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Assessment of techno-economic feasibility of centralised seasonal thermal energy storage for decarbonising the Swiss residential heating sector

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ABSTRACT

A major part of heat in Swiss residential buildings is supplied by fossil fuel boilers, leading to large CO_2 emissions. Heat supply can be decarbonised by replacing boilers with renewable energy sources (RES) such as solar thermal, but the mismatch between heat supply and heat demand needs to be overcome. Seasonal thermal energy storage (STES) can be used to store heat from solar collector (SC) thereby reducing the usage of boilers. A centralised heat pump (HP) is also an attractive alternative for heating. This paper assesses the techno-economic feasibility of different heating systems for decarbonising the Swiss residential heating sector. It uses the simulation method for assessing hourly energy flows in 500 and 1,000 multifamily households connected by a district heating (DH) system. Four different configurations of DH system are assessed by simulating hourly energy flows. The required capacity of equipment, cost of different systems, and the cost of decarbonisation of heat are calculated. Levelised cost of heat, CO_2 emissions and share of RES are compared. Peak electricity load due to use of HP and the impact of using different emission factors for electricity is examined. Results show that the heating system with a centralised HP has the least cost of decarbonisation but it adds a high peak load on the electricity grid infrastructure. A heating system with a SC, a STES, HP and a boiler emerges as a cost competitive option for decarbonising heating for 1,000 dwellings.

1. Introduction

Heating and cooling contributed to about 50% of the final energy consumed in EU-28 countries (2015). Space heating (SH) contributed to 27% of energy end use, followed by process heating (16%); hot water (4%); other heating, space cooling, and process cooling (1% each) [1]. It is estimated that about 75% of heating (and cooling) in EU-28 countries was supplied by fossil fuels leading to large greenhouse gas (GHG) emissions [2]. In order to lower emissions, the European Commission (EC) proposed a ‘European Green Deal’ in December 2019, which raises the 2030 target of reduction of GHG emissions to 50–55% and aims to reach net-zero GHG emissions by 2050 [3]. The European parliament adopted the resolution on European Green Deal on 15 January 2020 and will continue to work on specific measures and policy actions [4].

Switzerland shows similar trends with heating contributing to 49% of the final energy consumption. In 2018, SH demand was 219 PJ (30%), hot water demand was 46 PJ (6%) and process heat demand was 95 PJ (13%) [5]. The residential sector contributed to about 66% of SH demand (145 PJ) and 70% of domestic hot water (DHW) demand (32 PJ). Oil was the largest source of heat (39%); followed by gas (25%); electric resistance heating (10%); wood (10%); ambient heat (7%); district heating (DH) (5%); electricity used in heat pump (HP) (4%); and solar heat (1%) [6]. As a high share of heat is produced by fossil fuels, the Swiss residential heating sector needs to be decarbonised and some strategies were examined in Ref. [7].

Use of fossil fuels for heating leads to poor exergy efficiency and

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Abbreviations

ATES Aquifer thermal energy storage
B Boiler
CRF Capital recovery factor
DH District heating
DHW Domestic hot water
EC European Commission
EF Emission factor
ETC Evacuated tube collector
GHG Greenhouse gas
HE Heat exchanger
HIU Heat interface unit
HP Heat pump
HWT Hot water tank
KPI Key performance indicator
MFH Multi-family household
MILP Mixed integer linear programming
O&M Operation and maintenance
PES Primary energy supply
PTES Pit thermal energy storage
RES Renewable energy sources
SC Solar collector
SFH Single-family household
SH Space heating
SIG Services Industriels de Geneve
STES Seasonal thermal energy storage
TES Thermal energy storage
TRNSYS Transient system simulation
WWTP Waste water treatment plant

List of symbols

A_{avg} Average heated surface area of dwelling [m^2]
$AC_{el.HP}$ Annual cost of electricity for HP [CHF/yr]
AC_{gas} Annual cost of natural gas [CHF/yr]
AC_{sys} Total (capital and O&M) annualised cost of heating system [CHF/yr]
AC_{dec} Annualised cost of decarbonisation [CHF/ton CO_2]
B Length of bottom of STES [m]
C_A Area of solar collector [m^2]
CC_{eqpt} Specific capital cost of equipment [CHF/unit]
$C_{o\&m}$ O&M cost factor [%]
$C_{y.avg}$ Average annual SC yield [Wh/m^2]
C_y Annual SC yield [Wh/m^2]
dQ_{int} Internal energy change in the STES over the year [Wh]
d_t, d_s, d_b Thickness of insulation of STES (top, side and bottom, respectively) [m]
$EF_{el.cat}$ Emission factor of electricity (category = 1,2,3) [g CO_{2-eq}/kWh]
EF_{gas} Emission factor of natural gas [kg CO_2/kg]
$E_{in.boil}$ Primary energy input to boiler [Wh]
$E_{in.el}$ Primary energy input to HP [Wh]
EM_{el} CO_2 emissions from electricity [tons CO_2]
EM_{gas} CO_2 emissions from gas boiler [tons CO_2]
EM_{sys} Total CO_2 emissions from heating system [tons CO_2]
F_{cc} Capital cost factor [-]
F_{ic} Installation cost factor [-]
H Height of STES [m]
LCOH Levelised cost of heat [CHF/MWh]
n Lifetime of equipment [yr]
N Number of dwellings [nos.]
$O\&M_{eqpt}$ Annual fixed operation and maintenance cost of equipment [CHF/yr]
$P_{gas.pow}$ Power charges for natural gas [CHF/kW/yr]
$P_{el.type}$ Price of specific type of electricity [CHF/kWh]
$P_{gas.type}$ Price of specific type of natural gas [CHF/kWh]
$P_{gas.sub}$ Subscription charges for natural gas [CHF/yr]
Q_{amb} Heat extracted from waste water [Wh]
Q_{boil} Heat supplied by boiler [Wh]
Q_{dem} Total annual heating demand [Wh]
$Q_{DH.loss}$ Heat loss in DH system [Wh]
Q_{dir} Heat supplied directly by SC to DH system [Wh]
Q_{el} Heat supplied by electricity [Wh]
Q_{exc} Excess heat [Wh]
Q_{HE} Heat extracted from STES by HE [Wh]
Q_{HP} Total heat supplied by HP [Wh]
$Q_{in.HP}$ Heat extracted from STES by HP [Wh]
Q_{in} Heat into STES [Wh]
$Q_{initial}$ Heat content in the STES at the start of year [Wh]
Q_{loss} Heat loss from STES [Wh]
$\dot{Q}_{max.boil}$ Maximum capacity of boiler [W]
$\dot{Q}_{max.HP}$ Maximum capacity of heat pump [W]
Q_{max} Maximum heat storage capacity of STES [Wh]
Q_{min} Minimum heat storage capacity of STES [Wh]
Q_{spec} Annual specific heat demand of dwelling in MFH [kWh/m^2]
Q_{sto} Heat stored in STES [Wh]
Q_{sum} Heat supplied to DH system [Wh]
Q_{sup} Heat generated by SC [Wh]
r Discount rate [%]
R Length of top of STES [m]
R_A Required roof area [m^2]
RES_{sh} Percentage share of RES in total heat supply [%]
Sh_{cc} Share of capital cost of equipment as a percentage of total cost [%]
Sh_{ic} Share of installation cost as a percentage of total cost [%]
$Sh_{RE.el}$ Percentage share of RES in PES for producing electricity [%]
S_r Global solar irradiance on a vertical plane [Wh/m^2]
$T_{avg.soil}$ Average (yearly) temperature of soil (around the STES) [°C]
T_{DH} Average (yearly) supply temperature of DH system [°C]
$T_{max.sto}$ Maximum temperature in STES [°C]
$T_{min.sto}$ Minimum temperature in STES [°C]
$T_{rtn.DH}$ Average (yearly) return temperature of DH system [°C]
T_{sto} Average temperature of STES [°C]
$T_{top.sto}$ Estimated temperature at top of STES [°C]
T_{water} Ambient temperature of waste water [°C]
V Volume of STES [m^3]
η_{boil} Thermal efficiency of natural gas boiler [%]
η_{col} Solar collector efficiency [%]
η_{el} Efficiency of conversion of PES to electricity [%]
η_{HP} HP efficiency [%]
η_{sys} Solar collector system efficiency [%]
η_{STES} STES storage efficiency [%]
λ_{soil} Thermal conductivity of soil [W/m. K]
λ_t, λ_s, λ_b Thermal conductivity of insulation of STES (top, side and bottom, respectively) [W/m. K]

hence heat demand in buildings ought to be met by low temperature heat sources. HP and solar collector (SC) can replace fossil fuels boiler in single-family household (SFH). Centralised solar thermal plant and ambient heat from river, lake, waste water treatment plant (WWTP) and geothermal heat can be harnessed using large HPs and this heat can be distributed by a DH system thereby replacing/lowering the use of boilers.

One limitation of solar energy is that it is available only during the day and has relatively low output in winter, while heat demand peaks in winter months. In order to overcome the temporal mismatch between availability and demand of heat from renewable energy sources (RES), thermal energy storage (TES) can be used to store heat over shorter (hourly, daily) and longer (monthly, seasonal) time frames. Short term heat storage can lower electricity use for HP, thereby lowering CO_2 emissions [8]. Seasonal thermal energy storage (STES) can also enhance grid stability while enabling smart grids. Lastly, there is a growing trend of decarbonisation and digitalisation of the energy system and TES along with DH system, solar thermal and HPs can play an important role in enabling a global energy transition.

TES have been analysed in Annex 30 (TES for cost-effective energy management & CO_2 mitigation) and Annex 32 (Modelling of energy storage for simulation/optimisation of energy systems) undertaken by the International Energy Agency [9]. Details and guidelines for design of TES systems were presented in Refs. [10,11]. Studies have also examined the techno-economic feasibility of solar DH assisted by STES at a country level for Spain [12]; Denmark [13–16]; China [17,18]; Greece [19]; UK [20]; Finland [21] and Europe [22].

Use of solar thermal with an existing DH system has been examined in Ref. [23–25] analysed the integration of HP into solar DH systems with STES [26]; reviewed the current applications of different STES with a HP in low temperature buildings and [27] used simulation models for evaluating the feasibility of integration of TES at building and neighbourhood scale [28]. models TES system as a mixed integer linear programming (MILP) distributed energy resource model while the design and optimisation of solar DH with STES in multi energy systems has been examined in Ref. [29–33]. Specific models have been designed to examine the feasibility of installation of TES in the context of project 'Sunstore' [34]. The Effective Integration of Seasonal Thermal Energy Storage Systems in Existing Buildings (EINSTEIN) tool has also been used for examining the feasibility of using STES in existing or retrofitted buildings [35]. Most of these studies use TRNSYS (Transient system simulation tool) and are country specific.

