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Research Paper

Techno-economic feasibility evaluation of air to water heat pump retrofit in the Canadian housing stock

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HIGHLIGHTS

- Techno-economic feasibility of air to water heat pump is assessed for Canadian houses.
- A state-of-the-art housing stock model is used for techno-economic analysis.
- AWHP retrofit reduced 36% of end-use energy consumption in the Canadian housing stock.
- AWHP retrofit decreased 23% of GHG emission of the Canadian housing stock.
- Aerothermal energy captured by HP can be assumed as renewable energy in most provinces.

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ABSTRACT

This study was conducted to assess the techno-economic feasibility of converting the Canadian housing stock (CHS) into net/near zero energy buildings by introducing and integrating high efficient and renewable/alternative energy technologies in new construction and existing houses. Performance assessment of energy retrofit and renewable/alternative energy technologies in existing houses in regional and national scale is necessary to devise feasible strategies and incentive measures. The Canadian Hybrid Residential End-Use Energy and GHG Emissions model (CHREM) that utilizes a bottom-up modeling approach is used to investigate the techno-economic feasibility of air to water heat pump retrofit in the Canadian housing stock. The proposed energy retrofit includes an air to water heat pump, auxiliary boiler, thermal storage tank, hydronic heat delivery and domestic hot water (DHW) heating. Energy savings, GHG emission changes and economic feasibility of the air source heat pump retrofit are considered in this study. Results show that there is a potential to reduce 36% of energy consumption and 23% of GHG emissions of the CHS if all eligible houses undertake the retrofit. Economic analysis indicates that the feasibility of air to water heat pump systems is strongly affected by the current status of primary energy use for electricity generation and space and DHW heating as well as energy prices and economic conditions. Legislation, economic incentives and education for homeowners are necessary to enhance the penetration level of air to water heat pump retrofits in the CHS.

1. Introduction

Shrinking the energy footprint of residential buildings is a promising option to reduce national greenhouse gas (GHG) emissions. While developing and implementing improved building codes for new construction is necessary, it is not sufficient to achieve this goal. A housing policy with focus on retrofitting existing houses is an essential part of a strategic plan to reduce the GHG emissions associated with the housing stock [1]. While the most feasible and effective retrofit options might be improving building skin, installing high efficiency heating systems and incorporating renewable energy systems [2], adding an air to water heat pump (AWHP) system to a house could also be a suitable option to reduce energy consumption [3]. AWHP system can provide space and domestic hot water (DHW) heating energy requirement from a single source. While the AWHP system is well established in Europe and Japan, it is relatively new to the Canadian market [4]. Thus, an accurate and comprehensive study is needed to investigate the feasibility of integrating AWHP systems into the Canadian housing stock (CHS). Recently, such studies have been conducted

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Nomenclature

ACSH	annual cost savings for the house due to energy savings in a uniform series, continuing for n periods ($/year)
ATTCCH	average tolerable capital cost per house ($)
CO_{2e}	equivalent CO_2 emitted per unit input energy (kg/kW h)
c	specific heat (kJ/kg K)
E	energy saving per period for each fuel type (unit depends on fuel type)
E_{RES}	thermal energy considered from renewable sources (PJ)
e	fuel cost escalation rate (decimal)
F	fuel price per unit of each fuel type ($/unit)
h_{store}	storage tank height (m)
K_{AB}	heat exchange coefficient between water and working fluids (kW/K)
i	interest rate (decimal)
M	mass of control volume (kg)
$\dot{m}$	mass flow rate (kg/s)
NH	number of houses that received the upgrade
n	acceptable payback period (year)
P_C	compressor power (kW)
$P_{el,pump.SH}$	pump power in space heating loop (W)
$P_{el,pump.DHW}$	pump power in DHW loop (W)
$P_{nom,burner}$	nominal power of auxiliary boiler (W)
Q_{usable}	gross final thermal energy delivered by heat pump (kJ)
RH_{amb}	relative humidity of ambient air (%)
SPF	seasonal performance factor
TCC	tolerable capital cost ($)
TCCH	tolerable capital cost of the retrofit for the house ($)
T_{amb}	ambient temperature (K)
T_c	reference temperature for boiler efficiency (K)
T_r	return water temperature (K)
t_{def}	defrost time (s)
t_{tr}	duration of transient operation of boiler (s)
UA	heat loss coefficient (kW/K)
V_{store}	storage tank volume (m^3)

Greek letters

η	ratio between total gross production of electricity and the primary energy consumption for electricity generation
η_b	boiler efficiency (%)
η_0	full load boiler efficiency at the reference temperature (%)
φ	slope of the boiler efficiency curve (degree)
Δt	simulation time step (s)

Abbreviations

AB	Alberta
AL	appliances and lighting
ASHP-WH	air source heat pump water heating
AT	Atlantic Provinces
AWHP	air to water heat pump
BC	British Columbia
CHREM	Canadian hybrid residential end-use energy and GHG emissions model
CHS	Canadian housing stock
COP	coefficient of performance
CSDDRD	Canadian single-detached double/row database
DHW	domestic hot water
EIF	emission intensity factor
GHG	greenhouse gas
ICE	internal combustion engine
MB	Manitoba
NB	New Brunswick
NF	Newfoundland and Labrador
NG	natural gas
NS	Nova Scotia
NZEB	net zero energy building
OT	Ontario
QC	Quebec
PCM	phase change material
PE	Prince Edward Island
PR	Prairie Provinces
SDHW	solar domestic hot water
SE	Stirling engine
SK	Saskatchewan
SNEBRN	smart net-zero energy buildings strategic research network

for various regions of the world. For example, Kelly and Cockroft [5] developed a numerical model to evaluate the performance of AWHP retrofit into a building in Scotland. The simulation results were validated by laboratory data and the model was integrated into a whole building performance simulation software. The model was well representative of the AWHP operating conditions in the field trial. An equivalent condensing natural gas boiler and an electric heating system were used as alternative heating systems for the building, and annual energy consumption of the three systems were compared. The results showed that GHG emissions of AWHP were lower compared to that of the condensing natural gas boiler and the electric heating system. While the operating cost of the AWHP exceeds that of the gas condensing boiler, incentives available for renewable thermal energy may make up the difference. In another study, Kelly et al. [6] used the AWHP model to estimate the effectiveness of integrated AWHP and thermal storage tank with phase change material (PCM) to restrict the AWHP operation to the off-peak periods. The results showed that through manipulation of the PCM chemistry, heat storage tank volume could be reduced by 50% with a minimum impact on heat supply to the building in the UK climate. Cabrol and Rowley [7] used a numerical model to study the performance of air source heat pump water heating (ASHP-WH) system with hydronic heat delivery in various UK locations. A sensitivity analysis was conducted to evaluate the impact of the building construction materials and off-peak period operation. The GHG emissions and operating cost of ASHP-WH were found to be lower compared to those of an equivalent size gas boiler, and the annual coefficient of performance (COP) of the ASHP-WH was found to be about 3.5 and 4 for cold and mild UK climates, respectively. Johnson [8] found that in the UK context the heat pump GHG emissions due to electricity consumption were higher compared to gaseous fuels and lower compared to heating oil. Using a model for ASHP-WH system model based on measured data from a field trial campaign Madonna and Bazzocchi [9] found that climate has a significant role on the performance of ASHP-WH, and depending on climate, the energy requirement for space heating could be reduced by up to 79% in new buildings in Italy. A study by Hewitt et al. [10] that investigated AWHP retrofit options for existing houses in the UK recommended using variable speed compressor, advanced evaporators and improving heat delivery system to enhance the performance of AWHP in the European maritime climate conditions. Bertsch and Groll [11] designed, simulated, constructed and tested an ASHP water or air heating system with an operating range of −30 °C to 10 °C and return water tempera-