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The potential of lake-source district heating and cooling for European buildings

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ABSTRACT

Lake-source thermal district networks can efficiently supply heating and cooling to buildings and thus save energy and CO_2 emissions. However, it remains unclear to which degree they are a sustainable alternative at a larger geographical scale. An evaluation of the potential of developing technically and economically feasible lake-source district systems in Europe was performed in this study, with an integrated spatial explicit techno-economic assessment that accounts for different boundary conditions, such as electricity price, CO_2 price and climate change. The feasibility of covering building energy demand near lakes was found to be particularly sensitive to the relationship between capital costs from network design and operational costs from heat pumps, associated electricity consumption and CO_2 emissions. Results suggest a European techno-economic potential of 1.9 TWh/y considering only direct cooling and 11.3 TWh/y if thermal networks supply both direct heating and cooling by heat pumps. Respective electricity savings are 0.36 TWh/y and 0.78 TWh/y. An estimated 17% of the cooling demand near European lakes can thus be covered by viable cooling-only lake-source systems. For combined systems, the viable potential is estimated to be 7% of the total combined heating and cooling demand. Lake-source district systems are found to be particularly promising for Italy, Germany, Turkey and Switzerland. The integration of lake-source thermal networks should rarely lead to severe lake water temperature alteration and therefore not limit the techno-economic potential. The introduced methodology allows for a combined evaluation of technological, ecological and economic boundary conditions for using lakes as a source for district heating and cooling. Thereby, a more realistic estimation of their potential implementation becomes possible, enabling informed energy planning for central or decentral system configurations.

1. Introduction

Lakes are an effective energy source to heat and cool buildings [1]. In Europe, lakes commonly have a deep-water temperature lower than the ambient air in summer, when cooling is required, and a higher temperature during several winter periods, especially in heating-dominated countries. Water from deep lake layers can be employed as a source for increasing the operational efficiency of heat pumps for heating and as a direct source of cooling (free cooling) to save CO_2 emissions for operating buildings [2]. Buildings account for 10% of global emissions [3] and reducing their energy consumption is essential for decarbonizing current energy systems. While in Europe emissions from heating dominate, efficient cooling is gaining importance due to a warming climate [4]. Expanding district thermal network systems is part of the European energy strategy [5]. Integrating lakes in these systems can increase the attractiveness of district systems, especially when they are compared to individual heat pumps in buildings.

Whether a centralized system (i.e. district network system) can outperform a decentralized system generally remains to be established for lake-source district heating and cooling. However, the challenge of determining the optimal degree of centralization applies to different infrastructure systems such as wastewater [6], water [7], electricity

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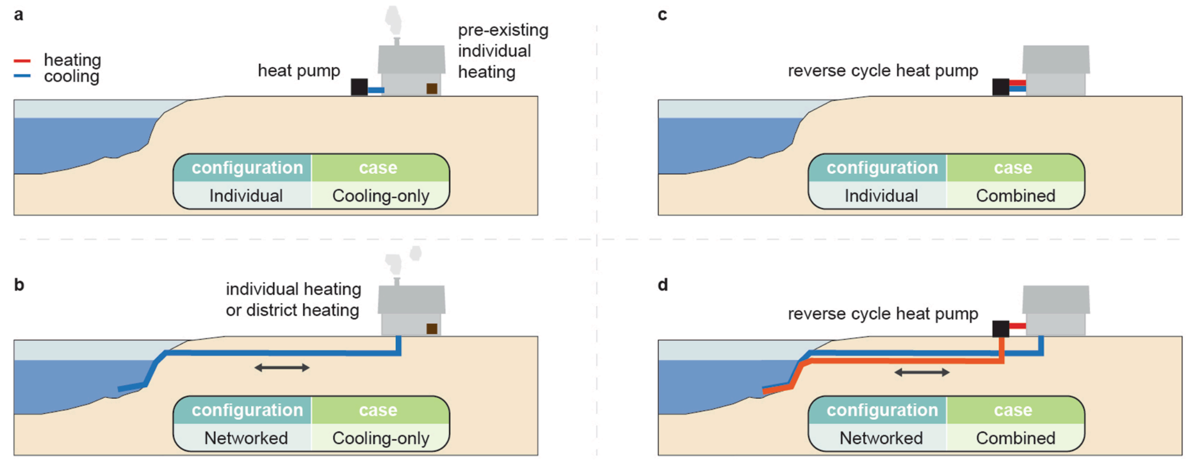

Fig. 1. System configurations with (Networked) and without (Individual) lake-source thermal networks, providing only cooling (Cooling-only) or both heating and cooling (Combined). For Cooling-only (a,b), the heating system is assumed as given and is not part of the techno-economic comparison. Cooling is provided directly in the Networked configuration (a) or via a heat pump in the Individual configuration (b). In the Combined case (c,d), both heating and cooling are provided through a reverse cycle heat pump.

generation [8] or district heating [9] and depends on various exogenous factors. From an economic point of view, the system's lifetime and its costs, electricity prices or costs associated with CO_2 emissions are important. District systems such as thermal networks have, for example, large up-front investment costs, which can make projects fail [10]. From an ecological point of view, the impact on the lake temperature from exchanging heat with lakes is relevant. The implementation of lake-source thermal networks is thus constrained by costs, the availability of large lakes, the thermal response of the water bodies and the availability and spatial distribution of building energy demand near lakes.

So far, the techno-economic feasibility of lake-source systems has only been explored for individual case studies in different geographies, for example in Canada [11], Switzerland [12] or the United States [13]. However, no integrated analysis has been undertaken at national or European scale. Additionally, studies on the anthropogenic impact on the heat budget of lakes are rare [14], and few studies assessed the potential of using lakes for heat extraction or disposal [15]. Notable exceptions are the quantification of heat demand for district lake-source heating in Denmark [16] or the comparison of the amount of heat that can be extracted or disposed to Swiss lakes based on admissible lake temperature deviation [17]. Studies that evaluated opportunities for lakes to cover buildings' thermal demand typically lack an explicit spatial focus and do not model the required networks. Some studies considered ecological constraints [17], but omitted the techno-economic feasibility of thermal networks in comparison to individual heating and cooling alternatives. Introducing spatial-techno-economic constraints in evaluating the potential of lake-source district networks enables going beyond the quantification of the resource or demand potential, and allows more accurately estimating the role that lakes could play in supporting the provision of sustainable heating and cooling.

The overall ambition of this work is to take these major shortcomings as a starting point for assessing the potential lake-source district systems. The goal is to perform a combined exploration of technological, ecological and economic boundary conditions to evaluate the potential of lake-source district systems across Europe. Such an evaluation is not only important for obtaining more genuine and spatial explicit estimations of which buildings can be efficiently served by lake-source systems today, but also in the future, under changing future climate or cost scenarios.

2. Methods

The introduced assessment (cf. Supplementary Information (SI) Note A) of different system configurations (Section 2.1) relies on publicly available data sources (Section 2.2) and requires combining different methodological steps: building heating and cooling thermal energy demand is calculated (Section 2.3), thermal networks are synthetically simulated and evaluated (Sections 2.4-2.7), and the thermal response of lakes is modelled (Section 2.8).

2.1. System configuration

As a first step, different lake-source district system configurations are defined (Fig. 1). A lake-source *Networked* system configuration, where all the buildings are connected to a thermal district network connected to a lake, is compared to an *Individual* configuration, where each building relies on an air-source reverse-cycle heat pump instead, that covers both heating and cooling. This analysis is performed under different electricity costs, interest rates and CO_2 prices, exploring the impact of these boundary conditions. The performance is analysed for the case where the system is meeting only cooling demand *(Cooling-only)* or covering both heating and cooling demand *(Combined)*. Heating-only is ignored, as a heat pump would be anyway required for lake-source heating, and this would be a less attractive solution than the Combined case by design. For each simulated district network, the techno-economic feasibility is assessed by calculating the capital and operational costs, which are conflicting objectives when minimizing the cost of these networks [18].

