Applied Energy 190 (2017) 439–452

Contents lists available at ScienceDirect

Applied Energy

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

# Techno-economic assessment of solar assisted heat pump system retrofit in the Canadian housing stock

S. Rasoul Asaee [a,*], V. Ismet Ugursal [a], Ian Beausoleil-Morrison [b]

[a] Department of Mechanical Engineering, Dalhousie University, Halifax, NS B3H 4R2, Canada
[b] Sustainable Building Energy Systems, Department of Mechanical and Aerospace Engineering, Carleton University, Ottawa, ON K1S 5B6, Canada

## HIGHLIGHTS

- Techno-economic performance of SAHP in the Canadian housing stock is investigated.
- A dual tank system is used to maximise the solar energy capture during a day.
- Several energy performance indicators are used to evaluate the system performance.
- SAHP enhance the energy savings compared to conventional solar thermal systems.
- About 19% of GHG emission of the Canadian housing stock is reduced by SAHP retrofit.

## ARTICLE INFO

*Article history:*
Received 18 October 2016
Received in revised form 20 November 2016
Accepted 11 December 2016
Available online 7 January 2017

*Keywords:*
Solar thermal
Heat pump
Building performance simulation
Residential energy consumption
Residential GHG emission

## ABSTRACT

The techno-economic feasibility of retrofitting existing Canadian houses with solar assisted heat pump (SAHP) is investigated. The SAHP architecture is adopted from previous studies conducted for the Canadian climate. The system utilizes two thermal storage tanks to store excess solar energy for use later in the day. The control strategy is defined in order to prioritise the use of solar energy for space and domestic hot water heating purposes. Due to economic and technical constraints a series of eligibility criteria are introduced for a house to qualify for the retrofit. A model was built in ESP-r and the retrofit was introduced into all eligible houses in the Canadian Hybrid Residential End-Use Energy and GHG Emissions model. Simulations were conducted for an entire year to estimate the annual energy savings, and GHG emission reductions. Results show that the SAHP system performance is strongly affected by climatic conditions, auxiliary energy sources and fuel mixture for electricity generation. Energy consumption and GHG emission of the Canadian housing stock can be reduced by about 20% if all eligible houses receive the SAHP system retrofit. Economic analysis indicates that the incentive measures will likely be necessary to promote the SAHP system in the Canadian residential market.


## 1. Introduction

Solar energy is one of the main sources of renewable energy for residential applications. Solar thermal energy is used for space heating and cooling as well as domestic hot water (DHW) heating in the residential sector. The non-concentrating liquid cooled thermal collector (e.g. flat plate collector) is the most popular technology to utilize solar energy in buildings. Depending on the geographical location, climatic condition and solar thermal collector installation, water supply temperature from a flat plate collector may vary widely through the year. Thus, traditionally an auxiliary source of energy is integrated into the solar based heating systems to supply energy when solar energy is either not available (i.e. at night) or not sufficient (e.g. on cloudy days) to meet the demand. Integrating solar thermal collectors with a heat pump (HP) system is an energy efficient alternative for this purpose. Heat pumps capture aerothermal, geothermal or hydrothermal energy at the expense of thermodynamic work. Solar thermal collector and HP systems can be combined in different ways. A common method is to deliver the solar thermal energy to the evaporator of the heat pump in a series configuration to enhance the system performance [1]. In this configuration, efficiency gains compared to standalone solar thermal and HP systems are realized because the high evaporator temperature increases the COP of the HP [1]. Thus, the solar assisted heat pump (SAHP) system is expected to provide superior performance compared to conventional solar thermal systems such as solar domestic hot water (SDHW) and

* Corresponding author.
*E-mail address:* asaee@dal.ca (S.R. Asaee).

