Master Thesis

Spatial techno-economic assessment of district cooling potential with lakes for Switzerland

Ruihong CHEN

Supervisors: Prof. Dr. Anthony Patt

Dr. Sven Eggimann

Dr. Massimo Fiorentini

Date: 11.03.2022

Contents

Abstract

To meet the growing cooling demand in buildings and mitigate climate change, sustainable cooling technologies are crucial. District cooling systems using lake water as heat sink has great potential as a sustainable cooling alternative due to the high heat capacity and thermal inertia of water. This thesis assesses the economic potential and environmental impact of constructing district cooling networks for lakes in Switzerland using geospatial analysis and thermal behavior simulation of lakes. The spatial distribution of building cooling demand is simulated to identify potential locations of cooling networks. A minimum spanning tree is used to approximate the required pipe length of the cooling networks. The levelized cost of energy and electricity consumption of a centralized district cooling network is calculated and compared to a decentralized system configuration relying on air-source heat pumps.

It is found that both cost savings and energy savings of lake water district cooling increase with higher cooling demand density per unit pipe length within the potential district. Cost savings of the district network becomes positive once the demand density exceeds 1400kWh/m. The temperature increase of all simulated lakes after rejecting the heat from the district cooling networks remains below 0.05°C. Lakes with volumes bigger than $1km^3$ and major cities within close proximity to the lake tend to be economically and environmentally more suitable for district cooling networks. Limitations of this simulation include simplified piping connection and lake temperature modelling.

Acronym

ACs	Air conditioners
ASHP	Air-source heat pump
API	Application programming interface
CAPEX	Capital expenditure
EER	Energy efficiency ratio
IPCC	Intergovernmental Panel on Climate Change
LCOE	Levelized cost of energy
MFH	Multi-family home
MST	Minimum spanning tree
OPEX	Operational expenditure
OSM	OpenStreetMap
RCP	Representative concentration pathways
SFH	Single-family home
TAC	Total annualized costs
TMY	Typical meteorological year

Nomenclature

Variable	Description	Unit
$e_{b,day}$	Cooling energy demand of a building on a certain day	kWh/day
e_{year}	Aggregated annual demand of each grid point	kWh
E_{year}	Total annual cooling energy demand within each catchment	kWh
$E_{day,max}$	Maximum daily cooling energy demand of the catchment region	kWh/day
$SED(T)$	Specific energy demand of a building type as a function of T	$kWh/m^2/day$
T	Local daily average air temperature	℃
A	Building area in	m^2
Lvl	Number of building levels	
EI	Economic Index of each grid point	
k_1	Weighting of the demand per distance	m/kWh
k_2	Weighting of the demand itself	kWh^{-1}
L	Shortest distance between the grid point and the lake exterior	m
th_{EI}	Threshold of EI to select major demand points	
D_{pipe}	Demand density per unit pipe length for each catchment	kWh/m
L_{pipe}	Total pipe length within each catchment	m
$CAPEX_a$	Annualized capital costs	$million\ CHF$
$OPEX_a$	Annual operation costs	$million\ CHF$
C_{inv}	Initial investment costs	$million\ CHF$
r	Discount rate	%
τ	Lifespan of the system	$year$
c_{in}	Cost of creating each inlet	$million\ CHF$
N_{in}	Number of inlets created at each lake	
c_{pipe}	Unit cost of piping	CHF/m
c_{pump}	Installation costs of pumps	CHF/kW
P_{pump}	Required power of pumps	kW
$c_{chiller}$	Installation costs of vapor compression chillers	CHF/kW
$P_{chiller}$	Required power of chillers	kW
P_{max}	The highest daily cooling power demand	kW
SF	Safety factor	
c_{elec}	Electricity price of Switzerland	CHF/kWh
sv_e	Savings in electricity consumption	MWh
TAC	Total annualized cost	$million\ CHF$
$LCOE_c$	Levelized cost of energy for cooling	CHF/kWh
sv_c	Savings in levelized cost of energy	%
q_t	Specific lake surface heat loss	MJ/m^2
q_{lw}	Specific long-wave radiation between the lake and ambient air	MJ/m^2
q_{eva}	Specific heat loss via evaporation	MJ/m^2
q_{conv}	Specific convection	MJ/m^2
q_{sw}	Specific short-wave radiation from the sun	MJ/m^2
w_0	Average wind speed on a certain day	m/s
h_0	Heat transfer coefficient at wind speed w_0	$MJ/(m^2 \cdot K \cdot day)$
h_{01}	Heat transfer coefficient at 1.85m/s wind speed	$MJ/(m^2 \cdot K \cdot day)$

h_{02}	Heat transfer coefficient at 3.70m/s wind speed	$MJ/(m^2 \cdot K \cdot day)$
T_{diff}	Temperature difference between the air and lake on the same day	K
A_{surf}	Lake surface area	m^2
Q_t	Heat gain of the lake water from the air during a certain day	MJ
r	Radius of lake surface in the cone model	m
h	Depth of lake in the cone model	m
V_{lake}	Volume of the lake	m^3
T_m	Modelled lake temperature	℃
ρ	Water density	kg/m^3
h_{water}	Water heat capacity	$MJ/(kg \cdot K)$

1. Introduction

1.1 Climate change and lake cooling

The globally growing number of residents in cities, as well as climate change, lead to the much higher cooling demand in densely populated cities, especially during heatwaves in summer. The global energy demand for cooling alone is projected to triple by 2050 (International Energy Agency 2018). Without sustainable cooling alternatives, the result would be the installation of 10 new air conditioners (ACs) every second for the next 30 years (Khosla et al. 2021).

Current air-conditioning technologies in households still utilize refrigerants with much higher global warming potential than carbon dioxide. To mitigate the effects of climate change and meet the constantly growing cooling demands, sustainable cooling alternatives are necessary. The high heat capacity and thermal inertia of large water bodies, i.e. suitable heat source/sink, pose an interesting sustainable cooling approach. District energy systems are efficient, environmentally beneficial, and cost-effective for densely populated regions (Rezaie and Rosen 2012). A district cooling system using lake water as the heat sink is particularly interesting since it could potentially offer great economic and environmental advantages.

Different examples of lake water cooling systems have been explored. The lake water cooling systems for deep mines in Canada have been proved to be cleaner and more profitable compared to conventional air conditioning (Kuyuk et al. 2019). Thus, it is interesting to see how the system performs when applied to buildings.

The regional potentials of lakes and rivers in Switzerland for heat extraction and disposal have been estimated, and it was found that the potentials exceeded the demands by a considerable amount in most cases (Gaudard, Wüest, and Schmid 2019). The electricity consumption for cooling would reduce significantly if these potentials are effectively utilized.

The techno-economic feasibility of district-scale lakewater free cooling in Zurich has been studied (Mosteiro-Romero et al. 2020), and it is concluded that district cooling saves about 58% of electricity consumption, but the capital cost of installation is more than double that of vapor-compression chillers.

Existing studies for lake cooling systems have several limitations:

- Simplified building demand estimation: Typically average building demand is used based on population estimates (Gaudard et al. 2019), which is not accurate enough for spatial explicit network planning.
- Lack of large-scale spatial explicit network modelling: Piping network for district cooling of residential buildings at different lakes has not been modelled. No conclusions have been drawn on the circumstances where a lake becomes suitable for lake water district cooling.

1.2 Research questions

To assess the potential of such a district cooling system with lake water, there are three overarching research questions which are addressed in this thesis:

1. How to find a fit-for-purpose estimation of the cooling demand of buildings at a large scale?
2. How to plan and design the cooling distribution network to test whether it would economically make sense for practice?
3. How to develop a simplified lake model to simulate the thermal response of the lake water after discharging the heat into the lake?

2. Methodology

To assess the techno-economic feasibility of a lake-water district cooling system, there are four main tasks: building cooling energy demand calculation (Section 2.1), network planning (Section 2.2), economic assessment (Section 2.3), and lake modelling (Section 2.4). To test and validate the proposed method, a case study on Greifensee was carried out before upscaling to Switzerland.

The overall steps of the whole analysis are shown below in Figure 1. The first main task of building cooling energy demand calculation consists of three steps: data mining, data post-processing, and demand calculation. Data mining includes searching and downloading spatial data for buildings and lakes, as well as gathering weather data for locations near the lakes to be studied. After downloading the needed data, post-processing is performed to remove unmeaningful data entries and fill in missing information for the demand calculation. The second main task network planning requires aggregated demand and finding the shortest-path network for pipes, which can be achieved by selecting catchment regions and finding the minimum spanning tree for piping in the district. A catchment is defined as an area that would be covered by the local district cooling network corresponding to one inlet from the lake. The last two tasks economic assessment and lake modelling can be carried out based on the obtained piping network. Detailed methodology for each step would be explained in the following subsections through the case study on Greifensee (Section 2.1 - 2.4), and the upscaling to Switzerland will be addressed in Section 2.5.

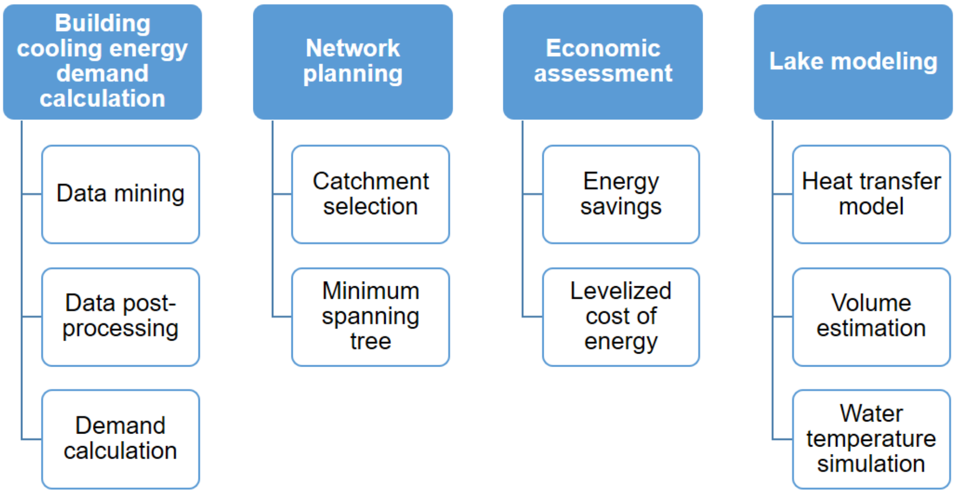


Figure 1: Four main tasks of the methodology and their respective sub-tasks.

All the simulations are run in Python with standard Python packages such as Shapely, Pandas, GeoPandas, Numpy, and NetworkX.

2.1 Building energy demand simulation

To obtain the spatial distribution of cooling demands around the lake, the demand of each building needs to be calculated. This occurs in three steps (Section 2.1.1 - 2.1.3).

2.1.1 Data mining

The required data for building energy demand calculation is listed below:

- Lakes: geometry and volume

- Buildings: geometry, floor levels, and building types
- Local weather: air temperature and wind speed

Geospatial data for lakes and buildings can be downloaded from OpenStreetMap (OSM), a free editable geographic database of the world (OpenStreetMap 2021a). To download all Swiss lakes from OSM, a query to Overpass API (OpenStreetMap 2021b) was written to access the data of the lakes, which contains lake geometry, lake names, and Wikidata ID. Geometry contains coordinates that define the shape and location. The geometry of the lake is used to create a buffer polygon that covers the area within 3km from the lake exterior. 3km is the assumed maximum building distance from the lake that could be connected to the district network. Another query is subsequently written to access the data of the buildings located within the created buffer polygon. The data was then converted into GeoDataFrame from GeoPandas, a python package for reading and processing geospatial data, and saved as shape (.shp) files. A typical GeoDataFrame includes indices, geometry, and other available attributes. Attributes of the buildings include floor levels and building types. It should be noted that only the building geometry (shape and location) has complete data, while levels and type only have partial data. For example, the downloaded lake and buildings of Greifensee are shown in Figure 2.

