Drinking water supply as low-temperature source in the district heating system: A case study for the city of Copenhagen

Hubeck-Graudal, Helga; Kirstein, Jonas Kjeld; Ommen, Torben; Rygaard, Martin; Elmegaard, Brian

Published in:
Energy

Link to article, DOI:
[10.1016/j.energy.2019.116773](https://doi.org/10.1016/j.energy.2019.116773)

Publication date:
2019

Document Version
Peer reviewed version

[Link back to DTU Orbit](#)

Citation (APA):
Hubeck-Graudal, H., Kirstein, J. K., Ommen, T., Rygaard, M., & Elmegaard, B. (2019). Drinking water supply as low-temperature source in the district heating system: A case study for the city of Copenhagen. *Energy*, 194, [116773]. <https://doi.org/10.1016/j.energy.2019.116773>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Drinking water supply as low-temperature source in the district heating system: a case study for the city of Copenhagen

Helga Hubeck-Graudal^{a,*}, Jonas Kirstein^b, Torben Ommen^c, Martin Rygaard^b, Brian Elmegaard^c

^aHOFOR, Ørestads Boulevard 35, 2300 Copenhagen S, Denmark

^bTechnical University of Denmark, Department of Environmental Engineering, Anker Engelundsvej 1, 2800 Kgs. Lyngby, Denmark

^cTechnical University of Denmark, Department of Mechanical Engineering, Anker Engelundsvej 1, 2800 Kgs. Lyngby, Denmark

Abstract

This paper explores the potential for using large-scale heat pumps (HPs) to extract energy from Copenhagen's drinking water network and deliver it to its district heating system. The system involves certain losses in terms of additional heat and power consumption for end-use water heating. The net potential for energy extraction was analysed by means of an EPANET model to simulate system-wide temperatures in a piped distribution network. The model was validated against measured data from the network. Heat transfer in service lines was computed analytically and included in the net potential for energy extraction, which was determined to be 21 MW in Copenhagen. Around 38% of the HP source demand was harnessed from the ground. With HP COPs between 2.8 and 3.2, the System COP was only 1.7, thus suggesting that the choice of drinking water as a low-temperature heat source should depend on the available alternatives. Drinking water HPs have the side-benefit of preventing high drinking water temperatures; if operated in the summer they increased the share of supplied water complying with a recommended upper temperature limit of 12 °C from 42% to 81%.

Keywords: energy efficiency; heat pumps; district heating; heat transfer modelling; drinking water supply.

1. Introduction

Electrically driven heat pumps (HPs) represent an excellent means of integrating the power and heating systems in areas with a significant heating demand and large amounts of intermittent renewable energy in the power system [1]. HP operation will be particularly relevant during hours when a substantial wind power production lowers the price and carbon emission of electricity. A low electricity price reduces the revenues earned by CHP plants, and thus CHP and HP technology can complement each other well in district heating (DH) systems.

* Corresponding author. Email address: helhub@hofor.dk

Nomenclature

A	amplitude of annual surface temperature [K]
C_p	specific heat [J/kg/K]
d	diameter [m]
D	damping depth of annual fluctuation [m]
$\dot{E}$	electrical power demand [W]
f	fraction of total consumption
h	height of soil layer above pipe [m]
H	corrected height of soil layer above pipe [m]
K_p	heat transmission coefficient per m [W/m/K]
l	height of fictitious soil layer above pipe [m]
L	length [m]
m	mass [kg]
$\dot{m}$	mass flow rate [kg/s]
$\dot{Q}$	heat flow rate [W]
r	radius [m]
R	thermal resistance [m ² K/W]
t	time [s]
T	temperature [K]
$\dot{V}$	volumetric flow rate [m ³ /s]
$\dot{W}$	electrical power [W]

Greek symbols

α	heat transfer coefficient [W/m ² /K]
δ	thickness [m]
Δ	change
η	efficiency [-]
κ	thermal diffusivity [m ² /s]
λ	thermal conductivity [W/m/K]
μ	dynamic viscosity [kg/m/s]
ρ	density [kg/m ³]
ϕ	correction factor [K·m ² /W]
ω	frequency [s ⁻¹]

Subscripts

0	initialization
A	case A
air	air
ave	average
B	case B
c	condenser
com	compressor
demand	demand
DH	district heating
e	evaporator
ext	extraction
i	inner
model	modelled
net	net
o	outer
pipe	pipe
return	return
soil	soil
source	heat source
supply	supply
sys	system
year	year
water	water
wall	pipe wall

Abbreviations

CHP	combined heat and power
COP	coefficient of performance
DH	district heating
HP	heat pump
MSX	Multi-Species Extension
PE	polyethylene

To complement, or perhaps in some hours even replace individual CHP units, a significant total capacity of HPs must be installed. In dense urban environments, this poses the challenge to find low-temperature sources of sufficient capacity. An in-depth assessment of all available heat sources is needed, and based on this, the full range of heat source options should be prioritized based on socio-economic and/or private-economic analysis. An example of how to assess individual heat sources based on availability and performance is given in [2].

Since suitable large-scale heat sources are not necessarily abundant in urban areas [3], it may be worthwhile to take into account a variety of smaller sources, including wastewater networks [4,5] and groundwater reservoirs [6], in possible combination with surface water [7]. Another potential source is the reduction of flow temperature from drinking water distribution mains, which are extensively available in the immediate underground of any city.

Advantages of using drinking water as the heat source for a HP include its stable temperature around the year; its purity, which reduces fouling and maintenance needs on the HP components; and the fact that cooling is beneficial to drinking water as it limits bacterial growth [8], thereby preserving its quality for human consumption.

A comprehensive review of energy use and recovery potential in urban water systems was provided by Elias-Maxil et al. [9]. They presented different ways of using water as a source for heat pumping, but stated that only few studies relate to the application of water before end-use. However, recent studies include the work of Blokker et al. [10] who analysed a drinking water HP supplying heat for 900 homes in Almere City, Netherlands. De Pasquale et al. [11] analysed the potential for using a part of Milan's drinking water network as a source for a 4.65 MW HP, and Jadwiszczak and Niemierka studied a system for integration into the DH system of Głogów, Poland [12]. Van der Hoek et al., in turn, investigated cold recovery from drinking water and the related microbiological effects [13].

A drawback of extracting heat from drinking water mains is that reduced water temperatures downstream give rise to increased end-use heat demand in households. The extra domestic heating demand is partly offset by additional heat transfer from the soil surrounding the water pipes, which is triggered by the increased temperature difference between soil and water upstream.

Since the heat transfer from soil to water is to a great extent what determines the energy balance of drinking water HPs, the use of this technology is comparable to ground-source heat extraction at a very large scale. In other words, the amount of additional heat transfer obtained from the soil determines the rationality of using drinking water as a heat source.

The purpose of the present study is to determine the technical potential for large drinking water HPs in the DH system of the City of Copenhagen, while taking into account a number of technical constraints related to their location. The potential is determined by modelling of the ground-source heat that is gained when HPs are installed at all water distribution mains with an average flow rate exceeding 50 L/s. The technical constraints include the operational profile of the HPs, their distance to a DH network, and differences in supply temperatures of various DH distribution networks. In addition to the HP potential, this study examines the derived water cooling effects experienced by consumers.

