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Solar assisted heat pump system for multifamily buildings: Towards a seasonal performance factor of 5? Numerical sensitivity analysis based on a monitored case study

Carolina Fraga *, Pierre Hollmuller, Floriane Mermoud, Bernard Lachal

Energy Systems Group, Section of Earth and Environmental Sciences, Institute Forel & Institute for Environmental Sciences, University of Geneva, Uni Carl Vogt, 66 boulevard Carl Vogt, CH 1211 Genève 4, Switzerland

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ABSTRACT

The present work analyses the potential of a combined solar thermal and heat pump (HP) system on new and existing multifamily buildings. The study uses numerical simulation as a complement to a monitored case study. After a description of the case study and a summary of the monitoring results, we present the numerical model developed for this study. Simulation results are validated with the monitored values, at component and system level, in terms of monthly profiles and yearly integrals. On this basis, we carry out an extensive sensitivity analysis concerning the principal sizing parameters of the system. Finally, we investigate the sensitivity of the system to space heating (SH) and domestic hot water (DHW) demands, in particular concerning the applicability of the analysed system in the case of building retrofit. For Geneva's weather conditions, a sizing factor of 3 m^2 solar collector per kW of HP capacity is a good compromise between system size and system performance, resulting in a system seasonal performance factor (SPF_{sys}) between 3.1 and 4.1, depending on the SH distribution temperature. The associated electricity consumption (ranging from 12 kWh/m^2 for a new low-energy building, up to 45 kWh/m^2 for a non-retrofitted building) strongly depends on the heat demand. Such is also the case for the collector area (from 0.08 m^2 per m^2 heated area for a new low-energy building, up to 0.20 for a non-retrofitted building). Finally, a SPF_{sys} of 5 could potentially be achieved, but only in newly constructed buildings with a high efficient envelope, a low SH distribution temperature, and with a collector area of at least 0.20–0.25 m^2 per m^2 heated area. However, the related investment may not be worthwhile, given the rather small associated electricity saving, not to mention that such a collector area would not fit on buildings with more than 4 storeys.

1. Introduction

Over the past decade, heat pumps (HP) have become a key technology for the increased use of renewable energy resources. One of the major issues concerning the use of HPs is their associated electricity consumption. The performance of HP systems is therefore commonly quantified: (i) at the level of the HP by the SPF_{HP}, defined as the ratio between the heat produced by the HP and the electricity consumed by the HP, in annual values; (ii) at the level of the heating system by the SPF_{sys}, defined as the ratio between total system heat production and related electricity consumption. Depending on the author and considered system, diverse system perimeters are taken into account for the definition of the SPF_{sys}. In the following literature review, SPF_{sys} is therefore used in a generic sense. For detailed information on the perimeter considered in each study, the reader should refer to the specific reference.

Nowadays, the most common HP systems use air or ground as their heat source (EHPA, 2015; Observ'ER, 2015). Erb et al. (2004), monitored 199 of such systems in Switzerland, both in new and renovated buildings. They observed, in average, an annual system performance factor (SPF_{sys}) of 2.7 for the 105 air source HP, and of 3.5 for the 94 ground source HP. In another study, Miara et al., 2010, monitored 74 HP systems, the majority with underfloor heating distribution systems. The observed SPF_{sys} were of 2.9 for the 18 air source HP systems and of 3.9 for the 56 ground source HP systems.

In view of increasing the system performance, focus has lately been set on combining HPs and solar thermal collectors. Solar and HP systems (SHP) are composed of at least a solar collector and a HP, but they can also include other heat sources (most com-

* Corresponding author.
E-mail address: carolina.fraga@unige.ch (C. Fraga).

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Nomenclature

Abbreviations

DHW domestic hot water
HP heat pump
SH space heating

Latin letters

A_{sol} area of solar collectors [m^2]
A_{st} area of storage envelope [m^2]
c_{wat} specific heat of water [J/K.kg]
COP coefficient of performance [–]
dt time step [s]
E_{dir} electricity, direct heating [kWh/m^2]
E_{hp} electricity, HP [kWh/m^2]
E_{tot} electricity, HP + direct heating [kWh/m^2]
$\dot{E}_{dir}$ electric load, direct heating [W]
$\dot{E}_{hp}$ electric load, HP [W]
G_{sol} global solar irradiance, in collector plane [W/m^2]
G_h global solar irradiance, in horizontal plane [W/m^2]
$h_{sol,0}$ heat loss coefficient of solar collector, without wind [$W/K.m^2$]
$h_{sol,v}$ heat loss coefficient of solar collector, proportional to wind speed [$W/K.m^2$ per m/s]
h_{st} heat loss coefficient of storage [$W/K.m^2$]
$P_{max.dem}$ maximum hourly heat load, DHW + SH [W/m^2]
$P_{max.dhw}$ maximum hourly heat load, DHW [W/m^2]
$P_{max,sh}$ maximum hourly heat load, SH [W/m^2]
$P_{nom,hp}$ nominal capacity, HP (at 0 °C evaporator input/35 °C condenser output) [W/m^2]
$P_{nom,sh.0°C}$ nominal heat load, SH (at 0 °C outdoor) [W/m^2]
Q_{dem} heat demand, DHW + SH [kWh/m^2]
Q_{dhw} heat demand, DHW [kWh/m^2]
Q_{evap} HP heat input (evaporator) [kWh/m^2]
Q_{hp} HP heat production [kWh/m^2]
$Q_{hp,dem}$ HP heat production, to DHW + SH [kWh/m^2]
$Q_{hp,dhw}$ HP heat production, to DHW [kWh/m^2]
$Q_{hp,sh}$ HP heat production, to SH [kWh/m^2]
$Q_{hp,st}$ HP heat production, to storage [kWh/m^2]
Q_{sh} heat demand, SH [kWh/m^2]
Q_{sol} solar collector heat production [kWh/m^2]
$Q_{sol,dem}$ direct solar heat production, to DHW + SH [kWh/m^2]
$Q_{sol,dhw}$ direct solar heat production, to DHW [kWh/m^2]
$Q_{sol,dir}$ direct solar heat production, to SH + DHW + storage [kWh/m^2]
$Q_{sol,hp}$ solar collector heat production, to HP [kWh/m^2]
$Q_{sol,sh}$ direct solar heat production, to SH [kWh/m^2]
$Q_{sol,st}$ direct solar heat production, to storage [kWh/m^2]
$Q_{st,dem}$ storage heat discharge, to DHW + SH [kWh/m^2]
$Q_{st,dhw}$ storage heat discharge, to DHW [kWh/m^2]
$Q_{st,in}$ storage heat input [kWh/m^2]
$Q_{st,loss}$ storage heat losses [kWh/m^2]
$Q_{st,out}$ storage heat output [kWh/m^2]
$Q_{st,sh}$ storage heat discharge, to SH [kWh/m^2]
$\dot{Q}_{evap}$ HP input (evaporator), heat rate [W]
$\dot{Q}_{hp}$ HP production, heat rate [W]
$\dot{Q}_{sol}$ solar collector production, heat rate [W]
$\dot{Q}_{st,in}$ storage input, heat rate [W]
$\dot{Q}_{st,loss}$ storage losses, heat rate [W]
$\dot{Q}_{st,out}$ storage output, heat rate [W]
SPF_{sys} seasonal performance factor, system
SPF_{hp} seasonal performance factor, HP
T_{cond} temperature of condenser output [°C]
T_{evap} temperature of evaporator input [°C]
T_{ext} temperature of ambient [°C]
T_{room} temperature of technical room [°C]
$T_{sh.0°C}$ temperature of SH distribution, at 0° outdoor temperature [°C]
$T_{sh.15°C}$ temperature of SH distribution, at 15 °C outdoor temperature [°C]
$T_{sh.off}$ temperature on/off set-point for SH [°C]
T_{sol} temperature of solar collector [°C]
T_{st} temperature of storage [°C]
$T_{st,t\text{-}1}$ temperature of storage, previous time step [°C]
v wind speed [m/s]
V_{st} volume of storage [m^3]

Greek symbols

η_{sol} optical efficiency, solar collector
ρ_{wat} specific weight of water [kg/m^3]

monly air or ground), storages or other components. Furthermore, they can be used for space heating (SH), domestic hot water production (DHW), cooling or any combination of the latter. Consequently, their classification can become quite complex (Buker and Riffat, 2016).

SHP systems were closely analysed by the IEA SHC Task 44 (Hadorn, 2015). Co-authors of latter task, Frank et al., 2010, propose a system classification that focuses on the interaction between the solar collectors and the HP. Usually, this interaction results from the following configurations: (i) the collectors and the HP are not interconnected and supply heat independently (parallel systems); (ii) the collectors supply heat to the HP evaporator, either exclusively or with an additional source (series systems); (iii) the collectors are used for regeneration of the HP heat source, such as the ground (regeneration). Note that these configurations are not exclusive and can be combined. An analysis of the market availability of such SHP systems (Ruschenburg et al., 2013) shows that 61% of the available systems are parallel only, 6% series only and less than 1% regeneration only; the remaining 33% are a combination of the different configurations.

Simulation of SHP systems for residential buildings has been carried out by several authors. Concerning air + solar HP systems, Banister and Collins (2015), compare a parallel/series system to a solar only system and to an electric only system; Lerch et al. (2015), compare different concepts (parallel only, as well as diverse parallel/series combinations, involving different components); Carbonell et al. (2016), validate a model of a parallel/series system with ice storage with measured data and carries out sensitivity analysis; Winteler et al. (2014), focus on a series system with ice storage; Li et al. (2014), analyse the influence of major parameters on the performance of a dual HP system (an air + solar parallel HP and a seasonal energy storage HP); Haller and Frank (2011), analyse the impact of a series connection in a parallel/series system; In another study, Haller et al. (2014b), study the influence of hydraulic integration and control on a parallel system with a solar combi-storage; Mojic et al. (2014), study a parallel system as well as solar + ice storage HP systems in different locations/weather as well as different building demands.

Regarding ground + solar HP systems, both Girard et al., 2015, and Bertram, 2014, simulate the impact of adding solar collectors to a ground source HP system; Haberl et al., 2014, analyse the performance of a parallel system as well as it's optimization; Both Cimmino and Eslami-Nejad, 2016, and Rad et al., 2013, evaluate the performance of regeneration systems; Reda, 2015, studies dif-