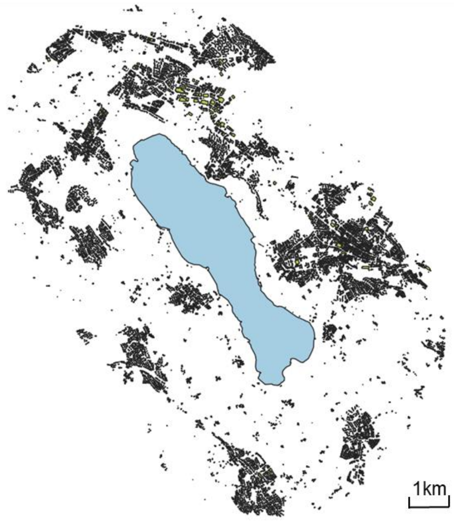


Figure 2: Downloaded lake and buildings within 3km from the lake exterior for the example lake Greifensee (Data source: OpenStreetMap).

Lake volumes are not available from OSM, but they can be obtained from Wikidata, which is an open online central storage for structured data of Wikipedia (Wikidata 2021b). A script to access Wikidata API is written using a Python 3 package Pywikibot to obtain the volume data (Wikidata 2021a). The Wikidata ID of each lake is needed to access the claims of the item, which is available from OSM. The majority of major Swiss lakes have available volume information on Wikidata. In case of missing volume data, an estimate would be needed. Lake volume estimation will be discussed in Section 2.4.2.

The air temperature and wind speed were obtained from a site that contains climate data designed specifically for building simulations (Climate.OneBuilding.Org 2021). All the weather records in EnergyPlus Weather format (.epw) in Switzerland are downloaded from there, which contains data on location, time, dry bulb temperature, wind speed, and solar radiation. It should be noted that all the records are in Typical Meteorological Years (TMY), meaning for each month in the year the data have been selected from the year that was considered most "typical" for that month (European Energy Efficiency Platform 2021). The local weather data is obtained at the location closest to the centroid of the lake geometry, excluding the weather records at high altitudes (>1000m). For instance, the weather data used for Greifensee is from Dübendorf, a town around 6km away from the lake.

2.1.2 Data post-processing: floor level estimation

As mentioned in Section 2.1.1, the building types and levels in the building DataFrame are not complete from OSM. Among the available level data, entries with incorrect format need to be removed. For instance, in the available datasets, some attributes are difficult to interpret, such as Strings like *'2s'* and *'2:3'*. Since these are rare cases, buildings with non-null but non-numeric level values are removed from the DataFrame to avoid converting errors from String to Integer. Non-null and numeric level values are all converted to integer for later calculation. Additionally, buildings that do not require any cooling or would not be considered are removed, which are the building types *'farm'*, *'greenhouse'*, *'farm_auxiliary'*, and *'industrial'*. The indices of the building DataFrame are then reset for conformity of later iterations.

There are a considerable number of buildings with '*NULL'* level information. However, to calculate the cooling demand, the total floor area that requires cooling in each building is needed, which is estimated by multiplying the building area by the number of levels. Thus, an estimation of the number of levels needs to be determined when there is no data available.

The algorithm for estimating the missing building levels based on the building type and building area is shown in Figure 3. The method can be summarized in the following points:

1. Any detached/semi-detached buildings or buildings without type information but with an area smaller than 200 m^2 are assumed to be single-family households with 2 levels.
2. Any office buildings without level data would take the average of the known office levels within the whole considered buffer area. In the case of no level information of offices, all office levels are assumed to be 6.
3. For buildings with neither type nor level information and bigger than 200m^2:
   - If the closest 15 buildings contain at least 5 with levels data, the estimation would take the average of the available data.
   - If not, the levels would be estimated by multiplying the building area by the average level-to-area ratio of all buildings with known levels in the buffer area. In the case of no level information of any building, the average level-to-area ratio is assumed to be 0.015, which is similar to that of a single-family household.

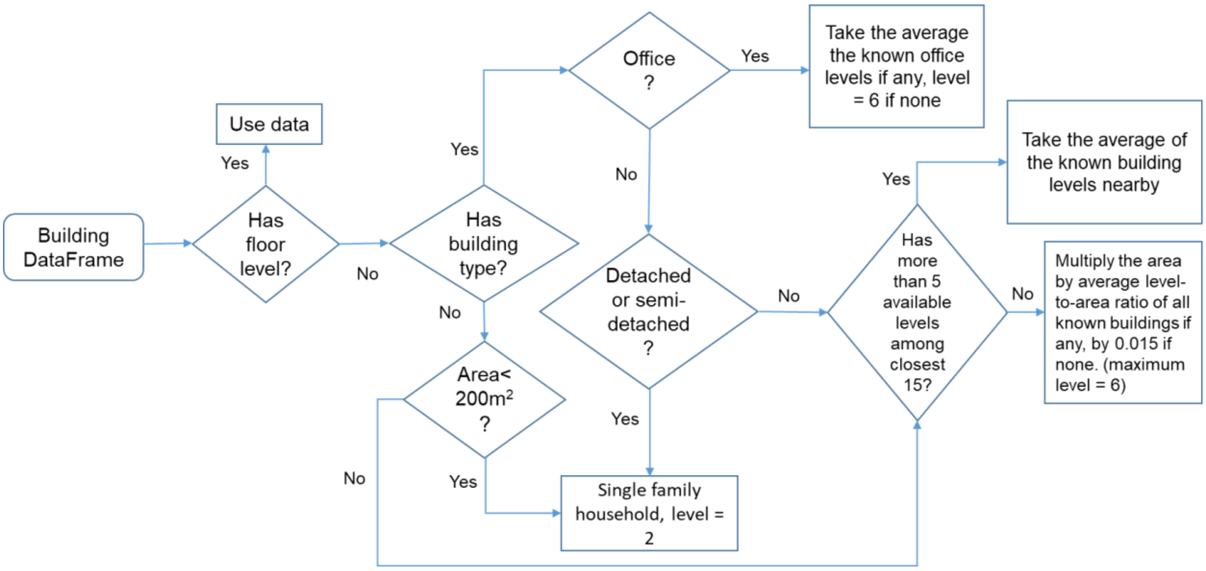


Figure 3: Building levels estimation based on building type, building area, and nearby buildings.

2.1.3 Building cooling energy demand calculation

The chosen method for demand calculation is from a paper on building stock clustering for heating and cooling energy demand simulation (Eggimann et al. 2022), which uses the energy signatures of various building types. Energy signatures are regression models that relate outdoor climatic variables with a building's energy use in a simple yet accurate way (Eriksson, Akander, and Moshfegh 2020). They are presented as heating/cooling energy demand per unit floor area per day as a function of ambient temperature and building age for different building types. An example energy signature of a single-family home (SFH) is shown in Figure 4.

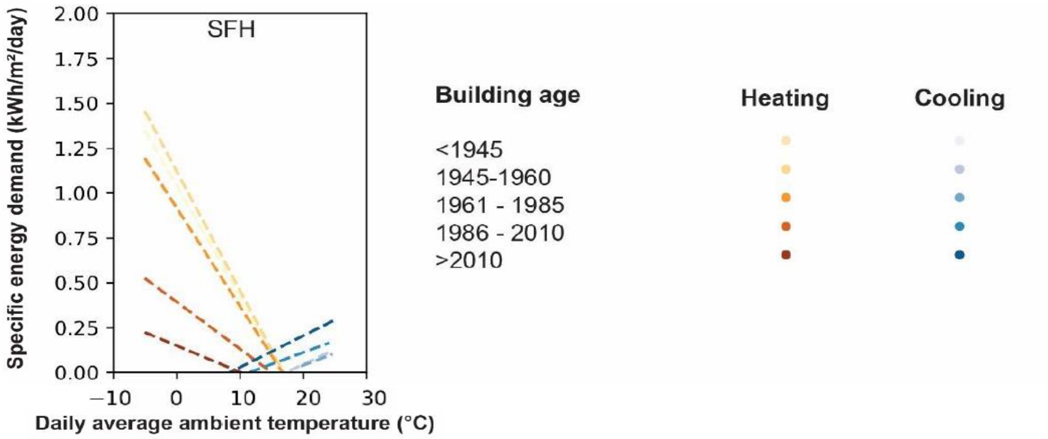


Figure 4: Example energy signature of a single-family home as a function of ambient temperature and building age (Eggimann et al. 2022).

Energy signatures are available for six main types from the same paper (Eggimann et al. 2022): single-family home (SFH), multi-family home (MFH), office, shop, hospital, and school. Details of the energy signatures can be found in the appendix. With these energy signatures, the building cooling demand can be estimated according to Eq. 1:

$$e_{b,day} = SED(T) \times A \times Lvl \qquad \text{Eq. 1}$$

Where,

$e_{b,day}$: Cooling energy demand of a building on a certain day $[kWh/day]$

$SED(T)$: Specific energy demand of a building type as a function of T $[kWh/m^2/day]$

T: Local daily average air temperature [℃]

A: Building area in $[m^2]$

Lvl: Building levels

To match the six energy signatures, the detailed building types from OSM need to be reassigned into the six main categories mentioned above. The classification is shown below in Figure 5.

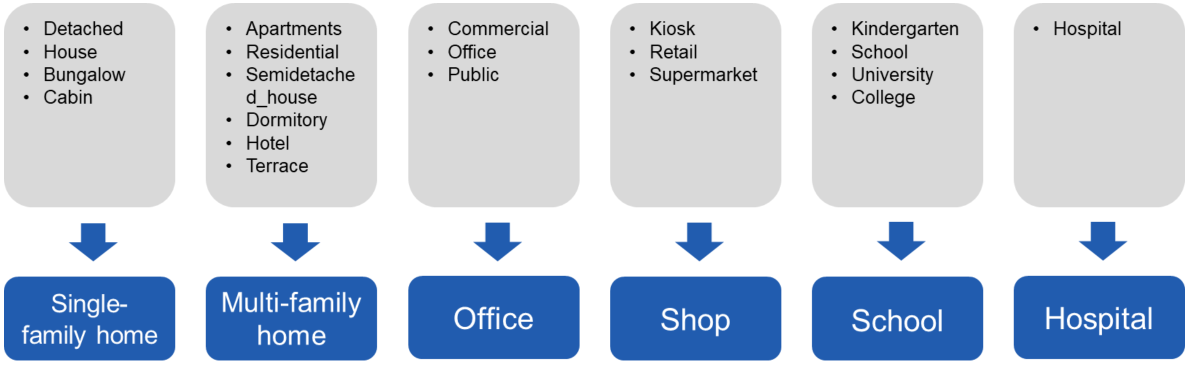


Figure 5: Reassignment of detailed building types from OSM into six main categories with energy signatures.

The air temperature data was in hourly resolution and the daily average was used in the calculation to obtain the specific cooling energy demand on each day. It is assumed that 100% of the building floor area is cooled, which would lead to a more conservative estimate of the cooling demand.

With the energy signatures, building types, building levels, and daily temperature records, the cooling demand of each building on each day in a year within the buffer area can be calculated.

2.2 Synthetic district cooling network generation and planning

2.2.1 Catchment selection

To plan the district cooling network, the spatial distribution of cooling demands around the lake needs to be derived, meaning demands of individual buildings need to be aggregated to determine which region has a significant amount to be connected to the lake. To achieve this, an equally spaced grid was generated by creating a bounding box of the considered area and dividing it with a desired grid cell length. Each building is subsequently assigned an ID of the cell that contains it. The buildings are then grouped by the cell ID. The demands with the same cell ID are summed up and assigned to the centroid of that cell to obtain the regional demands.

Two grids with different unit cell sizes, 2km and 0.5km, are generated. The coarse grid with a unit cell length of 2km is used to determine the number of catchment regions and their respective inlets at the lake. An inlet here means the deep lake water inlet that captures water for transport to the district. The fine grid with a unit length of 500m is used for determining the local connection of pipes within the chosen regions to find the total pipe length. The two calculated grids with annual demands are shown in Figure 6 for the example lake Greifensee.

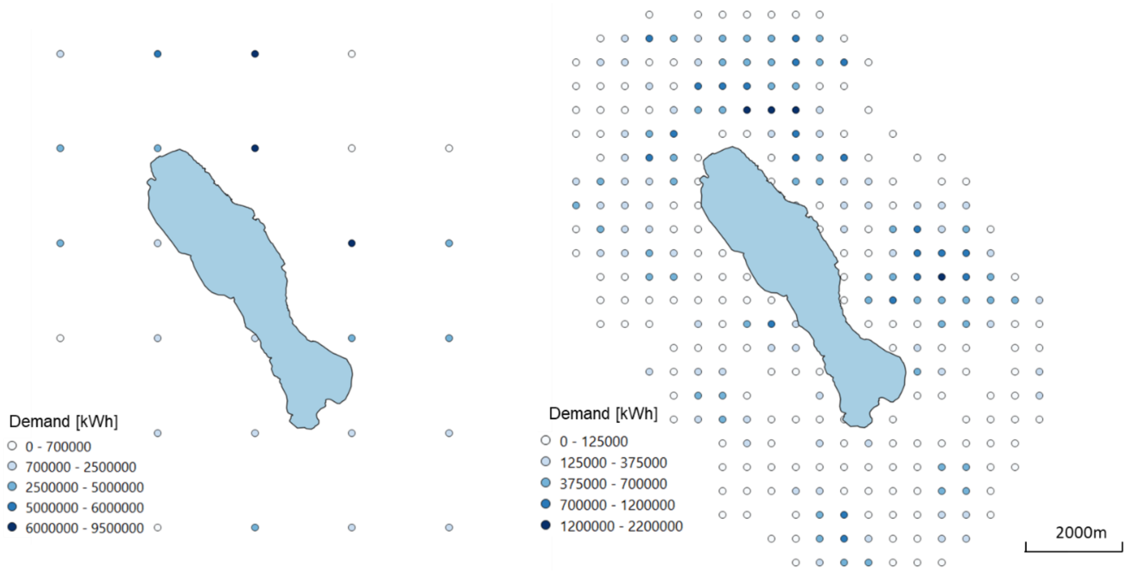


Figure 6: Annual building cooling demand aggregation in grids with 2km (right) and 0.5km (left) unit lengths for the example lake of Greifensee.

To determine which grid points make most economic sense to be connected to the lake, an Economic Index (EI) is proposed for the pre-selection of points to be connected. The index of each grid point is defined as the sum of different weightings of the ratio of the aggregated demand to its distance from the lake and the aggregated demand itself, as shown in Eq. 2. The second term, the weighting of the aggregated demand, is added to balance the index of points that have low demand but also a short distance to the lake that its first term, demand per unit distance from the lake, is high.

$$EI = k_1 \times \frac{e_{year}}{L} + k_2 \times e_{year} \qquad \text{Eq. 2}$$

Where,

e_{year}: Aggregated annual demand of each grid point $[kWh]$

L: Shortest distance between the grid point and the lake exterior $[m]$

k_1: Weighting of the demand per distance $[m/kWh]$

k_2: Weighting of the demand itself $[kWh^{-1}]$

The two weightings k_1 and k_2 as well as the threshold of EI (th_{EI}) are calibrated manually to match the major city/town nearby. Their final values selected for this study are $k_1 = 10^{-4}$, $k_2 = 10^{-6}$, and $th_{EI} = 8$, respectively, based on the case study of Greifensee (lake) to match the two major towns nearby, Greifensee (town) and Uster.

After calculating the EI for each point and selecting the ones above th_{EI}, which are referred to as major points, the next step is to determine the number of catchments at the lake. The major points are sorted according to their distances from the lake. The ones that are within 1500m from the lake, referred to as close points, are used to create inlets at the lake, which are chosen as the closest point on the lake exterior from the close points. Each of the close points is assigned with an inlet, while the points that are further than 1500m away from the lake need to find the most nearby close point and share the same inlet. A combined region of that catchment is created by connecting the major points sharing the same inlet with the shared inlet and buffering the line with 1000m. For example, the two catchments created for Greifensee are presented in Figure 7. The inlets are marked by the red dots, and the two catchment regions are generated by buffering the two black lines connecting the major points with their respective inlets.

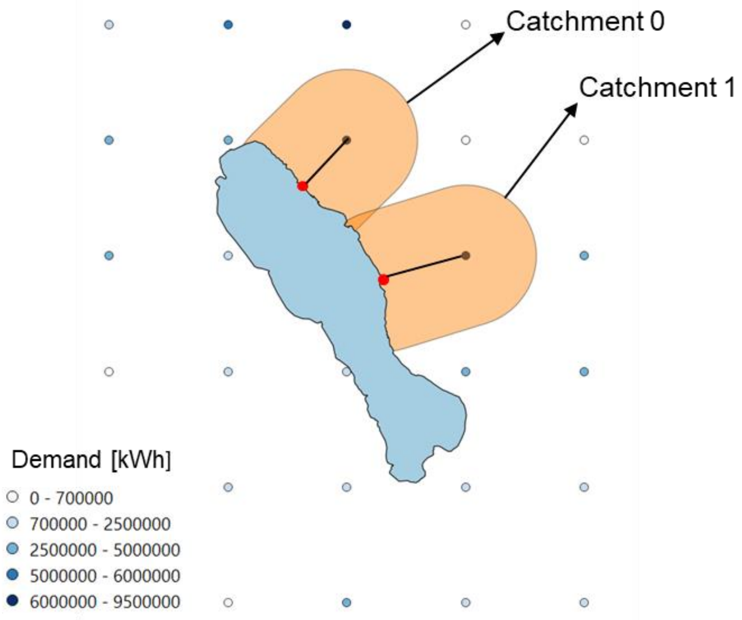


Figure 7: Two catchment regions of Greifensee with respective inlets.

2.2.2 Minimum spanning tree

After obtaining the catchment region, the local piping network can be determined by finding the minimum spanning tree (MST) of the points from the 500m fine grid. The network is formalized as consisting of nodes and edges according to graph theory. A minimum spanning tree is a collection of edges, each connecting two points, such that all points are connected and the total length of the network is as short as possible (Zvoleff et al. 2009). In each catchment region, the points of the fine grid whose cooling demand is lower than 1% of the total demand within the catchments (25MWh/year in this case) are ignored. The MST obtained using Python package NetworkX is shown in Figure 8, which can provide an estimate of the total pipe lengths. It should be noted that this simplified estimation does not consider the connection on a household level.

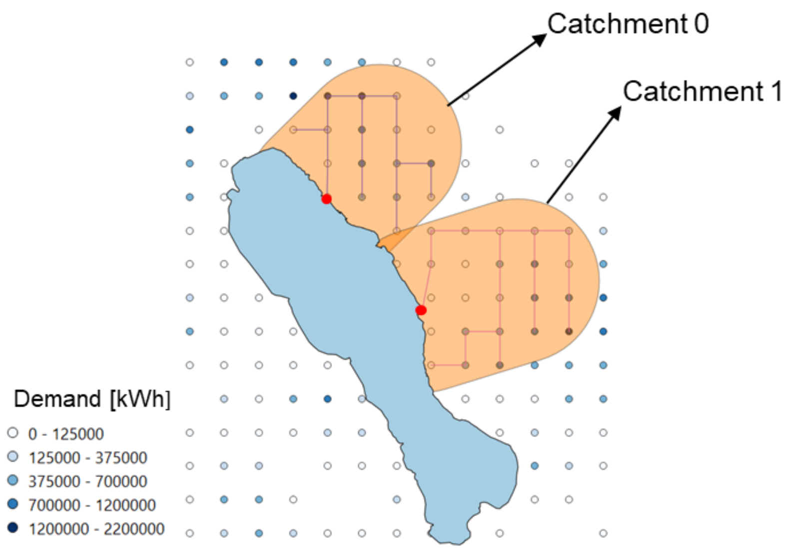


Figure 8: Minimum spanning tree within each catchment region.

After obtaining the pipe lengths, the demand density per unit pipe length for each catchment can be calculated.

$$D_{pipe} = \frac{E_{year}}{L_{pipe}}$$

Where,

D_{pipe}: Cooling energy demand density per unit pipe length for each catchment [kWh/m]

E_{year}: Total annual cooling energy demand within each catchment [kWh]

L_{pipe}: Total pipe length within each catchment [m]

2.3 Economic assessment

After obtaining the total length of the pipes for the network, the infrastructure costs of the district cooling system can be estimated and compared to that of decentralized air-source heat pumps (ASHP) (Mosteiro-Romero et al. 2020). A decentralized ASHP is a chiller for each household with a vapor-compression refrigeration process that uses outdoor air as the heat sink when in cooling mode (Wikipedia 2022).

2.3.1 Annualized capital and operational costs

The capital costs of the district cooling system consist of water intake, piping, and pumps, while the capital costs of ASHPs only include installation costs of chillers.

The annualized capital cost ($CAPEX_a$) is calculated as below:

$$CAPEX_a = C_{inv} \frac{r \cdot (1+r)^{\tau}}{(1+r)^{\tau} - 1} \qquad \text{Eq. 3}$$

Where,

C_{inv}: Investment costs [$million\ CHF$]

r: Discount rate [%]

τ: Lifespan of the system [$years$]

The investment costs of the district cooling system (C_{inv1}) is estimated as follows:

$$C_{inv1} = C_{inlet} + C_{pipe} + C_{pump} \qquad \text{Eq. 4}$$

$$C_{inlet} = c_{in} \times N_{in} \qquad \text{Eq. 5}$$

$$C_{pipe} = c_{pipe} \times L_{pipe} \qquad \text{Eq. 6}$$

$$C_{pump} = c_{pump} \times P_{pump} \qquad \text{Eq. 7}$$

Where,

c_{in}: Cost of creating each inlet [$million\ CHF$]

N_{in}: Number of inlets

c_{pipe}: Unit cost of piping [CHF/m]

L_{pipe}: Total length of pipes [m]

c_{pump}: Installation costs of pumps [CHF/kW]

P_{pump}: Required power of pumps [kW]

It should be noted that the unit cost of piping is assumed to be uniform for the whole network. There is no differentiation between pipe to district and pipe in the district. The costs of small pipes within the district and big pipes to the district are estimated to be 5000CHF/m and 15000CHF/m, respectively (Mosteiro-Romero et al. 2020). The assumed cost of piping cost in this study is 5000CHF/m.

The investment costs of decentralized chillers (C_{inv2}) are only dependent on the power capacity.

$$C_{inv2} = c_{chiller} \times P_{chiller} \qquad \text{Eq. 8}$$

Where,

$c_{chiller}$: Installation costs of vapor compression chillers [CHF/kW]

$P_{chiller}$: Required power of chillers [kW]

The required powers of pumps and chillers are determined by the highest daily power demand throughout the year. It is assumed that cooling is needed only during the daytime. Thus, the highest daily cooling power demand is estimated with a safety factor:

$$P_{max} = SF \times \frac{E_{day,max}}{12hours} \qquad \text{Eq. 9}$$

Where,

SF: Safety factor

$E_{day,max}$: Maximum daily cooling energy demand of the catchment region [kWh/day]

With assumed energy efficiency ratios EER, defined as the ratio of cooling power delivered to consumed electricity to supply it, the respective required power (P_{req}) of pumps and chillers can be calculated.

$$P_{req} = \frac{P_{max}}{EER} \qquad \text{Eq. 10}$$

Where EER of district cooling (EER_1) and air-sourced vapor compression chillers (EER_2) are assumed to be 6.7 and 2.8, respectively (Mosteiro-Romero et al. 2020), meaning the district cooling system saves 58% electricity in operation compared to chillers.

The annual operation costs $OPEX_a$ of both systems consist of electricity use and maintenance. For the calculation of $OPEX_a$, as shown in Eq. 11, the electricity use depends on the EER, and the maintenance fee is assumed to be 1% of the annualized capital costs ($CAPEX_a$).

$$OPEX_a = 1\% \times CAPEX_a + c_{elec} \times \frac{E_{year}}{EER} \qquad \text{Eq. 11}$$

Where,

c_{elec}: Electricity price of Switzerland [CHF/kWh]

2.3.2 Savings in energy and Levelized Cost of Energy

As assumed in Eq. 11 above, the energy consumption of both systems is only electricity. Therefore, the energy savings (sv_e) of the district system compared to chillers in [MWh] can be calculated in Eq. 12.

$$sv_e = \frac{E_{year}}{EER_2} - \frac{E_{year}}{EER_1} \qquad \text{Eq. 12}$$

The total annualized costs TAC for both systems can be estimated by simply summing up $CAPEX$ and $OPEX$ in each year.

$$TAC = CAPEX_a + OPEX_a \qquad \text{Eq. 13}$$

After annualizing the total costs for both systems, their Levelized Cost of Energy for cooling ($LCOE_c$) in [CHF/kWh] can be calculated as below:

$$LCOE_C = \frac{TAC}{E_{year}} \quad \text{Eq. 14}$$

The $LCOE_c$ here represents the average net present cost per unit cooling energy delivered that would be required for constructing and operating a cooling system during its assumed lifetime (Ferrari 2021). It is a good indicator for investment planning and comparison of different alternatives.