2.2. Spatial data acquisition

Lakes with a top surface larger than 400 ha were downloaded from OpenStreetMap with the Overpass application programming interface [19]. The lake volumes were queried from WikiData, and in case of missing data, this information was taken from the global lake dataset HydroLAKES [20]. Spatial information on buildings and streets within a 3 km buffer from each lake was obtained from OpenStreetMap as well. The building-conditioned floor area, used for space heating and cooling demand calculations, was derived by multiplying the building footprint by the number of floors. As the number of floors attribute is not always available for OpenStreetMap buildings, an estimation method based on building type, footprint area and surrounding buildings was introduced for buildings missing this attribute. Buildings were then classified into

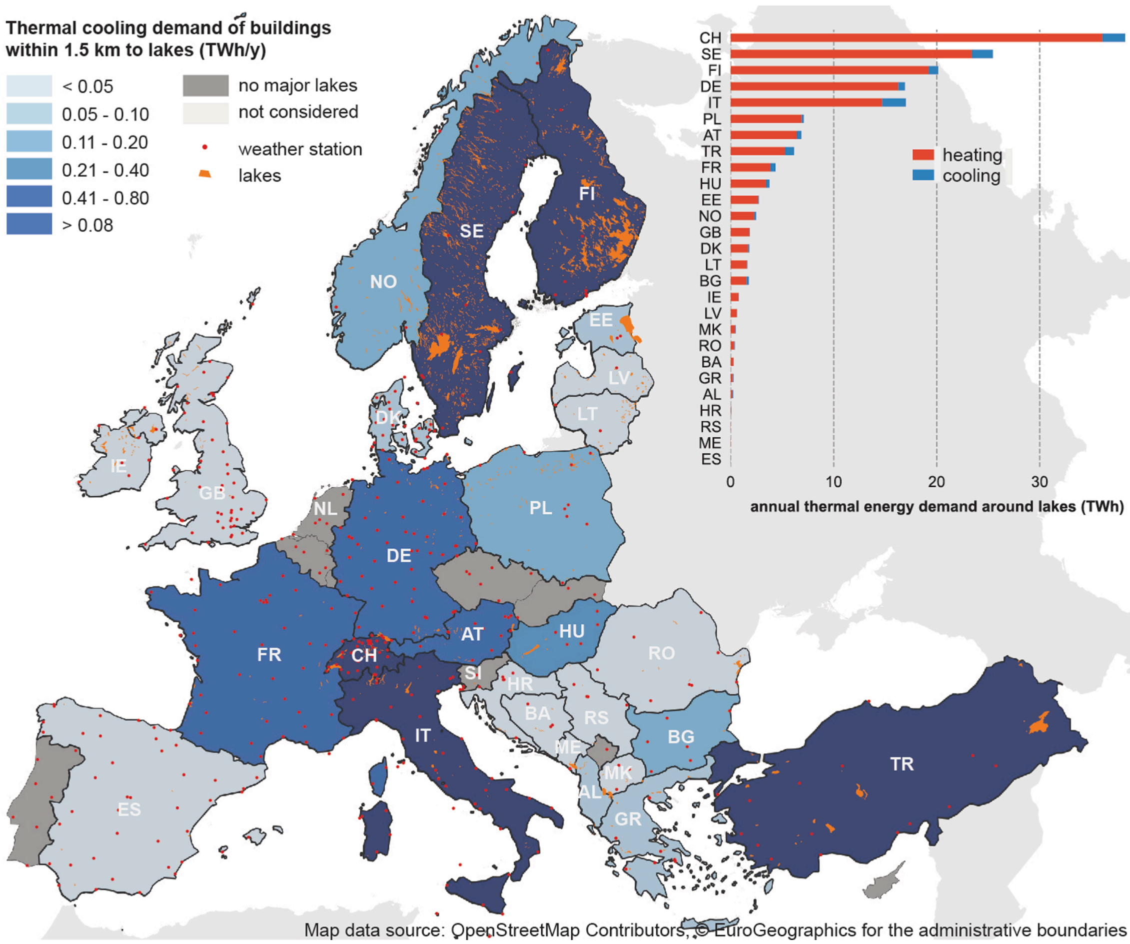

Fig. 2. European lakes and thermal energy demand of buildings around lakes. Lakes with a lake surface larger than 400 ha are shown. The cooling and heating demand of all buildings within a 1.5 km reach of lakes was calculated based on the building floor area, average daily ambient temperatures of the closest weather station and country-specific energy signatures.

single- and multi-family homes, offices, shops, schools and hospitals. Detailed information on the building type classification and floor level estimation is provided in SI Note B. Historic and future weather files with an hourly resolution were obtained from Meteonorm [21] for the building energy demand simulation. Typical meteorological years are used, which are a collation of a set of meteorological data, where for each month, meteorological data have been selected from a historical year that was considered the most typical for each month. Each lake and corresponding buildings were associated with the closest weather station (depicted in Fig. 2), whilst weather stations above 1′000 m above sea level were not considered to avoid spatially interpolating data with stations at a high altitude, which would need to be corrected for the influence of altitude [4].

2.3. Buildings heating and cooling demand calculation

A large number of buildings needed to be analysed to obtain the thermal demand of European buildings potentially coverable by lakes. The demand calculation was achieved by applying a streamlined approach requiring minimal data inputs using energy signatures [22]. Energy signatures are regression models which set into relation outdoor climatic variables with a building's specific energy demand, which is typically related to the building age and type [23]. To derive the total demand per building, each building's energy signature is multiplied by the conditioned floor area and outdoor temperature. A comprehensive energy signature database from Switzerland [24] was adapted to estimate the signatures of buildings located in other countries according to country-specific physical building properties. We rely on OpenStreetMap to obtain the building geometry and attributes such as building type. OpenStreetMap was shown to contain accurate building footprints and provides data for entire Europe. As OpenStreetMap is user-generated, the completeness of buildings and some attributes differs across countries and may be incomplete. However, neither the exact positioning nor errors in terms of geometry alter the overall results, and the building type and building-level information are estimated based on rule-based algorithms to obtain complete datasets (see full explanation in SI Note B). Country-specific building daily heating and cooling demand were calculated based on the energy signatures method presented in Eggimann et al. [24], fitting linear relationships from detailed simulations results performed in EnergyPlus. These simulations to obtain the energy signatures were performed with a tool [25] based on EnergyPlus [26] for batch simulations employing Swiss building archetypes, calculating daily average energy demand as a function of ambient temperatures for different building types and building age classes. As these energy signatures refer to Swiss buildings, they were generalized to estimate the energy signatures of buildings in the rest of Europe. This was achieved by making a curve fit to relate the coefficients of the signatures heating and cooling lines to the R-value of the walls of the building. To calculate the signatures in other European countries, the wall R-values for typical buildings with different years of construction were sourced from the European TABULA database [27] (SI Note C). An average energy signature for a defined building stock in a country is then calculated by assuming the same age distribution of buildings as in Eggimann et al. [24]. As building age information is not readily

