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Low-temperature heat emission combined with seasonal thermal storage and heat pump

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Abstract

We studied the application of a stratified seasonal hot water storage tank with a heat pump connected to medium-, low- and very-low-temperature space heat emissions for a single-family house in Stockholm, Sweden. Our aim was to investigate the influence of heat emission design temperature on the efficiency and design parameters of seasonal storage in terms of collector area, the ratio of storage volume to collector area (RVA), and the ratio of height to diameter of storage tank. For this purpose, we developed a mathematical model in MATLAB to predict hourly heat demand in the building, heat loss from the storage tank, solar collector heat production, and heat support by heat pump as a backup system when needed. In total, 108 cases were simulated with RVAs that ranged from 2 to 5 ($m^3\,m^{-2}$), collector areas of 30, 40, and 50 (m^2), height-to-diameter-of-storage-tank ratios of 1.0, 1.5, and 2.0 ($m\,m^{-1}$), and various heat emissions with design supply/return temperatures of 35/30 as very-low-, 45/35 as low-, and 55/45 (°C) as medium-temperature heat emission. In order to find the best combination based on heat emission, we considered the efficiency of the system in terms of the heat pump work considering coefficient of performance (COP) of the heat pump and solar fraction. Our results showed that, for all types of heat emission a storage-volume-to-collector area ratio of 5 $m^3\,m^{-2}$, with a collector area of 50 m^2, and a height-to-diameter ratio of 1.0 $m\,m^{-1}$ were needed in order to provide the maximum efficiency. Results indicated that for very-low-temperature heat emission the heat pump work was less than half of that of the medium-temperature heat emission. This was due to 7% higher solar fraction and 14% higher COP of heat pump connected to very-low-temperature heat emission compared to medium-temperature heat emission.

Keywords: Seasonal thermal energy storage; Stratified storage tank; Heat pump; Low-temperature heat emission

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1. Introduction

The building sector uses about 40% of total primary energy and contributes to 35% of global greenhouse gas emissions (European Commission, 2011). The EU's roadmap for long-term low carbon development is to decrease carbon emissions by 80% by 2050 compared to the 1990 level in order to keep temperature change below 2 °C (European Commission, 2011). This shows the importance of improving heating systems in the residential sector, which accounted for almost 15% of total European greenhouse gas emissions in 2011 (European Commission, 2011). Using renewable energy such as solar energy, and biomass or low-carbon heat sources, such as district heating, heat pumps or heat storage instead of fossil fuels would greatly reduce CO_2 emissions and the environmental loads of fossil fuels. In Swedish district heating system, the heat source of more than 60% of heat production was from renewable

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Nomenclature

$\bar{\mathrm{h}}$	average convective heat transfer coefficient between layers (W m^{-2} K^{-1})
$\dot{m}_{\mathrm{coll}}$	mass flow rate to collector array (kg s^{-1})
$\dot{m}_{\mathrm{H}}$	mass flow rate to the heating system (kg s^{-1})
a	experimentally determined linear loss coefficient of collector (W m^{-2} K^{-1})
A	collector area (m^{2})
$A_{\mathrm{base,layer}}$	base area of layer (m^{2})
A_n	surface area of layer (m^{2})
b	experimentally determined quadratic loss coefficient of collector (W m^{-2} K^{-2})
COP	coefficient of performance of heat pump (–)
c_p	specific heat capacity of water (J kg^{-1} K^{-1})
g	gravity (m s^{-2})
Gr	Grashof number (–)
HDR	height-to-diameter ratio of storage tank (m m^{-1})
HP	heat pump
k_f	thermal conductivity of fluid (W m^{-1} K^{-1})
L_{c}	characteristic length, defined as a ratio of the layer's base area to its perimeter (m)
LTH	low-temperature heat emission
m_{layer}	mass of water in each layer (kg)
MTH	medium-temperature heat emission
n	layer number from 1 to 10
η_0	collector efficiency (%)
η_{c}	Carnot efficiency of heat pump (%)
Nu	Nusselt value (–)
P_{in}	input power for each layer (W)
P_{natural}	free convection (W)
P_{out}	output power from each layer (W)
Pr	Prandtl number (–)
Q_{hd}	heat demand in the building (kW h)
Q_{loss}	heat loss from storage tank (kW h)
Q_{storage}	storage capacity (kW h)
Q_{c}	heat production by solar collector (kW h)
Q_{HP}	heat provided by heat pump (kW h)
q_{r}	solar radiation (W m^{-2})
Ra	Rayleigh number (–)
Re	Reynolds number (–)
RVA	ratio of storage volume to collector area (m^{3} m^{-2})
SF	solar fraction (%)
U_{tank}	heat transfer coefficient of storage tank (W m^{-2} K^{-1})
VLTH	very-low-temperature heat emission
W_{HP}	electricity consumption by heat pump (kW h)
β	thermal expansion coefficient (K^{-1})
Δt	time span between two calculations (h)
θ_{amb}	ambient temperature (°C)
θ_{coll}	collector temperature (°C)
θ_{H}	water supply temperature to heat emission (°C)
$\theta_{\mathrm{in,coll}}$	supply temperature to the collector from the lowest layer of seasonal storage (°C)
$\theta_{\mathrm{in,HP}}$	supply temperature to the heat pump from the top layer of seasonal storage (°C)
θ_{n}	layer temperature (°C)
$\theta_{\mathrm{out,coll}}$	outgoing temperature from collector to the top layer of seasonal storage (°C)
$\theta_{\mathrm{out,HP}}$	outgoing temperature from heat pump to the lowest layer of seasonal storage (°C)
θ_{soil}	ground temperature (°C)
v	kinematic viscosity (m^{2} s^{-1})

sources and only 13% came from oil products by 2012 (Swedish District Heating Association, 2012). In high-latitude countries, however, the scarcity of solar radiation during winter highlights the application of seasonal thermal energy storage (Lund, 1984). In seasonal thermal energy storage, heat is stored during summer and is used during winter (Hasnain, 1998). This heat can be stored in rock, soil, aquifers or water tanks (Novo et al., 2010; Xu et al., 2014; Pavlov and Olesen, 2012). Sweden became the first country to implement a seasonal storage, following the oil crisis of the 1980s (Ochs et al., 2009). Since then, several seasonal heating systems have been built and designed in Europe and other countries, (Schmidt et al., 2004; Paksoy et al., 2004; Wang et al., 2010; Fischa et al., 1998; Sibbitt et al., 2012; Milewski et al., 2014)

Due to heat losses, unpredictable living habits and weather condition, an auxiliary heat source is essential to cover the peak load and total heating demand during the whole heating season. A heat pump (HP) is recommended as an efficient supplementary system to be combined with seasonal storage (Lund, 1984; Hesaraki and Holmberg, 2015). Due to the use of renewable energies stored in air, ground or water, heat pumps typically use three to four times less electrical energy than direct electrical heaters to deliver the same amount of heat. There are different ways to combine heat pump with seasonal thermal energy storage and solar thermal collector, including parallel, serial, and parallel-serial configurations (Sparber et al., 2011). In parallel configuration, heat pump and solar collector (seasonal storage) work independently to meet the heat demand in building. In serial combination, however, solar collector (seasonal storage) acts as a source for heat pump, exclusively or in addition to other sources. With regards to serial–parallel method, heat pump or collector provides heat to the building, dependently or independently. Combining heat pump with seasonal storage in serial, or serial–parallel configuration is beneficial because it reduces the return temperature to the storage tank. This reduction