The study employs a hydraulic model provided by HOFOR, the Greater Copenhagen Utility [14], which was modified to include a heat transfer model to be solved in the EPANET Multi-Species Extension (MSX) [15,16], which enables computation of the water temperature change throughout the distribution system. Service lines were not included in the distribution network model, but to account for a potentially significant share of the total heat transfer in the pipelines, their contribution was computed outside the model. The EPANET-MSX approach for modelling heat transfer in drinking water networks was first used by Blokker et al [17], and later improved by De Pasquale [11]. The present work contributes with a heat transfer model validated against measurement data from the drinking water network, enabled in particular by the use of an accurate measure of the undisturbed soil temperature.

2. Methods

2.1. System description of drinking water heat pumps

A visualization of the analysed case study is presented in Fig. 1, where the energy flows in the traditional energy system (case A, the baseline) are compared to a system with drinking water HPs installed (case B). In case A, water from the waterworks is distributed in the city and exchanges heat, $\dot{Q}_{\text{soil,A}}$, with the surrounding soil along its way through the network. The water is heated by warmer soil during summer, and cooled by colder soil during winter. The water consumers of Copenhagen have a demand for DH, $\dot{Q}_{\text{demand,A}}$, to cover their hot water needs, e.g. for showering. The DH system in Copenhagen covers more than 98% of the heat demand, so there is practically full overlap between water consumers and DH consumers in the system. The DH is produced mainly by CHP plants, waste incineration and peak-load boilers. The water consumers also demand electricity, $\dot{E}_{\text{demand,A}}$, for water heating, e.g. in washing machines and for cooking. The electricity production may be based on, inter alia, wind turbines and CHP.

In case B a number of HPs driven by electricity, $\dot{W}_{\text{com}}$, utilize low-temperature heat from the water supply network, $\dot{Q}_e$, and deliver it to the DH network, $\dot{Q}_c$. Due to the operation of HPs, water temperatures are reduced downstream. Compared to case A, this prompts a higher end-use DH and electricity demand, $\dot{Q}_{\text{demand,B}}$, and $\dot{E}_{\text{demand,B}}$, for water heating for hot water consumption. However, the increase in demand is partly offset by

increased heat transfer from soil to water pipes, $\dot{Q}_{\text{soil},B}$, which is triggered by the increased temperature difference between soil and water when the water is cooled upstream. The system's net gain in energy, compared to case A, is the outcome of one of two situations: 1) If the soil is warmer than the water, the heat flow from soil to water increases. 2) If the soil is colder than the water, the heat loss from water to soil is reduced.

Case A: current system

Case B: system with heat pumps

Fig. 1. Energy system model without (A) and with (B) drinking water heat pumps (inspired by [11]).

The additional DH demand in case B compared to case A depends on the amount of additional heat transfer from the soil to the water distribution network, and on the fraction of total water consumption that is heated by means of DH:

$$\Delta \dot{Q}_{\text{demand}} = \dot{Q}_{\text{demand},B} - \dot{Q}_{\text{demand},A} = ((\dot{Q}_e - \dot{Q}_{\text{soil},B}) + \dot{Q}_{\text{soil},A}) \cdot f_{\text{DH}} = (\dot{Q}_e - \Delta \dot{Q}_{\text{soil}}) \cdot f_{\text{DH}} \quad (1)$$

The potential for heat utilization from the drinking water supply was defined as a function of the acceptable temperature reduction in the drinking water main flows, and of the additional end-use DH demand. It is the thermal capacity effectively gained by the DH system from the drinking water HPs:

$$\dot{Q}_{\text{net}} = \dot{Q}_e - \Delta \dot{Q}_{\text{demand}} \quad (2)$$

The power consumed by the HP is converted to thermal energy and contributes positively to the overall DH balance. This heat does not necessarily contribute directly to the reheating of cooled drinking water, but it will ease the load on other heat-producing units in the DH system. Leaving out this term allows us to assess a potential for the heat extraction that is independent of the concrete technology and COP of the HP applied.

The gross potential for heat extraction from the water supply is then the thermal energy yield at the HP evaporator, which is given by the potential temperature decrease of the drinking water:

$$\dot{Q}_e = \dot{V}_{\text{water}} \cdot \rho_{\text{water}} \cdot c_{p,\text{water}} \cdot \Delta T_{\text{source}} \quad (3)$$

When entering buildings, the water is thermally affected by the indoor ambient temperature, and was assumed to gain 1 K or more between the end of the service line and the first tap [18]. To warrant end-use temperatures higher than 4 °C, considered as the acceptable limit, the modelled exit temperatures would thus have to be higher than 3 °C.

The degree of heat utilization achieved from the water supply was described as:

$$\eta_{\text{util}} = \dot{Q}_{\text{net}} / \dot{Q}_e \quad (4)$$

The ratio defines a measure of the thermal yield effectively gained from the drinking water HPs against the thermal yield extracted from the evaporator. A heat utilization degree that only considers the contribution made by heat transfer from the soil was defined:

$$\eta_{\text{util,soil}} = \Delta\dot{Q}_{\text{soil}}/\dot{Q}_e \quad (5)$$

The COP of the HPs is given as:

$$\text{COP} = \dot{Q}_c/\dot{W}_{\text{com}} \quad (6)$$

The additional end-use electricity demand in case B compared to case A is given by:

$$\Delta\dot{E}_{\text{demand}} = \dot{E}_{\text{demand,B}} - \dot{E}_{\text{demand,A}} = ((\dot{Q}_e - \dot{Q}_{\text{soil,B}}) + \dot{Q}_{\text{soil,A}}) \cdot f_{\text{el}} = (\dot{Q}_e - \Delta\dot{Q}_{\text{soil}}) \cdot f_{\text{el}} \quad (7)$$

To account for the additional electricity end-use and the additional DH end-use, a system COP was defined:

$$\text{COP}_{\text{sys}} = \frac{\dot{Q}_e - \Delta\dot{Q}_{\text{demand}} + \dot{W}_{\text{com}}}{\dot{W}_{\text{com}} + \Delta\dot{E}_{\text{demand}}} \quad (8)$$

where the numerator states the net thermal energy output of system B compared to system A, and the denominator states the net difference in electrical energy input.

2.2. Assumptions on water, heating and electricity use

Table 1 shows the assumed distribution of water use among different water services, and the energy source used to provide these services. The resulting f_{DH} of 0.37 was applied for summer. In winter, one third of the cold water stagnant in domestic pipes and cisterns was assumed heated to room temperature, which results in a larger f_{DH} of 0.47. In both summer and winter, f_{el} was assumed to be 0.33. The remaining water fractions of 0.2 (in winter) or 0.3 (in summer) were assumed not to be heated.

Table 1. Shares of water use for different purposes, and the energy source needed to heat it (based on [19]). Numbers in parenthesis apply to the summer situation.

Water services	Share of use [%]			Heat source	Share of water service that is heated [%]
	Households	Workplaces	Total		
Shower and personal hygiene	46	10	37	district heating	100
Toilet flushing	17	50	25	district heating	33 (0)
Clothes washing	13	5	11	electricity	100
Dish washing	10	20	13	electricity	100
Cooking	7	15	9	electricity	100
Miscellaneous	7	0	5	district heating	33 (0)
Total share heated by district heating			47 (37)	district heating	
Total share heated by electricity			33	electricity	
Total share unheated			20 (30)	-	

2.3. Case study network

The case study investigated the heat transfer in the drinking water network of the City of Copenhagen. The water utility of Copenhagen, HOFOR, extracts groundwater from 7 waterworks and supplies drinking water to the entire

city and some neighbouring municipalities. The system includes a reservoir that balances supply and demand by directing water to the reservoir at night when consumption is low. The network consists of a mix of cast iron, steel-reinforced concrete and polyethylene (PE) pipes. It is made up of 126 km transport lines ($d_o = 650$ mm to 1,250 mm), 157 km main lines ($d_o = 300$ mm to 1,200 mm), and 787 km distribution lines ($d_o = 50$ mm to 290 mm) [20]. A hydraulic network model of this system [14] was implemented in EPANET. The total average discharge rate from the 7 waterworks in the model is 2,165 L/s. The demand pattern applied in most nodes represents typical city consumption in an average 24-hour period.