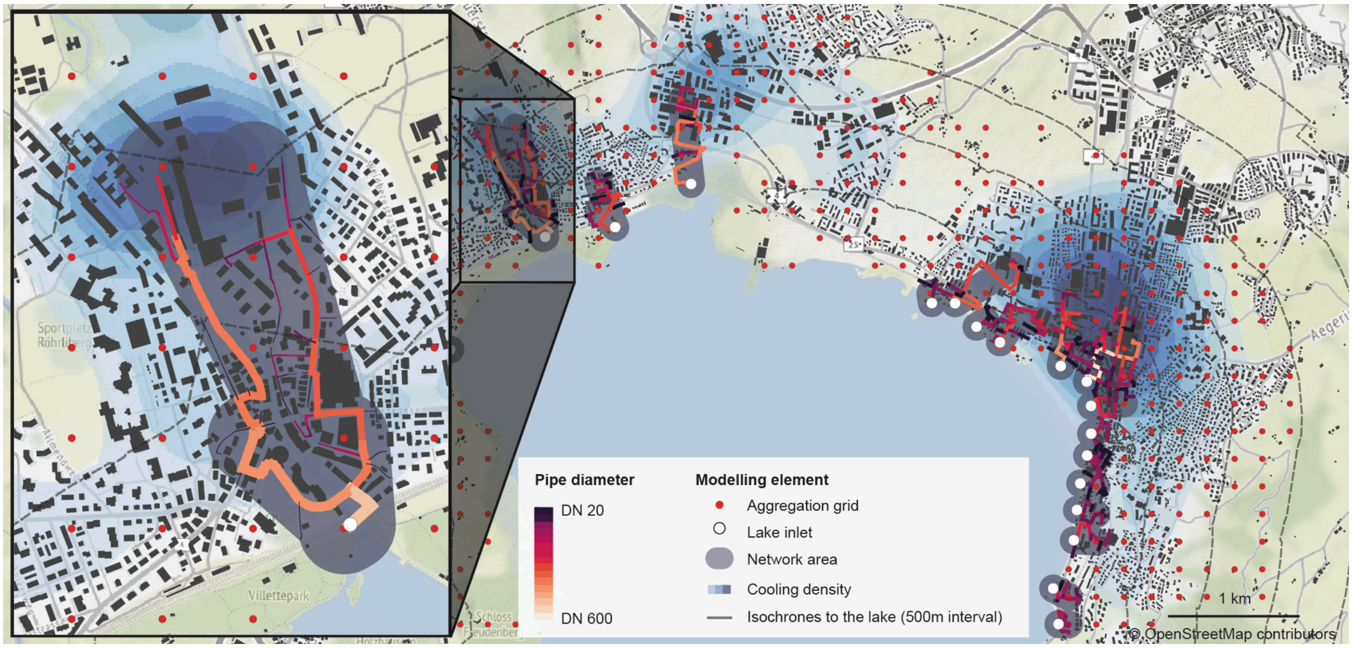

Fig. 3. Examples of generated lake-source thermal networks of different sizes. The network layouts are generated based on aggregated buildings' cooling demand and the street network layout for a lake in Switzerland (Zugersee).

available across Europe, the simplifying assumption of equal age class distribution across Europe is made. Detailed age distribution information could improve the age-class weighted energy signature, however, uncertainties from relying on OpenStreetMap for the building type and energy reference area calculation pre-dominates uncertainties related to building age distribution. Even though the energy signature method is simplified and does not account for detailed factors such as shading, exposition or microclimatic properties, they provide a surrogate model for fast energy demand estimation. Relying on the building classification result, thermal energy demand was calculated for all single-family homes, multi-family homes and service buildings using the total floor area of the building dataset. A factor of 0.9 was assumed to convert the total floor area to the conditioned reference area. Industrial energy demands were ignored, even though in case a building is not identified as an industrial building in OpenStreetMap, the building and corresponding demands are included.

2.4. Identification of techno-economic potential district network regions

Several steps were required to identify, design and evaluate the techno-economic feasibility of thermal districts (SI Note D). First, potential sites were identified with an economic index, calculated for a grid with aggregated energy demands, which relates obtained thermal energy demand densities and their distance to the lake, providing a first estimate of the relationship between the cost of the network infrastructure and the potential energy and consequent cost savings of a lake-source system. Synthetic district thermal networks were generated with a three-step process, i) identification of areas suitable for district heating and cooling networks using a lake as a source, ii) generation of detailed piping network considering local spatial constraints and iii) estimation of the system costing and buildings' heating and cooling demand covered by the centralized system. To identify the areas where lake heating and cooling could be a viable solution, the heating and cooling demand of all the buildings in the considered distance from the lake (1.5 km) were aggregated on a grid with a resolution of 200 m. An approximate techno-economic potential of the installation of a thermal network was then estimated with the help of a proxy indicatory (*EI*) as presented in Eq. (1):

$$EI = \frac{c_{el} \times E_c \times (\varepsilon_c + \varepsilon_h)}{\overline{c}_{pipe} \times d \times \alpha} \quad (1)$$

where c_{el} is the cost of electricity, d is the distance of the considered raster cell to the lake inlet, E_c is the aggregated thermal annual cooling demand of all the buildings within the considered raster cell, $\overline{c}_{pipe}$ is the average pipe network cost per meter of distance to the considered lake, α is a coefficient representing the spatial layout of buildings, ε_c and ε_h are coefficients that represent the electrical energy saved per unit of thermal energy in heating and cooling operations when comparing the lake-source heating and cooling network to decentralized reverse-cycle heat pumps using ambient air as a source. These coefficients are calculated for each lake based on air and lake temperature values for cooling and heating (see energy efficiency ratio calculation). This proxy provides a first indication of the comparative cost of a lake-source district thermal network versus a conventional approach employing air-source reverse-cycle heat pumps, considering only the expected reduction in yearly operational costs compared to the approximate cost of a network covering the selected area. The network is sized to meet the cooling demand and it is assumed that an equivalent amount of heating can be covered. To select the most promising grid points and generate a potential district thermal network, a threshold value (EI^*) was used. In this study, the average cost of the piping per meter distance from the lake $\overline{c}_{pipe}$ was assumed to be equal to 2000 €/m with an α of 0.5, and the value of EI^* is set to be equal to 0.02, resulting in a break-even point between the two approaches in approximately 50 years. A district network region was then generated for each selected grid cell by starting from the pixel centroids closest to the lake. The pixel centroids are connected to the closest point of the lake by a straight line, i.e. the lake inlet. A buffer polygon with a buffer distance of half the raster resolution is then applied along this line. In case the lake is further away than another potential pixel centroid, the same process is repeated but with connecting and merging the pixel centroid to the closest pixel centroid. If lake inlets are too close (here 130 m) to another lake inlet point, the network regions are merged to prevent parallel lake inlets. The entire procedure to generate the district network regions is schematically visualized in SI Note E.

2.5. District thermal network design

For each identified potentially viable district neighbourhood, a minimum-spanning tree was applied on the street network to connect all buildings to a lake inlet with minimum pipe distance. Demands were aggregated along the network to derive norm pipe diameters and costs based on the peak cooling demand. Detailed thermal networks are generated from the demand of all buildings falling inside the identified network region that make up a thermal network with a maximum norm pipe diameter of DN 1200. In case the available cooling demand within a network region exceeds the maximum pipe diameter, the buildings are iteratively removed from the network region, starting from the building most distant to the lake until the maximum demand is reached. Building demand is first assigned to the street network. All street network nodes with demands are then connected with a minimum spanning tree to approximate the required network distance (see Fig. 3 for example networks). The cumulated heating and cooling demands were then calculated for each network segment according to the network flow. All pipes forming part of the fringe of the networks with a smaller annual heating or cooling demand than 1 GJ/m were removed to exclude the connection of isolated buildings with a small energy demand [28]. The piping diameter of each branch of the network was then sized considering the peak heating and cooling demand and a design temperature difference of the network when heating or cooling, whichever would result in a larger pipe diameter. More information on this process is provided in SI Note E. A cost was assigned to each network section based on the branch length and diameter, using literature sources for piping prices [29], which are scaled according to comparative price levels for each country [30]. Total system costs were then calculated by summing individual network segment costs.

2.6. Performance and economic evaluation of the identified lake-source thermal networks

After establishing the network properties, lake temperatures were simulated at a 6-hour resolution to calculate the efficiency of the Networked configuration and the impacts of the heat injection and extraction on lake water temperature. The heat budget of lakes was calculated using a lumped capacitance model with either one or two temperature nodes depending on the presence of stratification. Lakes with a simulated freezing duration longer than one month were ignored, even though water extraction is technically still possible if only the top surface layer freezes. The Networked and Individual system configurations were then compared with each other, estimating capital and operational costs in both cases and annualizing costs with the expected lifetimes of the equipment employed [31]. To assess the techno-economic potential of the identified thermal networks, two energy supply cases (Cooling-only and Combined) and two configurations are introduced to serve the same buildings (Fig. 1). The introduced network configurations are Networked and Individual, where the same buildings are heated and cooled either by a lake-source thermal network system for the Networked configuration or by individual reverse-cycle heat pumps for the Individual configuration. The lake-source thermal network is assumed to provide cooling directly without a heat pump. When the Combined supply type is considered, heating is delivered using the lake water as a source for a heat pump that provides a temperature lift to the required space heating temperature. In the Networked configuration, the pumping energy is assumed as 3% of the thermal energy delivered to the buildings [32]. In the Individual configuration, reverse-cycle heat pumps provide both the required heating and cooling using the ambient air as a source.

The costing of each system configuration comprises capital expenditure costs (capex), which, for the Networked configuration, include the piping and inlet costs in the Cooling-only case and adds the heat pump costs in the Combined one (Eqs. (2)–(3)):

$$capex_{netw}^{cool} = c_{inlet} + \sum\nolimits_{j=1}^{n_p} c_{pipe,j}^{DN} \times L_{pipe,j}^{DN} \quad (2)$$

$$capex_{netw}^{combined} = c_{inlet} + P_h^{max} \times c_{HP} + \sum\nolimits_{j=1}^{n_p} c_{pipe,j}^{DN} \times L_{pipe,j}^{DN} \quad (3)$$

Where j are the possible n_p norm diameters for the pipes, c_{pipe}^{DN} are the cost of piping as a function of norm diameter, L_{pipe}^{DN} the total length of pipes per norm diameter, c_{inlet} are the investment costs of a single lake inlet (assumed to be € 3 million) [12], c_{HP} the cost of the heat pump per kW thermal to supply the heating peak power P_h^{max}. For the Individual configuration, the capital expenditure comprises only the cost of the heat pumps, which are sized on the peak cooling demand for the Cooling-only case, and on the maximum between the peak heating and cooling demand for the combined case (Eqs. 4–5).

$$capex_{ind}^{cool} = P_c^{max} \times c_{HP} \quad (4)$$

$$capex_{ind}^{combined} = max\{P_h^{max}, P_c^{max}\} \times c_{HP} \quad (5)$$

The heat pump-related installation and system costs are sourced from literature [33]. The required thermal power is determined by the highest daily power demand cooling throughout the year and employing peak factors to estimate the intra-day peak. The capital costs of the different system components and total replacement costs are converted to annuities, representing uniform annual cash flows considering a discounting rate (SI Note H). Operating costs (opex) consist of the electricity used by the system to supply the thermal demand required by the buildings (E_c and E_h for cooling and heating, respectively), and are a function of the Energy Efficiency Ratio (EER) of the equipment. In the Networked configuration, when the Cooling-only case is considered, the cooling demand of the district is entirely met by the lake, and the EER only includes the consumption of the circulation pumps (Eq. (6)).

$$opex_{netw}^{cool} = \sum\nolimits_{i=1}^{365} \frac{E_{c,i}}{EER_{c,i}^{netw}} \times c_{el} \quad (6)$$

When considering the Combined case, electricity is required for cooling as well as heating. However, as the system is sized on the cooling demand, the entire heating demand might not be met. Consequently, a portion of the heat is assumed to be extracted by the lake (E_h^{lake}), constrained by the district system, and the remainder from the air (E_h^{air}) as shown in Eq. (7).

$$opex_{netw}^{combined} = \left(\sum\nolimits_{i=1}^{365} \frac{E_{h,i}^{lake}}{EER_{h,i}^{netw}} + \sum\nolimits_{i=1}^{i=365} \frac{E_{h,i}^{air}}{EER_{h,i}^{ind}} \right) \times c_{el} + \sum\nolimits_{i=1}^{365} \frac{E_{c,i}}{EER_{c,i}^{netw}} \times c_{el} \quad (7)$$

Opex for heating and cooling for the individual configuration is given in Eq. (8) and Eq. (9):

$$opex_{ind}^{cool} = \sum\nolimits_{i=1}^{365} \frac{E_{c,i}}{EER_{c,i}^{ind}} \times c_{el} \quad (8)$$

$$opex_{ind}^{combined} = \sum\nolimits_{i=1}^{365} \frac{E_{c,i}}{EER_{c,i}^{ind}} \times c_{el} + \sum\nolimits_{i=1}^{365} \frac{E_{h,i}}{EER_{h,i}^{ind}} \times c_{el} \quad (9)$$

Constant electricity prices c_{kWh} are assumed. The total annualized costs for each system configuration are estimated by summing the respective capital and operational costs. The Networked configuration is considered economically feasible if its combined annualized costs are lower than the costs for the Individual configuration. To compare costs across European countries, all costs are scaled according to comparative price levels of consumer goods and services [30], and country-specific electricity prices for the first half of the year 2021 are used for calculating operational costs [31]. For the district network and lake inlet, the assumed lifespan is 50 years, for heat pumps in single-family homes 16 years, and 20 years for multi-family homes [33]. Also, CO_2 emissions reductions associated with electricity savings from lake-source networks were calculated with averaged annual carbon electricity intensities in each country [34].

2.7. Energy efficiency ratio calculation

The estimation of the EER of heat pumps and chillers is undertaken using two relationships acquired from the literature [35], which were derived from experimental datasets for air-source heat pumps and water-to-water heat pumps. As the relationships are defined concerning the temperature difference between the supply temperature and source temperature (ΔT), the same relationships are employed in this study for both heating and cooling [35]. For space heating, the supply temperature is assumed to equal 40 °C, and for space cooling equal to 6 °C. The equation is considered valid for $15 \leq \Delta T \leq 60$, and the minimum and maximum values of this relationship are used for smaller or larger ΔT.

$$\left\{EER_{h,i}^{ind}, EER_{c,i}^{ind}\right\} = 6.81 - 0.121\Delta T - 000630\Delta T_i^2 \tag{10}$$

In the Networked configuration, the cooling is assumed to be provided directly by the district system; therefore, the pumping power is considered to be the only electricity consumption determining the overall efficiency of the system (EER_c^{net} equal to EER_{pump}). For a low-temperature network, about 3% of the electricity is assumed to be used for pumping compared to the heat transported [32]. This results in a constant Coefficient of Performance (COP) for the Cooling-only case (Eq. (11)).

$$\{EER_{c,i}^{netw}, EER_{pump}\} = \frac{100}{3} \tag{11}$$

In the Networked configuration and Combined case, the heat pump consumption is added to the pumping power. Reported [35] water-to-water heat pump EER relationships were used to estimate the heat pumps efficiency in heating or when the lake is used as a source through the district thermal network ($EER_{h,i}^{HPw}$).

$$EER_{h,i}^{HPw} = 8.77 - 0.50\Delta T - 000734\Delta T^2 \tag{12}$$

The system efficiency in heating was calculated as in Eq. (13).

$$EER_{h,i}^{netw} = \left(\frac{1}{EER_{h,i}^{HPw}} + \frac{1}{EER_{pump}}\right)^{-1} \tag{13}$$

These efficiencies are also employed for the calculation of the economic index, which is used to identify potential network regions through the coefficients ε_c and ε_h (Eq. (1)). The coefficients are calculated using a yearly average of the EERs (Eqs.14 – 15).

$$\varepsilon_c = \frac{1}{EER_c^{ind}} - \frac{1}{EER_c^{netw}} \tag{14}$$

$$\varepsilon_h = \frac{1}{EER_h^{ind}} - \frac{1}{EER_h^{netw}} \tag{15}$$

2.8. Thermal lake modelling

Water temperature in lakes is affected by a combination of different heat fluxes, such as absorption of shortwave solar radiation, longwave radiation exchange with the sky, heat loss to the air due to evaporation and convection, and heat diffusion with turbulent mass transport due to buoyancy and wind shear stress [14]. A simplified resistance capacity lake model was developed in Python for fast calculations using minimum input data requirements and continuous integration into the overall modelling framework. When simulating the lake temperature, different layers need to be simulated: In temperate climates, such as those considered in this study, lakes tend to form three separate and distinct thermal layers during warm weather: a warm top layer called epilimnion, an intermediate layer called thermocline where most of the vertical temperature variation takes place, and a cold bottom layer called hypolimnion, typically used for lake-source thermal networks. Before running a lake temperature simulation, the average depth is approximated by dividing the lake volume by the lake surface to allow filtering of shallow lakes with too small volumes, which are not considered suitable for thermal networks. Only lakes with a surface area of at least 40 ha and an average depth of at least 7 m (or shallow lakes with a larger volume than 0.028 km^3) were simulated. Besides the dimensional constraint, also lakes which freeze longer than a month during winter were not considered suitable candidates due to the difficulty of extracting heat during the heating season. As a result of this initial screening, 171 lakes were selected as suitable candidates, of which 18 shallow lakes were simulated with a single capacitance model due to the small difference between the average depth and the estimated thermocline depth. The remaining 153 lakes were simulated with a two-capacitance model, thus capturing the thermal stratification. All lake simulations were performed with a time-step of 6 h for five consecutive years, and the fifth year was considered to avoid influence by the initial thermal transient, both with heat injection (cooling operation) only and with both heat injection and extraction (combined heating and cooling). Inflow and outflow of rivers, rainfall, snow and ice covers are ignored. A full description of the model is available in SI Note F. The lake temperature distribution of the developed simplified lake model was compared against the validated benchmark model Simstrat [36]. This comparison, outlined in SI Note G, shows an average annual deviation in the daily mean water temperature lower than 2 °C, with the highest mismatch occurring during the autumnal stratification break-up, i.e. when the coefficient of performance of the heat pumps does not play a significant role due to low heating and cooling demands.

