Energy 118 (2017) 246–263

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

District heating by drinking water heat pump: Modelling and energy analysis of a case study in the city of Milan

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ARTICLE INFO

Article history:
Received 19 July 2016
Received in revised form
14 November 2016
Accepted 4 December 2016

Keywords:
Energy efficiency
Drinking water heat recovery
Heat pump
District heating

ABSTRACT

This paper investigates the integration of a district heating heat pump for the production of about 4.65 MW_{th} with the drinking water network—playing the role of low temperature heat source -as an alternative to conventional fossil fuel heating. The heat recovery reduces water temperature from 15 °C to 12 °C, thus requiring partial reheating by the drinking water end-user that needs to be estimated to evaluate the energetic convenience of this solution. Heat transfer between water mains and surrounding soil is considered by a proper thermal model computing the temperature vs. time profile at nodes. The developed model, which exploits Epanet to simulate the water network, compares the primary energy consumption and CO_2 emissions of the studied system with a conventional district heating solution. Each component, which constitute the overall system, (i.e. heat pump, water network, heating by water end-user etc.) is analyzed and modelled. Assuming a fossil fuel based scenario, the investigated heat pump system reduces the overall primary energy consumption and CO_2 emission by about 3%. This value boosts to 41% in case all the electricity generation relies on renewables, thus proving this solution is a promising alternative to conventional district heating in future energy scenarios dominated by renewables.

1. Introduction

In order to mitigate air pollution and global warming, different solutions have been considered involving the reduction of fossil fuels consumption [1]. Focusing on municipal environment, cities can be identified as a sort of "climate change industry" [2,3] and, in particular, heating demand is recognized as one of the most important fields that deserves dedicated actions to mitigate the contribution to climate change.

This study analyses an option to reduce primary energy consumption for district heating in urban scenario through the replacement of conventional centralized boilers with heat pump systems. In particular, heat pump is recognized as a valuable alternative that can be more efficient -from a thermodynamic point of view- than traditional district heating systems based on fossil fuel combustion. In addition, the increase of thermal load covered by heat pumps can facilitate the management of electricity network in scenarios characterized by a high fraction of electricity from intermittent renewable energy sources. As a matter of fact, heat pumps could act as an interface between electrical and thermal networks in municipal smart grids, that are recognized as systems able to overcome the challenges implied by the fluctuating nature of electricity from renewable sources [4].

The first opportunity to integrate heat pumps in municipal environment and exploit existing resources is represented by the extraction of heat from waste water. It is estimated that, in residential areas, about 60% of the drinking water provided is heated, used as hot water and then discharged in the sewage system. The thermal energy loss (i.e. the residual thermal energy in discharged water from shower) is about the 15% of the global heat provided to the user (included space heating) [5]. In Ref. [6] it is estimated that, in a residential building, the average temperature of the discharged water is about 27 °C. On a small scale, it is possible to apply heat pumps that use the waste water collected in the sewer of a building as heat source. This is the case of a hospice in Switzerland, where a 30 kW heat pump is installed [5]. On a larger scale, the heat recovery process can directly involve sewage systems and waste water treatment plants. It is possible to apply heat pumps that extract thermal energy from the sewage water and make it available at higher temperature. For example, in Oslo about 8% of

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http://dx.doi.org/10.1016/j.energy.2016.12.014
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Acronyms

COP	Coefficient of performance
DAE	Differential algebraic equation
HP	Heat pump
HVAC	Heating ventilation and air conditioning
IGV	Inlet guides vane
IRR	Internal rate of return
MM	Metropolitana Milanese
NPV	Net present value
NG	Natural gas
ST	Storage tank

Nomenclature

C	Generic integration constant, –
c_p	Specific heat, J kg^{-1} K^{-1}
D	Diameter, m
d	Burying depth, m
E	Energy, J
F	CO_2 emission factor, g_{CO2} kWh^{-1}
h	Convective heat transfer coefficient, W m^{-2} K^{-1}
k	Thermal conductivity, W m^{-1} K^{-1}
l	Additional soil layer thickness, m
LHV	Lower heating value, MJ kg^{-1}
m	Mass flow, kg s^{-1}
M	Mass, kg
P	Pressure, Pa
Q	Thermal energy, J
$\dot{Q}$	Thermal power, W
$\dot{q}$	Specific heat transfer rate, W m^{-1}
S	Shape factor, –
T	Temperature, °C
t	time, s
U	Overall heat transfer coefficient, W m^{-2} K^{-1}
W	Electric power, W
x	x-coordinate, m
y	y-coordinate, m

Subscripts

A	Case A
B	Case B
compr	compressor
cond	condenser
DH	District heating
dom	domestic
el	electric
eva	Evaporator
f	fluid
in	inlet
mech	mechanical
NG	Natural gas
O	Initial state
off	Off-design
on	On-design
out	Outlet
p	Pipe
pp	Pinch point
prim	primary
ref	reference
RH	Reheating
SC	Sub-cooling
SH	Super-heating
ST	Storage tank
th	thermal
US	User

Superscripts

s	Superficial
t	Time varying
u	Undisturbed

Greek letters

Δ	Difference, –
α	Drinking water fraction to be heated, –
χ	Heat fraction, –
η	Efficiency, –
ρ	Density, kg m^{-3}
ω	Angular frequency, s^{-1}

thermal energy required by district heating is obtained by recovering heat from the sewage system [7]. A similar system was installed near the Olympic village in Vancouver [8,9]. Heat recovery downstream of water treatments (where large flows and stable temperatures are observed) is applied in about 20 cites in Switzerland. For example, in the Bremgarten quarter in Berna about 60% of the heat demand is provided by heat pumps that extract thermal energy from treated water [5].

Another thermal energy resource in cities is represented by the drinking water that constantly flows throughout the distribution network. This resource shows a vast potential in terms of exploitable thermal energy.

Few studies concerning heat recovery from drinking water are available in the literature. Compared to waste water, potable water generally has lower temperatures that penalize the energetic performance of heat pumps. However, there are many factors in favor of the use of the water supply system as heat source for heat pumps, namely: i) the increase of drinking water temperature in the distribution network can lead to bacteria growth, with consequent risks for users' health [7], ii) compared to the case of a geothermal heat pump using ground water, there is no significant increase of costs linked to the pumping of the fluid (since these are already included in the management of the aqueduct), iii) there is no need of additional drillings of aquifer and the risk of ground water pollution is limited, iv) compared to the case of a heat pump using waste water, fouling problems of the heat exchanger are much less significant and v) water mass flow is more stable than wastewater one, thus simplifying the heat pump operation.

In this paper the opportunity to use a heat pump that exploits drinking water as cold heat source is analyzed. The impact that this solution can have on end-users of the water service is assessed, considering that they receive cooler water and thus an additional heating is requested to maintain the same utilization temperature. The analysis both considers the energetic and the environmental aspect, by assessing primary energy balance and CO_2 emissions. The case study refers to a district of Milan, whose characteristics are provided by Metropolitana Milanese (MM) that is the municipal utility that manages the water service.

With the aim of evaluating the system performance, a tailored-made model, whose characteristics are discussed in the following sections, is developed. In particular, it is worth underlining that the developed model maintains a high level of flexibility that allows its