2.4. Model development

EPANET-MSX is a water quality modelling tool designed to track the flow and reaction of chemical species in discrete water volumes, which are transported through the pipes until they reach the junctions and undergo complete mixing [16]. Mathematically this is done by numerical integration of differential-algebraic equations. Temperature was modelled as a chemical species in EPANET-MSX, handled in concentration units.

EPANET and MSX use a Lagrangian model to describe the system hydraulics and changes in water quality. The energy balance for water at any point in the pipes is therefore the energy balance of a closed system, i.e. of a control mass that travels through the pipes. For the energy balance for the closed system, it is assumed that changes in kinetic and potential energy are negligible. Boundary work may be neglected since EPANET assumes that the density of water is constant [15].

For a non-insulated cylindrical pipe buried in a semi-infinite solid, the rate of heat transfer into the control mass from the ambience was computed as proposed by [21]:

$$\dot{Q}_{\text{soil}} = K_p \cdot L \cdot (T_{\text{water}} - T_{\text{soil}}) \quad (9)$$

The heat transfer processes taking place in the system comprise: convection of water in the pipe, conduction through the pipe wall, and conduction through the surrounding soil (Fig. 2). Drawing on heat transfer coefficients defined by [21] for DH and flue gas pipes, K_p , was defined as:

$$K_p = (R_{\text{soil}} + R_{\text{pipe}} + R_{\text{water}})^{-1} = \left(\frac{\ln\left(\frac{4+H}{d_o}\right)}{2 \cdot \pi \cdot \lambda_{\text{soil}}} + \frac{\ln\left(\frac{d_o}{d_i}\right)}{2 \cdot \pi \cdot \lambda_{\text{pipe}}} + \frac{1}{\alpha_{\text{water}} \cdot \pi \cdot d_i} \right)^{-1} \quad (10)$$

R_{soil} includes a correction for the convective resistance at the soil surface, which translates this resistance into an additional layer of soil [22] (Fig. 2):

$$H = h + \varphi \cdot \lambda_{\text{soil}} \quad (11)$$

where φ is defined as $0.0685 \text{ K} \cdot \text{m}^2/\text{W}$.

Based on the energy balance for a closed system and the heat capacity of the control mass, the following expression was used to describe the time rate of change of the temperature of water in all pipes:

$$dT_{\text{water}}/dt = \frac{K_p}{C_{p,\text{water}} \cdot \rho_{\text{water}} \cdot \pi \cdot d_i^2} \cdot (T_{\text{water}} - T_{\text{soil}}) \quad (12)$$

At the junctions, MSX computes the final water temperature as the mass-based weighted average of the temperatures of all incoming streams.

The output $T_{\text{water}}(t)$ from EPANET-MSX was used to compute the additional heat transfer from the soil to the water distribution network:

$$\Delta \dot{Q}_{\text{soil}} = \dot{m}_{\text{water}} \cdot C_{p,\text{water}} \cdot (T_{\text{water,A}}(t) - T_{\text{water,B}}(t)) \quad (13)$$

where A and B refer to the considered cases without and with HPs (Fig. 1).

Fig. 2: Thermal resistances, temperatures and correction terms included in the model [21,22].

2.5. Input parameters

2.5.1 Initial water temperatures

The initial conditions for Eq. 12 – the water temperature, $T_{\text{water}}(0)$, at the inlets of the system – are the temperatures of the water exiting the 7 waterworks and the reservoir. HOFOR measures these temperatures on a daily basis, and the data were used to calculate weekly averages for each source, covering the period July 2012 – September 2014. $T_{\text{water}}(0)$ varied from 8.2 °C (the coolest source in its coolest state) to 11.3 °C (the warmest source in its warmest state). The yearly mean water temperature across all the sources was 9.3 °C.

2.5.2 Undisturbed soil temperature

The water distribution network of Copenhagen is buried at a depth of approximately 1.5 m. In upper soil layers, the soil temperature changes with depth. The soil temperature depends on ambient air temperature, wind velocity, solar radiation, sky temperature, thermal diffusivity of the soil, and phase changes of the soil water [17,24,25]. The temperature of city soils, moreover, may be affected by non-natural heat sources such as nearby basements or DH pipes [26]. The soil surrounding water pipes is also thermally affected by the convection of the water flowing through the pipes.

The soil temperature applicable to the model is the *undisturbed* ground temperature, i.e. unaffected by heat transfer from the pipe. The soil temperature is sometimes taken as the temperature at the soil surface (or the air temperature) [11,23]; sometimes at the level of the pipe centre [22,14], but due to the thermal impact of the pipe on the surrounding soil, its accurate location lies somewhere between these two points (Fig. 2) and depends on the specific system [24].

The undisturbed soil temperature was estimated to be equal to the water temperature measured at the periphery of the network at a location with low demand and where the water is in thermal equilibrium with the soil. The measured soil temperature ranged from 6.2 °C in the winter to 20.3 °C in the summer during 2012-2014.

2.5.3 Soil, pipe and water properties

Information about pipe depths, pipe wall thicknesses, and the material of each segment were based on [27]. The physical properties of water at 10 °C were used. All input parameters used in EPANET-MSX are listed in Table 2.

The thermal conductivity of soil depends on its water content, mineral content and texture (pore and particle size). For moraine clay, the predominant superficial soil type in Eastern Denmark and Copenhagen, literature values range from 1.1 W/m/K to 2.9 W/m/K [28]. The few studies conducted on Danish soils (although none in Copenhagen) indicate a thermal conductivity for moraine clay in the range 1.6 W/m/K to 2.2 W/m/K [28]. A high water content of the clay increases the conductivity. Since Copenhagen is located by the sea, the upper-end value of 2.2 W/m/K was used.

For the validation of the model, the thermal conductivities of the three existing pipe materials were used. For the case study with HP simulation, all pipes in the network were assumed to be made of PE since HOFOR is in a process of gradually converting the entire piping network into this material.

2.6. Soil temperature evaluation

In order to validate the heat transfer model and determine the magnitude of heat transfer correctly, the empirically determined T_{soil} was compared with the measured air temperature, T_{air} , and a modelled soil temperature at 1.5 m depth, $T_{\text{soil,model}}$ – both commonly used approximations of the soil temperature. The measurement data for both T_{air} and T_{soil} were fitted by the least squares method to a sinusoidal function [31], which describes soil temperature at a given depth and time during the year as a function of air temperature:

$$T_{\text{soil}}(h, t) = T_{\text{air,ave}} + A_{\text{air}} \cdot e^{-h/D} \cdot \sin(2 \cdot \pi(t - t_0)/t_{\text{year}} - h/D - \pi/2) \quad (14)$$

Where D is given by $(2\kappa/\omega)^{0.5}$, κ is defined as $\lambda_{\text{soil}}/(\rho_{\text{soil}} C_{p,\text{soil}})$, and ω is $2 \cdot \pi/t_{\text{year}}$. $T_{\text{soil,model}}$ was modelled as T_{air} fitted to Eq. 14 and computed at $h = 1.5$ m.