3. Results and discussion

As a result of our analysis, nearly 2′000 lakes were identified, whereby the geographic distribution of the lakes depends on the geological context (Fig. 2): Some countries, such as Switzerland, Finland and Norway, show many lakes due to past glacial activities. Other countries have limited opportunities to use lakes as a resource, such as Portugal, Spain, the Czech Republic, or Slovenia, mostly because large lakes are either scarce or nonexistent. Countries with a warmer climate and, therefore, higher cooling demand tend to have fewer water bodies. The climatic setting affects the viability of lake-source thermal networks, which relies on an efficient and economically viable cooling and heating supply. The demand shows no north–south pattern, as the total demand depends on the presence of lakes. After considering the minimum size and lake volume as well as that lakes must not freeze for longer than one month, 171 lakes remained.

3.1. Techno-economic potential of lake-source heating and cooling

Assessing the techno-economic potential requires explicitly estimating the spatial distribution of buildings and required networks (Fig. 2). Annualized capital costs make this analysis sensitive to the life expectancy of the equipment, which is generally long for thermal networks, and to boundary conditions such as electricity prices, interest rates and CO_2 prices, which determine the relevance of the operational savings over the capital investment and thus the overall economic feasibility. For example, higher interest rates increase upfront investments into centralized infrastructure due to the long lifetime of the piping network and thereby decrease their economic feasibility, while higher electricity costs improve it as the operational savings from energy efficiency increase. Five cost scenarios were explored to evaluate the impact of these two boundary conditions: four were created combining an interest rate of 2 or 8% with current or quadrupled country-specific electricity prices. A fifth *Base* cost scenario assumes the mid-point of these interest rates and electricity prices. Additionally, the impact of climate change was assessed for the year 2050 with the Representative

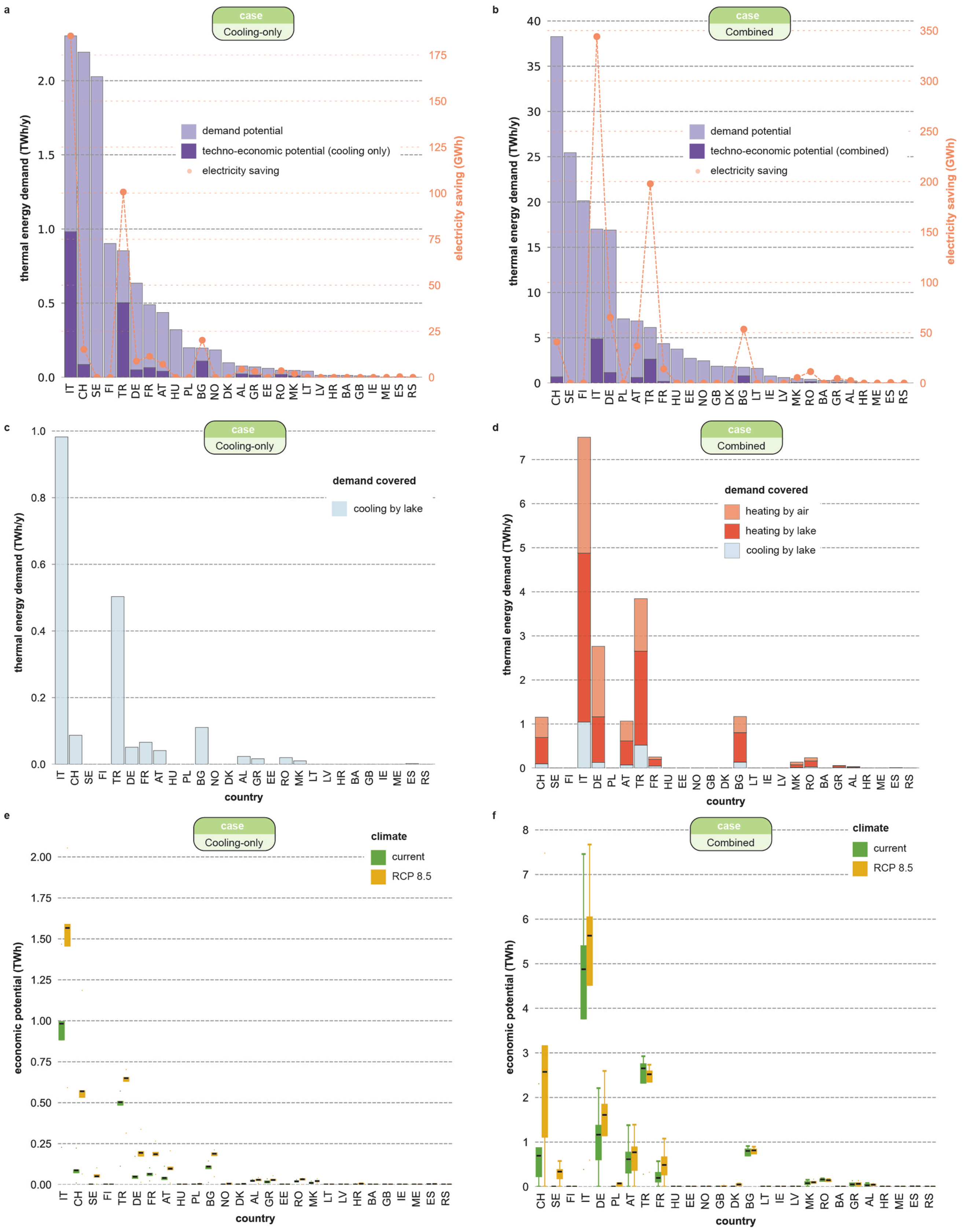

Fig. 4. Overview of the simulated techno-economic potential for lake cooling and heating in Europe for the Base cost scenario. The annual demand potential and the techno-economic potential are shown for using lakes for Cooling-only (a) and combined heating and cooling (b) (cf. system configuration in Fig. 1). Economically feasible cooling and heating demand met by thermal district networks for the Cooling-only and Combined case are shown in (c) and (d), respectively. The boxplots show the techno-economic potential for all cost scenarios for the current climate and the RCP 8.5 for the Cooling-only (e) and the Combined (f) case. See SI Fig. 7-10 and Tables 6–13 for results of other cost scenarios.

