flow of 30 m^3/h (Fig. 10, left) and a maximum discharging flow of 50 m^3/h (Fig. 10, right) is presented below.

The simulation shows that the HRF (equation (5)) reaches a quasi-plateau in the 10th year of operation. In the first year, only 35–45% of the stored heat can be recovered, as ATES systems do not use insulation and heat is transferred to the subsurface and partly lost due to conductive heat transfer and convection. Subsequently, the HRF rises logarithmically: In the second year the HRF equals 45–55% compared to 50–60% in the third year. Depending on the storage operation conditions and on the used load profiles, in the 10th year the HRF of the ATES varies in between 67% and 75% although the amount of stored heat is quite low (the storage would only be used with ≈ 30% of its maximum capacity of over 10 GWh), leading to a comparably high A/V-ratio (the larger the amount of stored heat, the higher the HRF). However, a HRF of 75% is tantamount to only 25% unused heat energy over an annual cycle (charging from April to September, discharging from October to March), resulting in a very efficient seasonal storage option. Along with this seasonal heat storage, each cogeneration unit runs over 8,700 h/a at full load, which leads to less equipment wear out and about 2.8 GWh more renewable electricity per year. A system comparison (with aquifer and without aquifer) shows an increase of cogeneration by 28%. In the same way, the conventional heat production with natural gas decreases by 2.3 GWh/a (Table 2). Renewable electricity production rises by 44% because of heat losses in the ATES that is primarily loaded with cogeneration heat.

Table 2
System comparison with and without ATES.

	without ATES	with ATES	Increase/Decrease
Heating demand	11.1 GWh	11.1 GWh	–
Contribution cogeneration	8.2 GWh	10.5 GWh	+2.3 GWh (+28%)
Renewable electricity	6.4 GWh	9.2 GWh	+2.8 GWh (+44%)
Conventional heat generation	2.9 GWh	0.6 GWh	- 2.3 GWh (- 79%)
f_{PE}	0.37	0.06	
η_ε	0.50	0.55	

Preliminary calculations of the economic efficiency of the storage revealed a static amortization period less than 15 years (total investment 3–4 Mio. €, specific storage costs 3–10 €/kWh, operational costs ≈ 40,000 €/a. Revenue is generated by renewable electricity production and highly sensitive to feed-in tariffs and biomethane prices). Exergy efficiencies calculated in analogy to the methodology given in section 2.2 are similar to the baseload-CHP and CHP with ATES scenarios given in section 3.1. The primary energy factor also shows large improvements due to credits for surplus baseload electricity and is even lower than the originally projected f_{PE} of 0.11 with ATES.

3.5. Climate neutrality and sustainability

Based on the CO_2-balance of biomethane (50–80 g CO_2-eq./kWh) [51–53], natural gas used in peak load vessels (245 g CO_2-eq./kWh) and credits for surplus baseload electricity fed into the grid (821–921 g CO_2-eq./kWh) [54–56], the CO_2-balance of the campus system can be calculated based on equations (7) and (8). Certified renewable electricity taken from the grid based on hydropower is balanced with 5 g/kWh. For PV electricity produced on-site, specific emissions of 80 g CO_2-eq./kWh were assumed (cf [57]).

Table 3 shows the CO_2-balance with and without the HT-ATES based on simulations for heat and electricity as well as business trips and other emissions comprising meals (up to 500 t/a), carbon dioxide emissions during construction of the new building, calculated over a minimum lifetime of the new building of 50 years (≈ 250 t/a), water and paper (≈ 50 t/a).

Counting the external effects, i.e. climate-neutral heat supply for the residential and mixed area of the Bockelsberg district and surplus electricity fed into the grid, a far negative CO_2-balance is achieved. The surplus savings can be used to offset emissions from commuters traffic, which however show a decreasing tendency (due to measures like rentable bikes and direct bus lines to promote sustainable mobility, a large share of train usage, and a higher share of renewables in the grid) and/or electricity used in the Bockelsberg district (around 2 GWh/a from ≈ 425 residual units).

Credits given for baseload electricity fed into the grid depend on the current energy system. However since nuclear plants in Germany are phased out (baseload electricity production from coal

Table 3
Annual CO_2-balance (CO_2-eq.) with and without aquifer storage (2015 data plus the projected demand of the new building).

	w/o ATES	with ATES	f_{EM}	w/o ATES	with ATES
Biomethane (CHP)	16.6 GWh	23.3 GWh	80 g/kWh	1,328 t	1,864 t
Natural gas (vessels)	3.4 GWh	0.7 GWh	245 g/kWh	833 t	172 t
Electricity production (CHP)	6.4 GWh	9.2 GWh	- 821 g/kWh	- 5,254 t	- 7,553 t
Electricity consumption (campus, renewable)	2.7 GWh	2.7 GWh	5 g/kWh	14 t	14 t
	0.55 GWh PV	0.55 GWh PV	80 g/kWh	44 t	44 t
Cars and business trips				599 t	599 t
other				≈ 800 t	≈ 800 t
Balance				**-1,636 t**	**-4,060 t**

fired power plants currently fill this gap and are substituted by fed-in surplus electricity for example from CHP units), this value is still rising. The values used for carbon balancing in Table 3 are very conservative, as the upper value was taken from the range given in the literature for biomethane and the lower value for credits given for baseload (CHP) electricity fed into the grid. Lower values for biomethane emissions result in - 498 t/a for the system without ATES and - 699 t/a for the system with ATES. If the higher value for baseload electricity of 921 g/kWh is used, the calculated emissions are lower by - 640 t/a for the system without and - 920 t/a for the system with ATES, respectively. In total, the negative emissions would increase by a maximum of 69% (additional -1,138 t/a savings compared to -1,636 t/a for the system without ATES) and by 40% (-1,619 t/a compared to - 4,060 t/a for the system with ATES).

On the other hand, if natural gas is used instead of biomethane, the emissions would be 2,739–3,237 t/a higher for the system without ATES and 3,844–4,543 t/a higher for the system with ATES. As a consequence, a climate neutral balance could only be achieved for the system with ATES. Without ATES, a climate neutral balance could only be achieved without counting in emissions from cars and business trips and other emissions, in the best case. Offsetting external emissions and even business trips thus is not possible. The agricultural land used to provide the biomethane, which is to be mentioned as an adverse effect on the sustainability of the system, is around 1 km^2 compared to 0.25 km^2 of the Bockelsberg district.

The results show the importance of using renewable energy even in an exergy optimized scenario. However, even without renewable fuels, enormous carbon dioxide reductions are possible using CHP-cogeneration and district heating systems, in accordance with theoretical exergy efficiencies.

4. Conclusion

The conversion of publicly owned structures like university buildings poses some special tasks. Technically, the buildings are often constructed economically and goal-oriented. Laboratories and workshops have special requirements. However organizational structures and sceptical staff often present the greater challenge. Also in this respect, universities serve as living labs and small cities.

In case of the Leuphana University, the imperative of sustainability lead to the definition of the goal to achieve climate-neutrality by the year 2012 and enabled the conversion process. The set goal was finally reached with the first climate-neutral energy balance for the year 2014 for heat, electricity and business trips by converting the local energy system based on CHP to renewable fuels (biomethane) and installation of a total of 720 kWp photovoltaics (east, west and southern faced, matching the grid connection maximal power) that provide 20% of the campus electricity consumption with a self-consumption factor of 95%. The use of renewable gas in CHP-based DHS enables offsetting of non-energy related emissions due to substitution of coal fired power plants on the system scale. The integration of heat storage options, which benefit from low-exergy 4th GDH, would result in an even better balance due to a higher share of biomethane-fired heat and electricity production from CHPs. This is an opportunity to offset emissions from commuters traffic and, energy system-wise, to provide baseload and, potentially, regulatory power that perfectly fits higher shares of self-produced electricity in households and renewables in the grid.

The case study represents an example of the conversion of an existing heating network: A climate-neutral carbon balance can be achieved for such systems economically. However political conditions and the structure of the local energy system and energy markets have a large influence on both the carbon balance including external effects and economics. In contrast, exergy calculations provide metrics independent from those circumstances. The results highlight the suitability of (renewable) gas-fired CHP units for GHG reduction, that can be combined with other renewable energy technologies and are very well suited for conversion of existing structures such as university campuses.

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