Table 2. Input parameters used in EPANET-MSX and for the soil temperature evaluation.

Parameter	Symbol	Unit	Value	Description
Initial temperatures of water leaving waterworks and reservoir	$T_{\text{water}}(t=0)$	[°C]	8.2 to 11.3	range of data measured at each waterworks/reservoir in July 2012 – Sept. 2014
Undisturbed soil temperature	T_{soil}	[°C]	6.2 to 20.3	range of water temperatures measured at HOFOR's laboratory in July 2012 – Sept. 2014
Pipe wall thickness	δ_{wall}	[m]	$1/9 \cdot d_i$	
Pipe depth	h	[m]	$1.4 + d_o/2$	
Thermal conductivity of soil	λ_{soil}	[W/m/K]	2.2	measured value for Danish moraine clay
Thermal conductivity of pipes	λ_{pipe}	[W/m/K]	55; 0.42; 1	for pipes made of cast iron, polyethylene and steel-reinforced concrete, respectively
Thermal conductivity of water	λ_{water}	[W/m/K]	0.56	
Specific heat of water at 10 °C	$C_{p,\text{water}}$	[J/kg/K]	4188	
Specific heat of soil	$C_{p,\text{soil}}$	[J/kg/K]	1100	
Dynamic viscosity of water at 10 °C	μ_{water}	[Pa·s]	0.001308	
Density of water at 10 °C	ρ_{water}	[kg/m ³]	999.7	
Density of soil	ρ_{soil}	[kg/m ³]	2000	

2.7. Heat pump modelling

For the integration with the DH distribution network, each HP was assumed to re-heat a partial stream of the return flow to reach the DH supply temperature (Fig. 3). With this configuration, the HP increases the DH temperature from between 45 °C and 50 °C up to between 70 °C and 90 °C, depending on whether the distribution

area is a low-temperature or high-temperature DH zone. In such configuration, the HP might be placed along the length of a DH main line. More upstream locations on the DH line, i.e. as close as possible to the local DH station,

Fig. 3. Configuration of heat pump connection to a DH line (from [29]). The heat pump increases the temperature of a part of the return flow ($T_{DH,return}$) to the supply temperature ($T_{DH,supply}$), via a reduction of the drinking water temperature (T_{source}).

were preferred to secure larger heat demands.

HPs for DH in Copenhagen tend to use ammonia as the working fluid, while other options include CO_2 , hydrocarbons, or one of the recently developed synthetic refrigerants with low global warming potential. Implementing HPs in the water supply requires special attention with respect to risk of contamination; avoiding leakage of working fluid into the water is crucial. The heat transfer from drinking water was therefore assumed to require either a double-walled heat exchanger, or a secondary heat transfer loop with a brine or heat transfer fluid such as CO_2 . Both solutions require a larger temperature difference between the heat source and the working fluid. The estimation of COP was based on the assumption of a brine system with 2 K minimum temperature differences in both heat exchangers. With reasonable design of the brine system, i.e. low temperature differences for heat exchange and insignificant maldistribution, this should not cause any issues related to the freezing point of clean water.

For the purpose of assessing $\dot{W}_{com}$ and the system COP, the COP of the HPs was estimated based on characteristics for similar HP equipment recently installed in the same DH network [30]. The assumed temperatures and the resulting COP for the HPs in high-temperature and low-temperature DH zones are listed in Table 3.

Table 3. Assumptions on temperatures, and estimation of COP for HPs in high-temperature and low-temperature zones.

Heat pump location	High-temperature	Low-temperature
Source inlet temperature [°C]	6	6
Source outlet temperature [°C]	1	1
Sink outlet temperature [°C]	90	70
Sink inlet temperature [°C]	50	45
Estimated COP [-]	2.8	3.2

A drinking water flow of 50 L/s subjected to a temperature reduction of 5 K would deliver 1 MW source to a HP, which was considered the minimum capacity of interest in this study.

The water flow would be subjected to additional pressure losses from the heat exchange process, manifold and additional piping, which requires increased pump power for the distribution of water. It is considered likely that the heat exchangers can be designed with a lower pressure loss than 50 kPa. In case of a 50 L/s water flow rate, and an increased pressure loss of 50 kPa, the isentropic pump power is approximately a factor of 100 less than the power required for the HP, and thus considered negligible in the study.

All major flows entering the city had volume flow rates exceeding the minimum value of 50 L/s. With a view to utilizing thermal energy from all of them, HPs were simulated in EPANET-MSX by application of a temperature reduction, ΔT_{source} , in 8 selected nodes on the drinking water network (Fig. 4).

The HPs were placed in spaces within a distance of 100 m from DH main lines, and priority was given to locations in low-temperature DH zones (HPs f) and g) met this criterion). Table 4 lists the average water flow rates of each HP location and the modelled source temperatures in February.

For Copenhagen, the economic benefit of integrating large HPs can mainly be reaped in winter when HPs may replace peak-load production. To assess the net potential, $\dot{Q}_{\text{net}}$, in the coldest month, the EPANET-MSX model was run with temperature data from February ($T_{\text{soil}} = 6.7^\circ\text{C}$) for a range of ΔT_{source} applied identically across the 8 nodes.

In most of the drinking water mains, the direction of the water flow is changing at night when water fills the reservoir during the low-demand period. The flow direction reverses up to 10 times over the course of 5 to 7 nightly hours. Running HPs in such situations would result in excessive cooling of the water. Consequently, HPs were simulated to operate only during periods with sustained unidirectional flow. Fig. 5 shows the daily water flow rates for the 8 locations when the ‘prohibited’ HP operation hours are left out (their water flow rates set equal to 0).

Fig. 4. Locations of modelled heat pumps on the water distribution mains (red). Heat pumps f) and g) are located in low-temperature DH zone, while the other heat pumps are located in high-temperature DH zones.

Table 4. Average daily water flow rate and modelled average source temperature in February at eight HP locations a–h (see Fig. 4).

Heat pump evaporator location	a)	b)	c)	d)	e)	f)	g)	h)
February mean source temperature [$^{\circ}\text{C}$]	8.7	8.7	8.6	8.6	8.5	8.4	8.4	8.4
Daily mean flow rate [L/s]	305	225	158	190	96	443	68	191

Fig. 5. Daily water flow rates at the 8 selected heat pump locations. The flow rate during hours with changing direction have been set equal to zero since the heat pumps do not operate during this period. Three locations (e, f and h) have unidirectional flow for 24 hours. In order to avoid excessively cold temperatures, the operation of node d is particularly constricted since a part of its stream has already been cooled by another heat pump during several hours.

2.8. Heat transfer in service lines

Service lines or private ground lines contribute to the total heat transfer between soil and water, as they increase the residence time through a) additional pipe length and b) velocities being particularly low in these pipes. Service lines alone add 17% to the total pipe length of the system [20]. Moreover, heat transfer in small-diameter pipes may be relatively large due to the high ratio of surface area to mass of water. The magnitude of the extra heat transfer in service lines was estimated outside the model.

The number of service lines in the City of Copenhagen is about 34,500 with a total length of 185 km [20], i.e. 5 m on average. The 34,500 lines serve a modelled demand of 1366 L/s, so the flow rate in a service line would be 0.04 L/s as a daily average. The typical service line has a diameter of 50 mm and was assumed made of PE. 34,500 such service lines were assigned to model nodes with a demand (a total of 8,674 nodes). Given that any node may contain several end users, the service lines were assigned by division of the demand in each node by the average demand of 0.04 L/s.