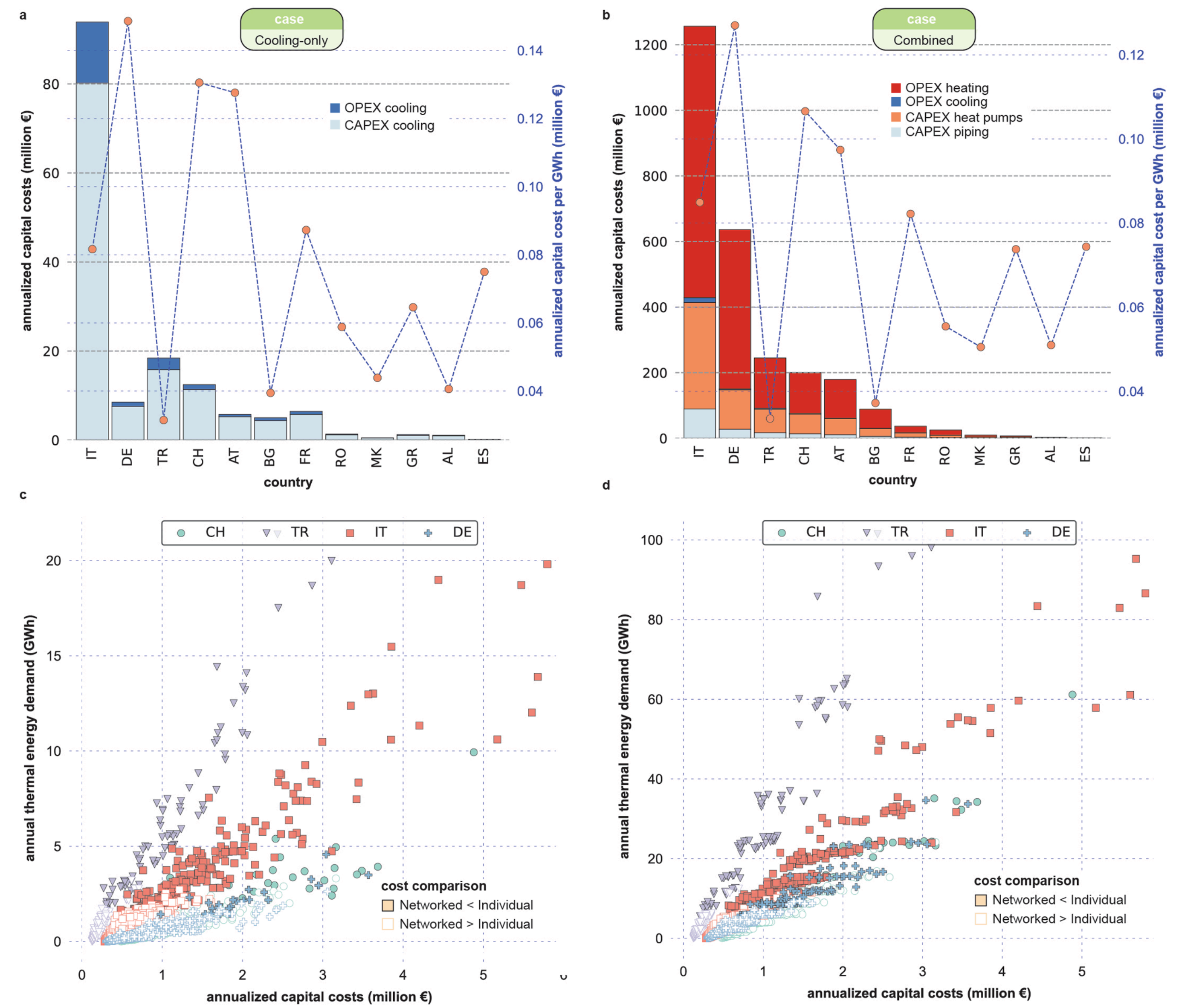

Fig. 5. Overview of the simulated costs and energy demands of the techno-economically feasible lake-source district systems in the Base cost scenario. Aggregated capital (capex) and operation (opex) costs are shown for the Cooling-only (a) and the Combined case (b). Individual network's thermal demand covered with the corresponding capital costs undertaken for an exemplary selection of countries is shown in (c, d), which are truncated for visualization purposes.

Concentration Pathway (RCP) 8.5, which reflects a climate scenario with no specific emission reduction measures [37].

Fig. 4 shows Base scenario results, highlighting (a) the portion of cooling-only or (b) combined heating and cooling demand of buildings that could be covered by an economically viable lake-source system (see Appendix A for country-specific results). The thermal energy demand of buildings around lakes in Europe (i.e. demand potential) is approximately 11 TWh for cooling and 150 TWh for heating. Under current climatic conditions, the annual techno-economic potential of lake-source district systems is 1.9 TWh for Cooling-only ones and 11.3 TWh for combined ones. The corresponding electricity savings are 0.36 TWh in the Cooling-only case and 0.78 TWh for the Combined one. The distribution of this techno-economic potential is heterogeneous: For cooling-only, the demand potential is larger for countries with many lakes (e.g. Italy, Switzerland and Sweden), but after considering the technical and economic constraints, lake-source systems are shown to have a significant benefit only in a few countries, namely Italy, Turkey, Bulgaria, Switzerland, France and Germany. When the Combined case is considered, a much larger heating and cooling demand potential was observed, with Switzerland leading with nearly 40 TWh per year (b). Nevertheless, for the Combined case, it is even more evident how techno-economic factors impact the feasibility of lake-source systems: countries where electricity is expensive compared to capital costs and the lakes are technically exploitable (e.g. Italy, Germany Turkey) could benefit more than countries with more demand potential but lower relative electricity prices (e.g. Switzerland). For Sweden and Finland, the techno-economic potential would probably increase if lakes with surface freezing were to be included. As expected, higher techno-economic potential coincides with higher electricity savings (Fig. 4). For Italy, electricity savings amount to 100 GWh per year for the Cooling-only case and approximately 350 GWh per year for the Combined case. Electricity savings are generally higher in the Combined case due to the share of heating provided by the district system. These thermal networks provide more heating than cooling, by generally one order of magnitude (c-d). However, this heating and cooling coverage ratio and the fraction of heat provided by air or by the lake are country-specific. Furthermore, with a warming climate, these networks are expected to be driven increasingly by the cooling demand which is

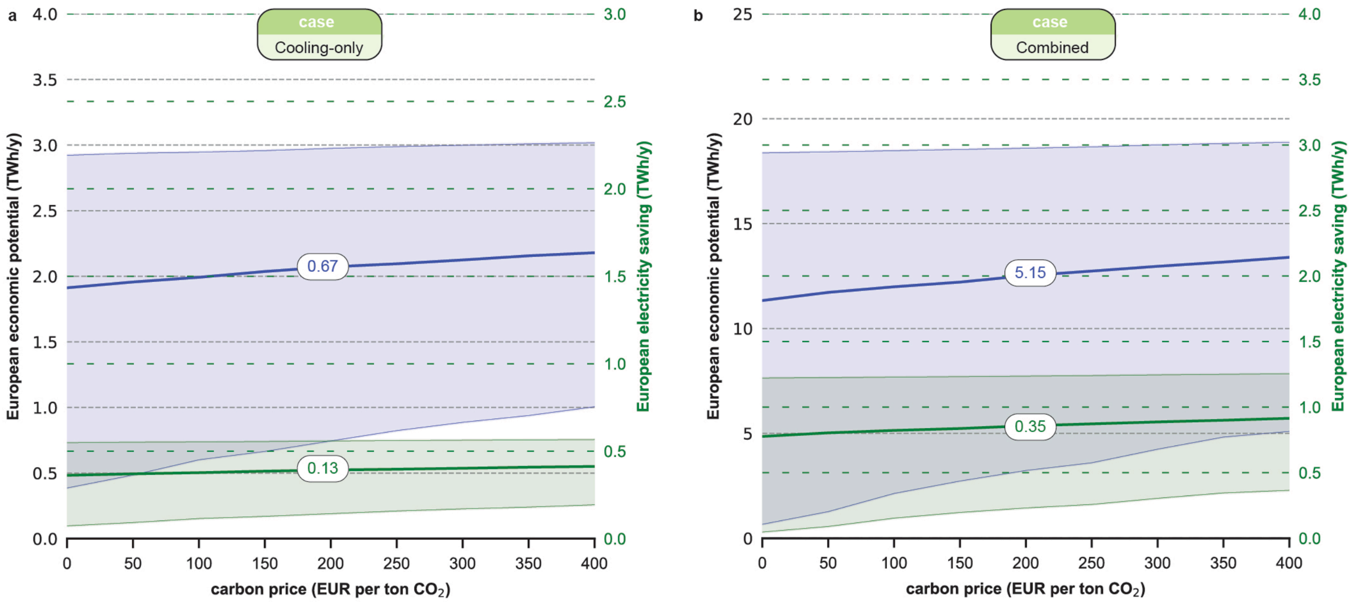

Fig. 6. Change in European techno-economic potential (blue, left axis) and electricity savings (green, right axis) for different CO_2 prices. For the Cooling-only (a) and Combined (b) case, European techno-economic potential is shown for the cost scenario range assuming current climatic conditions. Bold lines show the Base cost scenario. The thermal demand that is more economical to cover by thermal networks than individual heat pumps increases with higher CO_2 prices. The approximate change in GWh per Euro per ton of CO_2 is provided in the boxes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

highlighted in the distribution of the boxplots (Fig. 4e,f), showing the sensitivity of the techno-economic potential of lake-source district systems to different costs and climate scenarios. For the RCP 8.5 climate scenario, the annual European techno-economic potential increases to 3.7 TWh (+191% to current) for the Base scenario in the Cooling-only case and to 15.2 TWh (+134% to current) in the Combined one. This increase in potential is due to the general growth of cooling demand and reduction in heating demand with a warming climate, increasing the economic advantage of lower operational costs from using lakes for cooling. The same can be observed for the demand potential: the cooling demand increases from 11 to 17 TWh while the heating demand decreases from 150 to 121 TWh (SI Note I). The general trend that higher electricity prices favour thermal networks is also affirmed in this case.

