A Holistic Energetic Transformation Concept for the Heating and Cooling Supply of a University Campus

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Abstract

In order to achieve the highest CO_2 savings at a district level, a holistic planning of the renovation process is necessary in which the synergies between building retrofitting and the modernization of the energy supply are taken into account. In this study, an integrative energy retrofitting approach is applied to a small area of a university campus. It is shown that building renovations create valuable opportunities for the transformation and decarbonization of the heating and cooling supply. By considering specific boundary conditions during renovation, previously untapped waste heat potential from data centers and process cooling can be locally used for building heating, leading to CO_2-savings of 850 t/a. A modernization of the district heating network and the usage of a seasonal geothermal storage further increase the CO_2-savings up to 1100 t/a. Furthermore, the presented concept is economically attractive, with a payback period of 5-10 years and a levelized cost of energy of up to 7.5 €cents/kWh.

Keywords: building renovation, district heating and cooling, energetic district retrofitting, waste heat, geothermal storage

1. Introduction

The heating and cooling sector accounts for 50% of Europe's final energy demand and is mainly based on fossil fuels. A rapid and efficient decarbonization of this sector requires not only the acceleration of building refurbishments but also increasing the share of renewable energies and promoting the integration of waste heat into the built environment (European Comission, 2016). Because of the different stakeholder structure of the supply side and of the demand side, improvements in the energy efficiency of buildings and district energy systems (DES) are rarely considered in tandem. However, combining building retrofitting, district heating and cooling improvements and renewable energy generation into an integrative approach allows for a more cost-effective and faster decarbonization of the building stock (BPIE, 2018). This has been recognized by the European Commission in its "Renovation Wave for Europe" strategy (Europeam Commission, 2020) which explicitly addressees the importance of an integrated, neighborhood-based approach in which the co-benefits of building renovation are used to decarbonize the heating and cooling sector.

Limited studies have investigated a holistic approach to renovation at district scale and the interactions between demand and supply side energy efficiency measures. For example, (Pozzi et al, 2021) has assessed the synergies between building retrofit and district heating networks (DHN) for the city of Milano and showed that for some areas of the city, the combination of building retrofit and 4th generation district heating (4GDH) can achieve a reduction in emissions of up to 65%, larger than for other scenarios. In (Delmastro et al, 2017), a methodology for analyzing the impact on building renovation projects on the investment strategies for DHN is proposed. Furthermore, (Lündstrom and Wallin, 2015) and (Le Truong et al, 2014) have proved the necessity for considering the interaction between end-use energy saving measures and supply systems for district-heated buildings. However, the majority of these studies consider a combination of building retrofit and the construction of new low temperature 4GDH or the effects of building retrofitting on existing district heating networks.Moreover, the cooling supply and local energy resources such as waste heat potentials or renewable energies are not assessed.

In this context, this study aims to present a holistic renovation concept that showcases the synergies between

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building renovations and the transformation of the heating and cooling supply for a small campus area. A transformation strategy for the DHN to support low-temperature waste heat integration while still being able to supply unrefurbished buildings with high temperature heat is also described.

2. Description of the case study

In the framework of the “Energy Efficient Campus Berlin-Charlottenburg (EnEff:HCBC) project, refurbishment scenarios and energy efficiency solutions for heating and cooling have been assessed at the scale of a university campus district. In the first phase of the project, a decision-support methodology for the integrated energy retrofitting of the university campus was developed (Stanica et al, 2021a). This consisted of a combination of energy conservation and renewable energy generation measures. The second phase of the project focuses on detailed feasibility analyzes for holistic energetic modernization concepts that examine both the demand side and the supply of heating and cooling.

For this study, a small area of a university campus consisting of 7 buildings with an annual heat demand of ca. 10.3 GWh/a and a cooling demand of 4.7 GWh/a has been chosen (buildings B1 to B7 in Figure 1:). The building complex presents with a high waste heat (WH) potential (5.9 GWh), from data centers and process cooling that currently can’t be used efficiently due to the high temperature requirements of the buildings. However, most of the buildings will be successively renovated in the next decade, creating an opportunity for the energetic transformation of the heating supply structure and for the efficient utilization of the waste heat potential. Since the building complex is supplied with heat by a branch of the 3-level municipal DHN (represented in violet in Figure 1:), a hydraulic separation of the branch from the main network is possible. This would allow a lowering of supply temperatures and the feed-in of decentralized waste heat sources into the network branch.

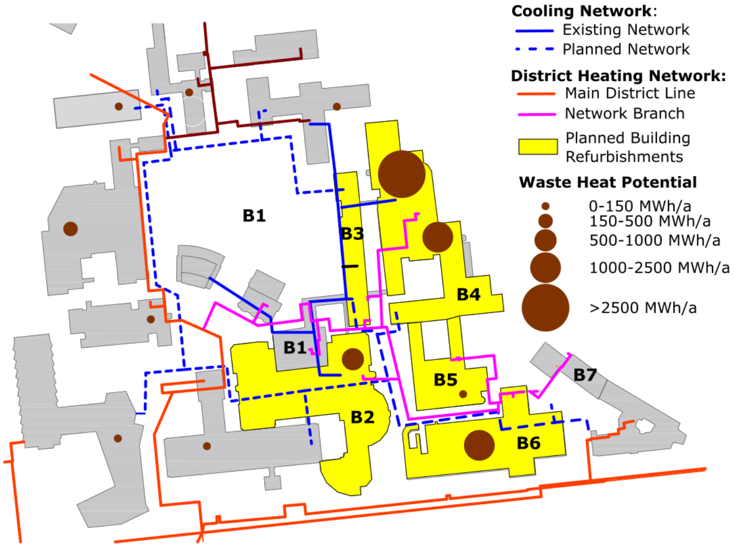


Figure 1: Campus and network layouts

To derive a holistic heating and cooling supply concept that considers the existing network infrastructure and the synergies with building renovations, a series of steps were necessary. Firstly, the existing waste heat potential was assessed and a concept for its efficient utilization was developed. Taking into account the technical requirements of the waste heat recovery and of the building heating systems, a concept for the transformation of the DHN branch was developed and its technical feasibility was assessed. Finally, the synergies and requirements for the building renovation were derived and the economic and ecologic feasibility of the proposed solutions were assessed for different scenarios.

3. Cooling supply and waste heat recovery

A concept for the modernization of the heating and cooling supply on the campus has been developed in which chillers also serve as heat pumps during the heating period (see Figure 2:). To achieve this, the temperature of the heat sink is raised in accordance with the temperature level of the building's heating system or that of the heating network in which the waste heat will be fed in.

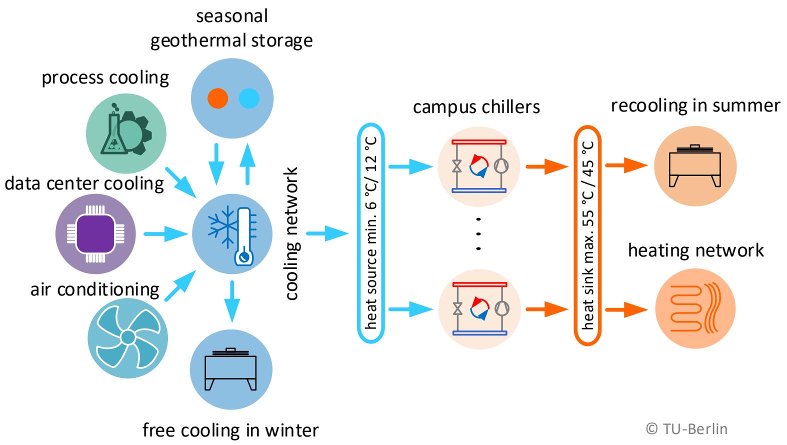


Figure 2: Waste heat recovery concept

For the concept design and the economic evaluations, a hydraulic diagram for the holistic heating and cooling generation was created (see Figure 3:.

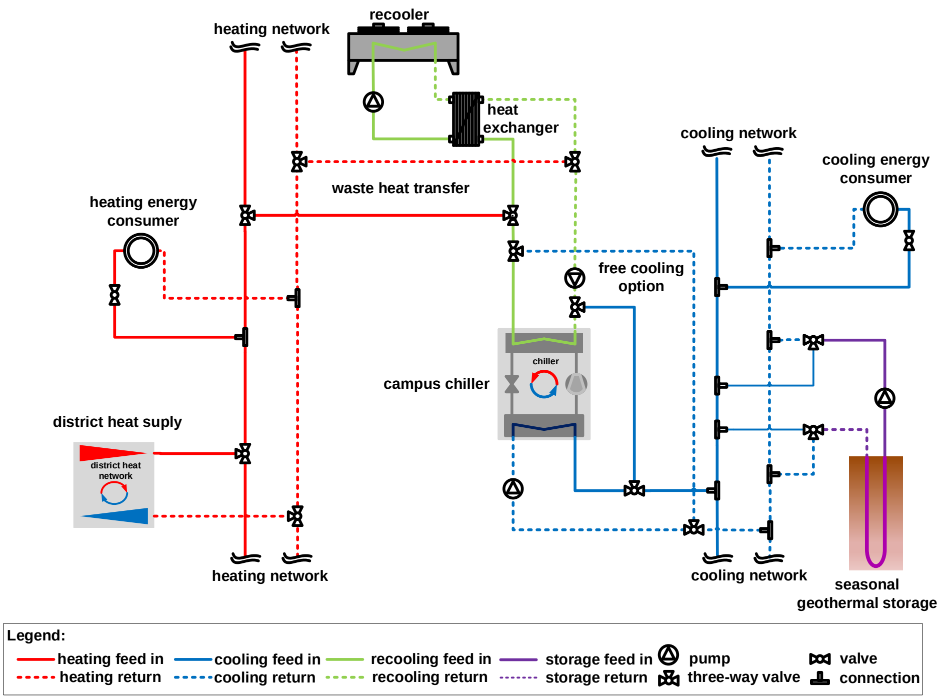


Figure 3: The hydraulic connection concept of the heating and cooling supply on campus

3.1 Cooling supply

The cooling demand of the buildings is covered by a cooling network that connects not only the buildings included in this study, but also additional buildings in their proximity. The existence of a cooling network enhances the flexibility of the concept since the cooling load can be shifted to the chillers with more favorable operating characteristics and a suitable waste heat feed-in location. By employing high-level control algorithms (Kononenko et all, 2021), the security of supply can be guaranteed and significant energy savings can be achieved.

Since the supply and return temperatures of the cooling network (6°C and 12°C respectively) are in the range of near-surface geothermal energy, a borehole geothermal system can be directly connected to the cooling network and act as a cooling storage. In winter, the geothermal borehole storage acts as an additional energy source for the heat pumps, enabling the generation of additional renewable heat. Through this process, the underground storage is cooled and can then be used for passive cooling of the buildings in summer, thus leading to electricity savings.

Another cooling efficiency measure is the use of free cooling for low outdoor temperatures. This requires a hydraulic separation between the recooling circuit and the cooling network. The manufacturer of the chillers recommended the use of a heat exchanger between the recooler and the chiller or the cooling network. Considering the temperature difference between the two sides of the heat exchanger means that free cooling can occur for outside temperatures above 0°C.

3.2 Heat recovery and feed-in

The waste heat recovery from the chillers can be achieved by using the chillers as a heat pump and setting the condensation temperature accordingly to that of the heat demand. For the existing chillers, this requires the exchange of the air-cooled condensers with new, water-cooled ones. However, the maximum heat temperature that can be achieved is 55°C. Additionally, a temperature difference of at least 10 K between the supply and the return of the condenser needs to be guaranteed. The generated heat will then be fed in into the district heating network (see Chapter 4 and distributed to the heat consumers.

This allows the utilization of approx. 3.3 GWh/a waste heat from cooling process to be used for the heating of the buildings. The additional electrical effort for heat generation depends on the desired temperature level. For example, in the case of medium temperature radiators (see Chapter 5 amounts to only 0.5 GWh/a, resulting in an average COP(Coefficient of performance) of 6. Furthermore, by using a geothermal borehole storage for passive cooling in summer and as a heat source for the heat pumps in winter, a further 0.5 GWh/a of the heat demand can be covered by renewable energies. In this case, the additional electrical effort and the average COP are of 0.48 GWh/and 8 respectively. The lower additional electrical effort is due to the fact that, through passive cooling with the geothermal storage in summer, the power consumption for cooling in summer can be reduced by about 0.18 GWh/a, thus offsetting a part of the additional electricity consumption for the waste heat recovery in winter. For both cases, the values are well above the usual performance for conventional heat pump applications (Miara et al. 2013).

The average COP is defined as annual energy ratio between the used heat ($Q_{hr,tot}$) and the additional electrical consumption for heat recovery (see also eq. 1). The last term will be defined as the difference between the total electrical energy consumption of the chillers with heat recovery ($P_{el., hr, tot}$) and the electrical energy consumption of the chillers in cooling mode only as a reference case ($P_{el.,cool,tot}$).

$$COP = \frac{Q_{hr,tot}}{P_{el.,hr,tot} - P_{el.,cool,tot}} \qquad \text{(eq. 1)}$$

For the scenario with geothermal storage, the term $P_{el.,hr,tot}$ also includes the electrical energy consumption of the storage pump. However, through the usage of the storage in the summertime for the passive cooling, the electrical energy consumption for cooling will be reduced and thus result in a higher COP.

4. Transformation of the district heating network (DHN)

Since the waste heat potential of some buildings exceeds their heat demand, an integration of the surplus heat into the DHN for transport to buildings without waste heat would increase its utilization rate and the CO_2-savings. Currently, the municipal district heating network is composed by two high temperature (80-110°C) supply pipes and a mixed return pipe.

In order to efficiently utilize the waste heat potential, multiple boundary conditions need to be considered. Firstly, waste heat is only available for temperatures above 0°C since below this temperature it is energetically more efficient to use free cooling. Furthermore, maximum supply and return temperatures of 55°C and 45°C respectively and a minimum temperature difference of 10K must be guaranteed on the condenser side. This means that, as a prerequisite for the waste heat integration following the renovation of the buildings, the temperature requirements for HVAC systems must be lowered (see Chapter 5). This will allow the transformation of the existing high-temperature (HT) network into a network with two temperature levels and decentralized producers as illustrated in Figure 4. In this concept, the remaining high temperature consumers (e.g. unrefurbished buildings) will continue to be supplied with municipal district heat by a high temperature level, whereas the renovated buildings will be supplied by a low temperature network level in which waste heat is fed in.

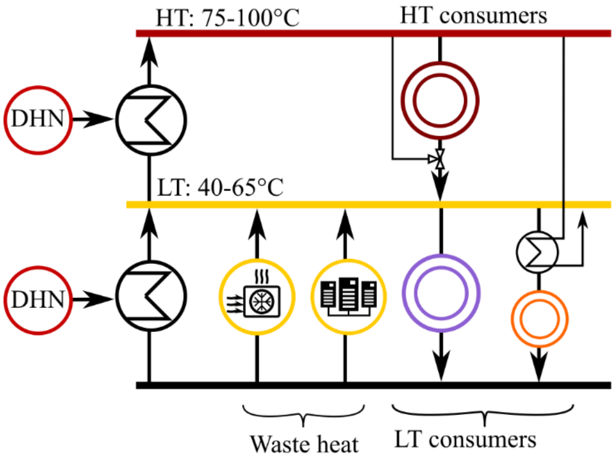


Figure 4: Concept for a DHN with two temperature levels and efficient integration of waste heat

In order to reduce the supply temperature and the pressure level in the network branch that supplies the building complex, the branch will be hydraulically separated from the primary DHN. The primary network will therefore act as a central producer to the secondary network whereas the waste heat sources will act as decentralized producers. It was shown in (Stanica et al, 2021b) that this cascading network configuration is ideal for districts with a heterogeneous building structure and for the transformation of existing high temperature networks. Because it allows an efficient integration of renewable energy resources in the heat supply of new and retrofitted buildings while also continuing to supply high temperature consumers with conventional sources, it is particularly convenient as an intermediary solution during long district renovation processes.

However, in order to transform an existing DHN branch into a cascading network with decentralized feed-in of waste heat, multiple technical constraints need to be considered.

4.1 Technical requirements for the feed-in

For the waste heat recovery to be efficient, a minimum temperature difference between the low temperature supply line and the return line of 10K needs to be guaranteed. Furthermore, after taking into account thermal losses, the maximum waste-heat feed-in temperature is of 50°C. This means that for outdoor temperatures of 0°C or higher, the temperature of the middle network line and, consequently, the supply temperature of the retrofitted HVAC systems, should be maximum 50°C. As explained below in Section 5, this can be achieved for heating systems with design temperatures of 60°C/45°C or lower.

4.2 Temperature constraints

The high temperature supply line will continue to supply the unrefurbished heating circuits of HVAC systems and the DHW systems. Due to safety regulations regarding the prevention of legionella, the DHW supply temperature needs to always exceed 70°C. Furthermore, to assure a reliable supply of the low temperature consumers, the return temperature of the high temperature consumers must not be lower than the setpoint value of the LT line. This can be achieved with the help of a controlled 3-way-valve that mixes warmer supply water into the return line when needed.

In case the temperature requirements of one or multiple consumers slightly exceed the supply temperature of the LT line, a temperature booster in the form of an electric heater or a heat exchanger supplying high temperature heat from the HT level can be installed (see Figure 4).

After considering these constraints, the supply temperature curves for the high temperature and low temperature levels of the network have been established (see Figure 5). For the low-temperature level, two scenarios have been considered: a mid-temperature level corresponding to radiators with design temperatures of 60/45°C and a low-temperature level corresponding to floor heating devices with design temperatures of 40°C/30°C.

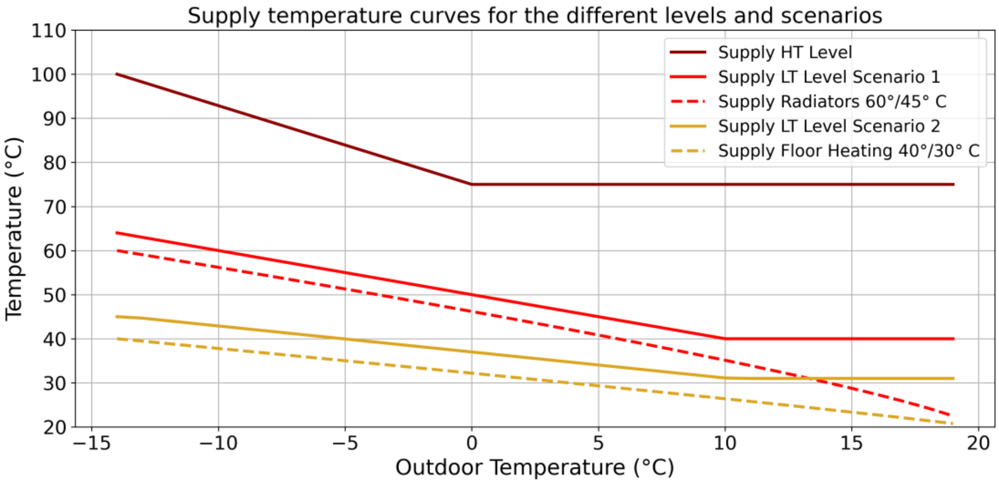


Figure 5: Temperature curves for the two supply levels and the two different scenarios

4.3 Dimensioning constraints

Due to the reduction of the supply temperature of the middle network level and to the connection of additional consumers to this level (refurbished HVAC systems that were previously connected to the HT level), an increase of the volume flow to be transported through the pipes is expected. It is therefore necessary to verify that the existing pipe diameters are sufficient and if not, to replace sections or the entirety of the LT level piping. A static analysis was carried out based on the design temperatures and expected nominal heat loads of the refurbished buildings. It could be shown that for the final state where all the planned renovations have been completed, the existing pipe dimensions are adequate. This is explained by the substantial reduction in heating load following the building renovations. This analysis can also give insights into the order of which the buildings should be retrofitted and the point at which the network transformation should be undertaken. For example, it could also be shown that the implementation of the network transformation is not possible before the renovation of the buildings B4 and B6 (see Figure 1), as in this case the existing pipes would be too small to transport the necessary heat load.

5. Building refurbishment case study

As part of the planned campus renovation and to meet current energy regulations, the building's envelopes will be refurbished and heat recovery systems for the air handling units will be installed. With the help of building simulations, the potential energy savings for the different retrofitting measures have been calculated (see Figure 6). It could be shown that the heat demand, and consequently the CO_2-emissions, of the building complex could be reduced by ca. 52% following the refurbishment. Such a significant reduction of the heat demand creates an opportunity for the lowering of the heating temperatures which in turn would allow waste heat to be used for heating.

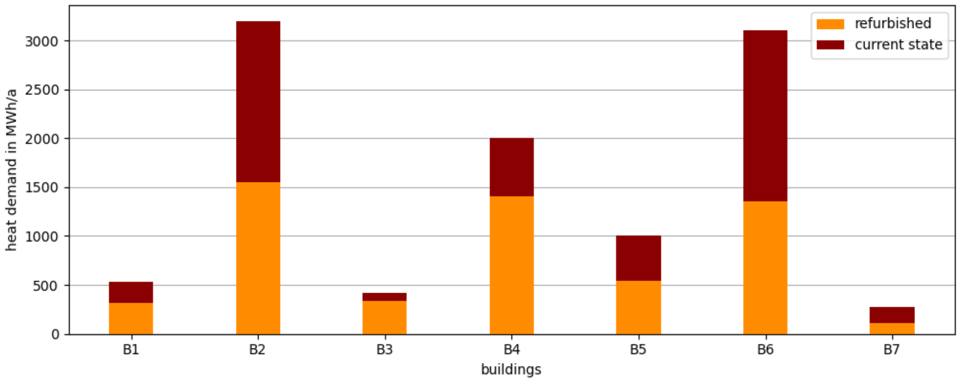


Figure 6: Heat demand of the buildings in current and refurbished state

For this, the boundary conditions of the waste heat recovery and of the heating network must be taken into account. Most buildings currently have radiators with system temperatures of 90/70 °C. As a minimum requirement, these temperatures must be lowered to 60°C/45°C as part of the renovation process (see Section 4.1). This ensures, that the buildings can use the waste heat of the chillers. However, given that the efficiency of the heat recovery depends on the temperature of the waste heat, the use of even lower temperature heating systems such as floor heating devices is recommended. Therefore, a comparative study of two systems: radiators with design temperatures of 60°C/45°C and floor heating devices with design temperatures of 40°C/30°C has been carried out.

In Figure 7: Comparison of the annuity of investment costs for radiators and floor heatingthe annual investment costs for the transformation of the heating systems in the buildings that will be refurbished is compared. An interest rate of 4% and component lifetimes from the VDI 2067-1 where assumed. It could be shown that the annuity of investment costs for installing floor heating is 57% higher than radiators.

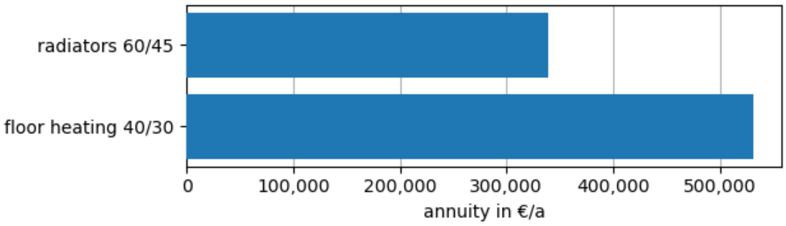


Figure 7: Comparison of the annuity of investment costs for radiators and floor heating

Furthermore, by retrofitting the air handling units with heat recovery systems, the heating demand for the air conditioning is significantly reduced, which in turn presents a good opportunity for the lowering of the supply air conditioning temperatures. If necessary, the heat exchanger of the air handling units (AHU) can be replaced in order to achieve even lower heat supply temperatures of the AHUs.

Following the implementation of the waste heat recovery measures and the transformation of the heating network, the low temperature consumers that were previously supplied by the high temperature network level (e.g the AHUs) need to be connected to the low temperature supply line of the network.

6. Seasonal geothermal storage

The heating and cooling network on the campus is to be supported by a seasonal geothermal energy storage system based on borehole heat exchangers (BHE). This will serve as a heat sink for the waste heat in summer and as a heat source for the heat pumps in winter. A central open area of 12,900 m² on the campus provides space for 120 to 150 BHEs in a hexagonal arrangement at a spacing of about five meters. Due to the good hydrogeological conditions, such as no groundwater flow and good thermal conductivity and capacity, seasonal geothermal storage is feasible and low storage losses can be expected. For the system of heating and cooling by means of chillers, the borehole thermal energy storage (BTES) should have a size of appr. 0.5 GWh (see Chapter 3). For the dimensioning of the BTES, a hydrogeological model was first created via the modeling Software FeFlow using the FEM method to determine the number of BHE and the temperature development in the underground. It should be noted that the outlet temperature of the BTES must be between the operating temperature of the chillers of 6 to 12 degrees. Initial estimates have shown that a total of approx. 80 BHE are sufficient for the needed storage size.

7. Results and conclusion

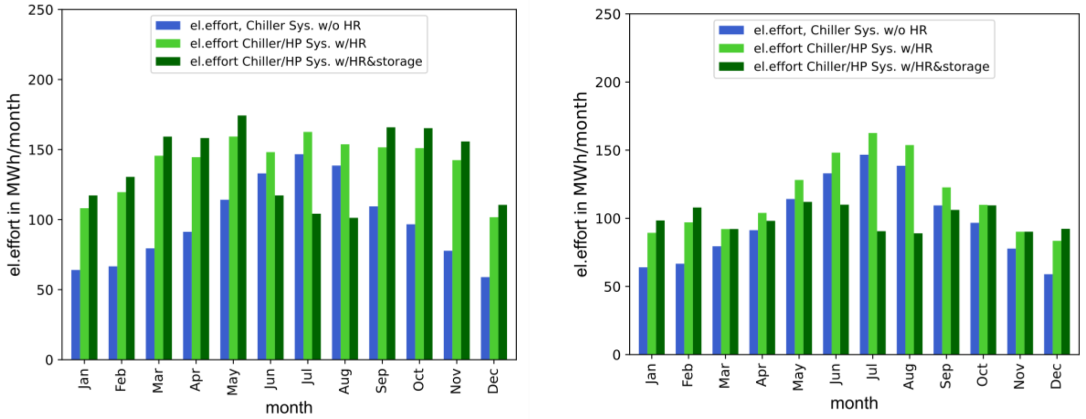
7.1 Heat recovery potential and efficiency

To assess the performance of the proposed energy retrofitting concept, an economic and ecological analysis of different scenarios has been carried out. A scenario without geothermal storage and a scenario with geothermal storage were assessed for the 2 different design system temperatures of the renovated buildings: 60°C/45°C, and 40°C/30°C, corresponding to radiators and floor heating devices (FHD) respectively. To calculate the waste heat potential and the associated electrical energy consumption, yearly simulations of the waste heat recovery from the chillers were carried out. Depending on the scenario, the condensation temperature was set in accordance with one of the two supply temperature curves illustrated in Figure 5:. The results are summarized in Table 1. The annual average COP was calculated according to the method described in Chapter 3. It could be shown, that while all the COP values are above those of conventional heat pumps, the usage of floor heating devices in the refurbished buildings significantly increases the efficiency of the waste heat recovery. Similarly, a geothermal storage not only increases the amount of waste heat usage in the buildings through load shifting but also decreases the amount of electricity consumption of the chillers.

Table 1: Heat recovery (HR) efficiency for different scenarios

Scenario	**Heating system design temperature**	**Waste heat recovered**	**Electrical consumption**	**annual COP**	**CO_2-Savings**
direct HR	60°C / 45°C	3.285 MWh/a	512 MWh/a	6	704 t/a
	40°C / 30°C		205 MWh/a	16	834 t/a
with Storage	60°C / 45°C	3.858 MWh/a	483 MWh/a	8	877 t/a
	40°C / 30°C		20 MWh/a	197	1071 t/a

To understand the very high efficiency of the scenario with storage and floor heating devices, a monthly comparison of the electrical consumption for the different scenarios is illustrated in Figure 8. It can be seen that for the scenario with the lowest supply temperatures, the additional electricity consumption for the heat recovery in winter is very low and almost entirely offset by the electricity savings in summer due to the passive cooling with the geothermal storage. This is due to the fact that for this scenario, the condenser outlet temperatures are only slightly higher than currently (e.g without waste heat recovery).



a. **supply conditions 60 °C/45 °C**

b. **supply conditions 40 °C/30 °C**

Figure 8: Monthly results to electrical energy consumption of supply system for the reference (w/o HR) case and two system conceptions: direct Heat Recovery and Heat Recovery with using geothermal storage

As a consequence of the waste heat recovery and feed-in into the transformed DHN branch, the heat demand from the municipal district heating network is reduced, leading to CO_2-savings of up to 1071 t/a[1].

Figure 9illustrates the heat demand from the municipal DHN for the reference scenario without heat recovery and for the two scenarios with waste heat feed-in into the network. It shows that the combination of building refurbishment, waste heat usage and seasonal storage has the potential to reduce the dependency on fossil fuel heating sources for this building complex by 90%, with municipal DHN heat only being required for the high temperature consumers and during the periods where free cooling is prioritized above waste heat recovery.

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[1] For the calculation of the CO_2-savings, the CO_2-emissions of the German electricity mix of 420 g/kWh were used (Umweltbundesamt, 2022). For the municipal DHN a CO_2-emissions factor of 280g/kWh according to (BAFA,2021) was used. It is important to note that these emission factors are specific to Germany and that for a different location, the results may differ.

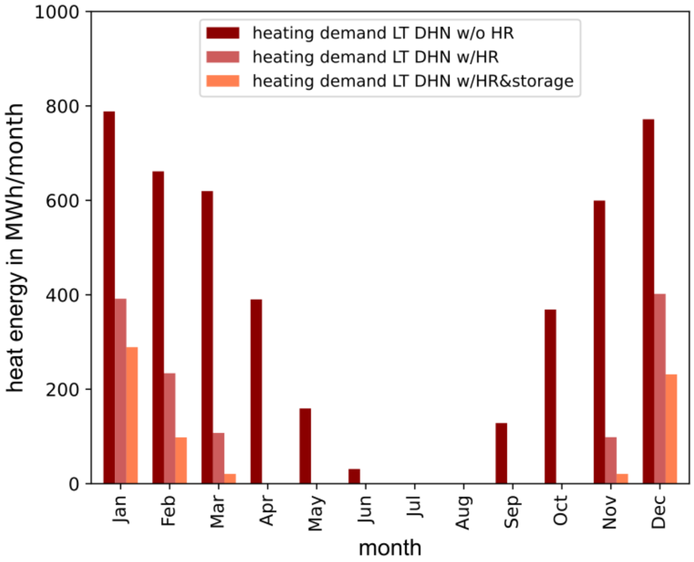

Figure 9: Monthly results of District Heat demand for the reference case (LT refurbished state w/o HR) and two system conceptions: direct Heat Recovery and Heat Recovery with using geothermal storage

7.2 Economical analysis

While it was proven that the presented concept is environmentally beneficial and leads to significant reductions in CO_2- Emissions, an economic analysis is necessary to determine its feasibility. For this, the investment costs were calculated according to manufacturer surveys and research data. The biggest investments are for the retrofitting of the chillers with heat recovery systems and for the purchase of the district network branch from the utility company (ca.0.4-0.5 million € each) closely followed by the borehole geothermal field (ca. 0.3 million €). The operation and maintenance costs were defined as a yearly percentage of the investment costs of each system. Furthermore, the cost of the additional electricity consumption for the heat recovery was added to the operation costs. The investments associated with the building retrofitting were not considered in this analysis, since these measures will be implemented regardless of the transformation of the heating and cooling supply. Therefore, the analysis only regards the economic feasibility of the heating and cooling network transformation.

A dynamic economic analysis was performed in which a service life of 20 years and an interest rate of 4% were assumed. The levelized cost of energy (LCOE) for the waste heat integration and the payback period were calculated for the 4 scenarios. It could be shown that all scenarios are profitable, with a LCOE of up to 7.5 €cents/kWh and a payback period of up to 10 years. As expected, the scenario with geothermal storage and lower temperatures largely outperforms the other scenarios, with an LCOE of 4 €cent/kWh and a payback period of 6 years. However, it is important to note that the installation of floor heating devices is more expensive than that of radiators. If the additional costs for FHD is considered, the LCOE of the low temperature scenario increases to 9 €/kWh and the amortization period to 23 years. Given that most components of the proposed system have a lifetime of over 25 years, this scenario is economically feasible. Moreover, it is important to note that for this economic analysis, the increase in energy prices has not been taken into account. Therefore, given the drastic expected increase in heating prices over the next years as well as the necessity to prioritize CO_2 savings before economic gain, the installation of FHD in the buildings is strongly recommended.

Regarding the geothermal storage, it was demonstrated that its usage increases the waste heat utilization by approx. 0,57 GWh/year and decreases the electricity demand for cooling in summer by 180 MWh/a. This results in additional CO_2-savings of ca. 200 t/a, 27% higher than the scenario without storage. Assuming a service life of 25 years, an interest rate of 4% and yearly operation and maintenance costs of 2% of the investment, a levelized cost of storage of 5.7 €cent/kWh was calculated, which is lower than the current cost of DHN heat.

7.3 Conclusion

In conclusion, this study has shown the benefits of a holistic renovation concept of a city district. It could be shown that considering the boundary conditions of the supply structure in the building renovation process creates favorable conditions for the decarbonization of the heating and cooling supply. In total, the proposed transformation of the heating and cooling supply results in a reduction of CO_2 emissions of up to ca. 1100 t/a. Its economic feasibility is underlined by the short payback period of up to 10 years and a LCOE of max 7.5 €cent/kWh, which is much lower than the current price of municipal district heating (8.5 €cent/kWh). It was also demonstrated that while the installation of floor heating devices in refurbished buildings is significantly more expensive than that of medium-temperature radiators, it increases the efficiency of the waste heat recovery and utilization process and consequently, the CO_2-savings. This results in lower operation costs that partially offset the increased investment, especially when considering the future increase in energy prices. This example underlines the necessity to take into account the synergies between energy conservation measures at building level and the supply of energy at district level.

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9. References

Bean, F., Volt, J., de Groote, M., Paardekooper, S., Riahi, L., 2018, Aligning district energ and building energy efficiency, Report, http://bpie.eu/wp-content/uploads/2018/11/EE-DES-BELGRADE-REPORT_WEB.pdf

Bundesamt für Wirtschaft und Ausfuhrkontrolle, 2021, Informationsblatt CO2-Faktoren, Report.

Delmastro, C., Martinsson, F., Dulac, J., Corgnati, S.P., 2017. Sustainable urban heat strategies: Perspectives from integrated district energy choices and energy conservation in buildings. Case studies in Torino and Stockholm. Energy. 138, 1209-1220, https://doi.org/10.1016/j.energy.2017.08.019

European Comission, 2016, Towards a smart, efficient and sustainable heating and cooling sector. Memo. https://ec.europa.eu/commission/presscorner/detail/en/MEMO_16_311

European Comission, 2020, A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives, Brussels

Kononenko, N., Reimann, A., Ziegler. F.,2021, Modellierung des Kälteverbunds und Evaluation der übergeordneten Regelungsalgorithmen zur Effizienzsteigerung der Kälteversorgung eines Hochschulcampus , Tagungsband Deutsche Klima-Kälte-Tagung (DKV), Paper AA II.1 01, Dresden , https://www.dkv.org/index.php?id=93

Lundström, L., Wallin, F., 2016. Heat demand profiles of energy conservation measures in buildings and their impact on a district heating system. Applied Energy. 161, 290-299. https://doi.org/10.1016/j.apenergy.2015.10.024

Le Truong, N., Dodoo, A., Gustavsson, L., 2014. Effects of heat and electricity saving measures in district-heated multistory residential buildings. Applied Energy. 118, 57-67. https://doi.org/10.1016/j.apenergy.2013.12.009

Miara, M., Bongs, C., Günther, D., Helmiling, S., Krammer, Th., Oltersdorf, Th., Wapler, J., 2013, Wärmepumpen(Heat Pumps), Bine-Fachbuch, FIZ Karlsruhe

Pozzi, M., Spirito G., Fattori, F., Dénarié, A., Famigletti, J., Motta, M., 2021.Synergies between building retrofit and district heating. The role of DH in a decarbonized scenario for the city of Milano. *17th International Symposium on District Heating and Cooling*, Nottingham, UK, 6-9 September.

Stanica, D.I, Karasu, A., Brandt, D., Kriegel, M., Brandt, S., Steffan, C., 2021a. A methodology to support the decision-making process for energy retrofitting at district scale. Energy & Buildings. 238, https://doi.org/10.1016/j.enbuild.2021.110842

Stanica, D.I, Bachmann, M, Kriegel, M.,2021b. Design and performance of a multi-level cascading district heating network with multiple prosumers and energy storage. Energy Reports. 7, 128-139. https://doi.org/10.1016/j.egyr.2021.08.163

Umweltbundesamt, 2022, Entwicklung der spezifischen Treibhausgas-Emissionen des deutschen Strommix in den Jahren 1990 – 2021, https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2022-04-13_cc_15-2022_strommix_2022_fin_bf.pdf