For case A and B, the additional heat transfer across the average service line was computed with the analytical solution to Eq. 12, while using the output temperatures from the EPANET-MSX simulation in February as input. The resulting new output temperatures were used to compute a new $\Delta\dot{Q}_{\text{soil}}$ that included heat transfer in service lines.

2.9. Neighbouring water distribution networks

The EPANET model contained four nodes that represented a special case since the water from these nodes is discharged to neighbouring municipalities. In reality, the water is distributed onwards in smaller, local distribution networks that were not included in the EPANET model. The four nodes had a total discharge of 184.5 L/s and were located downstream of the HPs. As all of the discharged water was affected by the HPs, these sub-networks had to be considered in the energy balance. To account for the heat transfer taking place in these local supply networks (including service lines), the results for the supply network of Copenhagen were extrapolated by assuming that the ratio of $\Delta\dot{Q}_{\text{demand}}$ to $\dot{Q}_e$ was identical for water discharged in the city and water discharged in the local distributions networks.

3. Results

3.1. Model validation

Fig. 6 shows a comparison between the measured T_{soil} (see section 2.5.2), the measured air temperature, and a modelled soil temperature at 1.5 m depth (see section 2.6). The figure also shows the best fits of the measured air and soil temperatures to Eq. 14, as well as the yearly mean values for both.

The measured T_{soil} has the flatter curvature expected for a temperature measured at some depth. Theoretically, T_{soil} would lie somewhere between T_{air} and $T_{\text{soil,model}}$ if atmospheric air were the only heat source affecting the soil temperature (as assumed in Eq. 14). As it appears, however, the yearly mean value of T_{soil} (12.5 °C) is 3 K higher than the yearly mean air temperature in Copenhagen (9.3 °C). This difference probably reflects that the impact from direct solar radiation and/or non-natural heat sources is too significant to ignore. Other empirical soil temperature studies have showed similar results, i.e. of air temperature-based models underestimating the soil temperature by 2 K to 4 K [32,33]. Based on these considerations, the measured soil temperature was deemed a plausible estimate for the true soil temperature.

Fig. 6: Daily values of measured soil temperature, T_{soil} , from 2013 (red dots), its best fit to a sinusoidal function (red, fully drawn), and its yearly mean (red, dotted); daily mean measured air temperature, T_{air} , from a private weather station [34] in Copenhagen in 2013 (grey), its best fit to a sinusoidal function (black, fully drawn), and its yearly mean (black, finer dotted); and a sinusoidal soil temperature modelled for a depth of 1.5 m, $T_{\text{soil,model}}$ (black, longer dotted).

The water temperature is measured every week at 20 end-use points on the distribution network. The model results were compared with measurements from 15 of these sampling points, the locations of which were all represented in the model. The full network model was thus compared with weekly measurements in 15 points from week 28 of 2012 to week 36 of 2014 (see Appendix).

The Pearson's product-moment correlation was computed to assess the relationship between the measured and modelled water temperature. The results indicate a strong positive correlation between the two variables that is statistically significant ($r = 0.95$, $n = 1497$, $p < 0.001$). The best fit of a linear regression model of the modelled vs. measured water temperatures (Fig. 7) yields an $R^2 = 0.91$. Results from weeks 30-32 of 2013 have been left out from the regression since a major interruption in operation happened during that period [35], and the corresponding measurements (the outliers clearly visible in the Appendix) appear unusual.

The regression line reveals a slight skew; the model slightly overestimates water temperatures in the winter and underestimates them in the summer. This would be the case if the model somewhat underestimates heat transfer. This may be due to the lack of heat transfer in service lines in the model, which is, conversely, reflected in the measurements. It is also possible that the thermal conductivity of the soil is larger than 2.2 W/m/K . In turn, the skew is not consistent with a different soil temperature input such as T_{air} or $T_{\text{soil,model}}$ (Fig. 6).

The main deviations between simulated and measured results as well as the largest weekly fluctuations in measured temperatures appear during the summer holiday season (see Appendix). Furthermore, the bias is particularly dominated by results for three locations that are possibly influenced by specific local conditions (see Appendix).

Since the correlation is strong, and the skew is not systematically present across sampling points, the heat transfer model was considered credible and suitable for the case study.

Fig. 7: Modelled water temperatures vs. weekly measured temperatures (1497 samples from 15 sampling points). The blue dots represent the peripheral location used to determine the soil temperature.

3.2. Characteristics of the system and degree of exploitation of the heat source

Figs. 8 and 9 show the temperature distribution from EPANET-MSX of the total amount of supplied water in February and August, respectively, in both case A and B with a ΔT_{source} of 5 K. In August, less than 1% of the distributed water reaches the soil temperature of 18.9 °C in the distribution network, whether or not HPs are used (Fig. 9). For 99% of the network the residence time of the water is shorter than the time required to heat the water to soil temperature. If the residence time of all water in the system were high enough, or if the heat flux in the network were higher, the water would approach the soil temperature, thereby decreasing the additional end-use heating demand. This substantiates the need to address the additional heat transfer occurring in service lines, where the residence time is prolonged due to additional pipe lengths and low velocities.

Case B in Fig. 8 provides a few insights on the degree to which the drinking water heat source is exploited. 69% of the supplied water (the part with temperatures below 6.7 °C) has been subjected to cooling by the HPs and has to some extent regained thermal energy from the soil. 31% of the total water supply (the part with temperatures above 6.7 °C) has not been in contact with HPs, or has been significantly mixed with unexploited flows. This is water that passes the HPs while they are not operating (at night), and water that leaves the distribution mains before reaching the HPs. 2.7% of the water supply reaches the soil temperature.

3.3. Potential for heat recovery from Copenhagen's water distribution network incl. service lines

The results of simulating the heat transfer in the water distribution network and service lines are shown in Fig. 10 where $\dot{Q}_{\text{net}}$ is plotted against $\dot{Q}_e$ for five different values of ΔT_{source} (1 K to 5 K). The change in the system energy flows resulting from a ΔT_{source} of 5 K is shown in Fig. 11 as a daily average. $\dot{Q}_{\text{net}}$ in this case ($\dot{Q}_e - \Delta\dot{Q}_{\text{demand}}$) is

Fig. 8. Temperature in the distribution mains of the accumulated water delivery in February without (A) and with heat pumps and a ΔT_{source} of 5 K (B).

Fig. 9. Temperature in the distribution mains of the accumulated water delivery in August without (A) and with heat pumps and a ΔT_{source} of 5 K (B).

20.7 MW. The utilization degree, η_{util} , at any ΔT_{source} is 71% of the thermal energy extracted at the evaporator (Fig. 10). The ground-source heat of Copenhagen's soils on its own returns 38% of the extracted heat to water consumers through additional heat transfer to the distribution and service lines (Fig. 12). Of the remaining 62% of the extracted energy, 20% (equal to 12%-points) is kept by the DH system because the water fraction for cold water consumption needs no reheating by end-users. Another 33% (or 20%-points) is kept by the DH system because this water fraction is not reheated by DH, but by electricity (Fig. 12).

The magnitude of the heat extraction does not affect the degree of utilization, so the technical potential for heat utilization, $\dot{Q}_{\text{net}}$, is the net potential resulting when the installed HP capacity is maximised without causing unacceptably low end-use temperatures. The potential of 20.7 MW is obtained with a ΔT_{source} of 5 K and an average evaporator yield of 29.2 MW. With a ΔT_{source} of 5 K, 8% of the modelled demand had temperatures between 3 °C and 4 °C, but these are assumed to increase to acceptable levels in indoor piping installations affected by the ambient air temperature.