Capital costs and thermal energy demands of potentially viable lake-source systems are shown in Fig. 5. The annualized capital costs vary between 0.04 to over 0.1 million € per GWh (a,b). In the Cooling-only case, the operational electrical energy is small due to the direct supply of cooling. In the Combined case, operational costs make up a much larger share of total costs. A first approximate assessment of the economic feasibility of thermal district networks is possible using (Fig. 5**c, d**), where the thermal supply and annualized cost for all simulated districts in selected countries are plotted. The relationship that makes these systems viable is not trivial and country-specific due to differences in prices, lake temperatures or spatial demand distribution. The established relationships provide a high-level overview and first guidance of whether a planned lake-source district network with a certain demand (y-axis) and a certain cost (x-axis) is economically more feasible than heating and/or cooling each house individually with heat pumps.

3.2. Introducing a CO_2 price

When introducing CO_2 prices, operational electrical energy savings become more relevant and generally, the relative cost of individual heating and cooling increases more compared to the Networked one. Fig. 6 shows the impact of the CO_2 price on the overall techno-economic potential and electricity savings. The thick lines represent the Base cost scenario, the shaded areas visualize the cost range of the different cost scenarios. Setting the CO_2 price to 400€/t_{CO2}, the annual European techno-economic potential increased, for example, from 11.3 to 13.4 TWh for the Combined case. The increase is more pronounced for scenarios where less potential was identified (bottom range). For cost scenarios where large potentials have already been simulated due to optimistic assumptions favouring district solutions (top of the range), introducing a CO_2 price only slightly increases the potential as most of the potential has already been reaped. The same relationships hold for electric savings. Savings are based on the operation of individual heat pumps and would increase if less efficient technologies are assumed. These calculations show the change in the techno-economic potential when assigning costs to carbon emissions. However, barriers to implementation are not costs alone, but institutional innovation is required [38] due to the socio-technical nature of the proposed infrastructure [39].

3.3. Thermal response of lakes

Thermal models of lakes were employed to estimate the efficiency of lake-source district systems and to evaluate their impact on lakes. Fig. 7 shows the calculated average temperature of the bottom layer of all lakes in a country (right axis), together with the average change in maximum and minimum lake temperature when all viable district systems are implemented (left axis). The Cooling-only case leads to higher variation in maximum temperature. For most analysed lakes, the maximum temperature increase is less than 0.5 °C. In the Combined case, the heat extraction in winter counteracts the injection in summer, leading to a smaller increase in maximum temperature but also a slight decrease in average minimum lake temperature (less than 0.1 °C). Countries employ different regulations for allowed temperature alterations: In Switzerland [40], for example, the allowed maximum temperature increase in lakes and rivers is 1.5 °C, and the maximum natural water temperature must not exceed 25 °C. Heat injection is thereby more critical from an ecological point of view [17]. The presented simulations are in line with other studies [17], which reported mean temperature

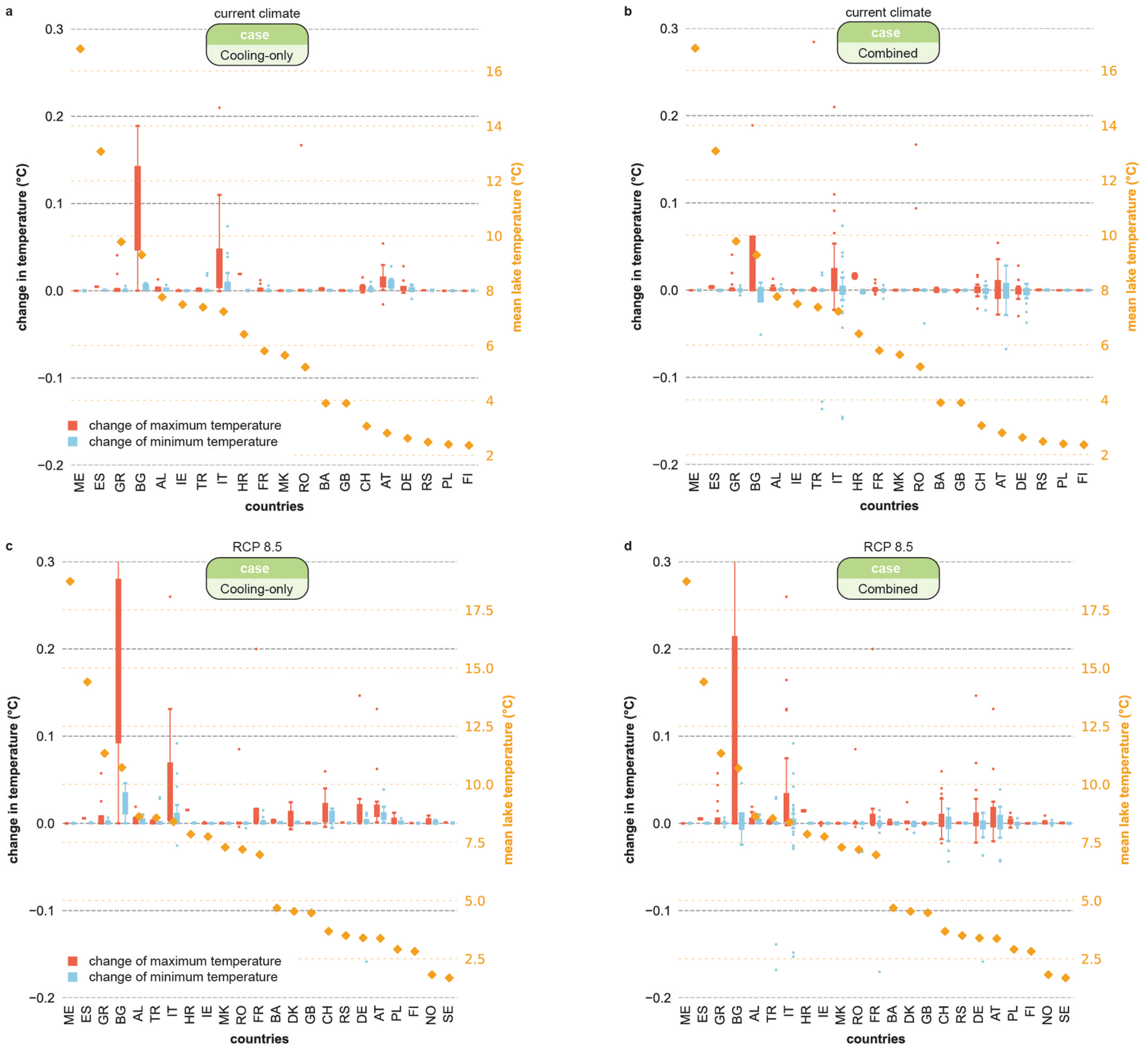

Fig. 7. Thermal response of lakes when lake-source systems are integrated. The change in the maximum and minimum temperature of the year of the deep-water layer (hypolimnion) for each lake and country as a result of extracting heat (a) and extracting as well as injecting heat (b). The mean lake temperature of all simulated lakes per country is provided on the right axis. Simulations are based on current climatic conditions (a,b) and for the RCP 8.5 (c,d). Outliers with a positive deviation above 0.3 °C are not shown (4 in a, 9 in b with a maximum deviation of 0.7 °C; 5 in c, 7 in d with a maximum deviation of 1 °C).

alterations typically considerably less than 1 °C [41], and suggest that integrating all techno-economically feasible district heating and cooling systems should not have severe temperature-related ecological implications for the majority of lakes. However, lake models could explore further criteria in more detail, such as the shift in the onset and break-up of lake stratification [42].