The savings in the cost of the district system compared to chillers (sv_c) in [%] can be determined using after obtaining the Levelized cost of energy of both systems ($LCOE_{C1}$ and $LCOE_{C2}$).

$$sv_c = \frac{LCOE_{C2} - LCOE_{C1}}{LCOE_{C2}} \times 100 \quad \text{Eq. 15}$$

The values of the assumed costs and other constants mentioned in Sections 2.3.1 and 2.3.2 are summarised in Table 1.

Table 1 – Summary of assumed values in the economic assessment

Variables	Name	Unit	Values	Source
$\boldsymbol{r}$	Discount rate	%	2	
$\boldsymbol{\tau_{district}}$	District system lifespan	$year$	60	[1]
$\boldsymbol{\tau_{chiller}}$	Chiller lifespan	$year$	20	[1]
$\boldsymbol{c_{in}}$	Cost of each inlet	$million\ CHF$	3	[1]
$\boldsymbol{c_{pipe}}$	Unit cost of piping	CHF/m	5 000	[1]
$\boldsymbol{c_{pump}}$	Unit cost of pump installation	CHF/kW	166	[1]
$\boldsymbol{c_{chiller}}$	Unit cost of chiller installation	CHF/kW	1977	[2]
$\boldsymbol{c_{elec}}$	Unit cost of electricity	CHF/kWh	0.20	[3]
$\boldsymbol{EER_2}$	Energy efficiency of chillers		2.8	[1]
$\boldsymbol{EER_1}$	Energy efficiency of district system		6.7	[1]
$\boldsymbol{SF}$	Safety factor		1.2	

[1]: (Mosteiro-Romero et al. 2020), [2]: (Murray et al. 2020), [3]: (GlobalPetrolPrices 2021)

2.4 Lake model

The goal of the lake model is to simulate the thermal response of a given lake to examine the impact of rejecting the heat from cooling operations into the lake in terms of maximum annual temperature increase.

2.4.1 Heat transfer model

To model the heat transfer on the surface of a lake, according to a simplified approach (Williams 1963), there are four components to be considered: short-wave radiation, long-wave radiation, evaporation, and convection, as shown in Figure 9 and Eq. 16. As suggested by the same paper, short-wave radiation and evaporation can be assumed to balance each other out for simplification (Eq. 17). The two heat transfer modes left, long-wave radiation and convection, can be approximated by a linear function of the temperature difference between the water and air. The combined heat transfer coefficients for natural water surfaces are estimated to vary from 40 to 50 $cal/(cm^2 \cdot day \cdot ℃)$ for average exposure conditions.

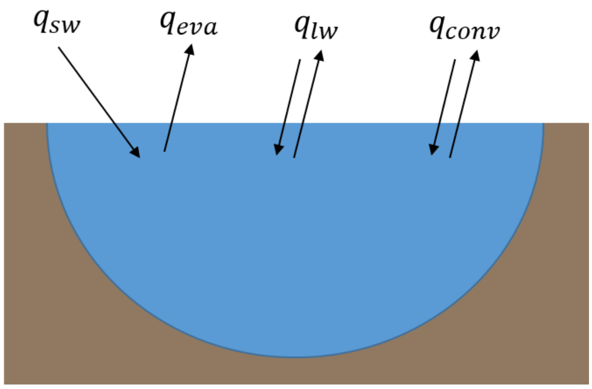


Figure 9: Lake surface heat transfer through short-wave radiation, long-wave radiation, evaporation, and convection.

$$q_t = q_{lw} + q_{eva} + q_{conv} - q_{sw} \qquad \text{Eq. 16}$$

$$q_{eva} - q_{sw} = 0 \qquad \text{Eq. 17}$$

Where,

q_t: Specific lake surface heat loss $[MJ/m^2]$

q_{lw}: Specific long-wave radiation between the lake and ambient air $[MJ/m^2]$

q_{eva}: Specific heat loss via evaporation $[MJ/m^2]$

q_{conv}: Specific convection $[MJ/m^2]$

q_{sw}: Specific short-wave radiation from the sun $[MJ/m^2]$

The heat flux equations for each day after converting the units are shown in Eq. 18:

$$\begin{aligned} q_t = q_{lw} + q_{conv} &= h_{01} \times T_{diff} \text{ (average wind speed 1.85m/s)} \\ &= h_{02} \times T_{diff} \text{ (average wind speed 3.70m/s)} \end{aligned} \qquad \text{Eq. 18}$$

Where,

h_{01}: Heat transfer coefficient at 1.85m/s wind speed $[1.674\ MJ/(m^2 \cdot K \cdot day)]$

h_{02}: Heat transfer coefficient at 3.70m/s wind speed $[2.092\ MJ/(m^2 \cdot K \cdot day)]$

T_{diff} is the temperature difference between the air and lake on the same day in $[K]$. The sign convention is positive when heat is absorbed by the lake, and vice versa.

$$T_{diff} = T_{air} - T_{lake} \qquad \text{Eq. 19}$$

Using the known wind speed during the day, the heat exchange coefficient with the air at the surface h_0 can be linearly interpolated as a function of wind speed w_0.

$$h_0 = \frac{h_{01} - h_{02}}{1.85 - 3.70} \times (w_0 - 1.85) + h_{01} \qquad \text{Eq. 20}$$

Where h_0 is in $MJ/(m^2 \cdot K \cdot day)$, and w_0 is in m/s.

Heat exchange with the air on each day can be then calculated:

$$Q_t = h_0 \times A_{surf} \times T_{diff} \qquad \text{Eq. 21}$$

Where Q_t is heat gain of the lake water from the air in MJ, A_{surf} is the lake surface area in m^2.

2.4.2 Lake volume estimation

For simplicity, the lake is treated as a lumped mass in terms of thermal response, meaning the temperature is assumed to be uniform across the whole lake. The volume of the lake is needed for the calculation of the temperature change.

In case of missing volume data from WikiData, an estimation needs to be given. The simplifying assumption is made here that the lake is a cone, as shown in Figure 10. With known surface area (A_{surf}) from OSM, the radius can be calculated using Eq. 22. The height/depth (h) is assumed to be half of the radius (r) with a limiting maximum value of 30m, as suggested in Eq. 23. The volume can then be calculated with Eq. 24.

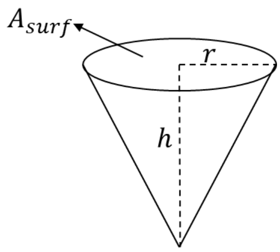


Figure 10: Cone representation of the lake with surface area, radius, and depth.

$$r = \sqrt{\frac{A_{surf}}{\pi}} \quad \text{Eq. 22}$$

$$h = \frac{r}{2} \quad \text{Eq. 23}$$

$$V_{lake} = \frac{1}{3} \times A_{surf} \times h \quad \text{Eq. 24}$$

Where,

r: Radius of the lake surface in a cone model [m]

h: Radius of the lake surface in a cone model [m]

A_{surf}: Surface area of the lake calculated from OSM [m^2]

V_{lake}: Volume of the lake [m^3]

2.4.3 Water temperature simulation and model validation

To examine the model accuracy, a 10-year water temperature profile is calculated and compared to the available temperature data from Meteolakes (Eawag 2021), an online platform for monitoring the biophysical state of Swiss lakes. The 10 years are used so that the water temperature can converge to a steady state of oscillation due to the repeated weather, reducing the impact of an error in the estimation of the initial temperature of the lake.

Assuming the starting temperature on January 1st (time step 0) to be 6°C, the calculation process over different days in ten years is shown below:

$$T_m(0) = 6 \quad \text{Eq. 25}$$

Where T_m is the lake temperature of the model.

$$\Delta T_m(i) = \frac{Q_t + E_{day}}{\rho \times V_{lake} \times h_{water}} \quad \text{Eq. 26}$$

$$T_m(i+1) = T_m(i) + \Delta T_m(i) \quad \text{Eq. 27}$$

Where $\Delta T_m(i)$ is the water temperature change during the i^{th} day in $[°C]$, E_{day} is the cooling demand on that day in MJ (set to 0), ρ is water density ($997 kg/m^3$), h_{water} is water heat capacity ($4.2 \times 10^{-3} MJ/(kg \cdot K)$).

The comparison of the temperature profiles of the example lake Greifensee is shown in Figure 11. As seen from the graph, the model gives a good estimate of the temperature profile except for an over-prediction in summer and a slight delay of seasonal change. This model is considered sufficient at this stage excluding the complexity of stratification.

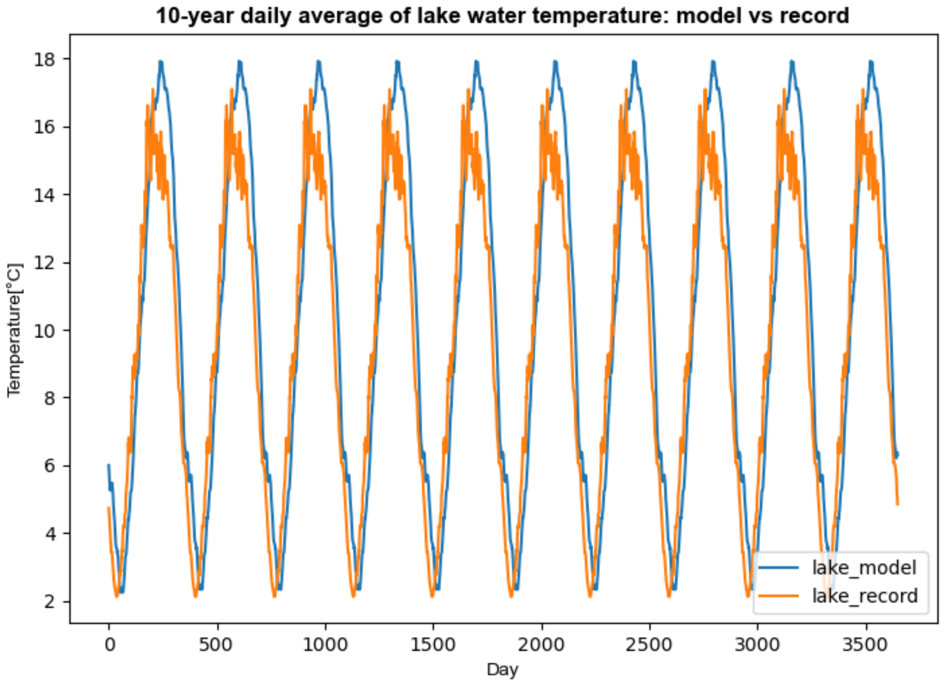


Figure 11: Lake temperature profile comparison for the example lake of Greifensee: modelled result vs records from MeteoLakes (Eawag 2021).

2.5 Upscaling

After finishing the simulation run of the case study on Greifensee, the analysis outlined in Section 2.1 - 2.4 is applied to the lakes across Switzerland to see which lakes make more economical and ecological sense to develop such a district cooling system.

All the lakes that have a surface area bigger than $0.5 km^2$ are simulated. It is assumed that lakes smaller than $0.5 km^2$ have insignificant cooling energy demand from the buildings in the proximity. For each simulated lake, the desired output results are the number of catchments selected, lake volume (V_{lake}), demand density (D_{pipe}), saving in $LCOE_c$ (sv_c), and energy savings (sv_e). The simulated lakes and their catchments are shown below in Figure 12. The catchments marked in orange correspond to the major lakeside cities/towns in Switzerland. Lakes without any catchments do not have a significant amount of cooling energy demand, and will not be considered in the results for upscaling.

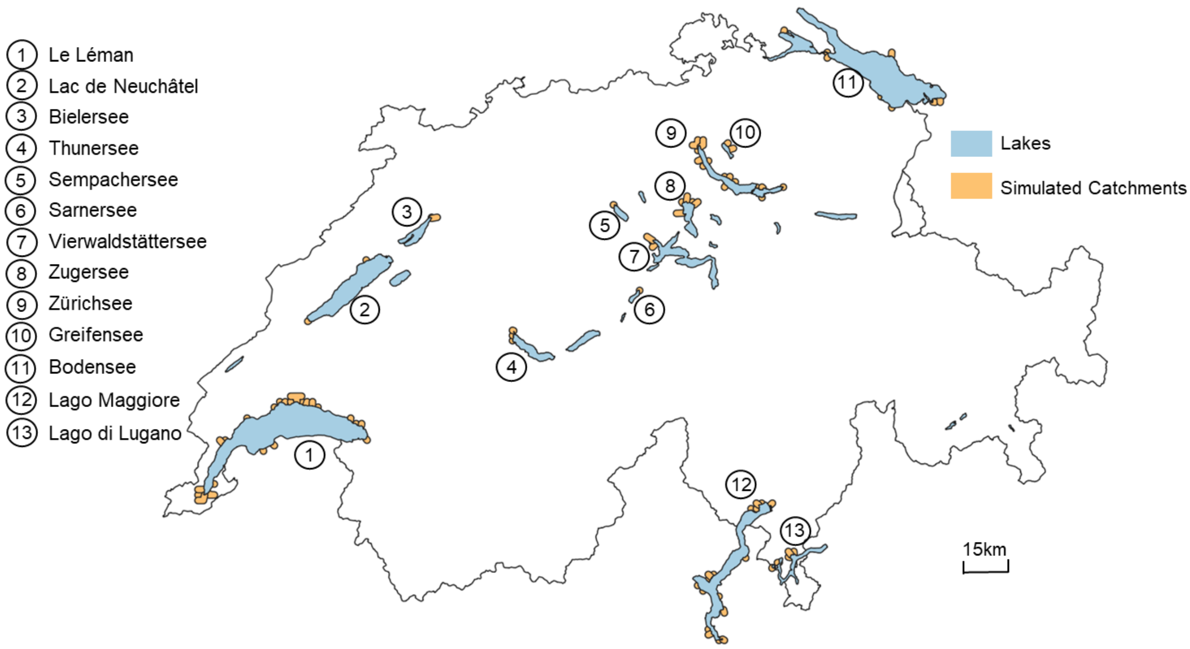


Figure 12: Simulated catchments for major lakes in Switzerland.

After obtaining all the results, the final assessment explores the correlations between cost savings, energy savings, lake volume, demand density, discount rate, and lifespan of the district system. The results are presented in the next section.

3. Results

3.1 Case study calculation and validation

For the case study of Greifensee, with the assumed discount rate of 2% and district system lifespan of 60 years, the simulation results regarding the two catchment regions shown in Figure 13 are shown in Table 2.

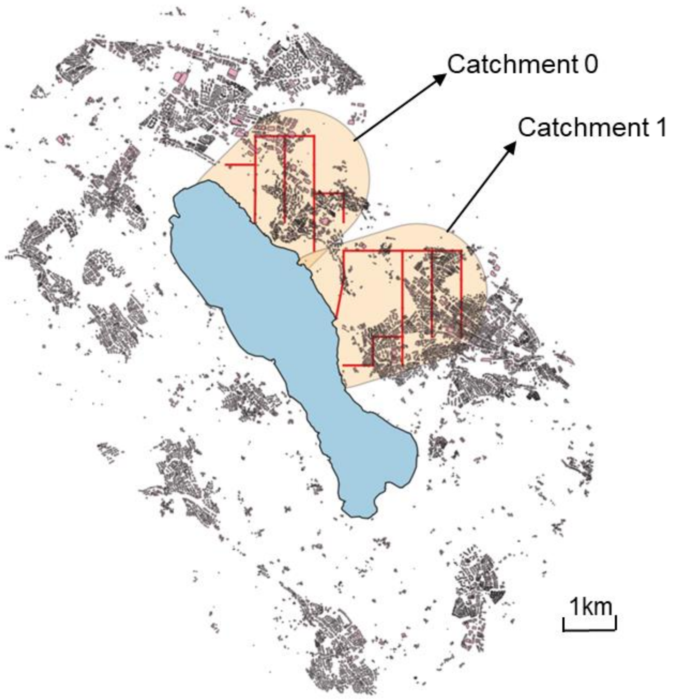


Figure 13: Two simulated catchments with piping networks and buildings of the example lake Greifensee

The MST, i.e. the simulated piping networks of the district system, marked in red in Figure 13, mainly covers populated neighborhoods with dense building distribution. However, there are small errors in capturing the buildings. In catchment 0, a small part of the MST passes through a region without any buildings. In catchment 1, the MST covers the buildings rather accurately, but the catchment does not capture the whole town.

Table 2 – Results for each catchment at Greifensee (demand density, LCOE savings, energy savings)

Lake	Volume [km^3]	Catchment ID	Demand density [kWh/m]	$LCOE_c$ Savings [%]	Energy savings [MWh]
Greifensee	0.1485	0	1239.0	4.0	1915.62
Greifensee	0.1485	1	1057.7	-7.6	2111.76

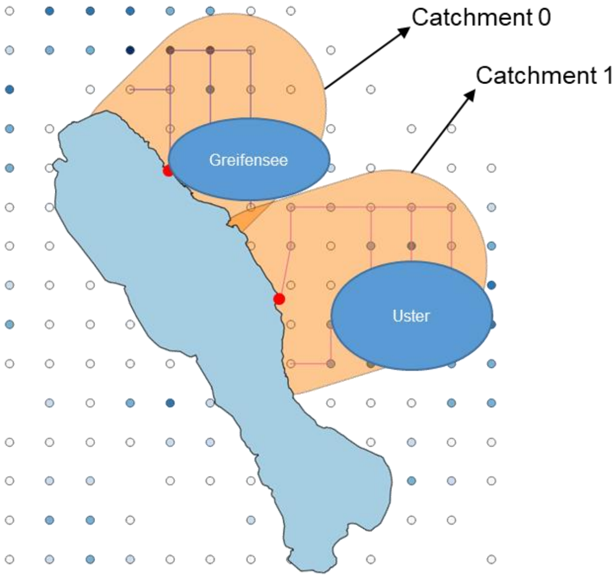


Figure 14: Two catchments of Greifensee and their corresponding towns.

As seen from Table 2 and Figure 14, catchment 0, which covers the town Greifensee, has a 4% lower LCOE for the district system, which means district cooling is more economically attractive than the de-centralized option in this town, while catchment 1, covering the town Uster, has the opposite. However, although the LCOE of district cooling in Uster is 7.6% higher than that of chillers, its savings in energy consumption is higher than the first town. The reason is that Uster has higher cooling demand but also a longer distance from the lake, hence longer pipes, than Greifensee (town).

The impact of the district system on the lake is mainly temperature increase due to the transported heat from households to the lake. The result for the simulated lake water temperature before and after disposing of the heat is shown below in Figure 15.

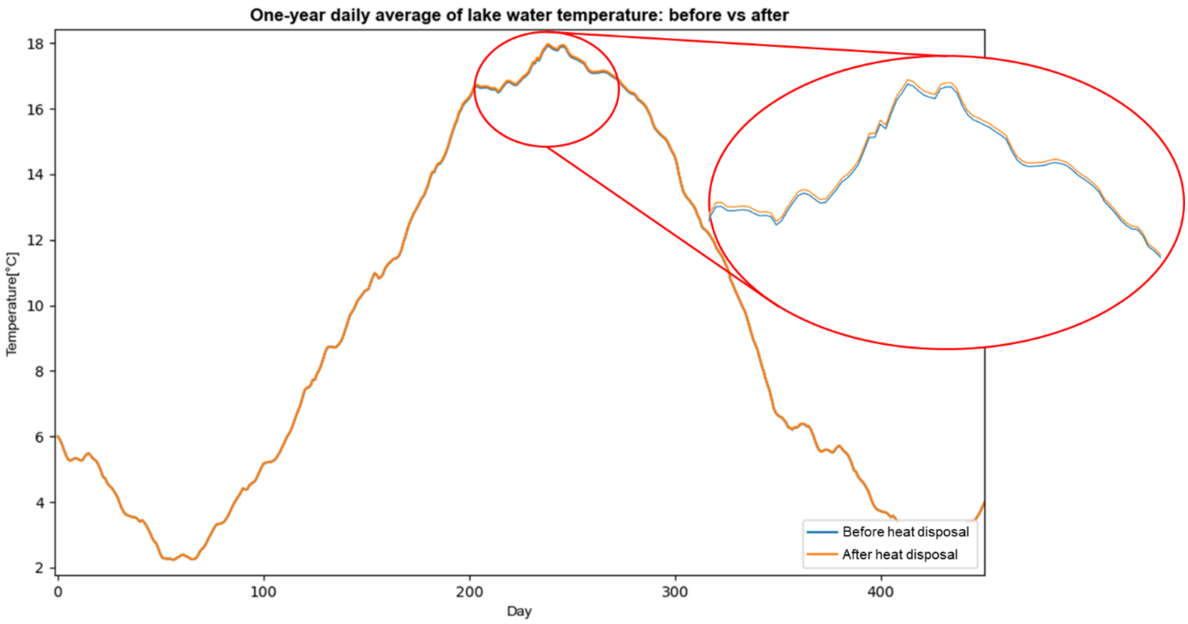


Figure 15: Greifensee lake temperature profiles: before and after absorbing the heat.

The figure shows that the temperature increase is only noticeable in summer, but this increase is still negligible, with the maximum difference being 0.045°C. The temperature difference goes down to almost zero in autumn/winter, meaning the heat gained in summer would dissipate through convection and long-wave radiation in colder weather.

3.2 National scale analysis for Switzerland

3.2.1 Economic assessment

The same analysis for Greifensee (Section 2.1 – 2.4) is applied to other Swiss lakes with varying discount rates (1 – 5%) and district system lifespans (60 – 100 years). The LCOE of the district cooling system in each catchment of all the simulated lakes are collected using different lifespans from 60 to 100 years, assuming the same discount rate of 1%. As suggested in Figure 16, the median LCOE of the district cooling system decreases from 0.12 to 0.09 CHF/kWh while the system lifetime increases from 60 to 100 years. As the lifetime increases, the range of LCOE also reduces, meaning the costs of cooling in each catchment tend to vary less.

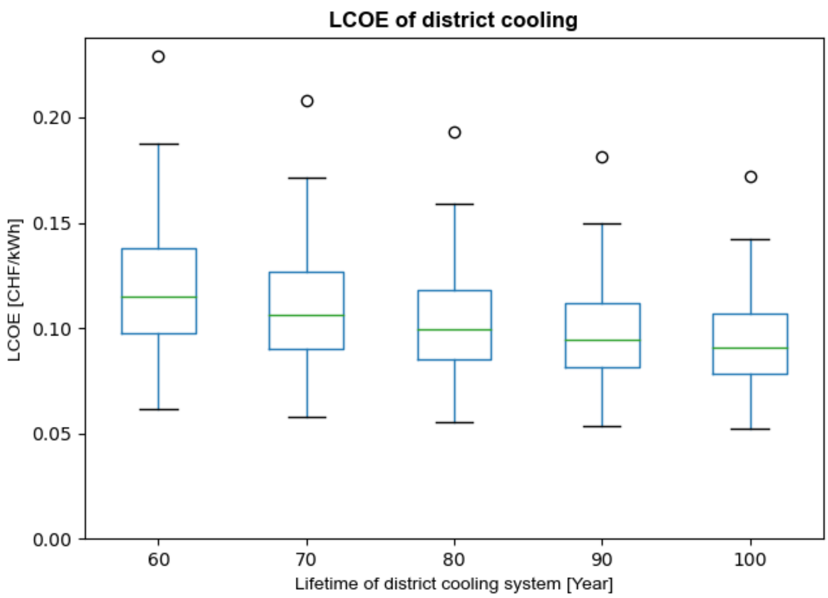


Figure 16: Levelized cost of energy of district cooling vs its lifespan.

To examine the influence of discount rate on the LCOE, LCOEs for both district cooling and decentralized chillers are calculated with their respective constant lifespan of 60 and 20 years while varying discount rates from 1% to 5%. The results are shown in Figure 17. The LCOEs of both systems increase as the discount rate goes up. However, the cost of the district system is more sensitive to the discount rate than that of the decentralized option. The median LCOE of district cooling increases from 0.12 to 0.24CHF/kWh, while the one for chillers only changes from 0.15 to 0.18CHF/kWh. The range of LCOEs for district cooling in each catchment is much bigger than that of chillers. Although the median district LCOE is lower than the median chiller LCOE when the discount rate is lower than 3%, the maximum value of district cooling is always higher than that of decentralized chillers.

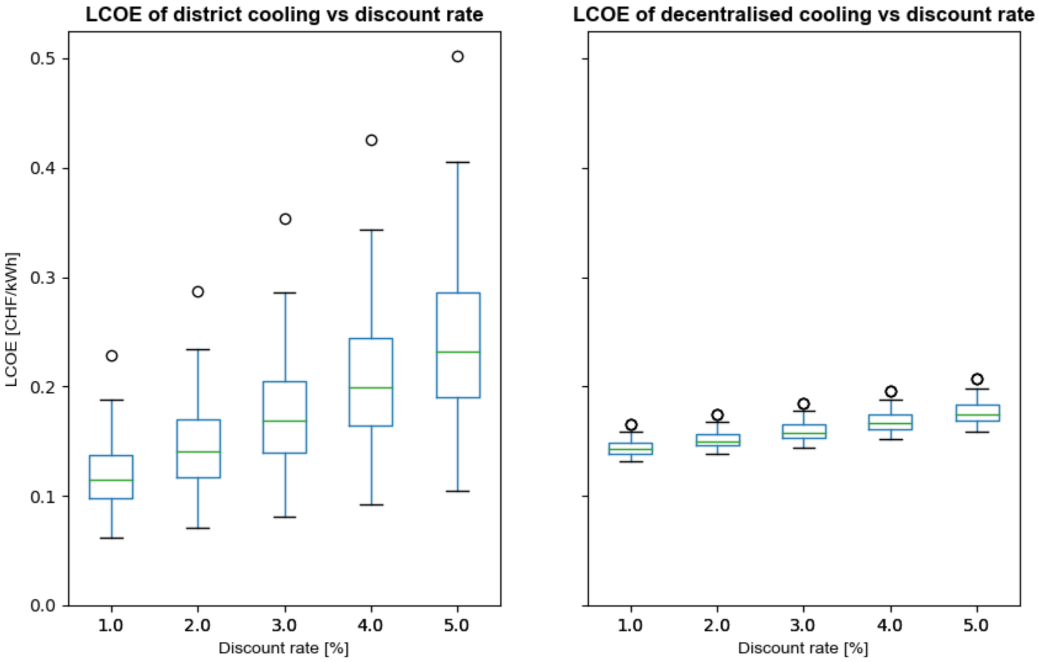


Figure 17: LCOE of district cooling and decentralized chillers vs discount rate.

Both savings in LCOE and energy consumption for each catchment together with its demand density are plotted in Figure 18. The size of the dots represents the demand density per unit pipe length, while the color represents to which lake the catchment belongs. The bigger dots tend to cluster at the top right corner, where both savings are high. The higher the demand density, the higher the savings in energy consumption and LCOE. For each lake, there are catchments with both positive and negative LCOE savings. The savings in energy consumption is always positive since the lake district cooling system intrinsically saves electricity compared to chillers.

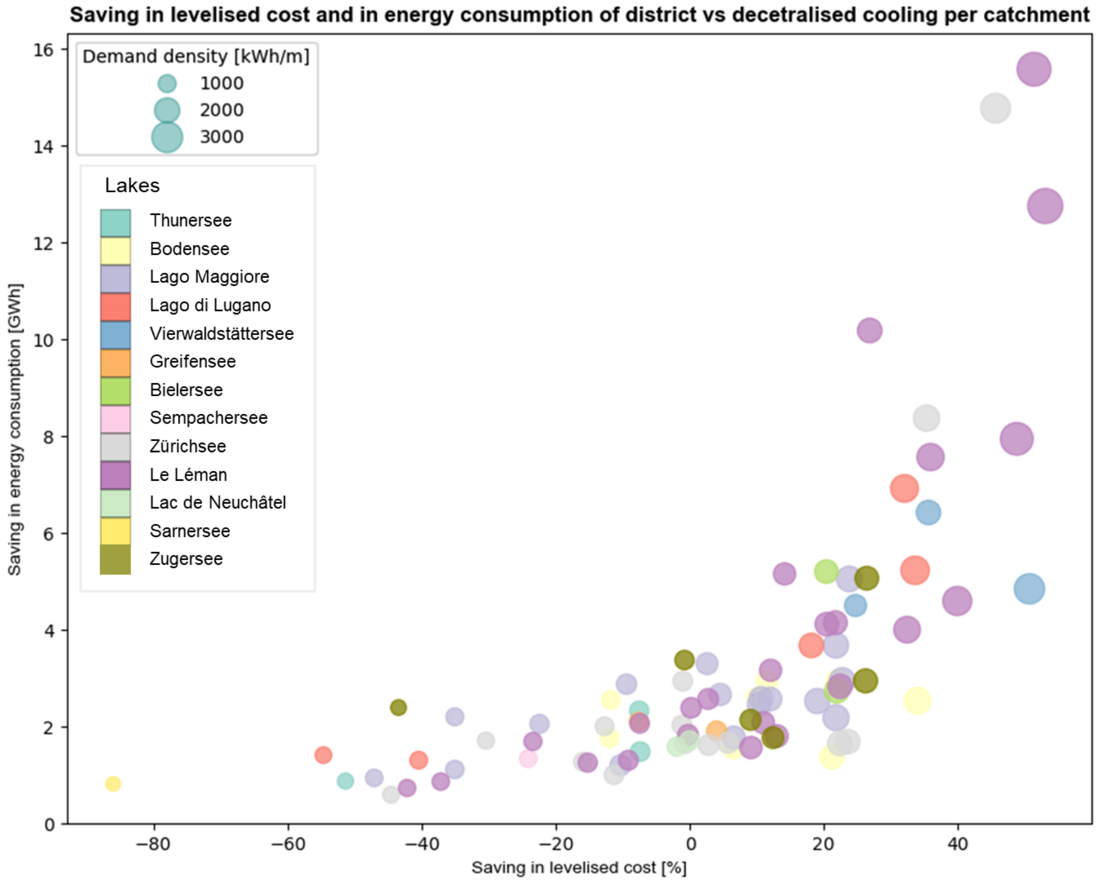


Figure 18: Annual energy saving vs LCOE saving for each catchment (dot size represents demand density, dot color represents the lake).

A clearer presentation of the correlation between LCOE saving and demand density is shown in Figure 19. The higher the demand density, the higher the saving in LCOE. As indicated by the horizontal line, the catchments become positive in saving once the demand density per pipe length exceeds around 1400kWh/m. However, LCOE savings of catchments with demand density between 1200 and 1400kWh/m can be either positive or negative.

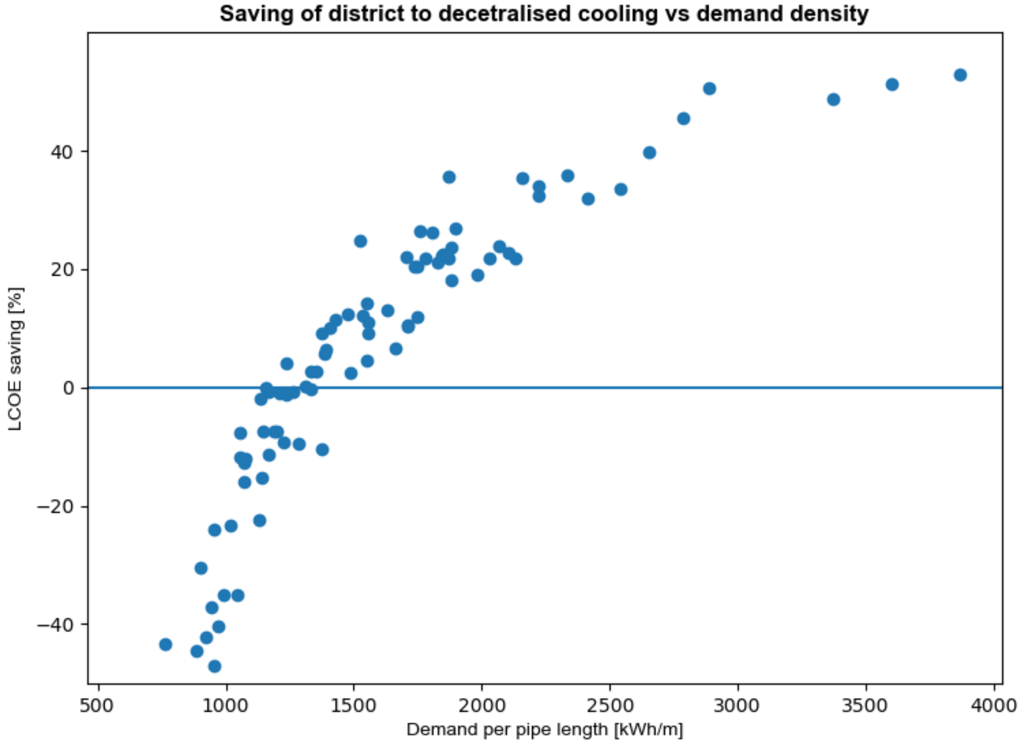


Figure 19: Positive correlation between levelized cost savings of district cooling system and demand density for each catchment.

The catchments with positive savings in LCOE, i.e. economic catchments, are shown in green on the map in Figure 20. The regions with clustered economic catchments are circled out in red, which corresponds to major lakeside cities in Switzerland: Geneva, Lausanne, Biel, Lucerne, Zug, Zurich, Locarno, and Lugano.

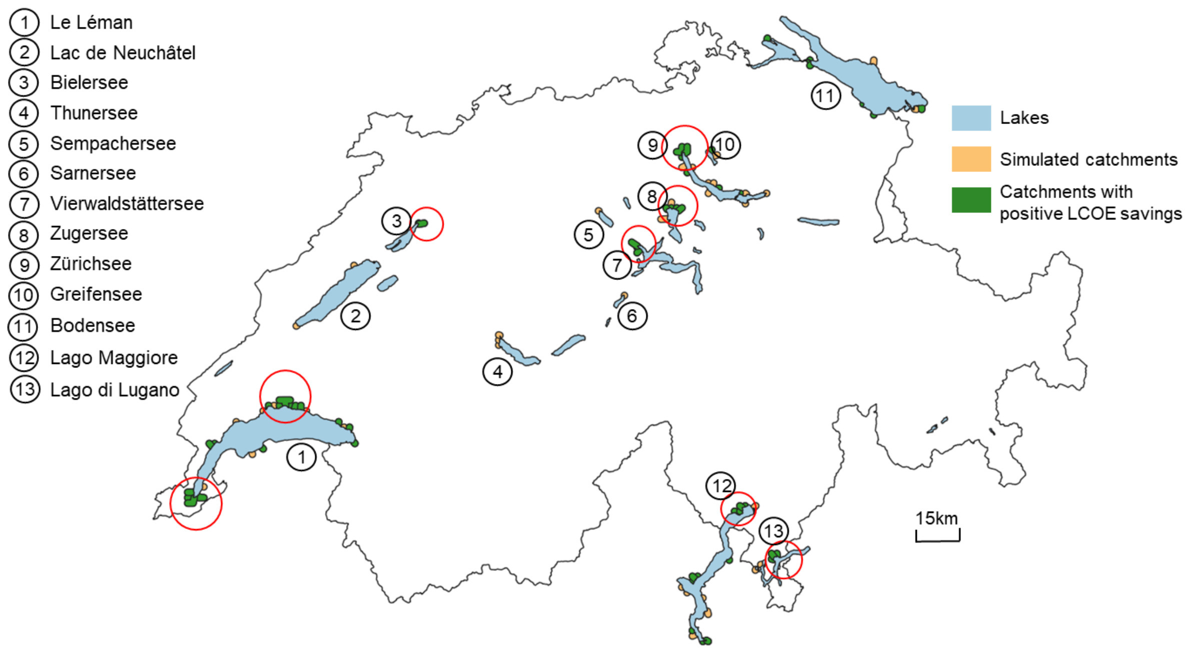


Figure 20: Catchments with positive cost savings (in green) and regions with clustered economic catchments (circled in red) in Switzerland.

3.2.2 Water temperature change

The temperature alteration ΔT of all the major lakes simulated are calculated and plotted against the LCOE saving with volumes indicated by the size of the dots of the scatter plot in Figure 21. The dots at the bottom right corner represents lakes with positive LCOE saving and low water temperature increase, whose volume are all above 1km³. The maximum temperature increase is at the lake Greifensee, which is 0.045°C. The rest stay below 0.03°C.

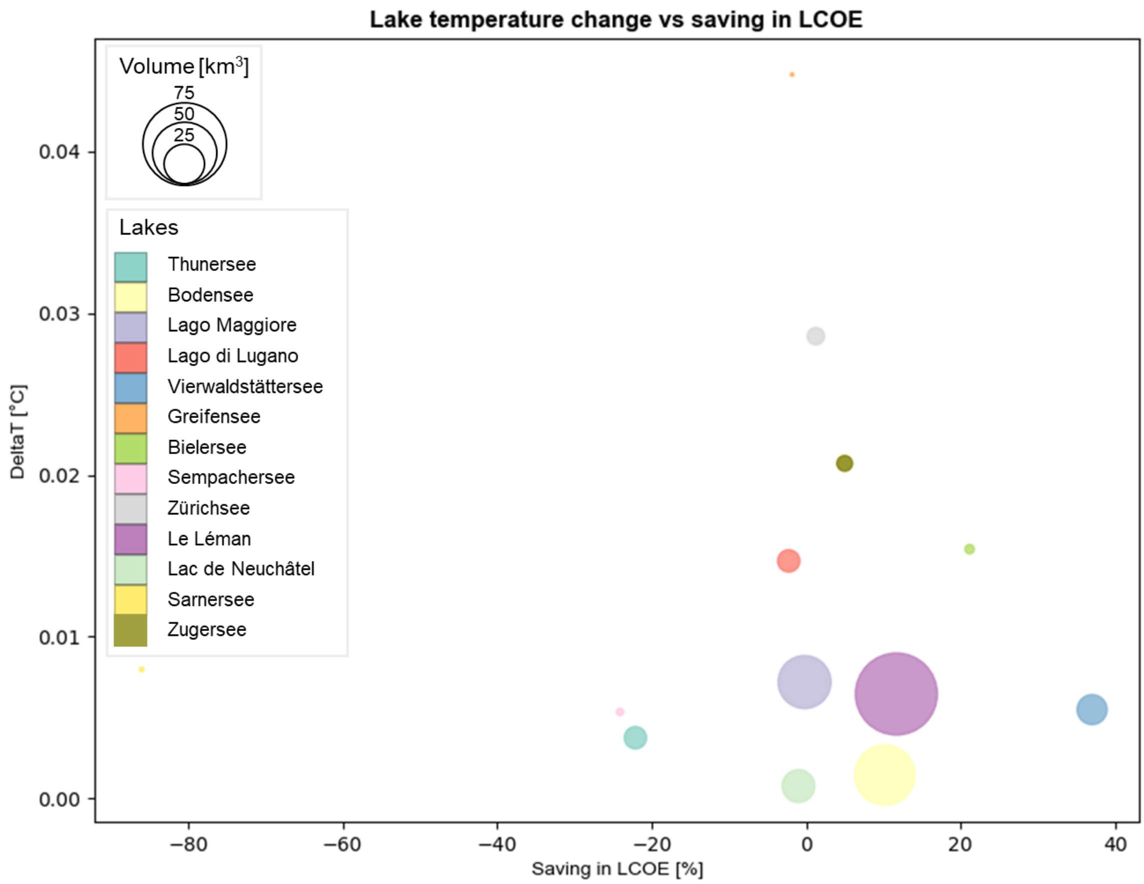


Figure 21: Temperature increase (DeltaT) of Swiss major lakes vs levelized cost savings.

4. Discussion

4.1 Case study on Greifensee

As shown in Table 2 and Figure 14, it is more economical to build a lake water district cooling network in the immediate vicinity (i.e. town Greifensee) of the lake. Further away towns (i.e. town Uster) would only become economically attractive if the cooling demand itself is much higher such that the demand density exceeds 1400kWh/m. The demand density directly affects the savings in LCOE. The energy savings reflects the amount of cooling energy demand, which is primarily linked to the size of the town/city. Although Uster is a bigger town than Greifensee and has higher energy demand, it fails to compensate for the further distance from the lake, which is critical for lake district cooling due to the high costs of piping.

According to Figure 15, under a lumped-mass assumption, the highest lake water temperature increase in summer is around 0.045°C, and the highest temperature is around 18°C. According to the Swiss regulation, the allowed maximum temperature increase in lakes and rivers is 1.5°C, and the maximum natural water temperature is 25°C (Waters Protection Ordinance 2021). These requirements apply after thorough mixing. The calculated results in this thesis are far below the legal requirements. Thus, the environmental impact of the lake district cooling system in the case of Greifensee can be treated as negligible. However, the results are optimistic due to the simple lumped-mass assumption of the lake.

4.2 All major Swiss lakes

As mentioned in Section 3.2.1, Figure 16 shows the decreasing trend of LCOE for district cooling with increasing lifetime, but the correlation is not linear due to the non-zero discount rate. With a higher discount rate, the decrease would become less steep, and vice versa. As the lifetime increases, the LCOEs of different catchments tend to get closer to one another. Theoretically, with an infinite lifetime, the LCOE of district cooling would become uniform for any catchment.

As seen from Figure 17, the LCOE of the district system is more sensitive to the change in the discount rate. If the discount rate is high, the future becomes less important. Thus, the high initial investment costs of district cooling in the present make it less economically attractive. District cooling would only be more economical in the majority of the catchments if the discount rate stays lower than 3%. As the discount rate increases, the range of LCOE for district cooling in different catchments increases considerably, indicating a more volatile system cost. On the other hand, decentralized chillers exhibit a more stable and reliable LCOE under a changeable discount rate. This difference between the two system costs results from their dependency on geographic features. District systems cost less when close to the lake and densely populated areas, while chillers usually cost the same regardless of the location.

Figure 18 shows that catchments with denser demands are economically and environmentally suitable for developing a lake water district cooling system. Catchments at Zurich and Geneva city centers have the highest savings in LCOE and energy consumption. These two cities are also the two most populated cities in Switzerland. Therefore, population and number of buildings could potentially have a strong correlation with both savings. Almost every lake has catchments with positive and negative cost savings in Figure 18. For catchments with negative cost savings, other incentives are necessary to build a lake district cooling network, such as climate change, change in assumed costs of system elements, policies, etc.

A strong correlation between demand density and LCOE savings is demonstrated in Figure 19, meaning the demand density is a good indicator of whether district cooling is economically beneficial in a catchment region. However, the threshold value of 1400kWh/m obtained from the results is only an approximation due to the simplified MST. A more realistic model of the MST on a building level would lead to a lower threshold value because of a longer piping network.

Figure 21 shows the sum of temperature change from all catchments of each lake versus its average LCOE saving. Lakes with bigger volumes (>1km^3) tend to have a positive saving in LCOE, and the temperature alteration of the lake water stays under 0.03°C, which is considered negligible as outlined in Section 4.1. As expected, big lakes with volumes bigger than 1km^3 are economically advantageous and environmentally friendly for developing a lake water district cooling system. However, as discussed in Section 4.1, the lumped-mass assumption gives an optimistic estimation of lake water temperature increase due to the large volumes. In practice, the temperature increase would be regional instead of lake-wise, and the value would be higher than the calculated results, depending on the mixing intensities of different lakes.

4.3 Limitations and future work

4.3.1 Building cooling energy demand calculation

The energy signature approach used for building cooling energy demand calculation is a simplified method that categorizes many different buildings into six main types. The building age is weighted averaged since there is no available information from OSM. The building level estimation method is not comprehensive enough, because many other building types are not considered, such as modern apartment buildings, which normally have five to seven floor levels. More data mining on building age and a more detailed estimation approach could improve the accuracy of the building energy demand calculation.

The simulation assumes a 100% energy reference area in each building. The energy reference area is defined as all actively conditioned areas, i.e. heated or cooled areas, of a building (Schluck, Streicher, and Mennel 2019). This assumption results in a more conservative estimation of the cooling demand since there is space such as hallways, stairwells, and balconies that do not require cooling. Further sensitivity analysis on cost savings regarding different percentages of cooled floor area can be done to examine whether the assumption of 100% is reasonable.

4.3.2 Synthetic network generation and planning

The economic index EI and its threshold for selecting economic demand points to include in the district network are subjectively chosen to match the location of major towns in the lake vicinity. More systematic selection criteria and a more comprehensive index could be developed to capture the major demands more accurately.

It was assumed in the analysis that inlets and pipes can be placed anywhere, as long as the distance is the shortest on the grid. However, in practice, this is not realistic. As indicated in Figure 13, the simulated piping network has errors in covering buildings with cooling demand. The inlet and pipe locations depend on the infrastructure on land. For example, inlets need to avoid shallow regions of the lake, and pipes need to follow existing pipelines or roads. More spatial constraints on pipes can be added for more accurate cost estimation.

4.3.3 Economic assessment

Apart from the pipe demand density, another potential factor that could influence the LCOE of a district cooling system is how scattered the buildings are around the lake. If many buildings are clustered together, district energy systems are advantageous due to their high efficiency and low average costs. An indicator/index on this building congregation is also worth exploring in future steps to examine whether there is a strong correlation between the average system costs of district cooling and building cluster.

The calculation of piping costs assumes a uniform unit cost per meter of pipe, which does not differentiate the cost between pipe to district and pipe in the district. For more realistic and accurate cost estimation, a method to determine the location of a distribution tower/center can be explored. Once the optimal location of the tower is obtained, the different costs for the main transport pipes to the district and smaller distribution pipes within the district can be applied. Moreover, the connection to individual households has not yet been considered, which means the overall LCOE of the district system is underestimated in the results. The costs of chillers are also underestimated since the renovation cost for installation in each household is not included. This renovation cost could potentially be higher than the installation cost itself because houses in Switzerland are not typically designed with heat pump integration.

The elevation height is not considered in this analysis. However, the elevation change is crucial to the costs of pumping. If the elevation gain from the deep lake intake to buildings is high, the pumping costs would increase substantially due to the water head loss. Thus, an elevation model could be included for a more accurate pump costs estimation.

The population distribution is assumed to be constant during the lifetime of the district cooling system. Since the assumed lifetime is long (60 years), there is a possibility that towns might grow or shrink. In the case of a growing population, the cooling energy demand would increase, meaning the cost savings of district cooling and lake water temperature change would also increase. On the other hand, if the population shrinks, the district cooling system would become less cost-effective. Therefore, the population trend could be another influencing factor for the levelized costs of the district cooling networks.

Big lakes and lakes with major lakeside cities are more economically and environmentally suitable for developing a lake water district cooling network. However, for the big lakes at the Swiss border, buildings outside of Switzerland are also included. The costs of pipes, chillers, pumps, and electricity can vary significantly in different countries. Thus, it is more reasonable to keep the simulation results on a catchment level instead of the whole lake so that catchments outside of Switzerland can be excluded.

4.3.4 Lake model

The modelling of lake water temperature uses a very simplified assumption where the lake is treated as a lumped mass with uniform temperature across the whole water body. A more complex and comprehensive model that takes into account lake stratification and heat exchange between different layers will be beneficial for understanding which depth is optimal for placing the inlet and outlet of the main transport pipes. An example would be the general lake model developed by the University of Western Australia, which takes into account surface energy balance, stratification, vertical mixing, as well as inflows and outflows (Hipsey, Bruce, and Hamilton 2014).

The weather record for each lake is from the closest weather station. Although the stations in high altitudes that are above 1000m have been avoided, the elevation of each lake is unknown. For a mountain lake, the weather record from the nearby mountain weather station would be more accurate. However, the elevation of lakes has not yet been taken into account in this thesis.

The volumes of the lakes that have no data available on WikiData are estimated by assuming a cone geometry. The depth is estimated to be half of the radius with a maximum value of 30m. This estimation is simplified without validation. In this thesis, all the lakes with catchments have volume data from WikiData. However, for further upscaling, there will be lakes without readily available measurements. A more accurate volume estimation method would be necessary for the water temperature modelling.

Climate change is not considered in this study. However, the warming up of lakes due to climate change would affect the outlook of lake water district cooling networks. According to an article on Nature, the surface and bottom temperatures of lakes are projected to increase by 0.9 and 0.48°C respectively by the end of the 21st century under the optimistic Representative Concentration Pathway (RCP2.6) (Råman Vinnå et al. 2021). A Representative Concentration Pathway (RCP) is a greenhouse gas concentration trajectory adopted by IPCC. The coefficient of performance of the district cooling network would be affected by the lake warming up due to the change in temperature of the heat sink. A more complicated model that considers climate change would provide more convincing results on the advantages of district cooling owing to its long lifetime.

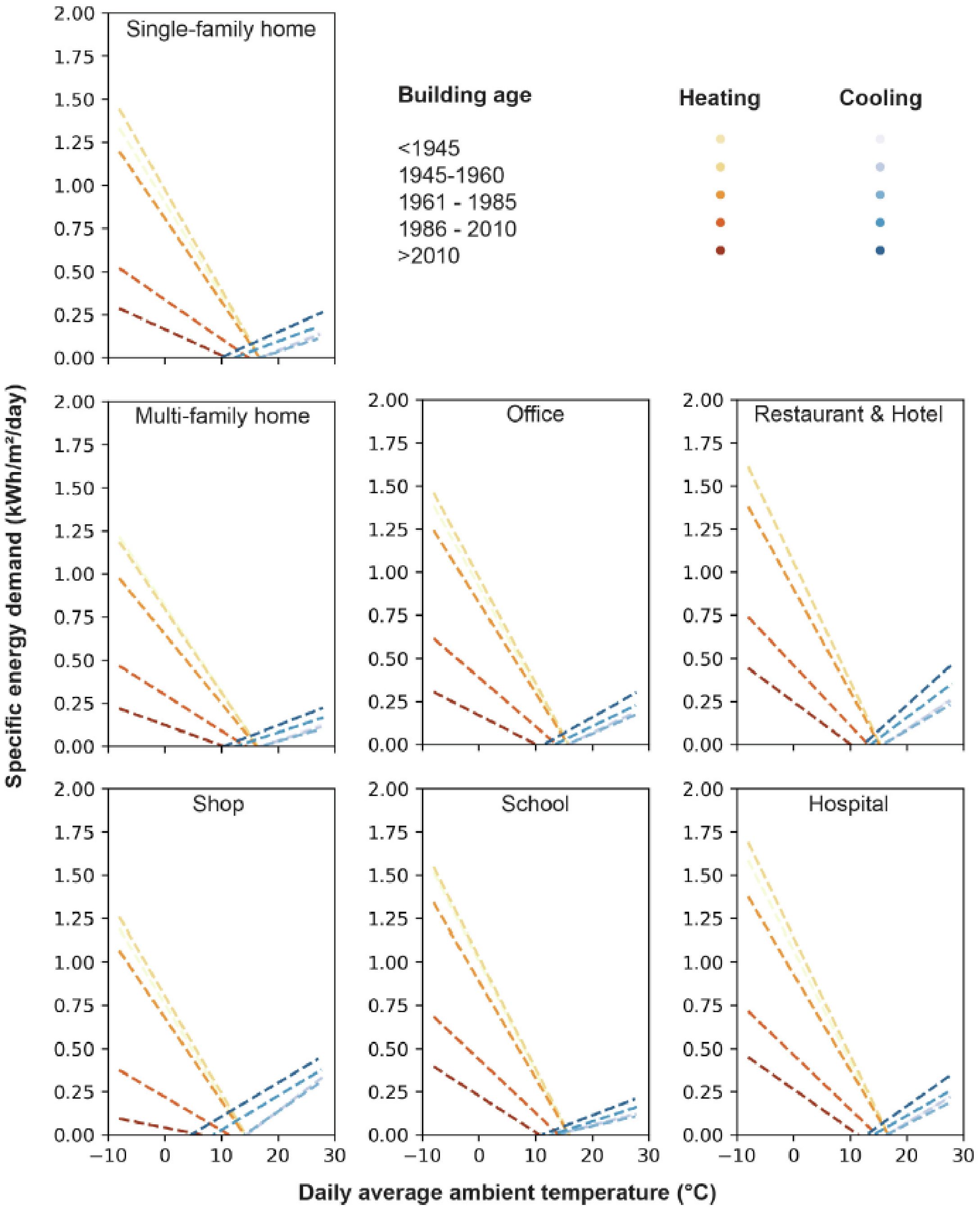
5. Conclusion

Spatial analysis with open-source data was developed to assess the techno-economic feasibility of district cooling systems with lake water in Switzerland. After calculating the cooling demand of each building, determining the number of cooling districts, and planning the corresponding piping network, the LCOE, energy consumption, and lake water temperature alteration of each catchment were determined with an assumed lifespan and discount rate. The results were then compared to that of a decentralized cooling method with air-source heat pumps with varying lifetime and discount rates.

Regarding the economic aspect, the district cooling system becomes economically more attractive with a longer lifetime and lower discount rate. However, the costs of the district system are more sensitive to the change in discount rate than that of decentralized chillers. On a catchment level, catchments with demand density per unit pipe length above 1400kWh/m save both LCOE and energy consumption. On a lake level, the temperature alteration of all the simulated lakes remains negligible. Lakes with big volumes (> 1km^3) having major cities nearby tend to show the highest potential for developing district cooling networks.

The simplifying assumptions in this analysis can underestimate the system costs and lake temperature increase. More comprehensive modelling in catchment selection, district network connection, and lake stratification is needed for more accurate results.

Appendix



Appendix 1: Used energy signatures for six main building types: SFH, MFH, office, shop, school, hospital (Eggimann et al. 2022).

Appendix 2: Table of building age distribution in Switzerland (Eggimann et al. 2022).

Building age	Percentage [%]
<1945	37.5
1945 – 1960	10.0
1961 – 1985	25.0
1986 – 2010	22.5
>2010	5.0

Reference

Climate.OneBuilding.Org. 2021. “Switzerland Climate Data.” Retrieved (https://climate.onebuilding.org/WMO_Region_6_Europe/CHE_Switzerland/index.html).

Eawag. 2021. “Hydrodynamic Model - Greifensee.” Retrieved (http://meteolakes.ch/#!/hydro/greifensee).

Eggimann, Sven, Natasa Vulic, Martin Rüdisüli, Robin Mutschler, Kristina Orehounig, and Matthias Sulzer. 2022. “Spatiotemporal Upscaling Errors of Building Stock Clustering for Energy Demand Simulation.” *Energy and Buildings* 258:111844. doi: 10.1016/j.enbuild.2022.111844.

Eriksson, Martin, Jan Akander, and Bahram Moshfegh. 2020. “Development and Validation of Energy Signature Method – Case Study on a Multi-Family Building in Sweden before and after Deep Renovation.” *Energy and Buildings* 210:109756. doi: 10.1016/j.enbuild.2020.109756.

European Energy Efficiency Platform. 2021. “Typical Meteorological Year (TMY).” *European Energy Efficiency Platform (E3P)*. Retrieved (https://e3p.jrc.ec.europa.eu/articles/typical-meteorological-year-tmy).

Ferrari, Joseph. 2021. *Introduction to Electric Utilities and How They Plan for the Future*.

Gaudard, Adrien, Alfred Wüest, and Martin Schmid. 2019. “Using Lakes and Rivers for Extraction and Disposal of Heat: Estimate of Regional Potentials.” *Renewable Energy* 134:330–42. doi: 10.1016/j.renene.2018.10.095.

GlobalPetrolPrices. 2021. “Switzerland Electricity Prices.” Retrieved (https://www.globalpetrolprices.com/Switzerland/electricity_prices/).

Hipsey, M. R., L. C. Bruce, and D. P. Hamilton. 2014. *General Lake Model v2.0 ß - Oct 2014*.

International Energy Agency. 2018. “‘The Future of Cooling Opportunities for Energy- Efficient Air Conditioning’International Energy Agency Website: Www.Iea.Org, 2018.”

Khosla, Radhika, Nicole D. Miranda, Philipp A. Trotter, Antonella Mazzone, Renaldi Renaldi, Caitlin McElroy, Francois Cohen, Anant Jani, Rafael Perera-Salazar, and Malcolm McCulloch. 2021. “Cooling for Sustainable Development.” *Nature Sustainability* 4(3):201–8. doi: 10.1038/s41893-020-00627-w.

Kuyuk, Ali Fahrettin, Seyed Ali Ghoreishi-Madiseh, Agus P. Sasmito, and Ferri Hassani. 2019. “Designing a Large-Scale Lake Cooling System for an Ultra-Deep Mine: A Canadian Case Study.” *Energies* 12(5). doi: 10.3390/en12050811.

Mosteiro-Romero, Martín, Emanuel Riegelbauer, Shanshan Hsieh, and Arno Schlueter. 2020. “District-Scale Lake Water Free Cooling in Zurich, Switzerland: System Performance Simulation and Techno-Economic Feasibility.” *33rd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS 2020), Osaka, Japan, 29 June – 3 July 2020* 1–4(June):1781–91. doi: 10.3929/ethz-b-000426953.

Murray, Portia, Kristina Orehounig, David Grosspietsch, and Jan Carmeliet. 2020. “A Comparison of Storage Systems in Neighbourhood Decentralized Energy System Applications from 2015 to 2050.” *Applied Energy* 231(August 2018):1285–1306. doi: 10.1016/j.apenergy.2018.08.106.

OpenStreetMap. 2021a. “OpenStreetMap.” *Wikipedia*. Retrieved (https://en.wikipedia.org/wiki/OpenStreetMap).

OpenStreetMap. 2021b. “Overpass API.” Retrieved (https://wiki.openstreetmap.org/wiki/Overpass_API).

Råman Vinnå, Love, Iselin Medhaug, Martin Schmid, and Damien Bouffard. 2021. “The Vulnerability of Lakes to Climate Change along an Altitudinal Gradient.” *Communications Earth & Environment* 2(1):2–11. doi: 10.1038/s43247-021-00106-w.

Rezaie, Behnaz, and Marc A. Rosen. 2012. “District Heating and Cooling : Review of Technology and Potential Enhancements.” *Applied Energy* 93:2–10. doi: 10.1016/j.apenergy.2011.04.020.

Schluck, Thomas, Kai Nino Streicher, and Stefan Mennel. 2019. “Statistical Modelling of the Energy Reference Area Based on the Swiss Building Stock.” *Journal of Physics: Conference Series* 1343(1):0–6. doi: 10.1088/1742-6596/1343/1/012031.

Waters Protection Ordinance. 2021. “Waters Protection Ordinance.” Retrieved (https://www.fedlex.admin.ch/eli/cc/1998/2863_2863_2863/en).

Wikidata. 2021a. “Wikidata:Pywikibot - Python 3 Tutorial/Data Harvest.” *Wikidata*. Retrieved (https://www.wikidata.org/wiki/Wikidata:Pywikibot_-_Python_3_Tutorial/Data_Harvest).

Wikidata. 2021b. "Wikidata." *Wikidata*. Retrieved (https://www.wikidata.org/wiki/Wikidata:Main_Page).

Wikipedia. 2022. "Air Source Heat Pump." Retrieved (https://en.wikipedia.org/wiki/Air_source_heat_pump).

Williams, G. P. 1963. "NRC Publications Archive Archives Des Publications Du CNRC Concrete Cl."

Zvoleff, Alex, Ayse Selin Kocaman, Woonghee Tim Huh, and Vijay Modi. 2009. "The Impact of Geography on Energy Infrastructure Costs." *Energy Policy* 37(10):4066–78. doi: 10.1016/j.enpol.2009.05.006.