Specifically, in the context of Switzerland, a study for installing a borehole TES to store waste heat and discharging it using a HP was undertaken for the Empa campus, Dubendorf [36]. [37] outlined the important projects undertaken in Switzerland for low and high temperature heat storage [38]. examined four cases (centralised/decentralised, short/long term energy storage) using MILP for 11 building neighbourhood in Switzerland and concluded that both short and long-term TES units are essential to integrate solar heat in residential buildings.

Although large STES have been implemented in different locations around the world, there is no comprehensive assessment for evaluating the feasibility of large STES in Switzerland. It is important to undertake such studies for different countries as heat demand, heat supply, cost of fuel, electricity, equipment, CO_2 emission intensity of electricity etc. differ across locations and hence may lead to different results. Further, in the face of stringent goals for net zero emissions, the objective of energy planners is gradually shifting away from least cost options to decarbonisation and hence it is important to calculate the cost of decarbonisation of heat.

The aim of this paper is to assess the techno-economic feasibility of centralised STES for decarbonising the Swiss residential heating sector. This paper fills an important gap as there is no reported study which examines the techno-economic feasibility of centralised STES in Switzerland. Such a pre-assessment which does not use proprietary tools (such as TRNSYS) and compares different heating system configurations, give energy planners a first estimate of size, cost and environmental benefits of integrating a STES for decarbonising residential heating. Section 2 presents the method and material for the assessment and section 3 presents the simulation results. Section 4 discusses the policy implications and section 5 concludes the paper.

2. Method and material

This study uses the simulation method for assessing hourly energy flows in DH system with STES developed and validated in Ref. [39]. It compares four different configurations of DH systems to examine the techno-economic feasibility of using STES for decarbonising heating. This assessment has been implemented on a spreadsheet and is intended to be made publically available.

2.1. Framework of assessment tool

The framework of the assessment tool is shown in Fig. 1. The tool consists of an 'energy system assessment' and an 'economic and environmental assessment' component. The former consists of four different heating system models (one for each configuration) which are integrated with a STES sub-model. Energy flows in different configurations of the heating system and temperature in the STES are calculated in this component. Various inputs such as heat supply and demand profiles, emission factors, costs, and other model inputs are provided exogenously to the tool and the simulation is undertaken for 8760 h of one year. The obtained hourly energy flows are aggregated and assessment parameters and key performance indicators (KPIs) are calculated.

The tool is designed to examine the pre-feasibility of four different heating system configurations and can be used for different number of dwellings. This paper examines the case for 500 and 1,000 dwellings connected to a centralised DH system in multi-family household (MFH) at Geneva, Switzerland. Specific inputs used for the simulation are explained ahead.

2.2. Heating systems configurations

Energy models of four different configurations (listed below) and their simplified energy flows are shown in Fig. 2. Natural gas boilers have been considered for the assessment.

- Configuration 1: System with only a boiler (B)
- Configuration 2: System with SC, STES with heat exchanger (HE), and boiler (SC/STES/B)
- Configuration 3: System with SC, STES with HE & HP, and boiler (SC/STES/HP/B)
- Configuration 4: System with only a heat pump (HP)

MFHs are connected to a DH system with a buffer tank. The DH system distributes hot water at T_{DH} (assumed to be constant over the year) for meeting the SH and DHW demand in different dwellings and the return temperature of water is $T_{rtn.DH}$. The basement of the building has a heat interface unit (HIU). A HE is used to provide hot water to the radiators fitted in different dwellings and a common hot water tank (HWT) meets the need of DHW. The total heat demand is

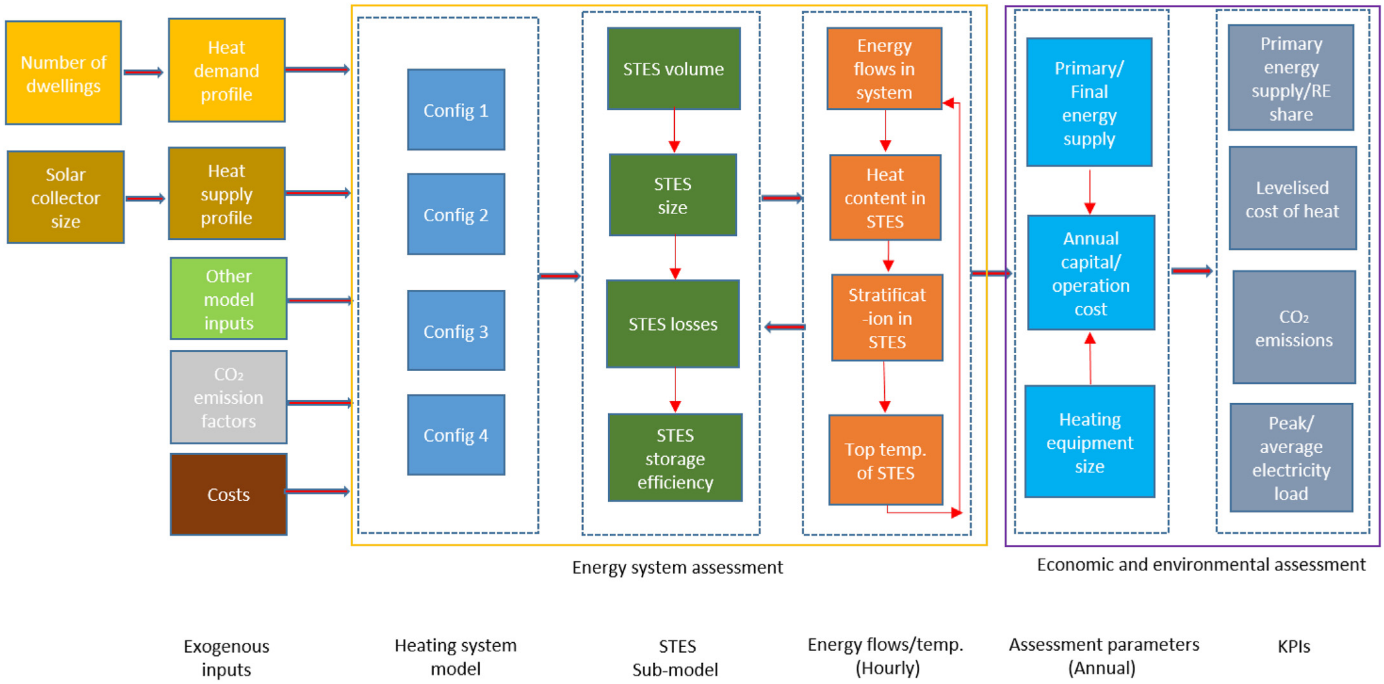

Fig. 1. Framework of the assessment tool.

Q_{dem} and the total heat supplied to the DH system is Q_{sum}, to account for the heat loss ($Q_{DH.loss}$) in the DH system.

In configuration 1, a centralised boiler with efficiency η_{boil} provides heat and the primary energy used in the boiler is $E_{in.boil}$. In configuration 2, evacuated tube collector (ETC) type SCs are fixed on the building rooftops and generate Q_{sup}. They supply the heat directly to the DH system (Q_{dir}) when the sun is shining and the excess heat (Q_{exc}) in summer is supplied to the STES (Q_{in}). A HE is used to extract heat from the STES (Q_{HE}) and provides it to the DH system when there is inadequate heat supply from the SC. The boiler provides the balance heat (Q_{boil}). Configuration 3 additionally has a HP with efficiency η_{HP} which extracts heat from the STES ($Q_{in.HP}$) and provides Q_{HP} to the DH system. Heat supplied by electricity for the HP is Q_{el} (equals electricity consumed by the HP) and the primary energy required to produce Q_{el} is $E_{in.el}$, where η_{el} is the conversion efficiency of primary energy supply (PES) to electricity. The heat loss from the STES is Q_{loss}. The priority of supply of heat is SC, HE, HP, and boiler. In configuration 4, a water-water HP is used to extract ambient heat (Q_{amb}) which is available at a higher than ambient temperature (T_{water}) from the WWTP.

2.3. STES

The physical design and the energy model of the STES have been explained in this section.

2.3.1. Heat storage capacity

Maximum heat storage capacity of the STES (Q_{max}) is decided based on the expected heat supply and demand, excess heat available and the strategy of operation of the STES. The size of the STES is optimised by system designers in order to have maximum utilisation of heat storage capacity, while minimizing the size (and hence the cost) of the STES. However, in this paper, the size of the STES is not optimised and is pre-decided. In order to determine Q_{max}, the expected heat demand from buildings is calculated using Equation (1).

$$Q_{dem} = A_{avg} \cdot Q_{spec} \cdot N \quad (1)$$

The average heated surface area (A_{avg}) of a dwelling in a MFH (in considered buildings) is around 76 m^2 and the annual specific heat demand (Q_{spec}) is around 106 kWh/ m^2 (Determined as explained later in section 2.4). The number of dwellings (N) is chosen as 500 and 1,000. Q_{max} is then pre-selected as 45% and 35% of Q_{sum}, for configurations 2&3, respectively as a design criterion (reason explained in detail later). An underground trapezoidal pit thermal energy storage (PTES) is considered suitable for storing large volume of water and the designed parameters for PTES are shown in Table 1. $Q_{DH.loss}$ is the heat loss in DH system and is assumed as 10%.

2.3.2. Volume and dimensions

The volume of the STES required for storing Q_{max} is calculated using Equation (2),

$$V = \frac{Q_{max} \cdot (3.6) \cdot 10^6}{(T_{max.sto} - T_{min.sto}) \cdot 4180} \quad (2)$$

where $T_{max.sto}$ and $T_{min.sto}$ are the designed maximum and minimum temperature of water stored in the STES.

The optimal dimensions of the PTES to store the required volume of water are calculated such that the surface area and hence the heat losses are minimized. The recommended dimensions (for non-cohesive soil) with 33° incline are given by Equation (3) [40].

$$R = \sqrt[3]{\frac{V}{0.221}}; H = 0.55 \cdot R; B = 0.175 \cdot R; \quad (3)$$

λ_t, λ_s, λ_b are the thermal conductivities of insulation and d_t, d_s, d_b are the thicknesses of insulation of the top, side and bottom of the PTES, respectively. λ_{soil} is the thermal conductivity of the soil and $T_{avg.soil}$ is the average soil temperature. Q_{sto} is the heat stored and T_{sto} is the average temperature in the PTES. The parameters of

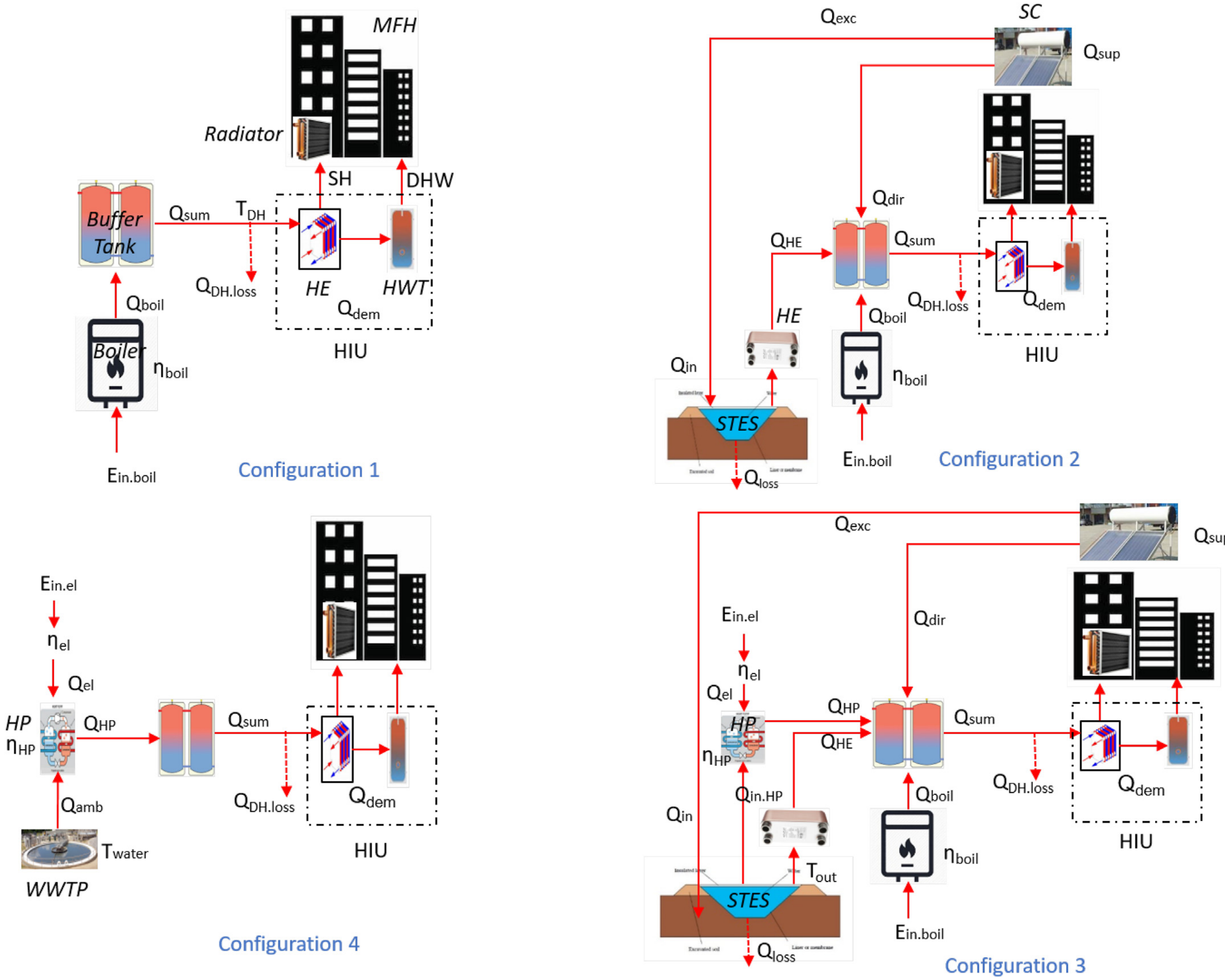

Fig. 2. Heating system configurations and simplified energy flows.

Table 1
Designed parameters for PTES.

Parameter	For 500 dwellings	For 1,000 dwellings	Comments
	Heat (MWh/year)		
Q_{dem}	4,008	8,015	Using Eqn (1)
Q_{sum}	4,408	8,817	Adding $Q_{DH.loss}$ to Q_{dem}
Q_{max} Config. 2	1,984	3,968	To provide 45% of Q_{sum}
Q_{max} Config. 3	1,543	3,086	To provide 35% of Q_{sum}

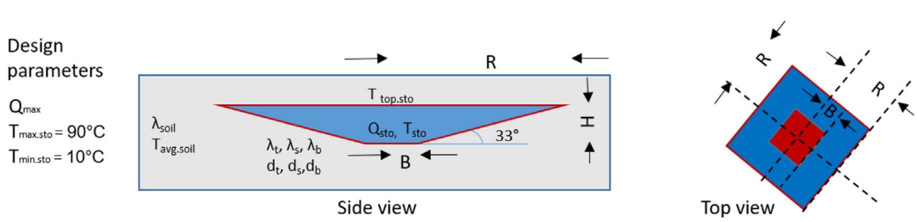

Fig. 3. Parameters and design of PTES.

the PTES are shown in Fig. 3 and the selected values are placed at Table 3.

2.3.3. Stratification

Stratification in a tank results in different temperatures and the assumed stratification model for STES has been explained in Ref. [39]. The expected temperature at the top of the PTES ($T_{top.sto}$) is a function of heat stored (Q_{sto}), and the stratification profile for PTES with 1,000 MFHs for configurations 2&3 is shown in Fig. 4. It is assumed that $T_{max.sto}$ is obtained when the heat content in the PTES is 80% of Q_{max}.

2.3.4. Energy flows and storage efficiency

Hourly heat losses from the PTES (Q_{loss}) are calculated for each configuration and its calculation is explained in detail in Ref. [39]. Heat content in the PTES changes based on the heat supplied (Q_{in}) and extracted (Q_{HE}, $Q_{in.HP}$) from the PTES. The operation of HE and HP is shown in Fig. 5.

The HE is operated if $T_{top.sto}$ is greater than T_{DH}. The HP is operated if the HE cannot be operated and if Q_{sto} is greater than $Q_{initial}$. It is assumed that at the beginning of the year, 60% of heat is available in the PTES ($Q_{initial} = 0.6 \cdot Q_{max.sto}$). STES storage efficiency (η_{STES}) is calculated using Equation (4).

$$\eta_{STES} = \frac{Q_{HE} + Q_{HP} + dQ_{int}}{Q_{in}} \quad (4)$$

where, dQ_{int} is the internal energy change in the STES.

2.4. Heat demand profile

The hourly heat demand profile is generated using the following steps and is provided exogenously. a) [41] developed a library of heat demand load curves based on measured data from various buildings in Switzerland. From these load curves, a probabilistic model of hourly heat demand was developed. Each building of the Swiss national building register was then linked to a normalized load curve randomly chosen from the library of load curves for that building type. The aggregate load curve for that building was then scaled depending on the number of dwelling units in the building as determined in Ref. [42]. b) As the load curves were associated with whole buildings, residential MFH buildings were randomly sampled from the building registry sequentially until the total number of dwellings were 500 and 1,000. The heat demand load curves for those MFHs were then retrieved from the database and aggregated into two different heat demand profiles for 500 and 1000 dwellings.

2.5. Heat supply profile

The size of SC and hourly solar radiation determines the heat supply profile which is calculated using Equation (5).

$$Q_{sup} = C_{y.avg} \cdot C_A \quad (5)$$

The average annual SC yield ($C_{y.avg}$) and the area of SC (C_A) is determined as shown ahead.

2.5.1. Hourly solar collector yield

a) Hourly solar radiation at Geneva for the year 2017 is used for the assessment. SCs are assumed to be fixed and do not track the sun.
b) The hourly global solar irradiance on a 35° tilted plane (South, East and West orientation) at Battelle monitoring station located at Geneva, Switzerland (Latitude: 46.17 N, Longitude: 6.14 E, altitude: 432 m) was used. The annual solar irradiance for South, East and West facing panels was calculated as 1.57, 1.23 and 1.26 MWh/ m^2 /year respectively.
c) The annual SC yield (C_y) for different orientations was calculated using Equation (6).

$$C_y = S_r \cdot \eta_{col} \cdot \eta_{sys} \quad (6)$$

where S_r is the global solar irradiance on a vertical plane and η_{col} and η_{sys} are the efficiency of the SC and SC system efficiency, respectively. The values of these parameters are shown in Table 3. C_y was calculated as 0.94, 0.73 and 0.75 MWh/m^2 -yr for South, East and West facing SC respectively and the $C_{y.avg}$ was calculated as 0.81 MWh/m^2 -yr.

2.5.2. Size of SC

As ground mounted SC are not suitable in a city due to lack of space, this study assumes that the area available for SC is limited by the roof area. A detailed assessment can be undertaken by identifying the roof area on specific buildings in a neighbourhood.

It is observed that the available roof area in column (f) is always greater than calculated value of R_A in column (e) in Table 2. This implies that the available roof area is sufficient to install C_A and it would be able to generate at least 80% of the heat supplied to the DH system over the year.

Table 2
Supply and demand parameters for different number of dwellings.

Dw. (nos.) (*a*)	Q_{sum} (MWh) (*b*)	Q_{sup} (MWh) (*c*) = 80%·(*b*)	C_A (m^2) (d) = (c)/$C_{y.avg}$	R_A (m^2) (*e*) = (*d*)·(4/3)	Available roof area (m^2) (*f*) = 12·(*a*)
500	4,408	3,527	4,360	5,813	6,000
1,000	8,817	7,053	8,720	11,627	12,000

a) Table 2 shows the calculated parameters for different number of dwellings.
b) Expected heat to be supplied to DH system (Q_{sum}) is known for different number of dwellings.
c) Q_{sup} is fixed as 80% of Q_{dem} as a design criterion.
d) C_A to generate required Q_{sup} is calculated using Equation (5).
e) It is assumed that (on an average) one fourth of the roof area will be facing North and this area is not covered with SCs as the annual solar irradiation is low. Hence the minimum roof area required (R_A) to generate Q_{sup} is calculated as shown in Table 2
f) It is to be ascertained that the available roof area is greater than R_A. The available roof area is calculated using the following assumptions.
i. 5 floors per building, 2 dwellings per floor, building footprint of 200 m^2
ii. Roof area available for SC per building = 120 m_2 (assuming 60% of roof is suitable)
iii. Roof area available per dwelling = 12 m^2

Table 3
Input parameters for the model.

Parameter	Value	Data source
Heating system		
η_{boil} [%]	87	[43]
η_{el} [%]	56.9	Table 9 [44]
η_{HP} [%]	50	Assumed
η_{Col} (ETC) [%]	63	[45]
η_{sys} [%]	95	Assumed 5% heat loss in pipes
$Sh_{RE.el}$ [%]	43.1	Table 9 [44]
$Q_{DH.loss}$ [%]	10	Assumed based on [46]
$T_{rtn.DH}$[°C]	51	Assumed [39]
T_{DH} [°C]	74	Assumed [39]
T_{water} [°C]	10: Jan–Mar 15: Apr–Jun,Oct–Dec 20: Jul–Sep	Assumed as average (monthly) ambient temperature of waste water from WWTP [47]
PTES		
$T_{avg.soil}$ [°C]	30	Assumed based on [39]
λ_t, λ_s, λ_b [W/m • K]	0.13, 2.0, 2.0	Assumed based on [39]
d_t, d_s, d_b [m]	0.24, 0.5, 0.5	Assumed based on [39]
λ_{soil} [W/m • K]	2.0	Assumed based on [39]

Kelvin (K) is generally used as the unit of temperature for λ. Temp. (K) = 273.15 + Temp. (°C).

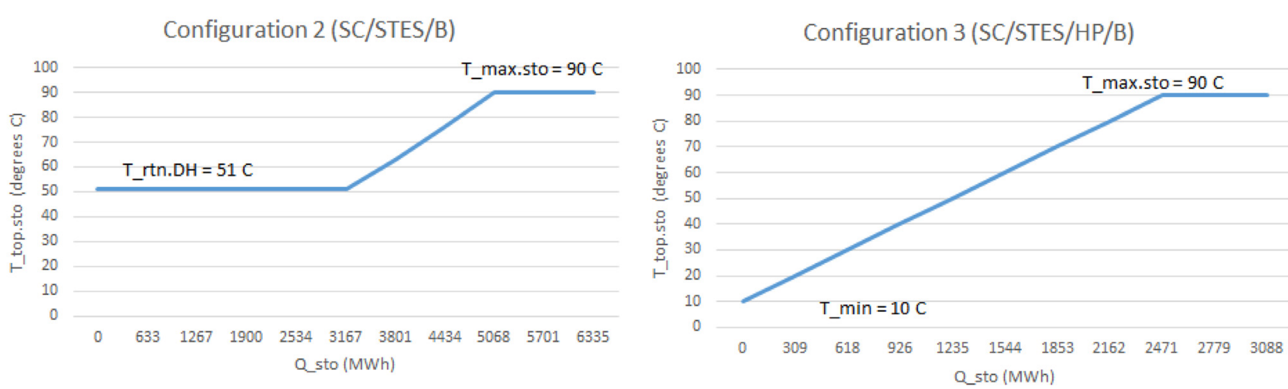

Fig. 4. Stratification profile for PTES (for 1,000 dwellings).

2.6. Other model inputs

Other input parameters are listed in Table 3.

2.7. CO_2 emission factors

Three different hourly emission factors (EFs) for electricity have been used and these are termed as $EF_{el.cat}$ (h), where cat = 1 for average supplier mix; = 2 for approach 1; = 3 for approach 2. The annual average EF for electricity in Switzerland ($EF_{el.1}$) was reported as 149.4 g CO_2- eq/kWh [48]. $EF_{el.2}$(h) and $EF_{el.3}$ (h) are based on the assessment undertaken in Ref. [49], in which the authors argue that Switzerland's position at the heart of the European grid causes electricity imports to have a significant impact on the GHG content of the national electricity consumption. The authors propose a method that accounts for the CO_2 content of electricity generated in surrounding countries. The authors estimated the hourly EFs for 2017 using two different approaches to account for the GHG impact of blast furnace gas units in Germany. In approach 1, CO_2 emissions from blast furnace gas combustion are fully assigned to the iron and steel industry, while no emissions are allocated to electricity generation. In approach 2, gases from blast furnaces are counted in the emissions of the electricity sector. The annual average EFs for Swiss electricity, were estimated as 108 ($EF_{el.2}$) and 196 ($EF_{el.3}$) g CO_2 -eq/kWh respectively ($EF_{el.1}$ is approximately the average of these values). The three different EFs (hourly) are shown in Fig. 13 (Appendix). Emission factor for natural gas (EF_{gas}) is assumed as 2.67 kg CO_2 /kg [50].

2.8. Costs

2.8.1. Energy cost

The prices used in this study are those charged by the local electricity and gas provider in Geneva, Services Industriels de Genève (SIG) in 2017. Natural gas charges for heating include a power charge ($P_{gas.pow}$), subscription charge ($P_{gas.sub}$), and consumption charge ($P_{gas.type}$). These tariffs are placed at Table 7 (Appendix). The annual cost of gas for the boiler (AC_{gas}) is calculated using Equation (7), where $\dot{Q}_{max.boil}$ is the maximum capacity of the boiler.

$$AC_{gas} = P_{gas.type} \cdot E_{in.boil} + P_{gas.sub} + P_{gas.pow} \cdot \dot{Q}_{max.boil} \quad (7)$$

The annual cost of electricity for HP ($AC_{el.HP}$) is calculated using Equation (8) and is summed over the entire year. Q_{el} (h) is the electricity consumed by the HP in hour 'h' and electricity tariffs ($P_{el.type}$) for different types of electricity are shown in Table 8 (Appendix).

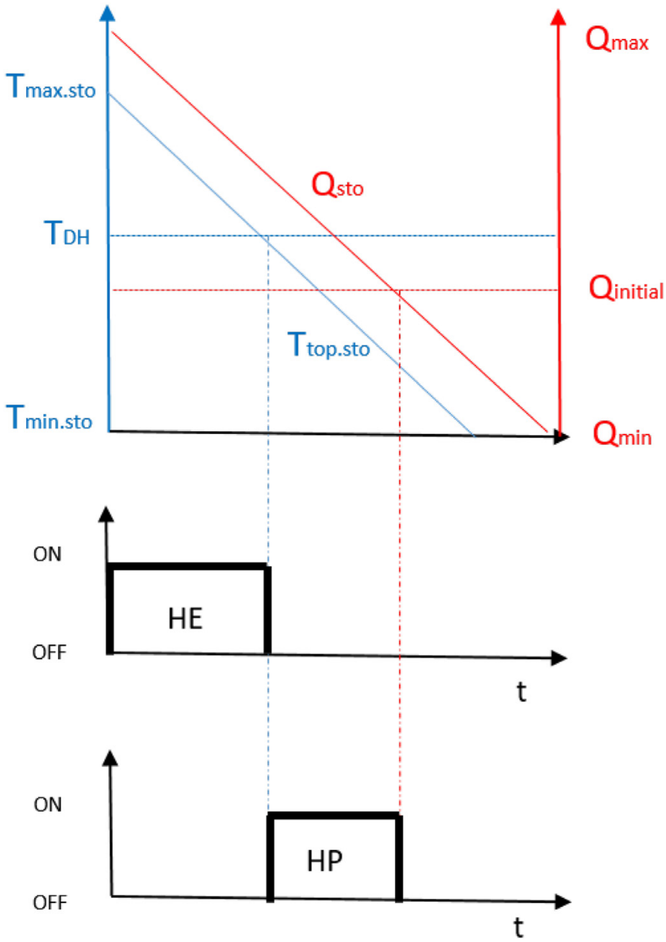

Fig. 5. Operation of HE and HP.

$$\sum_{h=1}^{8760} \mathrm{Q_{el}}(\mathrm{h}) \cdot \mathrm{P_{el.type}}(\mathrm{h}) = \mathrm{AC_{el.HP}} \tag{8}$$

2.8.2. Capital and O&M cost of main equipment

Specific capital cost of equipment (CC_{eqpt}) are shown in Table 4.

There are no large scale STES in Switzerland and hence its cost is modified from Danish data. The cost of equipment and labour costs in Switzerland are higher than Denmark and hence a capital cost factor (F_{cc}) and installation cost factor (F_{ic}) is used to translate the Danish costs to Swiss costs. Relative price levels between Denmark and Switzerland for different categories: "machinery and equipment" and "construction" (labour) are used to derive these factors [53]. For SC and HP, the costs are all inclusive and specific to Switzerland. For gas boilers, only capital cost is given and hence installation costs are added using the share of capital and installation costs (Sh_{cc}, Sh_{ic}). O&M cost factor ($C_{o\&m}$) is shown as a percentage of CC_{eqpt} and other associated factors are shown in Table 5.

Table 5
Lifetime and factors for cost calculations of main equipment.

Equipment	$C_{o\&m}$ (%)	Life (yrs)	F_{cc} , Sh_{cc} (-,%)	F_{ic} , Sh_{ic}(-,%)	Data source
PTES	1.25	40	1.35, -	1.53, -	[34,53–54]
SC (ETC)	1	25	–	–	[45,50]
HP	1.1	20	–	–	[43,52]
Gas Boiler	5	20	1.0, 60	1.0, 40	[43,56]

The total annualised cost of the heating system (AC_{sys}) can be calculated using Equation (9) and Equation (10) where the capital recovery factor (CRF) depends on the discount rate (r) and the life of the equipment (n). r is assumed as 3% [57].

$$\sum_{eqpt=1}^{4} \mathrm{CC_{eqpt}} \cdot \left(\mathrm{F_{cc}} + \mathrm{F_{ic}} \cdot \frac{Sh_{ic}}{Sh_{cc}}\right) \cdot CRF(r,n) + O\&M_{eqpt} \cdot F_{ic} = AC_{sys} \tag{9}$$

where, $\mathrm{O\&M_{eqpt}} = \mathrm{C_{o\&m}} \cdot \mathrm{CC_{eqpt}}$, and

$$CRF(r,n) = \frac{r\cdot(1+r)^n}{(1+r)^n - 1} \tag{10}$$

2.9. Key performance indicators (KPIs)

Levelised cost of heat (LCOH) is the financial KPI, and is calculated using Equation (11).

$$LCOH = \frac{AC_{gas} + AC_{el.HP} + AC_{sys}}{Q_{sum}} \tag{11}$$

The environmental KPI is total CO_2 emissions. Natural gas used in boilers and electricity used in HP contribute to CO_2 emissions in the heating system. Electricity consumption in other auxiliary equipment is neglected. Total CO_2 emissions from electricity are calculated as shown in Equation (12).

$$\sum_{h=1}^{8760} \mathrm{Q_{el}}(h) \cdot EF_{el.cat}(h) = EM_{el} \tag{12}$$

where, cat = 1,2,3.

CO_2 emissions from the gas boiler (EM_{gas}) are calculated using Equation (13) and total CO_2 emissions from the heating system (EM_{sys}) are calculated using Equation (14).

$$\mathrm{EM_{gas}} = \mathrm{E_{in.boil}} \cdot EF_{gas} \tag{13}$$

$$\mathrm{EM_{sys}} = EM_{el} + EM_{gas} \tag{14}$$

Table 4
Specific capital cost of main equipment.