Given a COP of 3.2 for HPs in low-temperature DH zones, and 2.8 in high-temperature DH zones (the weighted average COP being 2.9), a heating potential of 44.4 MW is obtained (Fig. 11). Subtracting the additional heating demand of 8.5 MW gives a net heating potential of 35.9 MW.

The system COP is only 1.7, which owes not least to the increased end-use electricity demand for water heating that is nearly half as large as $\dot{W}_{\text{com}}$ (Fig. 11).

The results indicate that a full-scale application of large HPs in the drinking water network would cover around 2.6% of the DH peak demand, after the additional end-use DH demand has been subtracted (Fig. 13).

Fig. 10. Potential for heat utilization ($\dot{Q}_{\text{net}}$) vs. heat extraction ($\dot{Q}_e$). The temperature reduction of the source is shown.

Case B minus A

Fig. 11. Change in the system energy flows resulting from a ΔT_{source} of 5 K.

Fig. 12. Heat utilization in February with heat pumps and a ΔT_{source} of 5 K. The full height of the bar is, the energy extracted from the water supply. The sum of the grey bar elements is the heat utilization from drinking water in the DH system; and their share of the full bar height is η_{util} . The white bar element is the needed water re-heating provided by the DH system. Also shown are the contributions to heat utilization from the soil, the unheated share of drinking water, and the water share re-heated by electricity.

Fig. 13. Drinking water heat pump potential as a share of the estimated annual DH demand [36]. The heat demand applies to Copenhagen and the other municipalities whose drinking water is utilized as a heat source in this study (the Greater Copenhagen DH system in its entirety covers a larger demand than what is shown).

3.4. Significance of heat pump COP

A HP elaborately designed for the case system could reach a COP higher than the values of 2.8 and 3.2 found in this study. However, as a number of factors affect the COP, it is also possible that a lower efficiency may be obtained.

Fig. 14 shows the system COP at various values of the HP COP. A HP COP of e.g. 2.0 reduces the system COP to 1.4, which is only a little more than that of an electric boiler. Increasing the COP to 4.0 increases the system COP to just 1.9. This difference is due to the fixed end-use power and heat consumption for water heating.

3.5. Significance of pipe and soil thermal resistances

Fig. 14. System COP vs. heat pump COP.

An assessment was made of the impact of converting the network from mainly cast iron to PE, which has a lower thermal conductivity. However, the resistance of the pipe material is insignificant compared to the soil resistance (Table 5). The results indicate that the thermal resistance of soil is the main impediment to heat transfer, leaving the pipe material to be of little importance.

The exact magnitude of the soil thermal conductivity in Copenhagen is uncertain, and it appears to be of some significance. A 32% increase or decrease in the thermal conductivity of soil changes $\eta_{\text{util,soil}}$ by 11% to 15% (Fig. 15). However, η_{util} only varies between 2% and 4%, so the potential for heat utilization is not affected much.

Table 5. Sensitivity analysis for different thermal resistances included.

Thermal resistances included	$\dot{Q}_{\text{net}}$ [MW]	η_{util}	$\eta_{\text{util,soil}}$
Soil, water, pipes of cast iron etc. (present network)	20.7	0.71	0.38
Soil, water, pipes of PE (future network; main results)	20.7	0.71	0.38
Water, pipes of PE	25.3	0.86	0.71

Fig. 15. Heat utilization at different thermal conductivities of soil. The full height of each bar is $\dot{Q}_e$, the energy extracted from the water supply. The sum of the grey bar elements is $\dot{Q}_{net}$, the heat utilization from drinking water in the DH system; and their share of the full bar height is η_{util} . The percentage label on $\Delta\dot{Q}_{soil}$ is $\eta_{util,soil}$.

3.6. Water cooling

HP operation is currently expected to be uneconomical during the summer when Copenhagen's entire DH demand is met by waste incineration. However, with growing fractions of waste being recycled instead of incinerated, a part of the summer heat demand may be covered by other production technologies in the future. Furthermore, operating HPs during the warm season would contribute to preventing high drinking water temperatures. Danish regulation [37] recommends an upper temperature limit of 12 °C at the tap, but large areas in Copenhagen have difficulties meeting this limit in warm periods. HP operation in August with a $\Delta T_{source} = 5$ K increased the share of water delivered from distribution lines complying with the 12 °C limit from 42% to 81% (Fig. 9).

4. Discussion and potential future developments

4.1. Comparison with a previous case study

As previously mentioned, the EPANET-MSX modelling approach has been used for modelling HPs in drinking water systems in Almere [10], Głogów [12] and Milan [11]. For the case study in Almere, the heat utilization of the system was reportedly very high, but the heat transfer model used there did not take into account the thermal resistance of soil (cf. Table 5). The case study in Głogów assumed no need entirely for the reheating of water in the buildings. Moreover, the COP of 5.2 assumed in the Głogów study [12], seems optimistic, while the COPs of 2.8 and 3.2 used in our study may be slightly conservative.

In the present work, the heat utilization degree from soil (38%) is more than three times higher than found by De Pasquale et al. (10.3%) in Milan [11]. De Pasquale compared their heat transfer model with a model similar to the one used in the present study, labelled the shape factor model. They used air temperature as input to the shape factor model, as opposed to a modelled soil temperature at 1.5 m depth for the De Pasquale model. Their results indicated that the shape factor model overestimated heat transfer compared to the De Pasquale model.

Using our heat transfer model as the basis, Fig. 16 shows the predicted heat transfer per unit pipe length as a function of three different soil temperature inputs displayed in Fig. 6. A case where the term H has been replaced by

a fictitious soil layer of magnitude $l = \sqrt{\kappa/\omega}$ was also assessed to mirror the main difference between the shape factor model and the De Pasquale model.

Air temperature is shown to predict larger heat transfer than the modelled soil temperature at 1.5 m depth (Fig. 16). The fictitious soil layer appears to be an insignificant alteration of the shape factor model when identical soil temperatures (at 1.5 m depth) were applied for both cases. We therefore conclude that the difference between the De Pasquale model and the model used in our study is in fact insignificant.

Fig. 16: Heat flux per unit pipe length when the three temperature curves in Fig. 6 (T_{air} , T_{soil} and $T_{\text{soil,model}}$) are applied as input, and when (in a fourth case) an additional fictitious soil layer is added to the heat transfer model (blue, dotted). The inner pipe diameter is 0.2 m, and the pipe material is cast iron. The water temperature is 9 °C, and the water flow rate is 10 L/s.

The difference in results is also not a consequence of the different choice of soil temperature. The empirical soil temperature in our case study provided a more accurate basis for validating the model's performance against measurement data. But whereas the soil temperature influences heat transfer, it does not influence the heat utilization degree.

Instead, the different results must pertain to the characteristics of the two systems. Firstly, the soil conditions in Copenhagen and Milan are different; Copenhagen has waterlogged clay soils that conduct heat relatively well, resulting in more favourable conditions for heat utilization. Sensitivity analysis showed that reducing the thermal conductivity of soil from 2.2 to 1.5 W/m/K reduced $\eta_{\text{util,soil}}$ from 38% to 32%. Disregarding the heat transfer in service lines would further reduce it to 28%.

