International Conference on Applied Energy 2020
Dec. 1 - Dec. 10, 2020, Bangkok / Virtual
Paper ID: 0550

Heat Supply Temperature Impact on the Seasonal Cost of Low Carbon Domestic Heat Pump Technology

Muhammad Abid[*a], Neil Hewitt[a], Ming Jun Huang[a], Christopher Wilson[a] Donal Cotter[a]

[a] Belfast School of Architecture and the Built Environment, Faculty of Computing, Engineering and the Built Environment, Ulster University, Jordanstown Campus, BT 37 0QB, Belfast, United Kingdom)

ABSTRACT

In this study the economic analysis of a 9kW variable speed compressor-based air source heat pump (ASHP) has been carried out. The HP system, developed with an aim to meet typical UK household heating demand for retrofitting application, was tested in the lab as per BSEN14511 standards at various constant definite heat load under steady state conditions. The thermodynamic performance of the HP is presented at nominal value of 9kW. The test house seasonal heating load demand was fulfilled at three constant water supply temperature (WST) of 35 °C, 45 °C, and 55 °C and the HP seasonal electric power consumption, cost, and carbon emissions were calculated. The HP average efficiency at supply temperatures of 35 °C, 45 °C, and 55 °C over the same ambient temperature conditions was found to be 363%, 291%, and 212% for meeting the house load demand completely by varying operating compressor speed. A comparative study of cost, carbon emission, and energy savings with other heating technologies, i.e. gas/oil boiler, electric heater is also conducted and presented.

Keywords: Air source heat pump, carbon emission, economic analysis, seasonal efficiency, water supply temperature.

NONMENCLATURE

ASHP	air-source heat pump
COP	coefficient of performance
CO_2	carbon dioxide
EWT	entering water temperature (°C)
HC	heating capacity(kW)
SCOP	seasonal Co-efficient of performance
WST	water supply temperature (°C)
Symbols	
A	Ambient
φ	relative humidity (-)
£	GBP
ω	frequency (Hz)

1. INTRODUCTION

The UK target is to reduce carbon emissions up to 80% to that of 1990 level by 2050, a legal requirement for the climate change act, 2008 [1]. This encourages the domestic heating sector to rely on the renewable energy-based heating technology instead of fossil fuel-based heating options to reduce heating carbon intensity. Existing heating systems in the UK rely mainly on fossil fuel technologies, i.e. gas/oil boilers for space heating and domestic hot water (DHW) demand. The heating distribution system installed is wet radiators which is designed for a supply temperature of 60 °C and above [2]. In contrast, heat pump (HP) technology works efficiently at low supply temperature. The replacement of the oil/gas heating technology with HP technology inside existing housing stock requires feasibility studies in terms of cost, thermal comfort, and carbon emissions. Previous studies conducted on variable speed compressor-based HP technology for retrofitting applications in the current housing stock highlight the cost as the major barrier for HP system installation in the UK [3,4]. The performance results of high temperature lift economized vapor injection (EVI) HP system for retrofitting applications has shown good potential for meeting typical household demand and were found expensive in terms of cost because of this high supply temperature of 60 °C [3]. In addition to the high capital cost for HP technology, in comparison to oil and gas boilers, the annual running cost also increases at higher water supply temperature, because of lower efficiency. The replacement of high temperature heating distribution systems in addition to the heating technology itself is required and were recommended for further studies with variable speed compressor HP [4]. Earlier studies with variable speed compressor ground source heat pump (GSHP) systems have investigated the efficiency increase at different supply/return temperatures but without considering the economic aspect and additional installations cost [5]. The only study that can be found from literature review combining an ASHP performance analysis with economic aspects for the variable speed HP system in comparison with fixed single speed, and two speed was at a single WST of 55 ^{o}C of which the aim was to investigate the benefit associated with the variable speed against the fixed speed [6]. The smallest annual energy consumption and higher performance was found to occur in the case of a variable speed HP system, but at the cost of the higher pay back period. In this study the performance analysis of the variable speed HP system at nominal heating capacity of 9 kW is presented at three different water supply temperature (35 ^{o}C, 45 ^{o}C, and 55 ^{o}C). The HP economic aspect, energy and carbon emission savings in comparison with the other heating options of oil/gas boiler, and electric heating have been evaluated in addition to the heat supply temperature impact on the HP performance for meeting the typical UK household seasonal heat demand.