Equipment	CC_{eqpt}	Comments	Data source
PTES (10,000–200,000 m^3)	$15,630 \cdot V^{-0.62} + 25$ [Eur/m^3]	All-inclusive	[51]
SC (ETC)	$3,801 \cdot C_A^{-0.173}$ [CHF/m^2]	All-inclusive	[45]
HP	$11,182 \cdot \dot{Q}_{max.HP}^{-0.247}$ [CHF/kW]	All-inclusive	[52]
Gas Boiler	756,000 [Eur/MW_{th}]	Only capital	[43]

Table 6
Parameters of PTES for different configurations and number of dwellings.

Dw.[nos.]	SC/STES/B (Config. 2)			SC/STES/HP/B (Config. 3)		
	V [m^3]	Size of PTES [m]	η_{PTES} [%]	V [m^3]	Size of PTES [m]	η_{PTES} [%]
500	43,808	58.3 (R), 10.2 (B), 32.0 (H)	36.1	21,356	45.9(R), 8.0(B), 25.2 (H)	55.6
1,000	68,145	67.5 (R), 11.8 (B), 37.2 (H)	35.2	33,221	53.2 (R), 9.3 (B), 29.2 (H)	63.0

The third KPI is the percentage share of RES in total primary energy supply (PES) for the heating system (RES_{sh}) and is calculated using Equation (15).

$$RES_{sh} = \frac{(Q_{amb} + Q_{sup} + Q_{el} \cdot Sh_{RE.el})}{(E_{in.boil} + E_{in.el} + Q_{sup})} \tag{15}$$

Q_{amb} is only applicable for configuration 4, while Q_{sup} is applicable for configurations 2&3 where SC are used. Q_{el} is applicable for configurations 3&4 which use HP. A part of electricity is generated from RE sources and this share ($Sh_{RE.el}$) is used to calculate the renewable part of electricity (excluding nuclear energy). Peak electricity demand and average electricity demand are compared along with the required capacity of the boiler ($\dot{Q}_{max.boil}$) and the capacity of the HP ($\dot{Q}_{max.HP}$) (restricted to one third of the peak heat demand by design) for different configurations.

3. Simulation results

3.1. Parameters of PTES

PTES volume, its dimensions and the calculated storage efficiency for different configurations and number of dwellings are shown in Table 6.

The minimum temperature in the PTES ($T_{min.sto}$) is determined by $T_{rtn.DH}$ (assumed to be constant over the year). As there is no HP in configuration 2, the temperature differential between $T_{max.sto}$ and $T_{min.sto}$ is only 39°C (90–51°C). This results in sub-optimal exploitation of the heat storage capacity of the PTES. On the other hand, in configuration 3, $T_{min.sto}$ is 10°C (as the HP can discharge the PTES below 51°C) and therefore $T_{rtn.DH}$ is not a limiting factor. Thus, as there is a temperature differential of 80°C (90–10°C), a much smaller volume of water is required to store the same amount of heat in configuration 3 as compared to configuration 2. The storage efficiency of PTES in configuration 2 is lower because heat stored in the PTES cannot be delivered to the DH system due to absence of a HP. This stored heat is subsequently radiated as heat loss to the ground resulting in low storage efficiency.

3.2. Hourly energy flows

Final energy supplied to the DH system for different configurations is shown for 1,000 dwellings in Fig. 6 and for 500 dwellings at Fig. 14 (Appendix). Hourly values are plotted with the 1st hour representing 00:00–01:00 h on 01 January and the last hour representing 23:00–00:00 h on 31 December. Heat supplied to the DH system by different sources is shown on the primary y-axis. Heat content in the STES is shown by the red line on the secondary y-axis.

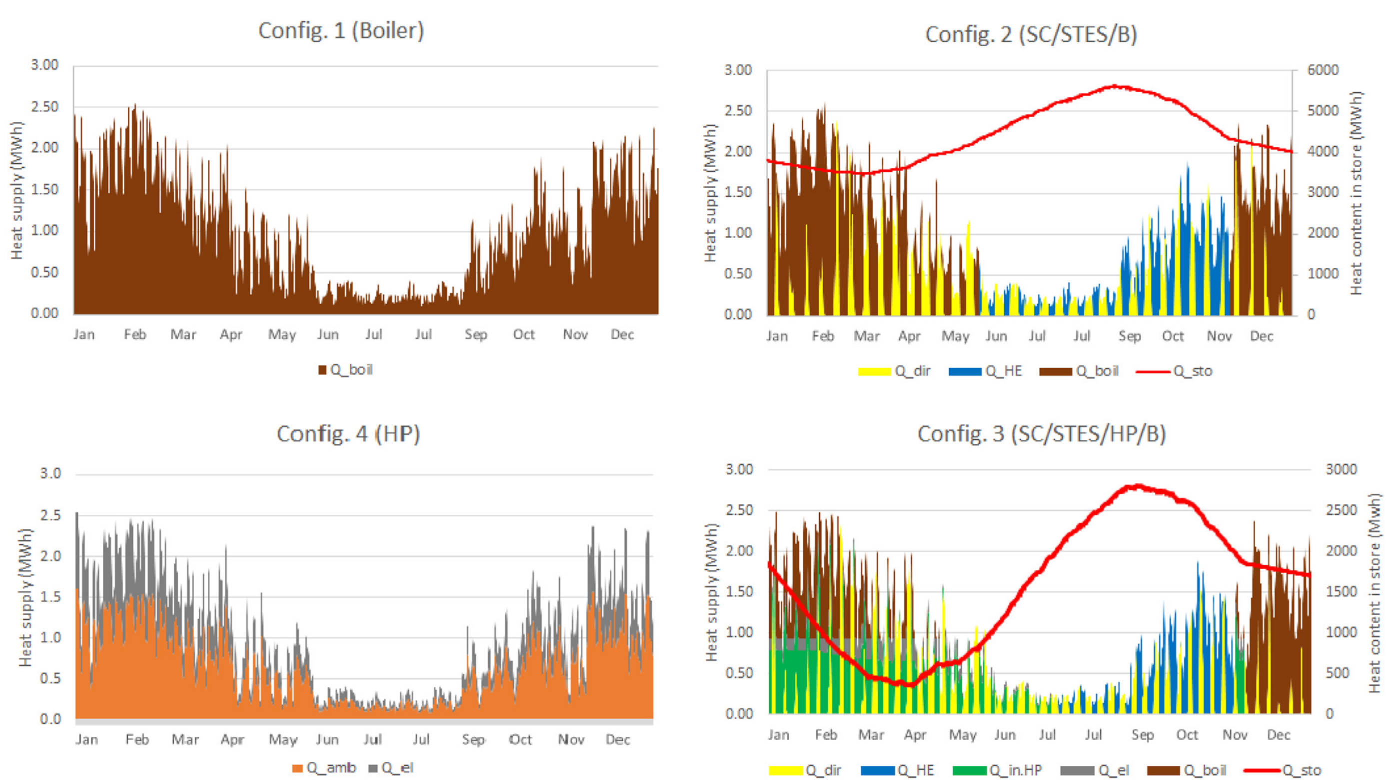

Fig. 6. Final energy supplied to DH system for different configurations (1,000 dw).

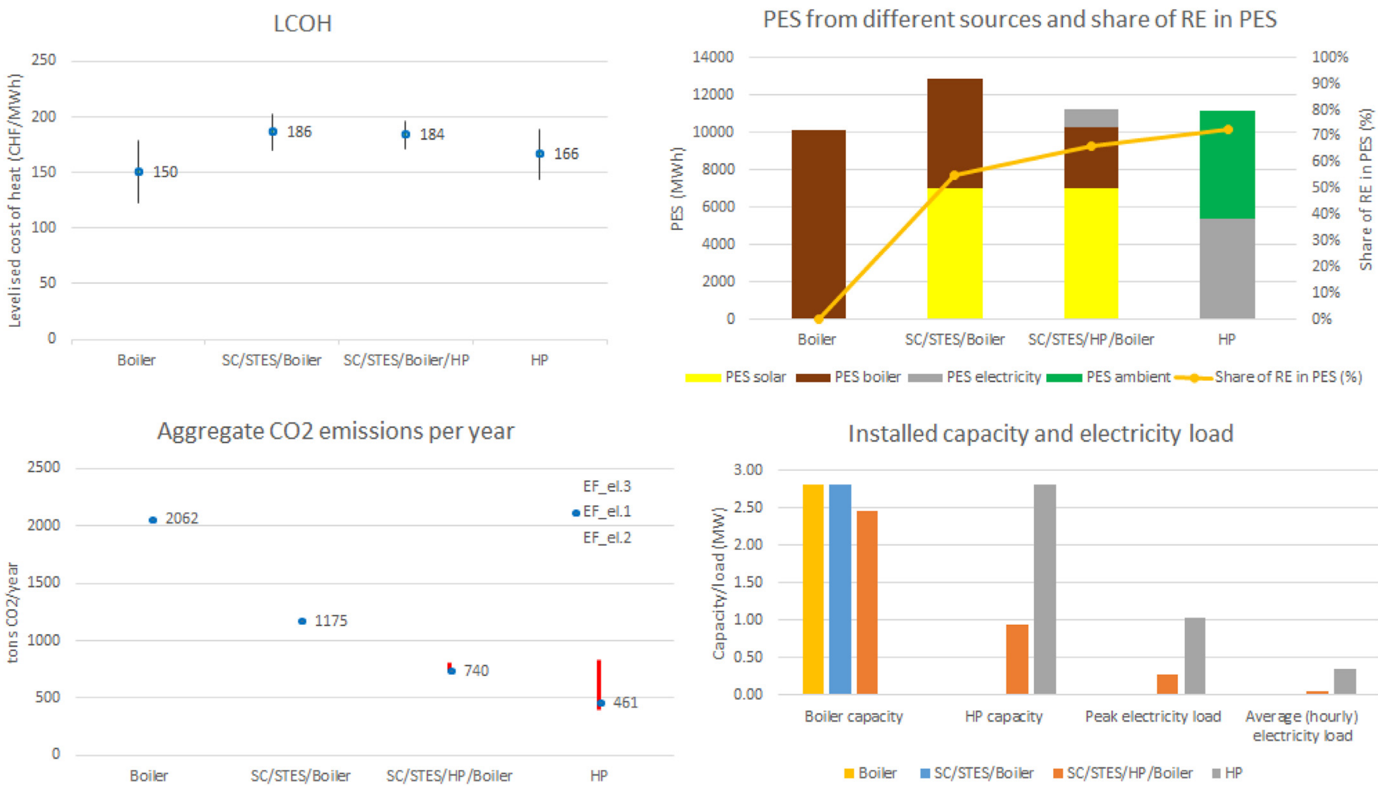

Fig. 7. KPIs for different configurations (1,000 dw).

In configuration 1, entire heat is supplied by the boiler, while in configuration 4, HP provides the heat composed of ambient and electrical energy. In configurations 2&3 heat is provided directly by the SCs whenever the sun is shining and there is heat demand. When heat from SCs is not available, heat from STES is supplied by the HE in configurations 2&3 (provided conditions are met) followed by the HP (only in configuration 3). Heat discharge from the STES is stopped (in the simulation) when Q_{sto} reaches $Q_{initial}$, to avoid over discharge of the STES. Thereafter, the balance heat in configurations 2&3 is provided by the boiler. As the simulation is undertaken for a duration of one year and progresses sequentially from the first to the last hour of the year, Q_{sto} at the end of 8760th hour may be different from Q_{sto} at the 1st hour. If Q_{sto} is lower at the end of the year, it implies that a larger amount of heat is extracted from the STES (dQ_{int} is negative); and if it is higher, it implies that heat is added to the STES during the year (dQ_{int} is positive). This heat balance is maintained over multiple years by system operators who control the heat discharged from the STES by starting/stopping the HE/HP. Selective operation of the HE/HP has not been simulated and the HE/HP is operated at full power as long as requisite conditions are fulfilled.

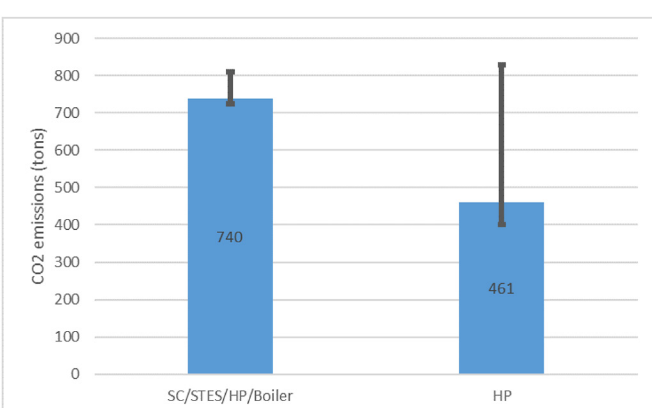

Fig. 8. Comparison of CO_2 emissions using different EFs.

3.3. KPIs for different configurations

Fig. 7 shows the selected KPIs for 1,000 dwellings and for 500 dwellings are placed at Fig. 15 (Appendix). Further discussions are undertaken in the context of 1,000 dwellings.

LCOH shows a range of values (using maximum and minimum prices for natural gas and electricity) and the average values are labelled. For configurations 2&3, the range of LCOH is smaller, due to relatively lower use of gas and electricity. LCOH for configuration 1 (only boiler) is the lowest, followed by configuration 4, 3 and 2 (prominent for 500 dw.). There is an overlap in the LCOH for configurations 1&4 which implies that if high price of gas and low price of electricity is considered, HP may be a cheaper option than gas boilers. In the case of 1,000 dwellings, LCOH for all configurations overlap and hence heating systems with a STES are cost competitive.

PES is calculated from final energy using conversion efficiencies shown in Table 3. It is observed that in configuration 4, ambient heat and electricity provide a similar share of PES. The percentage share of RES is the highest in configuration 4 followed by configuration 3 and 2.

Emissions are the highest when only boiler is used. In configuration 2, there is about 50% reduction in aggregate CO_2 emissions. As natural gas has a constant EF, there is a single value (instead of a

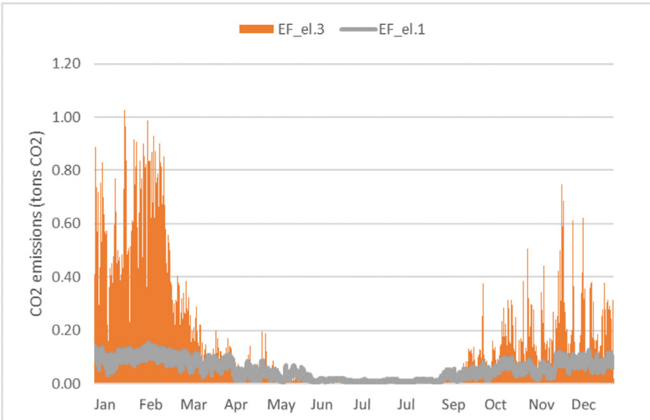

Fig. 9. Hourly CO_2 emissions from electricity (1,000 dw., config. 4).

range) for configurations 1&2. For configurations 3&4, three different EFs are used for electricity which lead to a range of CO_2 emissions. Configuration 4 uses a higher amount of electricity and since there is a substantial difference in hourly EFs of electricity especially in winter months, the range of emissions is higher.

The comparison of boiler capacity reveals that a smaller boiler is required for configuration 3. The capacity of the HP in configuration 3 is constrained to one-third of the peak demand (by design). Peak electricity demand for configuration 4 is about three times higher for 1,000 dwellings. The HP uses 546 MWh of electricity in configuration 3 as compared to 3,084 MWh in configuration 4 and the average (hourly) electricity demand in configuration 4 is around six times as that in configuration 3.

As all KPIs for configuration 3 are better than configuration 2, configuration 2 is sub-optimal and discarded for further discussions.

3.4. Impact of different EFs

Fig. 8 compares CO_2 emissions in configurations 3&4 for 1,000 dwellings using different EFs. The blue bar shows the emissions when $EF_{el.1}$ is used for calculation and the error bars show emissions when $EF_{el.3}$ and $EF_{el.2}$ are used. 461 tons of CO_2 is emitted if HP is used as compared to 740 tons in configuration 3, if $EF_{el.1}$ is considered. However, if $EF_{el.3}$ is used, the amount of emissions almost doubles to 850 tons in HP only configuration and becomes similar to configuration with STES. Hence, configuration 3 may be an equally effective option for decarbonisation.

Hourly CO_2 emissions from electricity using two different EFs for electricity are shown in Fig. 9 for HP only configuration. The large difference in emissions in winters as compared to when average EF is used is noteworthy and has policy implications.

3.5. Peak electricity load

Hourly electricity demand for 1,000 dwellings is compared for two configurations in Fig. 10. Electricity demand when only a HP is used, peaks in winter months and is significantly higher than configuration 3. It is observed that the peak electricity demand for 1,000 dwellings when only HP is used is around 1 MW (1 kW per dwelling) as against 0.28 MW when STES is used with a HP. A shift to HP only configuration for heating may therefore lead to a substantial increase in peak electricity load, unless measures are taken to shave off peak demand by reducing other residential electricity consumption.

3.6. Cost of decarbonisation of heat

In order to decarbonize, use of gas boilers should be lowered (can continue to provide peak demand) and need to be supplemented with other RES as shown in configuration 2,3 and 4, which will be more expensive. The cost of decarbonisation of heat (AC_{dec}) shows the additional cost to reduce 1 ton of CO_2 emissions and can be calculated using Equation (16). A lower cost is desirable and reflects the attractiveness of competing alternatives.

$$AC_{dec} = \frac{\Delta AC_{sys}}{\Delta EM_{sys}} \tag{16}$$

where Δ refers to the difference between the values for configuration 1 and the considered configuration (3 or 4).

The cost of decarbonisation of heat for different number of dwellings is shown in Fig. 11. The shaded bars show the cost using

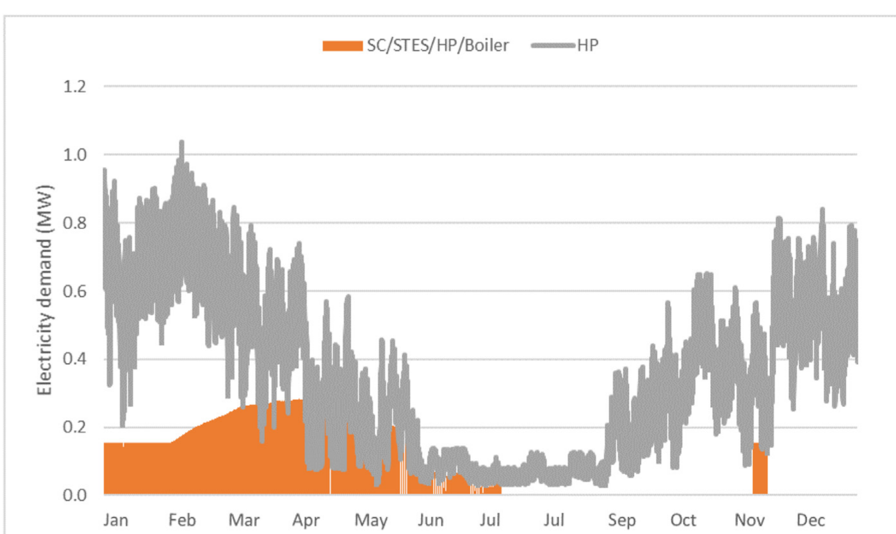

Fig. 10. Comparison of hourly electricity demand in configuration 3&4 (1,000 dw).

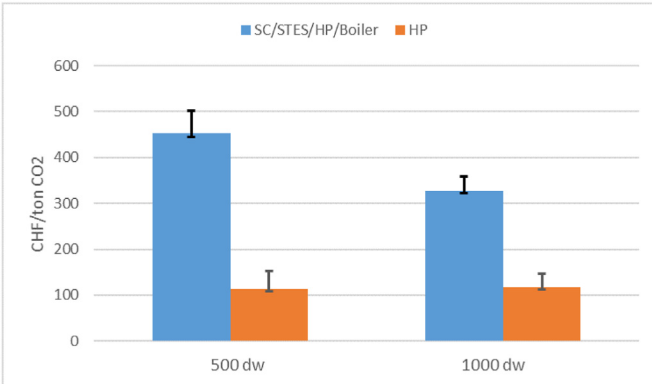

Fig. 11. Cost of decarbonisation of heat (replacement of gas boiler).

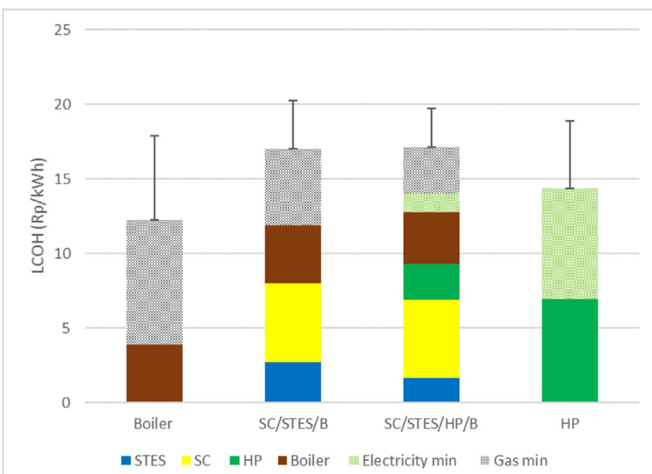

Fig. 12. Components of LCOH for different configurations (1,000 dw.).

$EF_{el.1}$ and the error bars show the variation in costs if $EF_{el.2}$ and $EF_{el.3}$ are used. For 1,000 dwellings the cost of decarbonisation is 113 ($EF_{el.2}$), 117 ($EF_{el.1}$), and 152 CHF/ton ($EF_{el.3}$) for configuration 4. As the number of dwellings increases from 500 to 1000, the cost of decarbonisation for configuration 3 (SC/STES/HP/B) reduces from 450 CHF/ton to 330 CHF/ton. This is about 2.3 times ($EF_{el.3}$) to 2.8 times ($EF_{el.2}$) higher than configuration 4.

Fig. 12 shows different components of LCOH using lowest fuel prices. The error bars show the additional cost if the highest electricity and gas prices are used. Fuel cost (shaded) contributes to about 70%, 30%, 25% and 50% respectively in configurations 1 to 4. SCs contribute to about 30% of the total LCOH for configurations 2&3 while the share of STES is about 10%.

4. Discussion

Results show that configuration 4 (HP only) has the lowest CO_2 emissions and provides the highest percentage share of RES with the considered assumptions and costs. An upfront capital investment of around 8,000 CHF per dwelling and an annual energy cost of 660 CHF per dwelling allows a reduction in CO_2 emissions per dwelling by 78% (from 2,062 kg–461 kg per year, if $EF_{el.1}$ is used) in the case of 1,000 dw. The LCOH for configuration 3 is comparable to configuration 4 when the number of dwellings are 1,000. This is due to economies of scale as specific capital costs of associated equipment decreases with an increase in size. In the case of Denmark, it is observed that the specific cost of PTES (60–85,000 m^3) was 36–48 Euro/m^3. This dropped to 24 Euro/m^3 when the volume of the PTES was increased to 2.1 million m^3 [58]. While the cost of PTES in Switzerland maybe higher because of higher labour and material costs, the economies of scale is expected to be maintained.

Configuration 4 implies the existence of an infinite heat source for the HP (WWTP) at zero cost. In contrast, SCs adds about 30% and STES adds 10% to the LCOH in configuration 3. Additional costs such as extending the DH network to a WWTP, connection costs, etc. will have to be added to configuration 4, which may result in higher LCOH. LCOH is also dependent on electricity prices and the reduction in CO_2 emissions depends on the considered EF of electricity. Hence, HP may not emerge as the optimal solution in every context.

A centralised HP (configuration 4) may be a good option for decarbonisation. However, this will result in a significant increase in annual electricity consumption and there will be an additional load on the electricity grid infrastructure. Hence the adequacy of the electricity grid has to be carefully examined.

For configurations with STES, the disadvantages are high storage losses and high capital costs. Building large STES (100 mts length, 30 mts depth for 1,000 dw.) may be difficult in dense cities like Geneva, where there is limited space. Depending on the geological conditions, aquifier thermal energy storage (ATES) provides an alternative to PTES and pilot projects are being undertaken in Geneva and Bern to store high temperature heat in underground aquifers [59]. The advantages of using STES over centralised HP is higher system flexibility as the operation of the DH system can be optimised to minimise CO_2 emissions or costs.

Further decarbonisation would incur additional costs. For example, e.g. if heating systems with an even higher share of RES are targeted, SCs could be added to configuration 4. On the other hand, SCs on roofs may not be favoured by home owners as there may be plumbing and water leakage issues. Nevertheless, a mix of SCs (for DHW), solar PV with electricity storage and air source HPs may be worth further investigation.

4.1. Policy implications

Assessment of annual fuel cost reveals that the relative cost of heating one dwelling using a centralised HP is about 11% lower than using a natural gas boiler. Lower electricity price for HPs or higher natural gas price (increasing carbon tax) could further increase the relative difference and would make it more attractive to replace gas boiler with centralised HP. The pricing of natural gas favours deployment of large boilers for heating as gas consumption charges are lower for larger consumers (See Table 7). Annual fuel costs are the lowest for configuration 3 but capital costs are higher. If configuration 3 is prioritised over configuration 4, capital costs of system components may need to be subsidised.

Hourly CO_2 EFs need to be considered (instead of using an average EF) as the use of electricity in HP increases. Policy makers could also consider pricing of electricity based on its CO_2 content so that prices reflect the higher CO_2 content, especially during winter months.

This pre-feasibility study is useful for city planners when assessing competing costs of heating systems and for federal agencies for designing energy policies to promote decarbonisation of heat. The choice of the configuration depends on the constraints. Configuration 3 may be preferable especially when waste heat is available throughout the year, e.g. from incinerators or industry. STES will also be helpful for decarbonisation in countries where electricity has a high CO_2 content. Configuration 4 may be preferred when there is no constraint on meeting the peak electricity demand and when EF of electricity is low.

4.2. Factors impacting results

The assessment has been carried out for a pre-determined shape, type and stratification profile of the STES. A constant loss of 10% has been assumed for the DH system but it may differ during the year. Heat demand profiles may be different for other locations. The heat supply profile would vary according to the specific location and solar insolation. DH supply and return temperature have a large impact on the energy flows in the system and results will differ if different DH temperatures are used.

The STES is charged during summer months and has the maximum heat content around end September. It is discharged over the following two quarters. Consequently, it is assumed that $Q_{initial}$ (on 01 January) is 60% of Q_{max} but this assumption may vary, which may impact energy flows in the system. The installed capacity of the HP in configuration 3 is selected as one-third of the maximum heat demand. This factor may vary depending on the system design. Selection of the size of the STES is an optimisation problem. A larger STES would lead to higher cost and lower capacity utilization, while a smaller STES would eventually have a risk that some of the heat generated from SC could be rejected if the STES is undersized.

The calculated costs do not include the cost of DH system as it is assumed to be pre-existing and is common to all configurations. However, if a new heat distribution system has to be built, it will substantially increase the LCOH. Cost of land for PTES is not included and it could be provided from public spaces as the space above the PTES could continue to be used as open spaces. The price of electricity and natural gas may differ for different cities. Specific capital cost of equipment, O&M costs, discount rate and cost factors may differ for different countries and will impact the calculation of LCOH.

4.3. Comparison with earlier work and future work

The paper offers improvements compared to earlier assessments of heating systems with STES. It uses hourly CO_2 EFs, electricity prices, heat supply and heat demand profiles in Switzerland. The required size and volume of the STES, SC, HP and boiler have been calculated and this can be used to undertake a preliminary assessment of the design, costing and siting of the heating system. As the paper uses thermal conductivity parameters from existing PTES, the simulation of losses reflects real life situation as compared to theoretical losses estimated by other studies. The method and the model is reproducible and transparent which enables the stakeholder to take an informed decision based on the KPIs.

Unlike models which undertake a monthly or annual assessment, the hourly resolution of energy flows offers a basis for optimising the operation of the HP and the use of STES so that the total cost of heating is minimized. Simulation of hourly electricity consumption by HP also reveals the impact of large-scale use of HP on the electricity grid, which can only be assessed with a model having a high temporal resolution. Use of hourly CO_2 emission factors is a novelty and ensures that emissions from electricity imports are correctly accounted for, especially in winter months. Consequently, appropriate operational profiles for using the HP and the STES can be designed for minimizing CO_2 emissions.

Other issues which can be analysed are the optimal size of SCs and STES and the impact of variation of these sizes on the KPIs. The sensitivity of various parameters assumed in the model can also be examined in detail to account for forthcoming developments such as low temperature DH systems and possible increase in the system efficiency of the HP. Waste heat from incinerators, industry, geothermal heat and ambient heat from river and lake water can be used as an alternate RES of heat. Other configurations such as a combination of solar PV and SCs, ground source HP, and multi energy sources can be integrated in the model. These aspects form a part of the future work.

5. Conclusion

This paper has undertaken an assessment of the techno-economic feasibility of centralised STES for decarbonising the Swiss residential heating sector. The study uses the simulation method for assessing hourly energy flows in a DH system. Four configurations of DH systems were studied for different numbers of MFH dwellings and the systems were compared using three KPIs viz., LCOH, CO_2 emissions and percentage share of RES. The impact of scale, use of different CO_2 EFs, and peak electricity demand was evaluated. Heating systems with a gas boiler have the least LCOH but highest CO_2 emissions. Heating system having only a HP have lower CO_2 emissions and higher RE share as compared to heating systems having a STES. LCOH for systems having a STES with a centralised HP decreases as the size of the DH system increases and is slightly higher in the configuration having only a HP. Based on the obtained results it can be concluded that a heating system with only a HP may appear to have the best performance, viz. least LCOH, lowest CO_2 emissions and highest percentage share of RES, but it requires a sizable heat source and adds a high peak load on the electricity grid infrastructure which may pose a constraint on the large scale use of HPs for heating. Further, this configuration may not be the best option especially when hourly CO_2 EFs from electricity imports are correctly accounted for and as electricity prices increase over time. A heating system with a SC, a STES, HE, HP and a boiler is a cost competitive option in the case of 1,000 dwellings with the heat store offering flexibility in system operation. Nevertheless, a detailed financial assessment is essential based on the specificities of the case before implementing a project. Overall, the results indicate that large STES is an option that should be considered more seriously by energy planners.

CRediT authorship contribution statement

Kapil Narula: Methodology, Software, Validation, Writing - original draft, Visualization. **Fleury De Oliveira Filho:** Methodology, Formal analysis, Writing - review & editing. **Jonathan Chambers:** Resources, Data curation, Writing - review & editing. **Elliot Romano:** Investigation, Formal analysis, Resources. **Pierre Hollmuller:** Conceptualization, Resources, Data curation, Funding acquisition. **Martin Kumar Patel:** Supervision, Project administration, Funding acquisition, Writing - review & editing.

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.

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Appendix

A. Hourly CO_2 emission factor for electricity

Fig. 13 shows three different hourly CO_2 EFs for electricity in Switzerland in 2017.

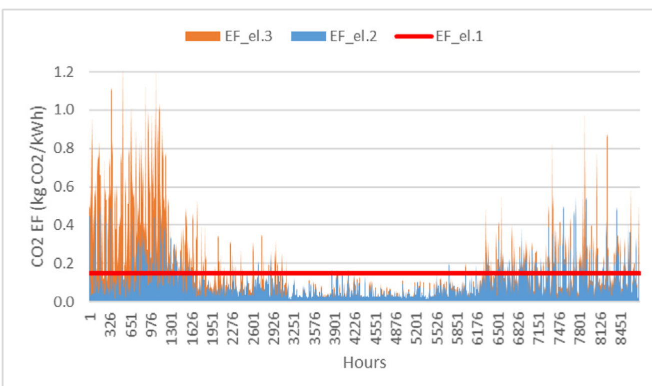

Fig. 13. Estimated hourly CO_2 EFs for electricity in Switzerland in 2017 [48,49].

B. Natural gas prices

In Geneva, consumers can choose the type of natural gas ($P_{gas.type}$, type = 1,2,3) which have different consumption charges based on its green component. Power charge ($P_{gas.pow}$) is fixed but subscription charge ($P_{gas.sub}$) and consumption charge ($P_{gas.type}$) is dependent on the annual consumption as shown in Table 7. The price of gas includes VAT and a CO_2 levy (96 CHF per tonne CO_2).

Table 7
Tariff for different types of natural gas [60].

Annual consumption (MWh/yr)	$P_{gas.type}$ (Rp/kWh)			$P_{gas.sub}$ (CHF/yr)	$P_{gas.pow}$ (CHF/kW/yr)
	$P_{gas.1}$ $^{+}$	$P_{gas.2}$ $^{++}$	$P_{gas.3}$ $^{+++}$		
0–120	7.93	8.85	12.8	50.76	22.95
120–260	7.73	8.65	12.59	289.44	
360–600	7.26	8.18	12.13	1396.44	
600-1,000	6.94	7.86	11.8	2839.32	
1,000-2000	6.67	7.59	11.53	4478.76	
2000–4000	6.62	7.53	11.48	5222.88	
4000–16000	6.57	7.49	11.44	5906.52	
16000–32000	6.53	7.45	11.39	10321.6	
32000–64000	6.48	7.39	111.34	48875.4	
Above 64000	6.42	7.34	11.29	110505	

$^{+}$ Bleu: CO_2 neutral gas.
$^{++}$Vert: 80% Bleu, 20% Vert.
$^{+++}$Gaz vitale vert: 10% Biogas, 90% offset.

C. Electricity prices

Similar to natural gas, three different types of electricity are supplied in Geneva. Consumers can choose the type of electricity at their residence and these have different prices ($P_{el.type}$, type = 1,2,3). Electricity tariff for a HP, connected to the low network voltage when electricity consumption is recorded separately by a dual meter for high (full/peak) hours and low (soft) hours are used for this assessment. The tariffs (incl. VAT) in 2017 promulgated by SIG are shown in Table 8.

Table 8
Tariff for different types of electricity for full and soft hours [61].

Type	Time (hours)		$P_{el.type}$ (Rp/kWh)		
	Weekday	Saturday and Sunday	$P_{el.1}$ $^{+}$	$P_{el.2}$ $^{++}$	$P_{el.3}$ $^{+++}$
High tariff hours	0700–2200	1700–2200	25.23	29.55	38.19
Low tariff hours	2200–0700	2200–1700	15.81	20.13	28.77

$^{+}$ 100% hydro power.
$^{++}$ 90.6% from hydro, 9.4% from solar and produced 100% locally.
$^{+++}$ For electricity prosumers.

D. Share of RES for electricity generation $Sh_{RE.el}$ and η_{el} are calculated as shown in Table 9

Table 9
Primary and secondary energy supply, Switzerland (2016) [44].

Primary energy supply	
Source	Mtoe
Oil products	0.01
Coal	0
Natural gas	0.22
Waste/biofuel*	1.27
Solar/wind*	0.12
Hydro*	2.98
Nuclear	5.54
Total PES	10.14
$Sh_{RE.el}$	43.1%
* considered as RES; = $Sh_{RE.el}$RES/total PES	
Secondary energy after conversion	
Output	Mtoe
Electricity output from power plant	5.25
Power losses	4.37
Heat from power plant	0.52
ηel	56.90%
ηel (%) = 100 − (Power losses/total PES)	

E. Selected results for 500 dwellings

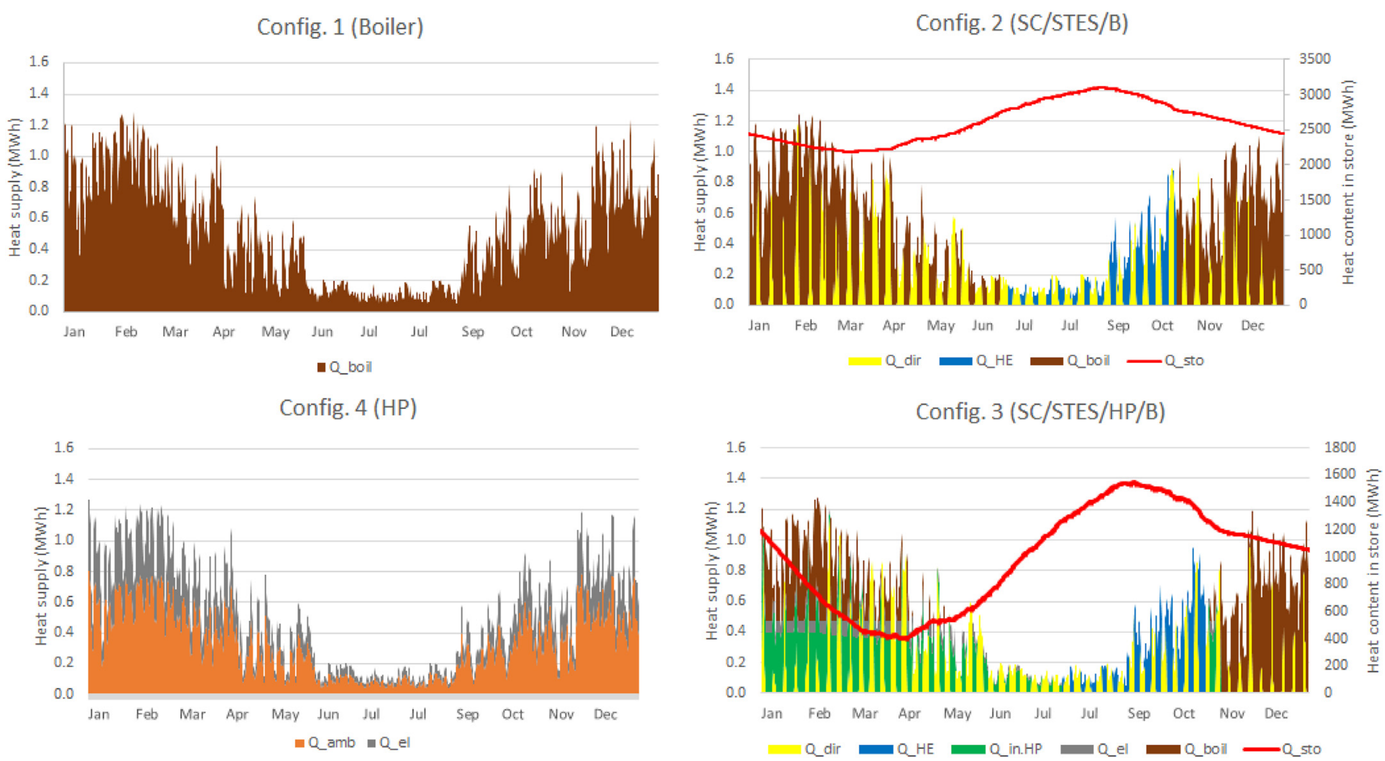

Fig. 14. Final energy supplied to DH system for different configurations (500 dw.).

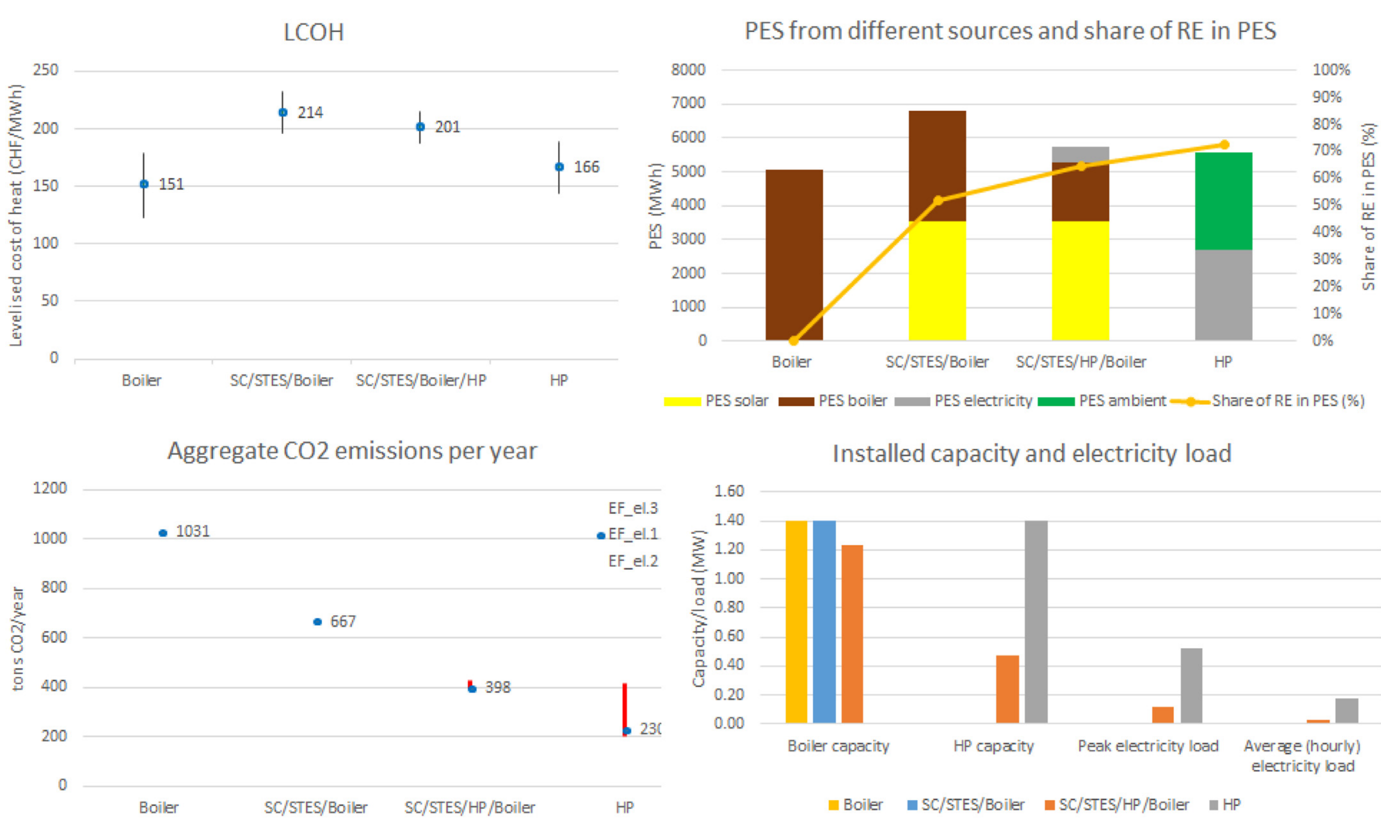

Fig. 15. KPIs for different configurations (500 dw.).

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