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Techno-economic review of solar heat pump systems for residential heating applications

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ABSTRACT

Solar heat pump systems (SHPs) have been investigated for several decades and have been proven to increase the share of renewable energy and reduce electric energy demand in residential heating applications. Many review articles have been published on the subject, however literature discussing the techno-economics of different solar technologies (thermal, photovoltaic and hybrid thermal/photovoltaic) in combination with heat pumps is lacking, and thus to directly compare the merits of different SHPs is not an easy task. The objectives of this study are: a) review the different system boundaries and the main performance indicators used for assessing energetic and economic performances; b) review techno-economic studies in the literature and identify which studies give enough information and are compatible enough for making an economic inter-comparison; c) present an economic inter-comparison based on the identified systems. The results show that there is a lack of studies including an economic assessment of solar photovoltaic and heat pump systems. Additionally, there are no consistent boundaries or approaches to the study structures, making comparisons between systems difficult. In conclusion, a standardized or broadly accepted definition of technical and economic performance for SHPs is needed. Despite this, the study has shown that there are clear trends for decreasing payback times for SHPs, both solar thermal (ST) and photovoltaic (PV), with decreasing heating degree-days and with increasing solar resource.

1. Introduction

The global contribution from buildings towards energy consumption has steadily increased in developed countries and has exceeded the other major sectors: industry and transportation [1,2]. In the European residential sector, where the main consumption of energy occurs in hot water production and space heating [3], heat production is largely based on non-renewable carbon rich sources [4] resulting in large emissions of greenhouse gases and other air pollutants. Therefore, the current practice is not sustainable.

The European Performance of Building Directive (EPBD) [5] implies an almost zero energy building (ZEB) standard for new buildings by 2021. This may lead to widespread diffusion of hybrid renewable energy systems in the household market. Solar heat pump systems (SHPs) are hybrid systems in which electrical (in most cases) heat pumps are combined with solar thermal (ST), solar photovoltaic (PV), or both ST/PV. Heat pumps combined with ST systems have a superior seasonal performance factor (SPF) compared to heat pumps with no solar, while heat pumps combined with PV use less electricity from the grid. On the other hand, SHPs have higher investment costs than conventional heat pumps due to the additional components and may not always be cost-effective for heating purposes in the residential sector.

The potential for improvement has led to much work being done in the field of SHPs for domestic applications and thus many review articles have been published. A summary of the available literature, which is presented below in Section 1.1, reveals that a majority of the existing reviews focus on technology, system design and configuration, performance characterization and system integration in buildings.

1.1. Summary of review studies on SHPs for residential heating applications

A general classification of the review studies on SHPs for residential heating applications is shown in Table 1. The studies are classified into three main categories: reviews on solar thermal heat pump systems, reviews on heat pumps with a marginal scope on solar and reviews on integrated systems for zero energy buildings.

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Nomenclature

ASHP	Air Source Heat Pump
BIPV/T	Building integrated photovoltaic/thermal system
COP	Coefficient of Performance (–)
DHW	Domestic hot water
DX-SAHP	Direct-expansion solar assisted heat pump
GSHP	Ground Source Heat Pump
HP	Heat pump
I	Annual solar radiation (kWh/year)
LCC/LCCA	Life Cycle Cost/ Life Cycle Cost Analysis
MPC	Model Predictive Control
NPV	Net Present Value
P	Electrical power
PV	Solar photovoltaic
PV/T	Photovoltaic and thermal collector
SAHP	Solar assisted heat pump
SH	Space heating
SHPs	Solar Heat Pump system(s)
SPF	Seasonal Performance Factor (–)
ST	Solar thermal
W	Annual electrical energy consumption (kWh/year)
ZEB	Zero Energy Building

Subscript

AS	*air source*
BU	*back-up unit*
BLDG	*building*
cpr	*compressor*
Ctr	*controller*
DHW	*domestic hot water*
dist	*circulation pumps*
EH	*auxiliary electrical heater*
el	*electrical*
HP	*heat pump*
n	*year*
pen	*penalties*
Q	*thermal load*
S	*South*
SC	*solar collector*
SH	*space heating*
SHP	*solar heat pump*
ST	*storage*
tot	*total*
V	*system variation*
45	*tilt angle of solar collector*
+	*with circulation pumps*

Direct-expansion solar assisted heat pump systems (DX-SAHPs) are systems in which the functions of both ST collector and heat pump evaporator are combined into one unit, the collector-evaporator unit, where the refrigerant evaporates by the effect of incident solar energy. DX-SAHPs were reviewed by Kara et al. [6], Omojaro and Breitkopf [7], and Amin and Hawlader [8]. Kara et al. reviewed the exergetic assessment of DX-SAHPs showing that the vast majority of reviewed studies included theoretical and experimental as well as energy analysis, while exergy analysis was covered by only a few. Omojaro and Breitkopf concluded that the availability of solar heat has a high impact on the performance of both the collector–evaporator and the compressor. Moreover, the authors highlighted the need for further investigation in the area of cooling applications. Ozgener and Hepbasli [20] highlighted the importance of using exergy analysis for better identifying process efficiencies and losses. Amin and Hawlader reviewed DX-SAHPs in Singapore and showed values of coefficient of performance (COP) close to 8 for a solar assisted heat pump system designed for hot water and drying application.

Kamel et al. [15] reviewed studies on ST collectors and hybrid photovoltaic–thermal (PV/T) collectors and their integration with heat pumps. The review revealed that systems for space heating (SH) and domestic hot water (DHW) preparation are mainly water based systems with sensible thermal storage ([15]). ST heat pumps for heating applications were reviewed by Buker and Riffat [12] and, in part, also by Shukla et al.[13]. Buker and Riffat addressed their review on the design of main components, the type of refrigerant and on performance characterization. The authors claimed that the economic payback period of SHPs has been decreased and that more attention is needed on the economic aspects of SHPs.

Haller et al. [18] reviewed the main component models for the simulation of ST and heat pump systems. The authors concluded that several collector models are available that include validation for heat gains due to condensation of water vapour on uncovered collectors. For heat pumps there are a wide range of models available, but there is a lack of data and validation for the model parameterization for capacity controlled compressors and for low temperature lift applications ([18]).

Ruschenburg et al. [22] did a statistical analysis on market-available ST heat pump systems and many technological and market-specific particularities were identified. One is that the application of PV/T collectors in market-ready systems is a rather young trend. The

Table 1
A generalized classification of the review studies on SHPs for residential applications.

Reviews on solar thermal heat pump systems		*Reviews on heat pumps with a marginal scope on solar*		*Reviews on integrated systems for Zero Energy Buildings*	
Ref.	Focus	Ref.	Focus	Ref.	Focus
[6] Kara et al. [7] Omojaro and Briedkof [8] Amin and Hawlader	Direct-expansion solar assisted heat pumps	[9] Zhu et al. [10] Zhai et al.	Ground source heat pumps	[11] Yang and Althienitis	Integrated PV/T systems
[12] Buker and Riffat [13] Skukla et al.	Solar water heaters	[14] Wang et al.	Multi-functional heat pumps		
[15] Kamel et al.	Solar systems and their integration with heat pumps	[16] Ibrahim et al. [17] Hepbasli et Kalinci	Water heaters		
[18] Haller et al.	Modelling	[19] Staffel et al.	Domestic heat pumps		
[20] Ozgener and Hepbasli	Exergy and Energy analysis	[21] Chua et al.	Advances in heat pumps		
[22] Ruchenburg et al.	Market available systems				
[23] Kapsalis and Karamis	Solar thermal storage and heat pumps				