2. METHODOLOGY

2.1 Heat pump (HP) operating conditions, and the performance at nominal heating capacity

The experimental results for an ASHP have been used to meet the considered household heat load demand at various supply temperatures and the range of experienced ambient temperature conditions in Belfast, UK.

The ASHP system can provide a range of heating capacities by varying compressor speed at different constant WST of 35 ^{o}C, 45 ^{o}C, and 55 ^{o}C typical requirements for underfloor heating, domestic hot water demand and medium/high flow temperature radiator space heating systems, respectively. The HP was tested as per BS EN14511(3) [7]in the laboratory conditions at -2 ^{o}C, 2 ^{o}C, 7 ^{o}C, 15 ^{o}C with constant definite heating capacity of 18kW, 15kW, 12kW, 9kW, 6kW, and 3kW. The mean efficiency for meeting the considered house heating demand at 35 ^{o}C, 45 ^{o}C, and 55 ^{o}C were found to be 363%, 291%, and 212 % over the same experienced ambient temperature conditions. The detailed description of the HP system, and the performance results with methodology, are presented in the authors' previous paper [8]. The thermodynamic performance of the HP at nominal heating capacity of 9kW is presented in Table 1. The COP values for 35 ^{o}C WST were 3.04, 3.43, 3.84, and 4.78, at -2 ^{o}C, 2 ^{o}C, 7 ^{o}C, 15 ^{o}C respectively. The corresponding COP values reduces at increased WST of 45 ^{o}C and becomes 2.62, 2.72, 3.11, and 3.75. The percentage reduction in COP values with change in WST from 35 ^{o}C, to 45 ^{o}C at the four ambient temperature conditions was 13.81%, 20.69%, 19.01%, 21.54% respectively. The percentage increase in COP values due to increase in ambient temperature from -2 ^{o}C to 15 ^{o}C were found to be 57.23 % and 43.12 % at 35 ^{o}C, and 45 ^{o}C WST, respectively.

Table 1: Thermodynamic performance results for the HP at nominal heating capacity of 9kW

Set point	EWT/WST (^{o}C)	HC (kW)	ΔT (^{o}C)	RH (%)	Amb (^{o}C)	ω (Hz)	P(kW)	COP
15A	25/35	8.98	10.01	91.87	14.95	45.60	1.88	4.78
	35/45	8.98	9.92	90.56	14.88	47.46	2.40	3.75
	45/55	8.98	9.88	91.10	14.61	50.52	3.06	2.94
7A	25/35	8.98		87.85	6.76	58.77	2.34	3.84
	35/45	8.99	10.05	88.42	6.86	59.69	2.89	3.11
	45/55	8.96	10.06	89.13	6.20	63.22	3.72	2.41
2A	25/35	9.00	9.98	87.04	2.13	67.19	2.63	3.43
	35/45	8.99	9.88	88.78	2.18	67.64	3.29	2.73
	45/55	8.99	9.91	87.93	2.02	69.37	4.07	2.21
-2A	25/35	8.98	9.98	82.23	-2.23	74.32	2.95	3.05
	35/45	8.98	9.88	83.25	-2.25	75.63	3.43	2.62
	45/55	8.98	9.91	81.69	-2.23	81.25	7.07	1.27

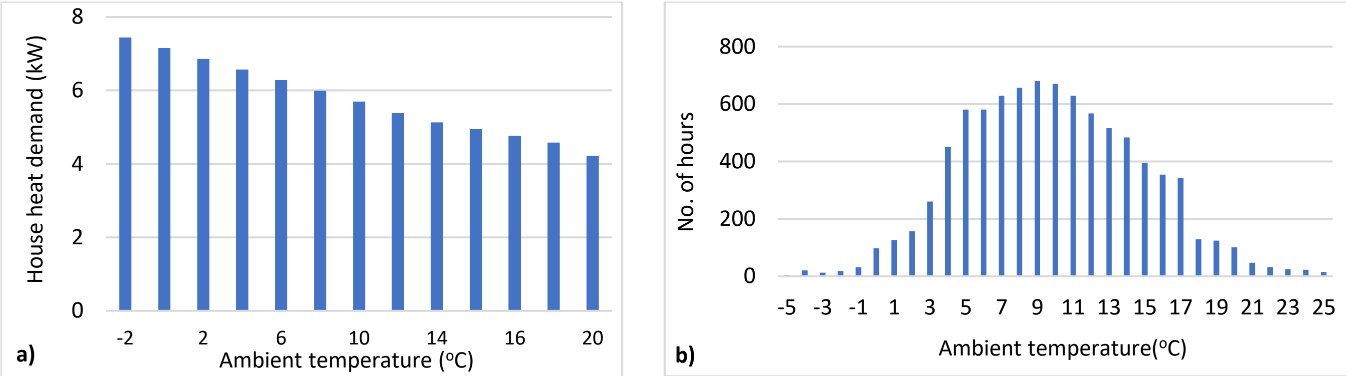


Fig.1. Case study under consideration, a) House heat load demand, b) Experienced number of hours at different ambient temperature conditions for Belfast, UK.

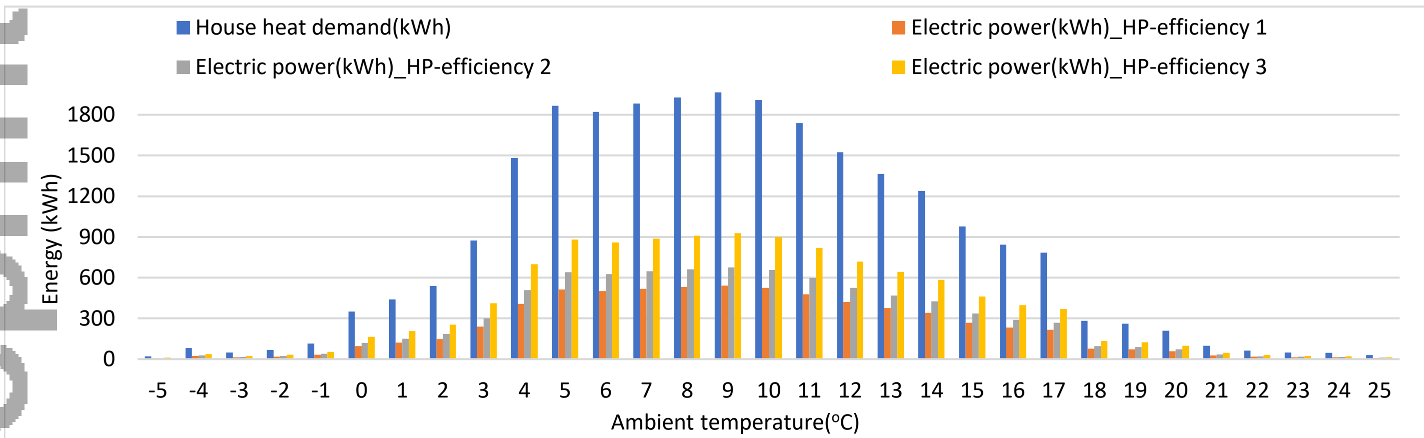


Fig. 2. The heat demand (space heating and DHW) with electric power consumption in each bin.

2.2 Case study: The test household heat demand and weather conditions

The case study under consideration is the annual heating Demand (DHW and space heating) experimentally calculated earlier for the test house, a typical 3-bedroom home with a floor area of 105 m^2, located in Carrickfergus, Northern Ireland (NI) [9,10]. The HP performance results were used and mapped against the household heat demand via interpolation and extrapolation. Fig 1 (a) shows the heat demand plotted against the experienced ambient temperature conditions for the test house. The ambient temperature conditions experienced in Belfast (UK) is shown in Fig.1(b). Each bin is 1 °C showing the ambient air temperature profile across the year. Researchers [11] have evaluated the SCOP value using bin method. The seasonal co-efficient of performance (SCOP) has been calculated by mapping the experimental results against the test house heat load demand in each bin.

2.2.1 Seasonal heat demand (for the considered test house)

The SCOP value for the HP system depends on the building heating demand, and WST, in addition to the operating frequency of the system and ambient temperature conditions in each bin. The test house heat load demand in each bin with electric power consumption while meeting the load demand at 35 °C, 45 °C, 55 °C WST in each bin have been calculated and can be seen in Fig. 2.

2.2.2 Seasonal running cost, carbon emission for the HP compared to other heating technologies

Table 2 shows the seasonal running cost, carbon emission, cost savings, and carbon emission savings in percentages for different heating technology at three different efficiencies. The greenhouse gas emission factors were sourced from the UK GHGs emission report [12]. The HP has been analysed at three different average efficiencies of 363%, 291%, and 212 % over the experienced ambient conditions with WST of 35 °C, 45 °C, 55 °C. The HP system cost and carbon emission increases with the increase of WST. The seasonal running cost, for the heat pump system when operating at 363%, 291%, and 212% efficiency at respective WST of 35 °C, 45 °C, 55 °C were found to be £1116, £1454.99, and £1997.18, respectively. Similarly, the HP carbon emission were found to be 2607.65 kg, 3252.34kg, and 4464.29kg, expensive both in terms of carbon emission and cost as well in all cases in comparison to the HP technology.

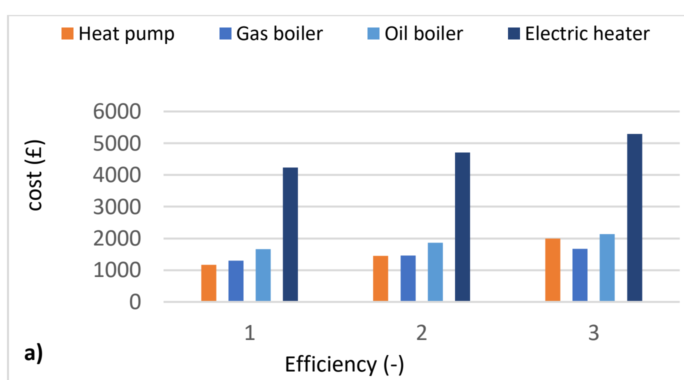
The oil boiler at 80% efficiency has been considered as the base case and the carbon emission savings, and cost savings calculated have been presented in Fig. 4. The HP have shown to reduce carbon emissions in all cases, with electric heating option the most expensive one both in terms of cost and carbon emission. The cost and carbon

Table 2: Seasonal running cost, carbon emission, cost savings, and carbon emission savings in percentages for different heating technology at three different efficiencies

Efficiency No.		**1**	**2**	**3**
Heat Pump	Efficiency (%)	363	291	212
	Seasonal heat output (kWh)	24906.06	24906.06	24906.06
	Seasonal input energy (kWh)	6861.17	8558.78	11748.14
	Cost (£)	1166.40	1454.99	1997.18
	CO_2 emissions (kg)	2607.25	3252.34	4464.29
	Cost saving (%)	37.55	22.10	-6.90
	CO_2 emissions saving (%)	65.53	57.00	40.98
Oil Boilers	Efficiency (%)	90%	80%	70%
	Seasonal oil used (kWh)	27673.44	31132.63	35580.08
	Cost (£)	1660.40	1867.95	2134.8
	CO_2 emissions (kg)	6724.64	7565.23	8645.95
	Cost saving (%)	11.10	-	-14.28
	CO_2 emission saving (%)	11.10	-	-14.28
Gas Boilers	Efficiency (%)	90%	80%	70%
	Seasonal gas used (kWh)	27673.44	31132.63	35580.08
	Cost (£)	1300.65	1463.23	1672.26
	CO_2 emissions (kg)	5617.71	6319.92	7222.75
	Cost savings (%)	30.37	21.66	10.47
	CO_2 emission saving (%)	25.74	16.46	4.52
	Efficiency (%)	100%	90%	80%
Electric Heater	Seasonal electricity used (kWh)	24906.06	27673.44	31132.63
	Cost (£)	4234.03	4706.48	5292.54
	CO_2 emissions (kg)	9464.30	10515.9	11830.39
	Cost saving (%)	-126.66	-151.95	-183.33
	CO_2 emissions saving (%)	-25.12	-39	- 56.37

at 363%, 291%, and 212% respective efficiency. The carbon emission and the annual running cost decreases with reduction in supply temperature for the same seasonal heat demand to a great extent evidenced from the values. Similarly, the gas, oil boiler and electric heating option have been shown at different percentage efficiencies.

The HP, gas/oil boiler and electric heater technology have been compared at three different efficiencies for the seasonal cost (Fig. 3a), and carbon emission in (Fig. 3b). The seasonal house heating demand have been chosen to meet by the gas boiler at three efficiencies (90%, 80%, 70%) and compared as case 1, case 2 and case 3 in the Table 2. The HP carbon emission is lower than the gas boiler in all cases, however the seasonal running cost at the HP efficiency No. 3(212%) is higher than the gas boiler. The oil boiler and electric heating option is emission savings for the HP at three efficiencies are 37.55%, 22.1%, -6.9%, and 65.53%,57%, 40.98% respectively. The HP seasonal cost increases at No. 3 efficiency and the carbon emission savings also reduces because of the low efficiency value at the higher heat supply temperature of 55 °C.



a)

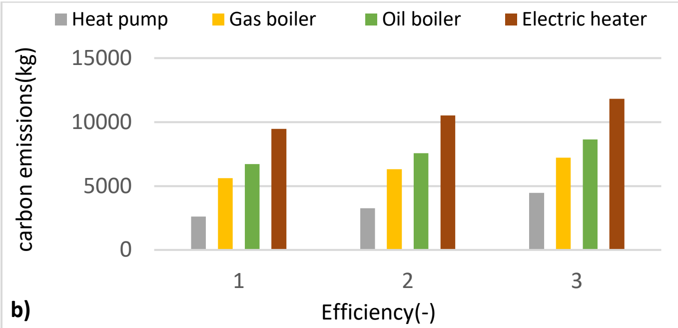


Fig. 3. a) Seasonal cost and b) Carbon emission against the efficiency for the HP, oil gas boiler technology for the three cases with efficiency of 90, 80 and 70%.