Secondly, the residence time of water in the pipes is likely to have an impact. Our modelled system has a demand nearly 7 times greater than the system studied by De Pasquale et al., and a number of pipes almost 11 times greater. The difference between these two ratios may support the assumption that the general residence time of water is higher in the Copenhagen network, which might explain the remaining difference to the Milan results. The layout of the pipe network (dimensions, length) and water velocities are key factors determining how much heat can be reaped. Individual analysis of any given water supply system therefore seems necessary to accurately assess its potential as a ground-source heat system.

4.2. Potential further model improvements

The empirical undisturbed soil temperature used in this study is considerably higher than the modelled temperatures commonly used (e.g. by [38]) to represent soil temperature at shallow depths in Denmark, but it proved more valid for Copenhagen. One limitation of this study is that when HPs operate, the radius of the soil layer that is thermally disturbed by the water pipes may increase, and so the undisturbed temperature may change as well. Developing a transient model that accounts for this situation could be a meaningful improvement. Service lines add significantly to the total pipe length and residence time of water in a system, and in our case increased $\eta_{\text{util,soil}}$ from 34% to 38%. Due to a lack of data, our study did not include private ground lines extending from the end of service

lines to the buildings. Moreover, our use of the hourly average water flow rate to compute the heat transfer in service lines is a simplification. A typical domestic demand pattern may involve great fluctuations and sustained periods with no use at all. How demand patterns and private ground lines influence the residence time and heat transfer deserves further investigation.

4.3. Competing heat sources and economic considerations

So far, the evidence points to a heat utilization degree of around 71% in Copenhagen, meaning that 29% of the evaporator capacity of a drinking water HP will be dedicated to covering the additional DH demand that arises due to its operation. The system COP is also affected, not least by the increased electricity demand. We therefore suggest that other potential heat sources should be considered before drinking water, in order to avoid the social costs involved.

Competing low-temperature sources for large HPs include air, seawater, wastewater and groundwater, but not ordinary ground-source heat. Ground-source HPs delivering 10 MW would require an area of 1 million m² for horizontal piping [39], which is hardly attainable in a dense urban environment. Ground-source HPs would also require significant investment and installation costs for new piping, which for drinking water HPs would be sunk costs.

Competing heat sources for HPs are not abundant everywhere [3], and in specific locations of interest drinking water HPs may be the only feasible option. In such cases, only an economic feasibility study will reveal if the benefits of their operation offset the cost of the additional demand. Such economic analysis depends on details related to the alternative heat supply technology, fuel and electricity costs, as well as taxation or subsidy schemes. A complete assessment considering both private-economic, such as presented in [2], and socio-economic analysis should be carried out to reflect the real value of new capacity.

4.4. Additional heat pump potential from the water supply

In [3] the estimated potential heating capacity of HPs using drinking water as heat source in Greater Copenhagen was 13.5 MW. The present work shows a potential more than 50% higher. The principal reason for this difference is that [3] only included reservoirs and waterworks, and not the water distribution mains.

This study has focused on the potential for applying large drinking water HPs in the City of Copenhagen, and this implied exploitation of roughly 69% of the water supply. The remaining 31% of the water is either distributed upstream of the HPs, or passes the HPs while they are not operating at night. A real implementation of HPs might permit some operation during the night if it would involve a system control of a set minimum exit temperature of the water. This would prevent excessive cooling even as the water changes direction several times. A minimum number of full load hours for the HP would be required to cover the installation cost. Thus, for several of the HP locations, the challenge with limited potential hours of operation (Fig. 5) would have to be overcome, or they could turn out infeasible.

The water that is distributed upstream of HPs represents an unexploited potential that could be harnessed by means of HPs upstream of Copenhagen or HPs smaller than 1 MW inside Copenhagen. Potential HP locations in neighbouring municipalities might thus be worth considering, not least the reservoir, which is located outside the city but within the same DH transmission area. Not only is the reservoir more accessible for installation and maintenance works; it also circumvents the problem with water flow reversal limiting HP operation on several main lines during the night.

5. Conclusion

This study investigated the potential for large drinking water HPs in Copenhagen's DH system, based on a number of technical constraints for the HPs, including their operational profile, their distance to a DH network, and differences in supply temperatures. The potential was assessed by determining the energy balance for drinking water

through simulation of the ground-source heat that is transferred to the water distribution lines after HPs have cooled the water. A heat transfer model was developed for simulation of system-wide temperatures in a piped water network using the EPANET-MSX model. Our simulations were validated against measured temperatures in an actual drinking water network, and the use of empirical urban soil temperatures proved key to achieving a valid model.

Model simulations showed that the ground-source heat of Copenhagen's soils returned 38% of the extracted heat to water consumers through additional heat transfer to the distribution lines. This is more than found in a previous study, probably due to better thermal properties of the soil and higher residence times of water in the supply system.

A share of the drinking water is not re-heated by end-users. Taking that share into account, the results showed a potential 71% utilization degree for water distribution mains used as a heat source for HPs in Copenhagen's DH system.

The simulations showed a total net potential of 20.7 MW (evaporator capacity) for eight large drinking water HPs. With HP COPs ranging from 2.8 to 3.2, the resulting net heating potential was 35.9 MW corresponding to 2.6% of the DH peak demand. The corresponding system COP of the drinking water HPs was 1.7. The results indicate that drinking water HPs should only be considered where other heat sources are unavailable.

The study also investigated the derived cooling effect experienced by end-users. This is an added value to be considered from drinking water HPs in warmer periods. Simulation of HP operation in August increased the share of distributed water complying with the 12 °C recommended upper limit from 42% to 81%.

Acknowledgements

We thank HOFOR A/S for providing the hydraulic network model and water temperature measurement data used in this study. We thank CTR I/S for providing air temperature measurement data.

Appendix

The heat transfer model results were compared with water temperature measurements from 15 sampling points at end-use nodes across the network. The full network model was thus compared with weekly measurements in 15 points from week 28 of 2012 to week 36 of 2014. Since sampling is undertaken in the morning, averaged model results for the five hours between 7 a.m. and 12 p.m. were used.

The model predicts the water temperature well for the 15 sampling locations, with a few exceptions. Locations m), n) and o) have measured summer temperatures somewhat higher than the modelled ones. It is possible that these test locations are influenced by specific local conditions such as very long service lines. A map of the three locations indicates service line lengths between 23 m and 50 m [40]. For these locations, the exact timing of the water sampling also seems key; the model predicts significant temperature differences between early morning hours and noon, which may explain the disparity.

Location f) has modelled temperatures generally higher than the measured ones. The locality of this sampling point has undergone significant development in recent years, so it is quite possible that the water demand has increased and the residence time has decreased since the hydraulic model was developed. This would explain the difference. In general, small alterations and simplifications in the network model compared to the real set-up can explain deviations between simulated and observed results.

Fig. 17: Measured and modelled water temperature data from 15 locations in Copenhagen from July 2012 to August 2014. Model averages are shown together with the minimum and maximum values obtained between 7 a.m. and 12 p.m.

References

- [1] H. Lund, S. Werner, R. Wiltshire, S. Svendsen, J. E. Thorsen, F. Hvelplund, B. V. Mathiesen, 4th Generation District Heating (4GDH) Integrating smart thermal grids into future sustainable energy systems, *Energy* 68 (2014) 1-11.
- [2] H. Pieper, V. Mašatin, A. Volkova, T. Ommen, B. Elmegaard, W.B. Markussen, Modelling framework for integration of large-scale heat pumps in district heating using low-temperature heat sources: A case study of Tallinn, Estonia, *International Journal of Sustainable Energy Planning and Management* 20 (2019) 67-86.
- [3] B. Bach, J. Werling, T. Ommen, M. Münster, J.M. Morales, B. Elmegaard, Integration of large-scale heat pumps in the district heating systems of Greater Copenhagen, *Energy* 107 (2016) 321-334.
- [4] S.S. Cipolla, M. Maglionico, Heat recovery from urban wastewater: Analysis of the variability of flow rate and temperature, *Energy and Buildings* 69 (2014), 122-130.
- [5] M. Abdel-Aal, A. Schellart, S. Kroll, M. Mohamed, S. Tait, Modelling the potential for multi-location in-sewer heat recovery at a city scale under different seasonal scenarios, *Water Research* 145 (2018), 618-630.
- [6] P. Fleuchaus, B. Godschalk, I. Stober, P. Blum, Worldwide application of aquifer thermal energy storage – A review, *Renewable and Sustainable Energy Reviews* 94 (2018), 861-876.
- [7] R. de Graaf, F.H.M. van de Ven, I.J. Miltenburg, B. van Ee, L.C.E. van de Winckel, G. van Wijk, Exploring the technical and economic feasibility of using urban water system as a sustainable energy source, *Thermal Science* 12(4) (2008), 35-50.
- [8] S. Liu, C. Gunawan, N. Barraud, S. A. Rice, E. J. Harry, R. Amal, Understanding, monitoring and controlling biofilm growth in drinking water distribution systems, *Environmental Science & Technology* 50 (2016) 8954-8976.
- [9] J.A. Elías-Maxil, J.P. van der Hoek, J. Hofman, L. Rietveld, Energy in the urban water cycle: Actions to reduce the total expenditure of fossil fuels with emphasis on heat reclamation from urban water, *Renewable and Sustainable Energy Reviews* 30 (2014), 808-820.
- [10] E. J. M. Blokker, A.M. van Osch, R. Hogeveen, C. Mudde, Thermal energy from drinking water and cost benefit analysis for an entire city, *Journal of Water and Climate Change* 4:1 (2013) 11-16.
- [11] A.M. De Pasquale, A. Giostri, M.C. Romano, P. Chiesa, T. Demeco, S. Tani, District heating by drinking water heat pumps: Modelling and energy analysis of a case study in the city of Milan, *Energy* 118 (2017) 246-263.
- [12] P. Jadwiszczak, E. Niemierka, Water pipe network as a heat source for heat pump integrated into a district heating, *E3S Web of Conferences* 22 (2017), art. no. 00210
- [13] J.P. van der Hoek, S. Mol, S. Giorgi, J.I. Ahmad, G. Liu, G. Medema, Energy recovery from the water cycle: Thermal energy from drinking water, *Energy* 162 (2018), 977-987.
- [14] Greater Copenhagen Utility, 2012. HOFOR, EPANET model of Copenhagen, version 2009, modified 2012. Received from C. Hansen on April 11 2014.
- [15] L. A. Rossmann, EPANET 2 Users Manual, National Risk Management Research Laboratory, Cincinnati, 2000.
- [16] F. Shang, J. G. Uber, L. A. Rossmann, EPANET Multi-Species Extension User's Manual, University of Cincinnati, Cincinnati, 2008.
- [17] E. J. M. Blokker, E. J. Pieterse-Quirijns, Modeling temperature in the drinking water distribution system, *Journal American Water Works Association* 105 (2013) E19-E28.
<https://doi.org/10.1002/awwa.1178>
- [18] A. Moerman, M. Blokker, J. Vreeburg, J.P. van der Hoek, Drinking water temperature modelling in domestic systems, *Procedia Engineering* 89 (2014) 143-150.
- [19] M. Rygaard, L. Alsbyørn, M. Ejsing, B. Godskesen, R. Hansen, B. Hoffmann, C. Jørgensen, K. Ledgaard, H.-M. F. Møller, M.-B. B. Poulsen, M. Schmidt, L. Tarp-Johansen, S. Vigso, K. Zambrano, Sekundavand i Nordhavn - En forundersøgelse til strategi for alternativ vandleverance, Technical report, Technical University of Denmark, Lyngby, 2013.
- [20] Københavns Kommune, Vandforsyningsplan 2012, Teknik og Miljøforvaltningen, København, 2012.
- [21] A. B. Lauritsen, Varme Ståbi, Nyt Teknisk Forlag, Copenhagen, 2009.
- [22] B. Kvisgaard, S. Hadvig, Varmetab fra fjernvarmeledninger. Heat loss from pipelines in district heating systems, Technical report, Technical University of Denmark, Lyngby, 1980.
- [23] Y. A. Çengel, Heat and mass transfer. A practical approach, McGraw-Hill, New York, 2007.
- [24] B. Bøhm, On transient heat losses from buried district heating pipes, *International Journal of Energy Research* 24 (2000), 1311-1334.
- [25] M. Ouzzane, P. Eslami-Nejad, M. Badache, Z. Aidoun, New correlations for the prediction of the undisturbed ground temperature, *Geothermics* 53 (2015) 379-384.
- [26] A. D. Rosa, H. Li, S. Svendsen, Method for optimal design of pipes for low-energy district heating with focus on heat losses, *Energy* 36 (2011) 2407-2418.
- [27] C. Hansen, personal communication. Emails to author from May 6, September 24 and October 29 2014.
- [28] C. Ditlefsen, I. Sørensen, D6 Overfladenære jordarters termiske egenskaber, 2014. (Technical report, Energistyrelsen, Energiteknologisk Udviklings- og Demonstrations-Program).
- [29] T. Ommen, W.B. Markussen, B. Elmegaard, Heat pumps in combined heat and power systems, *Energy* 76 (2014) 989-1000.
- [30] T. Ommen, J.K. Jensen, W. Meesenburg, P.H. Jørgensen, H. Pieper, W.B. Markussen, B. Elmegaard, Generalized COP estimation of heat pump processes for operation off the design point of equipment, *Proceedings of the 25th IIR International Congress of Refrigeration*, 2019.
- [31] D. Hillel, Introduction to soil physics, Academic Press, San Diego, CA, 1982.
- [32] J. Wu, D. L. Nofziger, Incorporating temperature effects on pesticide degradation into a management model, *Journal of Environmental Quality* 28 (1999) 92-100.

- [33] T. Kurevija, D. Vulin, Determining undisturbed ground temperature as part of shallow geothermal resources assessment, Rudarsko-geološko-naftni zbornik 22 (2010) 27-36.
- [dataset] [34] CTR I/S, Data from weather station, 2013.
- [35] Greater Copenhagen Utility, HOFOR, Rapport HOFOR Vand og Spildevand 2013, Technical Report, HOFOR A/S, København, 2014.
- [dataset] [36] Greater Copenhagen Utility, HOFOR, Estimated annual DH demand distribution, 2019.
- [37] BEK nr 1068 af 23/08/2018. Retrieved on <https://www.retsinformation.dk/forms/R0710.aspx?id=202768>, on February 1, 2019
- [38] Danmarks Meteorologiske Institut, Teknisk Rapport 2001-2010 Dansk Design Reference Year Supplerende Datasæt, Technical Report, Danmarks Meteorologiske Institut, København, 2013.
- [39] B. Bach. Integration of heat pumps in Greater Copenhagen. MSc thesis at the Technical University of Denmark, 2014.
- [40] Greater Copenhagen Utility, 2019. Service lines maps retrieved from <https://www.hofor.dk/privat/vand/kort-over-stopphaner/>

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49