http://dx.doi.org/10.1016/j.apenergy.2016.12.053
0306-2619/

**Nomenclature**

| | |
|---|---|
| ACSH | annual cost savings for the house due to energy savings in a uniform series, continuing for n periods (C$) |
| ATCCH | average tolerable capital cost per house (C$) |
| $CO_{2e}$ | equivalent $CO_2$ (kg) |
| E | energy saving per period for each fuel type (unit depends on fuel type; kg, liter, kW h, etc.) |
| $E_{aux}$ | energy consumption of auxiliary heating system (GJ) |
| $E_{ref}$ | energy consumption of reference heating system (GJ) |
| $E_{total}$ | total energy consumption (GJ) |
| $E_{total,ref}$ | total energy consumption of reference system (GJ) |
| e | fuel cost escalation rate (decimal) |
| F | fuel price per unit of each fuel type (C$/unit) |
| $F_R$ | collector heat removal factor |
| $f_{sav,ext}$ | extended fractional energy saving (%) |
| $f_{sav,therm}$ | fractional thermal energy saving (%) |
| $f_{sol}$ | solar fraction (%) |
| $G_T$ | solar radiation incident upon the collector ($W/m^2$) |
| i | interest rate (decimal) |
| m | number of different fuels used in a house |
| NH | number of houses |
| n | acceptable payback period (year) |
| $P_{el,pump.DHW}$ | pump power for DHW heating loop (W) |
| $P_{el,pump.SH}$ | pump power for heat delivery to the space (W) |
| $P_{nom,burner}$ | nominal capacity of auxiliary boiler (W) |
| $Q_{DHW}$ | thermal energy for domestic hot water heating (GJ) |
| $Q_{SH}$ | thermal energy for space heating (GJ) |
| $Q_{sol}$ | thermal energy delivered by solar system (GJ) |
| $SPF_{SAHP}$ | seasonal performance factor of solar assisted heat pump |
| TCC | tolerable capital cost (C$) |
| TCCH | tolerable capital cost of the upgrade for each house (C$) |
| TTCC | total tolerable capital cost (C$) |
| $T_{amb}$ | ambient temperature (K) |
| $T_c$ | cold side temperature (°C) |
| $T_h$ | hot side temperature (°C) |
| $T_{in}$ | collector inlet temperature (K) |
| $T_{ref}$ | reference temperature (°C) |
| $T_{ret}$ | return water temperature (°C) |
| $W_{el,SAHP}$ | electricity consumption of solar assisted heat pump (GJ) |
| $W_{HP}$ | electricity consumption of heat pump (GJ) |
| $W_{par}$ | parasitic power (GJ) |
| $W_{par,ref}$ | parasitic power of reference system (GJ) |

*Greek symbols*

| | |
|---|---|
| $(\tau\alpha)_n$ | normal-incidence transmittance–absorptance |
| $\Delta T$ | temperature difference |
| $\eta_b$ | boiler efficiency |
| $\eta_{el}$ | electrical efficiency (inclusive of electricity generation, transmission and distribution efficiency) |
| $\eta_{ref}$ | full load boiler efficiency at the reference temperature |
| $\varphi$ | slope of the efficiency curve |

*Abbreviations*

| | |
|---|---|
| AB | Alberta |
| AL | appliance and lighting |
| AT | Atlantic provinces (i.e. NF, NS, PE and NB) |
| AWHP | air to water heat pump |
| BC | British Columbia |
| CHREM | Canadian Hybrid Residential End-Use Energy and GHG Emissions model |
| COP | coefficient of performance |
| CSDDRD | Canadian single detached and double/row database |
| DHW | domestic hot water |
| EIF | emission intensity factor |
| GHG | greenhouse gas |
| HP | heat pump |
| ICE | internal combustion engine |
| IEA | international energy agency |
| MB | Manitoba |
| NB | New Brunswick |
| NF | Newfoundland and Labrador |
| NG | natural gas |
| NS | Nova Scotia |
| NZE | net zero energy |
| OT | Ontario |
| PCM | phase change material |
| PE | Prince Edward Island |
| PR | Prairie provinces (i.e. MB, SK and AB) |
| QC | Quebec |
| SAHP | solar assisted heat pump |
| SDHW | solar domestic hot water |
| SE | Stirling engine |
| SHC | solar heating and cooling |
| SK | Saskatchewan |

solar combisystem; however, long term field performance and economic feasibility require in-depth study. To address these issues, numerous studies were conducted, and results reported in the literature.

The International Energy Agency (IEA) Solar Heating and Cooling (SHC) programme launched Task 44 [2] with the goal to deliver optimized integration of solar thermal and heat pump systems, primarily for single family houses. Several systems were investigated and a series of recommendations were provided for SAHP system design and optimization. According to the survey conducted within the IEA SHC Task 44 most of the market ready SAHP systems are designed to serve both space and DHW heating [1]. Different system architectures are categorized under four main sections (a) parallel, (b) series, (c) regenerative, and (d) complex. A wide range of measured data was gathered from 50 different systems in seven European countries for one to two years. Simulation results within the IEA SHC Task 44 indicated that solar contribution can be significant to reduce primary energy consumption and greenhouse gas (GHG) emissions. It was concluded that the solar and HP systems will be a part of solutions to fulfill the demands for net zero annual energy balance [1].

The performance of SAHP systems in different climatic and operating conditions was studied by several researchers. For example, Chu et al. [3] assessed the feasibility of a SAHP system in a high performance house designed and built for the U.S. Department of Energy's Solar Decathlon 2013 Competition. A numerical model was developed in TRNSYS 17 [4] for this study. Results show that the free energy ratio (the energy not purchased such as solar energy divided by total energy used) of 0.583 can be achieved using SAHP system in Ottawa, Ontario. The study revealed that flat plate collectors provide a superior performance compared to evacuated tube solar collectors for SAHP applications. Impact of heat pump performance, source side and load side input temperatures, solar collector array area and stratifications in the thermal storage tank on the overall performance of the SAHP system were investigated. Bakirci and Yuksel [5] carried out an experimental study to evaluate the performance of a SAHP system for a residential application in Erzurum, Turkey. Data were collected from an actual system from January to June when the outdoor temperature was in