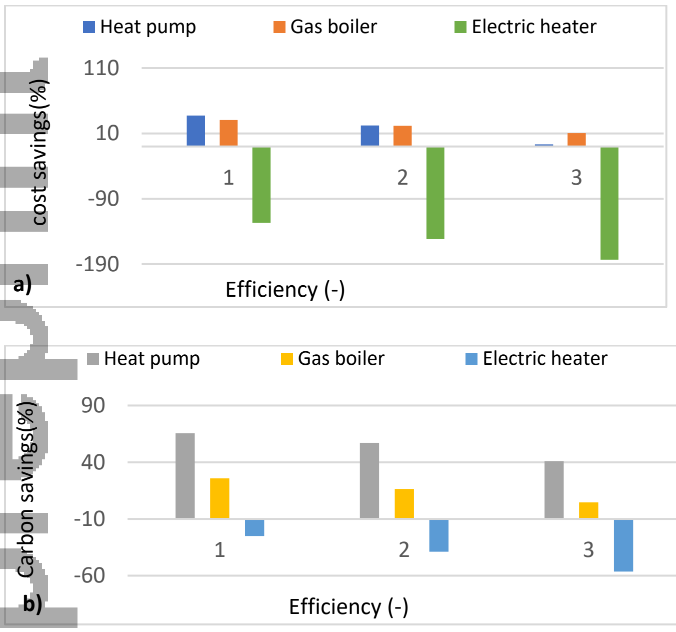


Fig. 4. Savings (%) considering oil boiler at 80% efficiency as a base case, a) cost, b) carbon emission.

2.3 Conclusions

The HP system outperforms the other heating technologies in terms of carbon emission at all three efficiencies, showing good potential for meeting the household heating demand efficiently in terms of seasonal running cost as well. The HP seasonal performance, running cost and the carbon emission are strongly dependent on the heat supply temperature but requires additional retrofit measure for installation of the heating distribution system with low supply temperature heating option. Upgrading UK housing stock installed with high temperature radiators with low supply temperature heating distribution system looks attractive because of the efficiency improvement and reduction in annual running cost with lower supply temperatures.

2.4 Future work

The HP techno economic aspect and carbon emission in retrofit application for meeting the domestic heat load demand.

ACKNOWLEDGEMENT

This project has been funded by the EU's INTERREG VA Program SPIRE2, managed by the Special EU Programs Body (SEUPB). The views and opinions expressed in this document do not necessarily reflect those of the European Commission or the Special EU Programmes Body (SEUPB).

REFERENCES

[1] Climate change act 2008. Tech. Rep., Parliament of the United Kingdom, http://www.legislation.gov.uk/ukpga/2008/27/pdfs/ukpga_20080027_en.pdf [Accessed online 29-10-2020].

[2] Palmer J, Cooper I. United Kingdom housing energy fact file. London, 2013. Tech. Rep., Department of Energy and Climate Change.; 2013.

[3] Matthew V Q. The development of a capacity controlled advanced cycle air source heat pump for domestic retrofit applications, PhD Thesis, CST, Ulster University, UK; 2012.

[4] Hewitt, NJ, Huang, MJ, Anderson M, Quinn M. Advanced air source heat pumps for UK and European domestic buildings. Appl Therm Engr, 2011; 31(17–18): 3713–3719.

[5] Karlsson F. Capacity control of residential heat pump heating systems. PhD Thesis, Building services engineering department of energy and environment Chalmers University of technology, Sweden; 2007.

[6] Marquand CJ, Tassou SA, Wang YT, Wilson DR. An economic comparison of a fixed speed, a two speed, and a variable speed vapour compression heat pump. Appl Energy 1984; 16: 59-66.

[7] European Standard EN 14511-3 - Air conditioners, liquid chilling packages and heat pumps with electrical driven compressors for space heating and cooling-part 3, Test Methods, AFNOR 2004.

[8] Abid M, Hewitt N, Huang MJ, Wilson C, Cotter D, "Experimental Study of the Heat Pump with Variable Speed Compressor for Domestic Heat Load Applications", submitted to the conference of "Compressor Engineering" to be held in May 2021 at Perdue.

[9] Huang MJ, Hewitt NJ, Minh N Field testing of an economized vapor injection heat pump 22nd IIR International Congress of Refrigeration 2007; Beijing, China.
[10] Huang MJ, Hewitt NJ. The experimental analysis of the effect of ambient factors on the defrosting of economized vapour injection compressor air source heat pump in marine climates, International Journal of Refrigeration 2013, 36, 3: 820-827.
[11] Dongellini M, Naldi C, Morini GL. Seasonal performance evaluation of electric air-to-water heat pump systems. Appl Therm Eng 2015; 90: 1072–1081.
[12]Greenhouse gas reporting: conversion factors 2018 - GOV.UK, https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors.