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Research Paper

Analysis on field trial of high temperature heat pump integrated with thermal energy storage in domestic retrofit installation

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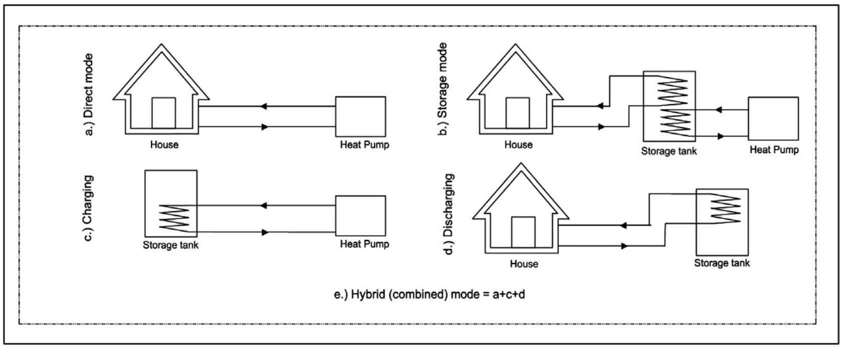
HIGHLIGHTS

- Presents 1-year field trial outcome of HTHP and TES in domestic retrofit setting.
- Heat pump average COP of 2.2 in direct mode to provide 75 °C flow temperature.
- Storage mode- high energy output during first call for heat but low system COP.
- Combined mode-benefits of combined operation of heat pump and TES at peak times.
- CO_2 emission saving potential of 30% with COP 2.5 compared to gas boiler.

GRAPHICAL ABSTRACT



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ABSTRACT

Heat pump and thermal energy storage are important technologies to decarbonise heat and electricity sector. Heat pump integrated with thermal energy storage can provide flexibility to electrical system operator to shift demand to accommodate non-synchronous generators. However, ageing housing stock and high temperature wet radiator central heating system possess some challenges for heat pump installation in the UK. To understand the challenges of retrofit technologies in the domestic sector, a field trial was carried out with a cascade heat pump integrated with a thermal storage tank. The heat pump replaced an existing gas boiler to provide flow temperature of 75 °C as a retrofit measure without any modification/replacement to existing controller or radiators in the house. The heat pump was integrated with a 600 l thermal store to meet heating demand and system performance was measured in different operation mode such as direct mode, storage mode and combined mode during one-year. The paper provides performance analysis of the system in different mode with operational experience, limitation and issues with the heat pump, house heat loss/insulation and sizing of thermal store in retrofit installation. Additionally, heat pump performance was compared with gas boiler to establish emission and cost saving benefits.

1. Introduction

UK's clean growth strategy reflects commitment to reduce greenhouse gas by decarbonising heat sector since heat sector accounts for 44% of total energy consumption [1] and 32% of total UK emissions [2]. Space heating (SH) and domestic hot water (DHW) consumes 82% of domestic energy [1], mainly supplied by central heating system (wet radiator system) and present in 90% of 27.5 million UK's housing stock

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Nomenclature

ASHP	air-source heat pump
COP	coefficient of performance
COP_{CM}	system performance in combined mode
COP_{DM}	system performance in direct mode
COP_{SM}	system performance in storage mode
DHW	domestic hot water
DSM	demand side management
GSHP	ground source heat pump
HTHP	high temperature heat pump
PCM	phase change material
P_E	total electrical energy consumption (including fans and pump) (kWh)
PV	photovoltaics
Q_C	heat to storage tank during charging mode by heat pump (kWh)
Q_D	heat to house by tank during discharge (kWh)
Q_H	heat to house (via central heating) (kWh)
Q_{HP}	heat output by heat pump in direct mode (kWh)
SPF	seasonal performance factor
$SPF_{H2\ or\ H4}$	seasonal performance factor in heating with boundary condition 2 or 4
ST	storage tank
SH	space heating
TES	thermal energy storage

which is highly dependent on gas as a fuel [3].

Renewables such as photovoltaics (PV), solar thermal and wind have good potential but fails to meet annual domestic energy demand due to intermittent supply in absence of energy storage. Heat pump has shown potential to address the dual challenges of fuel poverty and carbon emission reduction where heat pump market is growing steadily in the UK. However, heat pump installation is still limited in the UK compared to other European countries mainly due to old housing stock, poor insulation, size, lack of policy/grants, building regulations and capital/installation cost etc [4]. This also affects retrofit drives (such as with heat pump) in the UK [5]. In addition, most housing stock are fitted with high temperature (60 °C+) hydronic wet radiator system whereas heat pump performance drops at such high flow temperature [6]. There are several investigations on low/medium temperature heat pump application in domestic sector along with storage and renewable technologies which has been reviewed which leads to significance and need of presented work.

1.1. Literature review

Heat pumps investigations mainly focuses on two key streams: simulation/modelling and field/experimental trial. For example, Kelly et al. used building simulation model to present benefits and issues on heat pump electrical demand while using storage tank (ST) with phase change material (PCM) or water integrated with heat pump to operate in off-peak periods [7]. Similarly, Arteconi et al. presented TRNSYS model for heat pump with thermal energy storage (TES) to meet domestic heating demand using underfloor heating and low temperature radiators [8]. Heat pump operational benefits with TES has been clearly identified to shift electricity demand during peak time [9,10]. Kamel et al. provided benefits and limitation through their review that heat pump integration with solar energy requires ST for optimum use and efficiency whereas heat pump integration with PV/T requires optimum control strategy and further study in the area [11]. The impact of PV, electricity pricing and sizing of TES and heat pump is analysed by Fischer et al. [12] The study showed that oversizing of TES can be avoided by overheating of thermal store and rising variability of electricity tariff also increases need for TES. Love et al. presented impact of heat pump electrical load on national grid based on field trial data in the UK. The study presented that the peak demand arises between 6–9 am and 4–8 pm and 20% heat pump penetration would not have large enough effect on national grid load profile although this could be mitigated by implementing heat pump control strategies [13].

There are very few example of field trial of heat pump especially in retrofit application. Most heat pump field trial focuses on low temperature and/or underfloor heating system. Safa et al. presented experience of two stage variable speed heat pump and showed 20–40% higher coefficient of performance (COP) under part load compared to rated capacity for heating and cooling in Canadian climate for domestic building [14]. Kelly and Cockroft presented air source heat pump (ASHP) field trial and simulation model comparison for eight UK houses and showed 12% less carbon emission compared to condensing gas boiler where ASHP provided SH via 55 °C radiator and DHW demand was met by immersion heater [15]. Boait et al. presented case study based on experience of ground source heat pump (GSHP) in retrofit setting for domestic building. They concluded that larger floor area, part load operation (oversized heat pump) and parasitic losses reflects in low COP compared to other European field trials and better controls, design, small houses (new) would help to improve the performance of heat pump [16]. Wu et al. showed benefits of cascade heat pump integrated with TES to reduce pressure ratio at low ambient temperature [17] whereas Shah et al. showed benefits of engine driven heat pump in off/weak gas/electricity network area to achieve flow temperature in range of 70 °C with waste heat recovery from the engine [18,19]. It is also noted that DHW uses 3.5 times more power compared to SH for heat pump where vast installation of heat pump in poorly insulated housing stock could considerably impact peak electricity demand in the UK [20]. On other side, heat pump has potential to promote use of wind-generated electricity and increase wind power capacity utilization to decarbonise electricity in urban areas [21].

In the UK, two major field trials were carried out for heat pumps since 2000. The first field trial with ASHP and GSHP was carried out by Energy Saving Trust (EST) & DECC (Department of Energy and Climate Change) in two phases whereas the second field trial was based on the Renewable Heat Premium Payment (RHPP) installations facilitated by DECC. EST's field trial showed that mean seasonal performance factor (SPF_{H4}) of ASHPs and GSHPs was 2.45 and 2.82 respectively whereas water heating efficiency (SPF_{H2}) was 2.35 for both type of heat pumps [22]. The second field trial based on RHPP found mean SPF_{H4} of 2.41 and 2.77 for ASHP and GSHP respectively [23]. Both field trials considered flow temperature in a range of 30–55 °C, much lower in comparison to retrofit application requirement (above 65 °C). Details about different boundary condition of SPF can be found in [24]. EST's heat pump field trial resulted in a focus on the need for design and installation training. Similarly, Gleeson and Owen et al. highlighted need for proper heat pump installation practice and training which is still lacking in the UK compared to European installation/training practice [25,26]. Heat pump SPF in German field trial was 2.3 for ASHP and 2.9 GSHP. However, SPF was around 2 at flow temperature near 60 °C and it was suggested to have SPF above 2.3 to get higher advantage compared to condensing boiler in German market [27]. In the UK, GSHP heat pump trial showed average SPF of 2.38 with further suggestion on monitoring system location and standard practice [28].

1.2. Proposed work

The literature review clearly indicates lack of information on high temperature heat pump (HTHP) and TES in domestic retrofit settings. Following points highlights importance and novelty of the proposed work: