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Conference Paper

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Publication date:
2020-09

Permanent link:
https://doi.org/10.3929/ethz-b-000426953

PROCEEDINGS OF ECOS 2020 - THE 33RD INTERNATIONAL CONFERENCE ON
EFFICIENCY, COST, OPTIMIZATION, SIMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS
JUNE 29-JULY 3, 2020, OSAKA, JAPAN

District-scale lake water free cooling in Zurich, Switzerland: System performance simulation and techno-economic feasibility

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Abstract:
Lake water district cooling systems have been shown to reduce greenhouse gas emissions in several cases, including projects in heating-dominated climates. Due to the highly cooling-intensive functions in the *Hochschulquartier* area in Zurich, Switzerland, a district-scale free cooling network based on lake water has been proposed, but its feasibility has yet to be demonstrated.
This paper presents the methodology for thermal network simulation developed for the City Energy Analyst (CEA), an open-source software for energy demand simulation and system operation modeling and optimization. This methodology was then applied to simulate the free cooling system's operation for four scenarios of urban development for the area featuring different functional mixes. The results were then compared to decentralized vapor compression chillers in order to analyze the network's feasibility from an economic and environmental perspective.
The simulation results showed that the district cooling network would reduce the electricity demand for cooling in the area by about 60% compared to the use of standard vapor compression chillers. This improvement in performance was however achieved at the expense of much higher annualized costs due to the large investment associated with building the network. Thus, the proposed free cooling network might require further economic incentives for its construction.

Keywords:
District cooling, Free cooling, Thermal networks, Renewable energy systems, Sustainability.

1. Introduction

Lake water district cooling systems have been proven to reduce greenhouse gas emissions in several cases, including examples in heating-dominated climates, such as in the case of Cornell University in Ithaca (USA) and in the city of Toronto (Canada) [1]. A lake water free cooling network has been proposed to supply the *Hochschulquartier* district in central Zurich, Switzerland, an area that is home to two large universities (ETH Zurich and the University of Zurich) as well as the University Hospital of Zurich [2]. While the environmental viability of using lake and river water for district cooling in Zürich has been demonstrated, the economic feasibility of the proposed free cooling system for the master plan perimeter has not been shown.
The goal of this paper is to present the thermal network model in the City Energy Analyst (CEA) [3] and to use it to evaluate the performance of a deep lake water cooling system with Lake Zurich as a heat sink. Four different scenarios for development of the area are considered in order to evaluate the impact of the different functional mixes of each scenario on the feasibility of the free cooling network and their impact on the design of the cooling solution. The network's performance for each scenario

is evaluated by comparing the costs and CO_2 emissions associated with its operation to a "business-as-usual" air-based system in which each building's space and process cooling demands are supplied by decentralized vapor compression chillers.

2. Network performance simulation and assessment criteria

2.1. Thermal network modeling in the City Energy Analyst

The operation of the cooling network is simulated using the thermal network model we developed for the City Energy Analyst (CEA), an open-source software for energy demand simulation and supply system modeling and optimization. The network simulation tool performs thermal and hydraulic modeling of a "well-defined" network, that is, plant and consumer substations, piping routes and pipe properties (length and heat transfer coefficients) are already specified.

As a prerequisite to the simulation, therefore, a network layout was generated for each scenario using the CEA thermal network layout tool. The tool, which is based on the Networkx python package [4], uses a Steiner minimum spanning tree algorithm to find the shortest path to connect all buildings in the case study. For simplicity, all pipes were assumed to be laid in trenches under the streets and the network was assumed to be branched. All pipes in the area are assumed to be made of steel with polyurethane insulation.

The hydraulic calculation for branched layouts is largely based on Oppelt, T., et al. [5]. In this method, thermal networks are analyzed as a set of nodes and edges that represent, respectively, building substations and pipe junctions, and the pipes connecting them. Given this well-defined network of edges and nodes, the thermal network simulation can be carried out. The CEA thermal network simulation comprises a number of steps. First, the required heat exchanger area at each consumer substation is calculated according to the consumer demands and target supply temperatures at each substation using the Number of Transfer Units (NTU) Method [6]. Subsequently, the thermal network is sized by calculating the flow rate required at each edge at each time of the year in order to supply the temperatures and flow rates required at each consumer node according to mass conservation equations. The pipes are then sized to meet the maximum flow rate throughout the year. Finally, the hydraulic thermal simulation is carried out for each time-step. This calculation involves calculating the temperature and pressure throughout the network accounting for pressure and thermal losses in the system.

Pressure losses in the network can be classified as continuous losses throughout the pipes and local losses at distinct locations within the network. Due to the Siphon effect in the closed system, there are no geodetic height losses. The continuous losses in the pipes are calculated with the Darcy-Weisbach equation [7]:

$$\Delta p = \frac{8 \cdot \zeta \cdot \dot{m}^2 \cdot L}{\pi^2 \cdot D^5 \cdot \rho} \tag{1}$$

where Δp is the pressure loss over the pipe, $\dot{m}$ is the mass flow rate through the pipe, L and D are the length and diameter of the pipe, respectively, and ρ is the density of the fluid flowing in the pipe. ζ is the dimensionless Darcy friction factor, which is calculated using the Swamee-Jain approximation:

$$\zeta = \begin{cases} 64Re & \text{for } Re \leq 2300 \\ 0.316 \cdot Re^{-0.25} & \text{for } 2300 < Re \leq 5000 \\ 1.325 \cdot \ln\left(\frac{\mathrm{e}}{3.7 \cdot D} + \frac{5.74}{Re^{0.9}}\right)^{-2} & \text{for } Re > 5000 \end{cases} \tag{2}$$

The most relevant local losses are bending losses and pipe diameter change losses. In CEA, these are estimated by multiplying the continuous losses by 1.2, which was found to be an adequate simplification for this case study [8].

The node temperatures in the network are calculated at each time step iteratively. First the substation supply temperatures are calculated based on the nominal flow rate of each edge, and then the substation mass flow requirements and pipe mass flows are updated accordingly. The substation supply temperatures are subsequently recalculated with the updated pipe mass flow. This iterative process continues until the substation supply temperatures converge. The cooling required from the plant (in our case, the lake) is finally calculated based on the plant supply and return temperatures and total mass flow rate. The thermal losses in the thermal network are calculated through a resistance equivalency model:

$$\dot{Q} = \frac{\Delta T}{R_{pipe} + R_{insulation} + R_{ground} + R_{conv}} \tag{3}$$

where $\dot{Q}$ represents the thermal losses through the pipe, ΔT is the temperature difference between the fluid in the pipe and the ground, and R_i are the thermal resistances, calculated according to Wang et al. [9].

The thermal resistance of the pipe material R_{pipe} and of the insulation $R_{insulation}$ are calculated as a function of the interior and exterior diameter of the pipe or insulation layer (D_{int} and D_{ext}) and the thermal conductivity of the material (λ):

$$R_i = \frac{1}{2\pi \cdot \lambda_i} \cdot \ln\left(\frac{D_{ext,i}}{D_{int,i}}\right), i \in \mathbf{I} = \{pipe, insulation\} \tag{4}$$

The thermal resistance of the ground R_{ground} is in turn calculated as follows [9]:

$$R_{ground} = \frac{1}{2\pi \cdot \lambda_{ground}} \cdot \ln\left(\frac{2d}{D_{ext,ins}} + \sqrt{\left(\frac{2d}{D_{ext,ins}}\right)^2 - 1}\right) \tag{5}$$

where λ_{ground} is the thermal conductivity of the ground and d is the depth in the ground at which the network is placed. Finally, the convective heat transfer resistance induced by the moving fluid in the pipe is calculated according to the following equation [10]:

$$R_{conv} = \frac{1}{\pi \cdot \alpha_{thermal} \cdot D_{int,pipe}} \tag{6}$$

where $\alpha_{thermal}$ is the heat transfer coefficient, which is a function of the Nusselt number Nu and the thermal conductivity of the fluid in the pipe $\lambda_{thermal}$:

$$\alpha_{thermal} = \frac{\lambda_{thermal} \cdot Nu}{D_{int,pipe}} \tag{7}$$

2.2. Cost calculation

The investment costs for each technology were taken from the CEA database [3]. However, given the need to account for the difficulty of installing a thermal network in the middle of the city, the costs for the thermal network installation were adapted through discussions with planners and experts. The estimated cost of the piping outside of the district is much higher due to the need to carry out micro-tunneling and divert traffic. In addition to the construction costs we assumed a 7% planning fee for the consultants and an additional 10% to account for unforeseen events and risks. Operation costs comprise the cost of electricity for pumping water from the lake to the district as well as operation and maintenance costs. All costs are summarized in Table 1.

The systems are compared by their total annualized costs (TAC), comprising the operational expenditures ($OPEX$) and annualized capital expenditures ($CAPEX_a$):

$$CAPEX_a = C_{inv} \cdot \frac{r \cdot (1+r)^{\tau}}{(1+r)^{\tau} - 1} \tag{8}$$

where C_{inv} are the investment costs, r is the interest rate of the technology, and τ is the lifespan of the technology.

Table 1: Investment and operational costs (in Swiss Francs, CHF) for the deep lake water cooling system and the decentralized chiller alternative.

		Costs	Source
District Cooling	Water Catchment	3 million CHF	expert consultation
	Piping to district	15 000 CHF/m	expert consultation
	Piping in district	5 000 CHF/m	expert consultation
	Pumps	166 CHF/kW	[3]
	Maintenance	0.5%	[11]
Decentralized	Chillers	361 CHF/kW	[3]
	Maintenance	5%	[11]
Operation	Electricity	0.15 CHF/kWh	[3]
	Lake water usage	1.85 CHF/m^3	expert consultation

2.3. Environmental impact calculation

The embodied energy and emissions associated with district heating and cooling networks have typically been neglected in previous assessments [11]. This is due to previous findings that showed that a district cooling network solely relying on heat pumps and free cooling would lead to a much lower final energy consumption and greenhouse gas emissions [12, 13]. Nevertheless, we calculated a simple estimate for the embodied non-renewable primary energy (PEN) and CO_2 emissions of the thermal networks for each scenario (Table 2).

Table 2: Embodied and operational greenhouse gas (GHG) emissions and non-renewable primary energy (PEN) demand for the deep lake water cooling system and the decentralized chiller alternative.

		GHG emissions [kg CO_2]	PEN demand [kWh oil-eq.]	Lifespan [years]	Source
Embodied	Piping (per m)	30–500	135–2250	50	estimated
	Pump	neglected	neglected	25	[3]
	Chillers (per unit)	2910	6444	25	[3, 14]
Operation	Electricity (per kWh)	0.102	2.52	–	[14]
	Maintenance	neglected	neglected	–	–

The embodied CO_2 emissions and primary energy demand arise from the manufacturing of the pipe materials as well as from the excavation to place the pipes and transportation of the soil to disposal [15]. The embodied energy and emissions for the pipe materials were estimated by using reference values by volume from the KBOB database [14] for galvanized steel and polyurethane for each pipe size according to the CEA pipe catalog, as well as 30 kg of geotextile per km of thermal network [16]. The volume of excavated soil and the tons of soil transported to disposal for each pipe size was extrapolated from values from Frischknecht et al. [15]. The environmental impacts from transportation were again taken from the KBOB database, while for excavation they were taken from Swiss standards [17].
The embodied greenhouse gas emissions and non-renewable primary energy demand for manufacturing the chillers as well as the operational emissions from the Swiss user mix were also taken from the KBOB database.

3. Case study and system boundaries

The *Hochschulquartier* is a central area in Zurich comprising two universities (ETH Zurich and the University of Zurich) and the University Hospital of Zurich as well as a number of complementary building uses. The area is composed of buildings with mixed functions such as education spaces, research, health care, offices and other facilities with varying demands. The district cooling network analyzed in this paper has been proposed as part of a planned redevelopment of the area with the goal of increasing the usable floor space by 40%. Four scenarios for the development of the area and the main occupancy of each building are shown in Figure 1.

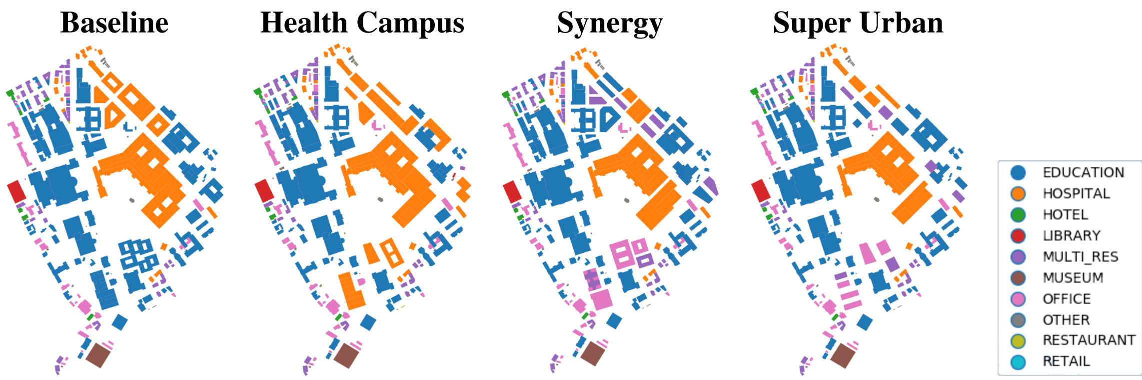

Figure 1: Functional mix of the four scenarios developed for this assessment.

The district lake water cooling system under assessment (depicted in Figure 2) comprises a lake water extraction point coupled to a closed water loop through a single, large heat exchanger near the shore. The clean water loop avoids the formation of bio-films within pipes and heat exchangers in the network that would occur if lake water were circulated through the area. The modeling and assessment of the lake-side heat exchanger is out the scope of this report. Further, we did not assess the operation of building-side heat exchangers and piping within the buildings in the district.

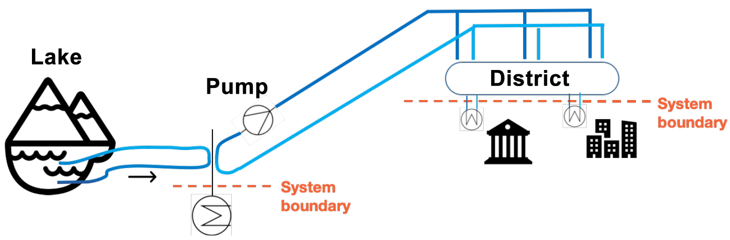

Figure 2: Schematic diagram of the deep lake water cooling system.

The temperature profile in the lake at the extraction location shows a stable temperature of around 5–8°C at a depth of 30 meters [18]. For the simulations, the plant supply temperature was fixed at 6°C, and therefore the amount of cooling delivered to each building in the area is only controlled by regulating the flow rate in the network. The layout of the network within the district generated by CEA for each scenario was manually adapted to create a backbone for the cooling network going through the main street in the district and the lake catchment location was connected to the district following the shortest viable path. Given the existing demands for process cooling in the area, decentralized chillers were assumed to be available at buildings that require lower temperatures in order to upgrade the cooling delivered by the network.

4. Results and discussion

As a result of the changes in building functions, the space cooling demands of the area also change from one scenario to another. The Health Campus scenario has the highest cooling demand due to the expansion of energy-intensive hospital spaces, while the cooling demands are lowest in the Synergy and Super Urban scenarios due to the introduction of uncooled residential buildings in the area. The cooling demands for the Synergy and Super Urban scenarios on the week of the hottest day of the year are very similar, as shown on Figure 3. During weekdays, the peak loads of the Baseline and Health Campus scenarios follow fairly similar patterns. On weekends and nighttime hours, however, the Health Campus scenario has a higher cooling demand due to the higher share of hospital buildings, which were the only occupancy types in the case study with cooling systems and off-peak occupancy.

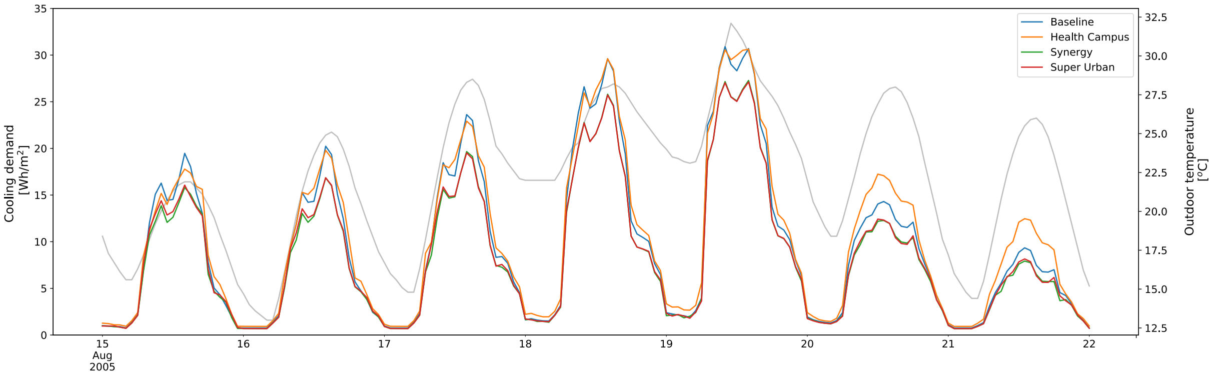

Figure 3: Hourly cooling demand for each scenario plotted against the outdoor temperature on the week of the hottest day of the year.

4.1. District cooling system evaluation

The network lengths are very similar for all scenarios, ranging from 14.17 km (Synergy scenario) to 14.31 km (Baseline scenario). Figure 4 shows the local distribution of network pressure losses along with the yearly cooling demand of each building connected to the network. From this we can observe that the maximum pressure losses in the secondary branches and smaller pipes are higher than the main pipes.

Based on the negative correlation between the pipe diameter and the pressure losses per meter from (1), we split the network into three categories of pipes, with each category making up a roughly equal amount of piping length (Table 3). Tier 1 corresponds to pipes that only transport cooling water from the lake side heat exchanger to the district and do not connect to buildings. Tier 2 pipes both transport and deliver cooling water, while the smallest tier, Tier 3, consists of pipes that deliver and transport water to buildings with lower cooling demands. The smallest piping tier has the highest overall pressure losses, with roughly a third of the piping making up 72% of the yearly pressure losses, while 26% of the cooling energy is provided through those pipes. We can further observe that large pipes only contribute very little to the overall pressure losses at 8% while they also make up roughly one third of the network length.

Table 3: Thermal network pipe tiers.

	Tier 1	Tier 2	Tier 3
DN [mm]	250 – 700	100 – 250	32 – 100
Length [m]	4589	4163	5562
Share of cooling delivered [%]	-	74	26
Share of pressure losses [%]	8	20	72

The distribution of pressure losses is directly linked to the cooling demand of each scenario (Fig. 5). The highest mean pressure loss can be observed in the Health Campus scenario (1.33 MPa/yr), which has the highest demand, while the network simulation for the Synergy scenario results in the lowest mean pressure losses (1.09 MPa/yr). The Baseline scenario, which had the highest peak demand, also has the highest maximum pressure loss while having a moderate total pressure loss.

Since the temperatures in the network were fairly similar for all scenarios, the hourly return temperature profile of the plant node in the Baseline case is shown as an exemple (Figure 6). The temperature is relatively constant during the heating season, with return temperatures rising over the cooling sea-

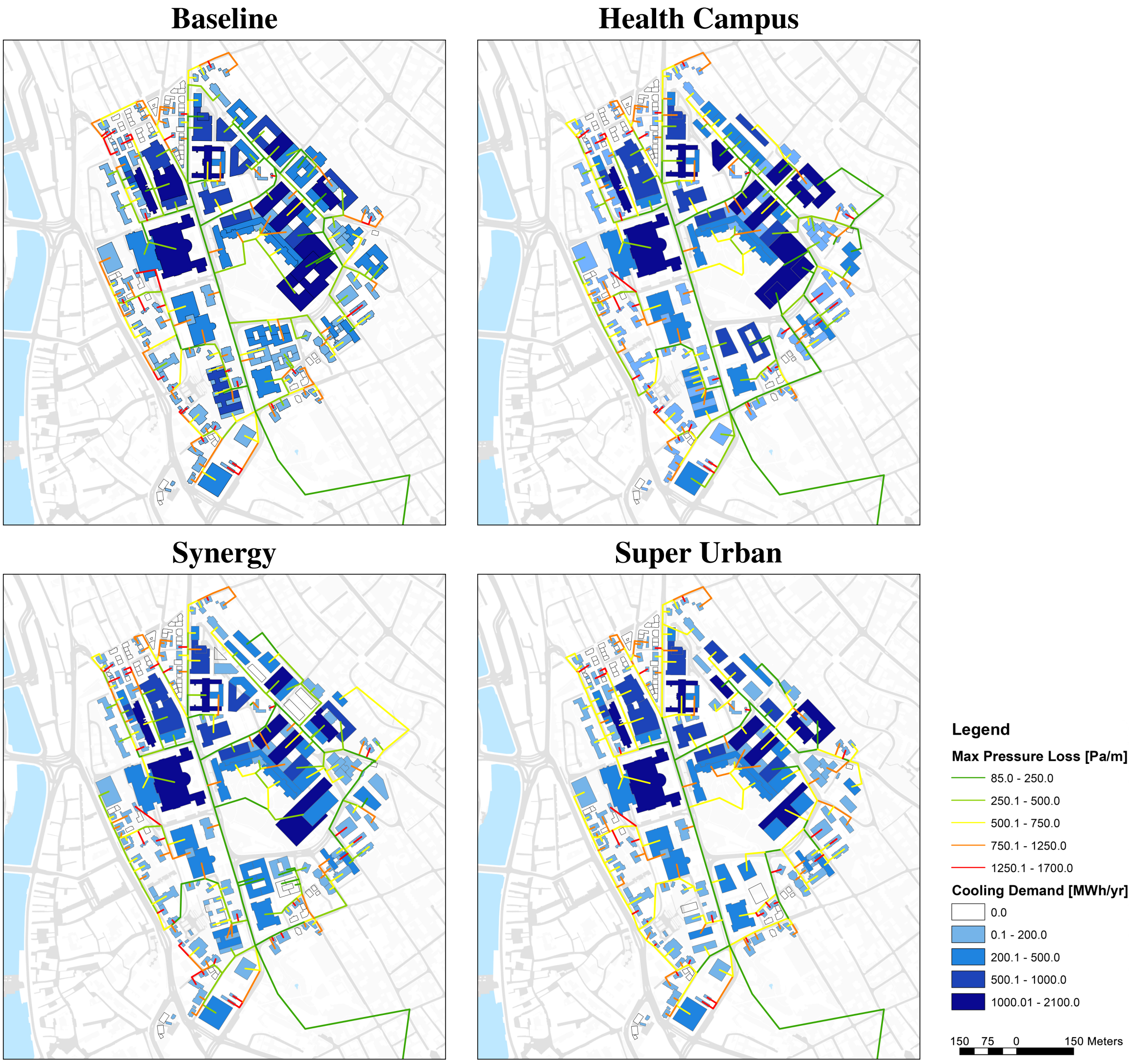

Figure 4: Network layout for each scenario along with the maximum pressure losses at each edge and the cooling demand of each building in the district.

son due to the increase in demand. The mean return temperature is 9.4°C, with a standard deviation of 1.6°C and a maximum of 15.2°C. Given that the supply temperature was set to be stable at 6°C, the maximum difference between the supply and return temperature of the plant node is 9.2°C for the Baseline scenario, which is well below the limit of 12°C [19], which implies legal feasibility of this cooling network design in this regard.

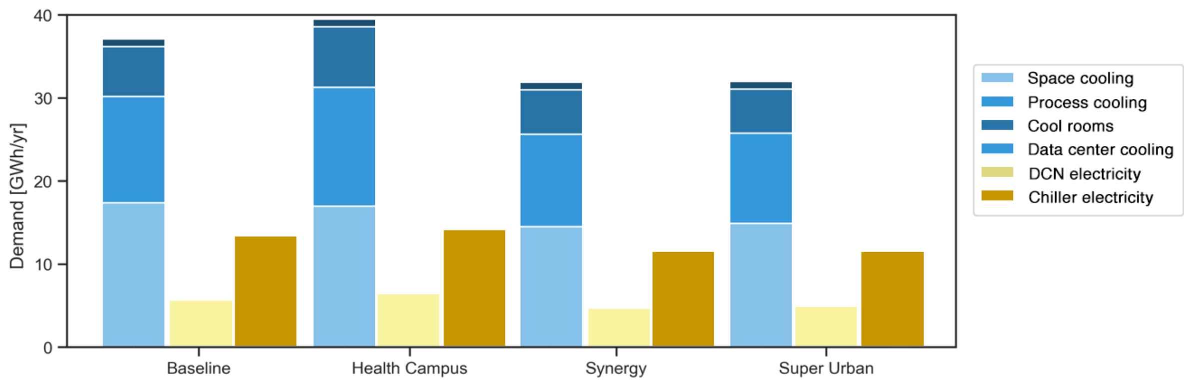

Figure 5: Yearly space cooling demand for each scenario along with the electricity demand required by the district cooling network (DCN) and the decentralized chiller alternative.

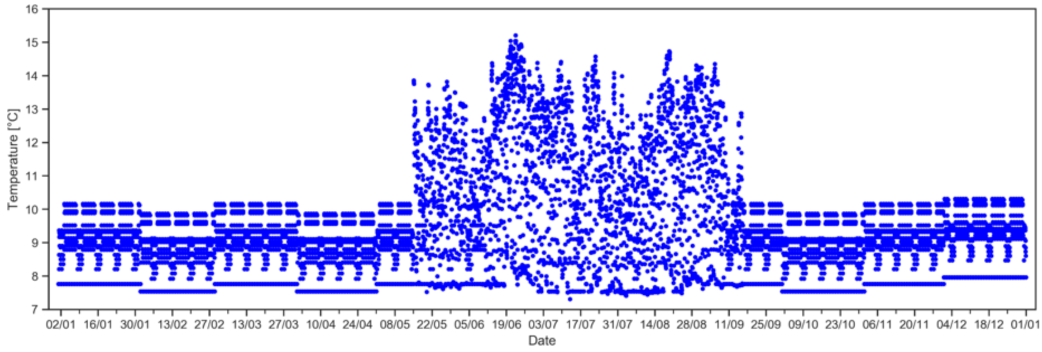

Figure 6: Hourly plant return temperatures for the Baseline scenario.

4.2. Environmental and economic assessment

In order to compare scenarios, we consider the energy efficiency ratio EER, defined as the ratio of cooling delivered to electricity demand to supply it (Figure 5). On average, the energy efficiency ratio of the free cooling network is 6.7, with the network in the Synergy scenario being the most efficient ($EER = 7.1$) and the Health Campus scenario the most inefficient ($EER = 6.2$). The district cooling system further saves an average of 58% in electricity compared to the air-based vapor compression chillers, which had an average EER of 2.8.
The investment costs for deep lake water cooling (Figure 7) are only partly dependent on the sizing and therefore the scenarios. The location of the water catchment and the piping connecting it to the university quarter are identical for all scenarios and make up roughly one third of the total investment costs. The piping within the university quarter is the largest component in the cost calculation, roughly half of the total. Due to its lower cooling demand, the Super Urban scenario has the lowest investment cost at 132.5 million CHF, which annualized over its 50-year lifespan adds up to 7.26 millon CHF/year. The Baseline scenario has the highest investment costs, leading to a $CAPEX_a$ of 7.41 million CHF per year. The overall investment for the decentralized chillers is roughly ten times lower than for the district cooling network ($CAPEX_a$ ranging from 0.75 to 0.95 million CHF/year).

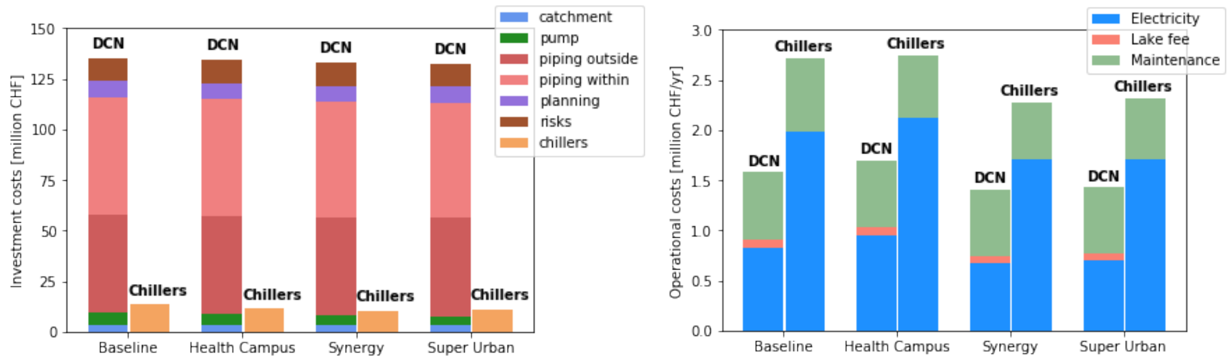

Figure 7: Investment (left) and operational costs (right) for the district cooling network (DCN) and the decentralized chiller alternative for each scenario. All technologies include the costs of installation.

The $OPEX$ (Figure 7) of the lake water cooling system consist mainly of the costs for the pump electricity. The maintenance costs of the system, which were calculated in relation to the investment costs, are also a major contributor to the operational costs. The reference cooling system has much higher operational costs, mainly due to the electricity costs for the decentralized vapor compression chillers, which is more than twice as high as the pump electricity costs for the district cooling network. Figure 8 shows the annualized costs as well as the environmental performance of each system for each scenario. It is apparent that the district cooling system is uneconomical for all scenarios. The district cooling network makes the most economical sense for the Baseline scenario, for which the TAC

increases by 5.3 million CHF/yr compared to the decentralized chiller alternative. Over the system's lifetime, however, this increase leads to an overall deficit of 60 million CHF. Due to the fact that it is the scenario with the lowest cooling demand, the Synergy scenario performs worst economically (5.7 million CHF/yr increase in TAC), however from an environmental perspective this scenario performs the best, with a 60% decrease in CO_2 emissions and primary energy consumption.

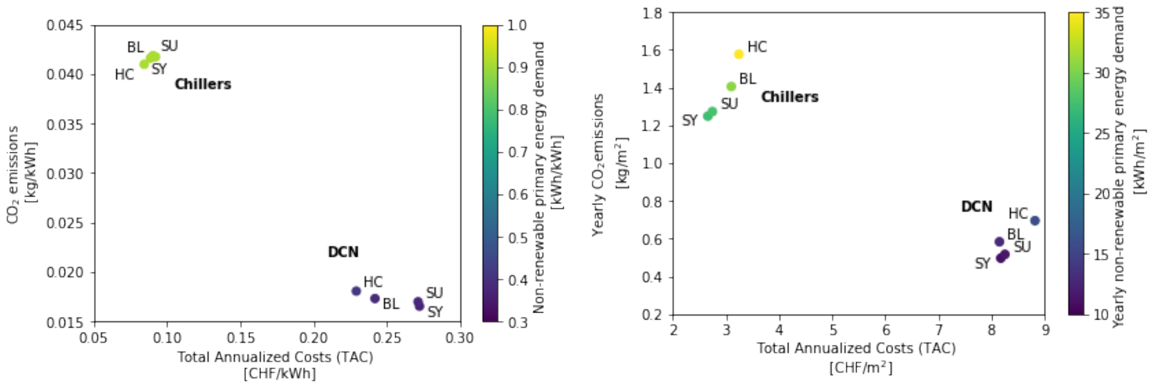

Figure 8: Comparison of the costs, CO_2 emissions and non-renewable primary energy demand per unit of cooling delivered (left) and per square meter of conditioned area (right) for the district cooling network (DCN) compared to decentralized chillers for each scenario (*BL*: Baseline, *HC*: Health Campus, *SY*: Synergy, *SU*: Super Urban).

The annualized embodied emissions for both systems are very similar to each other, however the operational greenhouse gas emissions for the lake water cooling system are much lower due to its much higher EER. The savings in operational emissions (56–60% lower) make the district cooling system an environmentally viable solution for cooling the Hochschulquartier. Similarly, while the district cooling network has substantially higher embodied primary energy demand than the chillers, the system has an energy payback time of only one year. Furthermore, the operational PEN demand of the decentralized chillers is more than twice as high as the district cooling, showing the advantage of the free cooling network in terms of environmental impact.

5. Conclusions

The simulation results showed that the district cooling system could meet the area's demands and reduce the electricity demand for cooling by about 60% compared to the use of standard vapor compression chillers. The designs analyzed also fulfilled the legal limits for the temperature change between outtake and input into the lake. However, the large capital costs to install the network might ultimately prove too onerous, as the annualized costs of the free cooling network were more than double the costs of the "business-as-usual" solution.

Due to the functional mix in the area, there are cooling demands throughout the year as large amounts of process cooling are required. The presence of such a large year-round base load would generally be beneficial for the construction of a district cooling network, and thus a free cooling network in the area could provide an elegant solution to supply highly efficient cooling throughout the year. However, the different scenarios tested in this project had a relatively minor effect on the feasibility of the district cooling system. The Synergy and Super Urban scenarios performed particularly poorly from an economic perspective due to the overall lower demand for process and space cooling, whereas the network was most beneficial for the Baseline and Health Campus scenarios, which had the highest demand and thus the utilization of the system was highest for these cases.

One aspect to consider could therefore be the inclusion of other buildings outside of the district's perimeter into the district cooling network to further increase utilization and justify the high overhead costs of the network. Furthermore, in the current analysis we assumed present day operating conditions throughout the network's lifetime. With rising temperatures due to climate change, however, the area's cooling demand will also increase, and thus the cost performance of the district cooling network is also likely to improve with time. Nevertheless, there might need to be further economic incentives for the construction of the free cooling network.

Acknowledgments

This research was developed as part of the project SPACERGY, within the JPI Urban Europe research framework.

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