4. Conclusions

This investigation provided the first combined exploration of technological, ecological and economic dimensions to evaluate the potential of using lakes as a source for district heating and cooling in Europe. Whereas lake-source thermal networks are constrained foremost by the availability of lakes, the spatial distribution of energy demand determines how much energy or emissions can be saved, and determines the relationship between operational costs and the required capital costs. The main findings of this study can be summarized as follows:

- The thermal demand of buildings within close proximity (1.5 km) of lakes was found to considerably exceed the techno-economically feasible potential. An estimated 17% of the cooling demand near European lakes can be covered by viable cooling-only lake-source systems, assuming a scenario with an interest rate of 4% and electricity prices twice as high as in the

year 2021. For combined systems, the viable demand is estimated at 7% of the total available combined cooling and heating demand.
- The development of lake-source thermal networks would lead to an annual electricity saving of 0.4 and 0.8 TWh for Europe, respectively, and assuming current CO_2 emission intensity of electricity, 128 and 270 kt of yearly CO_2 savings. For the Combined case, the European techno-economic potential increases by approximately 2.5 TWh/y with every 100% increase in electricity price and decreases by about 1 TWh/y with every additional per cent increase in the interest rate (Note SI I).
- In other explored cost scenarios, the techno-economical potential is smaller but still significant, particularly for Italy, Germany, Switzerland and Turkey.
- Climate change is expected to increase the techno-economical potential of systems providing only cooling as well as both heating and cooling.
- Next to the availability of lakes and nearby heating and cooling demand, the ratio between operational and capital costs (e.g. where a low price level results in low infrastructure costs combined with high electricity prices) is essential for making lake-source district systems viable. Boundary conditions such as CO_2 prices increase the techno-economic potential, with an average of 5.15 GWh per €/t_{CO2} of additional thermal demand covered, leading to 0.35 GWh per €/t_{CO2} of additional electricity saved.

Further benefits of integrating lakes could arise if the potential to reduce peak demands were to be considered, particularly in times of extreme temperature events. The presented approach can be easily extended or refined by introducing economies of scale or hourly prices for the cost calculation [43], including applications in addition to space-heating, or employing more detailed floor area estimations methods [44]. Further research could also focus on including socio-technical aspects, e.g. considering regulatory considerations [45]. Future energy demand calculations would need to consider how cities adapt to climate change [46], how buildings and districts are operated and integrated within low-temperature networks [47] or the state of buildings retrofit [48], which all affect the energy demand density, which is critical for evaluating the feasibility of thermal networks. Whereas this analysis focused on lakes, additional potential water sources are coastal waters [49], aquifers [50] and rivers [51], although heat injection in rivers is particularly ecologically challenging and could lead to curtailment of power generation [52].

In summary, this study found considerable opportunities for European lakes to reduce the energy use of buildings around them. Compared to overall European demand, the assessed techno-economic potential reveals that lake-source thermal networks provide a meaningful contribution in places with lakes. The implementation of lake-source thermal networks remains sensitive to boundary conditions such as electricity prices, interest rates and CO_2 prices and climate change. The integration of all viable district systems is expected to have minor impacts on lake temperature alterations for the majority of European lakes. The presented results could serve as a starting point to highlight all potentially feasible systems, leading to more detailed evaluations that carefully considering local conditions and constraints.

5. Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

6. Code availability

The code of this study is available from the corresponding author upon reasonable request.

CRediT authorship contribution statement

Sven Eggimann: Formal analysis, Methodology, Conceptualization, Writing – original draft. **Jacopo Vivian:** Formal analysis, Methodology, Conceptualization, Writing – original draft. **Ruihong Chen:** Formal analysis, Methodology, Writing – review & editing. **Kristina Orehounig:** Review & editing. **Anthony Patt:** Conceptualization. **Massimo Fiorentini:** Formal analysis, Methodology, Conceptualization, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A

Tables A.1 and A.2 provide the detailed country-specific values for Fig. 4a and 4b.

Table A1
Detailed numbers are provided for Fig. 4a. Countries are sorted according to their resource potential.

Country	Demand potential (TWh)	Techno-economic potential (TWh)	%*	Electricity savings (GWh)	CO_2 savings (million kg)
IT	2.3025	0.9822	42.7	185.4035	64.706
CH	2.1923	0.0870	4.0	15.1887	1.807
SE	2.0278	0.0000	0.0	0.0000	0.000
FI	0.9021	0.0000	0.0	0.0000	0.000
TR	0.8534	0.5030	58.9	100.6087	43.564
DE	0.6348	0.0510	8.0	8.8176	2.910
FR	0.4897	0.0658	13.4	11.3820	0.706
AT	0.4371	0.0411	9.4	7.1258	1.354
HU	0.3210	0.0000	0.0	0.0000	0.000
PL	0.1997	0.0000	0.0	0.0000	0.000
BG	0.1971	0.1104	56.0	20.1476	7.495
NO	0.1844	0.0000	0.0	0.0000	0.000
DK	0.0984	0.0000	0.0	0.0000	0.000
AL	0.0762	0.0234	30.7	4.4278	2.019
GR	0.0701	0.0164	23.3	3.1619	1.126
EE	0.0598	0.0000	0.0	0.0000	0.000
RO	0.0473	0.0198	41.9	3.6070	0.949
MK	0.0465	0.0102	22.0	1.9527	0.890
LT	0.0412	0.0000	0.0	0.0000	0.000
LV	0.0130	0.0000	0.0	0.0000	0.000
HR	0.0130	0.0000	0.0	0.0000	0.000
BA	0.0124	0.0000	0.0	0.0000	0.000
GB	0.0102	0.0000	0.0	0.0000	0.000
IE	0.0093	0.0000	0.0	0.0000	0.000
ME	0.0022	0.0000	0.0	0.0000	0.000
ES	0.0022	0.0019	87.9	0.3500	0.057
RS	0.0007	0.0000	0.0	0.0000	0.000

* (techno-economic potential / resource potential)*100.

Table A2
Detailed numbers are provided for Fig. 4b. Countries are sorted according to their resource potential.

Country	Demand potential (TWh)	Techno-economic potential (TWh)	%*	Electricity savings (GWh)	CO_2 savings (million kg)
IT	38.2742	0.6952	1.8	40.7558	4.850
CH	25.4420	0.0000	0.0	0.0000	0.000
SE	20.1346	0.0000	0.0	0.0000	0.000
FI	16.9989	4.8759	28.7	344.0259	120.065
TR	16.9027	1.1648	6.9	65.3565	21.568
DE	7.0930	0.0000	0.0	0.0000	0.000
FR	6.8656	0.6167	9.0	36.8245	6.997
AT	6.1420	2.6534	43.2	197.8633	85.675
HU	4.3578	0.1973	4.5	14.0078	0.868
PL	3.7666	0.0000	0.0	0.0000	0.000
BG	2.7325	0.0000	0.0	0.0000	0.000
NO	2.4673	0.0000	0.0	0.0000	0.000
DK	1.8641	0.0000	0.0	0.0000	0.000
AL	1.8055	0.0000	0.0	0.0000	0.000
GR	1.7476	0.8029	45.9	53.4805	19.895
EE	1.6178	0.0000	0.0	0.0000	0.000
RO	0.7788	0.0000	0.0	0.0000	0.000
MK	0.6092	0.0000	0.0	0.0000	0.000
LT	0.4861	0.0767	15.8	5.4861	2.502
LV	0.4077	0.1619	39.7	11.3707	2.990
HR	0.2861	0.0000	0.0	0.0000	0.000
BA	0.2852	0.0513	18.0	4.6117	1.642
GB	0.2388	0.0310	13.0	2.4963	1.138
IE	0.0416	0.0000	0.0	0.0000	0.000
ME	0.0071	0.0000	0.0	0.0000	0.000
ES	0.0070	0.0059	84.2	0.5041	0.082
RS	0.0056	0.0000	0.0	0.0000	0.000

* (techno-economic potential / resource potential)*100.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enconman.2023.116914.

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