High temperature heat pump operational experience as a retrofit technology in domestic sector

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***Abstract*---This paper presents operational experience of high temperature heat pump in domestic building as a retrofit technology where it displaced existing gas boiler without any modification/replacement to existing controller or radiators in the house. Heat pump was integrated with 600l thermal storage where their performance was measured for five months from November 2014 to April 2015. During five months, performance under different settings such as direct mode, storage mode and combined mode operation were analysed. Operational experience shows limitation and issues of heat pump, house heat loss/insulation and sizing of thermal storage. More details about heating demand, COP, power consumption fluctuation and storage mode performance etc., have been presented in details. This operational analysis on heat pump would give information to installer, designer and government organization regarding field trial of heat pump, design consideration and proper sizing and selection of heat pump and thermal storage as a means of demand side management technology for domestic retrofit application.**

***Keywords* - heat pump; thermal storage; DSM; retrofit; field trial**

I. INTRODUCTION

Heat pump is an efficient technology for heating/cooling which uses free energy from air, water or ground. However, in the domestic sector of UK, gas and oil boilers are most common technology for providing space heating and domestic hot water (DHW) through central heating system that contributes almost 78% in domestic energy consumption and 40% domestic heat related emission [1] [2]. For a retrofit technology (e.g. heat pump), it needs to meet certain criteria to replace existing heating system as existing wet radiator system requires higher flow temperature to meet their heat demand [3]. In addition, heat/electricity demand pattern during winter/summer and poorly insulated housing stock in the UK influences sizing of heat pump. Another issue is with electricity grid that has limitation on how many heat pumps can run at same time. In addition, it also curtails electricity generated from renewable sources such as wind.

Heat pumps are classified based on flow temperature it can provide from condenser. As per BS EN 14511-2013 [4], heat pumps are divided as low temperature (35˚C), medium temperature (45˚C), high temperature (55˚C) and very high temperature (>65˚C). In order, to work efficiently, heat pump needs possible low flow temperature whereas conventional wet radiator system works with high flow temperature. Radiators for central heating system are designed as per BS: EN 442 [5] that suggests 75˚C flow and 65˚C return temperature with mean temperature difference of 50˚C. In radiator, flow temperatures below or above design temperature changes heat emission capacity. For example, radiators are designed/installed to work with condensing gas boiler system to provide 8 kW heat output in test houses at Ulster University. If lower/higher flow temperature were supplied in those radiators then it would change heat output from radiators.

Fig. 1 shows such radiators heat output increment/decrement with flow temperature where temperature difference of 5K and 10K has been considered between returns and flow. If a standard heat pump which provides 55˚C flow temperature is installed with such existing radiator then it would

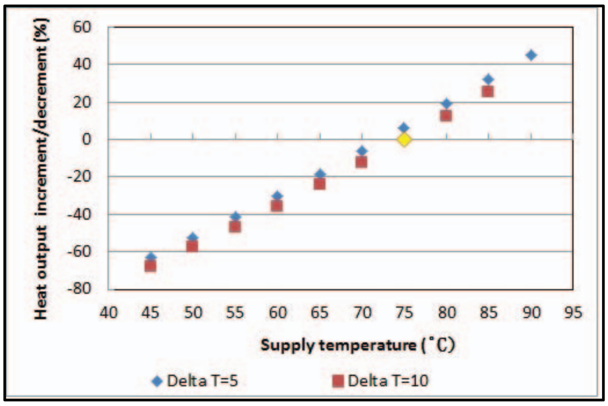

Fig. 1 Radiator heat output changes with respect to flow temperatures

reduce heat output by 41-47% based on temperature difference between flow and return and hence, thermal comfort would be reduced. In order to solve this problem, oversized/advanced radiators should replace conventional radiator or very high temperature heat pump should be installed. Even Energy Savings trust's heat pumps field trial did not cover any very high temperature heat pump instead they used standard heat pump with oversized/advanced radiators or underfloor heating [6].

In order to address all issues mentioned above, very high temperature heat pump was installed with thermal storage. Main aim of present work is to highlight performance data, potential, problems related to heat pump/thermal storage and demand side strategies to tackle electricity grid problems considering thermal comfort of a dwelling in centre.

II. EXPERIMENTAL SET-UP

In order to understand retrofit challenges of insulation, material, glazing and renewables technologies installation, two mid-terraced type test houses were built in 'Terrace Street' at the Jordanstown campus of the Ulster University. The houses were built to 1900 design specifications in order to allow detailed analysis of typical 'hard to heat' homes. They are of solid wall construction and have basic loft insulation (150mm) and PVC double-glazed windows and doors. Two guard chambers built on side of the house and maintained at 21˚C to replicate mid-terrace conditions. Such kind of dwelling represents most common types of housing stock (27.6%) across Northern Ireland [5].

Fig. 2 shows test houses built for testing purpose and the house on left was retrofitted with air-source heat pump. In order to keep existing gas boiler system and controller as it is and to accommodate heat pump, storage tank and other data monitoring/controller items, separate platform was built on backside of the house.

Fig. 3 shows platform prepared on the back side of the house. The shed consist all data monitoring, controlling

Fig. 2 Test houses at University of Ulster

Fig. 3Platform and sheds for heat pump-storage set-up

equipment along with storage tank and heat pump. The shed temperature is maintained around 18˚C in order to replicate boiler house scenario for tank heat losses. The selected heat pump was Daikin Altherma HT with 11 kW heating capacity which works as cascade unit to provide high flow temperature up to 80˚C. Outdoor unit extract energy from air and delivers it to indoor unit where indoor unit delivers heat to water for space heating or DHW application. Main purpose to select this heat pump is to provide high water temperature that is suitable for existing radiator system. Fig. 4 shows installation of heat pump indoor unit inside the shed along with storage tank and installation of heat pump outdoor unit.

Fig. 4 Heat pump indoor & outdoor unit along with storage tank

In addition to heat pump, 600l thermal storage tank was installed to store water. The tank has 75 mm thick insulation, removable top, custom designed heat

Fig. 5 Modification in boiler room with existing system

exchanger coil (two), seven temperature probe, two immersion heater and de-stratification pump. Main purpose of storage tank is to store energy by the help of heat pump during off peak electricity (e.g. night time) and utilise stored energy to meet house heating demand during the day time in order to shift electricity peak during the day/evening.

The connection between the shed and boiler house made using underground ductwork that carries water flow/return line along with other necessary cable work. The focus is on simple retrofit work without replacing or disturbing existing system as much as possible. To address it, existing gas boiler system was bypassed and kept as a back-up by two new shut off valve and two new pipes for flow and return were connected which goes to shed and connects to heat pump/storage tank. In addition, existing heating system controller also kept same and two new switches were added to switch over between heat pump and gas boiler if heat pump fails or maintenance work etc., Fig. 5 shows work carried out in boiler room to bypass gas boiler and connect new heat pump/storage system.

In order to monitor the performance of heat pump/storage system following sensors were placed:

1.) Temperature sensor: Inline and surface PT100 (± 0.2˚C),
2.) Flow meter: Electromagnetic flow meter (± 1%), pulse meter (± 1.5%)
3.) Current transducer (± 1%), voltage transducer (± 0.5%) and energy meter (± 1.5%)

Data were logged 24x7 in two schedules, schedule one runs every 15s whereas schedule two runs every 1 minute. All data were logged by data acquisition system and stored in dedicated PC and sky drive for data analysis purpose.

II.1 Test methodology

A selected house is occupied by 3-member family and their thermal comfort is reviewed by their feedback during each test conditions. In addition, each room temperature and humidity was measured by data monitoring system in guard chamber. After installing all sensors and equipment, performance data (mainly heat output) of gas boiler were obtained for first five days to have base case scenario and after that an air source heat pump replaced gas boiler on 26/11/2014. In order to assess performance of heat pump and storage system, tests were carried out in three stages.

1.) First stage (direct mode): Heat pump met house heating demand directly similar to gas boiler operation between 26/11/2014 to 10/02/2015.
2.) Second stage (storage mode): Heat pump provides heat to storage tank based on set point and storage tank meets house heating demand. This operation carried out between 11/02/2015 to 01/04/2015. In addition, during this period two subtests carried out with de-stat pump off and de-stat pump on to understand impact of stratification.
3.) Third stage (combined mode): In this mode, heat pump stores energy during night time (i.e. 2 am to 5 am) and when house calls for first heat (i.e. 6 am) then heat is provided from storage tank based on set-point on controller. After that heat pump takes over and provides heat to the house in direct mode for rest of the day. This operation started on 16/04/2015 onwards with possible modification in controller strategy to find optimum operation conditions.

Fig. 6 shows schematics of test set-up arrangement for the project work. Heat pump has its own variable speed pump, hence, during direct mode operation it bypassed house pump. For storage mode operation, new pump was installed near tank and it worked with house pump in order to maintain same flow rate conditions as gas boiler. In addition, heat pump flow temperature set at 76˚C that was similar to flow temperature of gas boiler. During COP calculation, electrical energy consumption includes parasitic losses, defrost energy including standby power consumption and hence, it gives overall COP of the system, a realistic picture of heat pump performance.

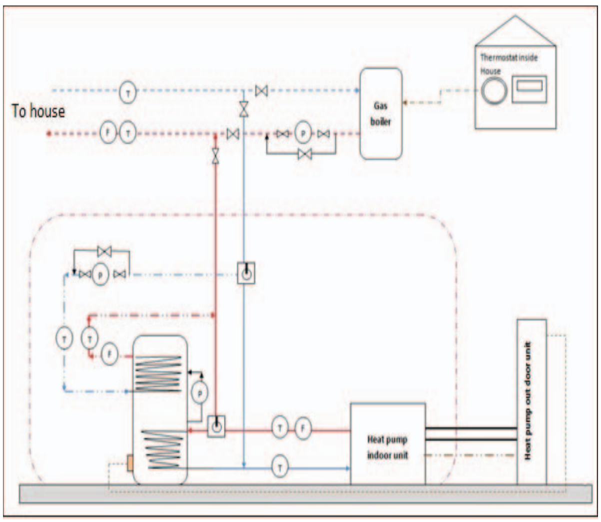

Fig. 6 Schematics of test setup

Additionally, temperature sensor for charging or discharging tank was installed at bottom compared to mid-position of the tank in order to store energy at higher temperature in the tank. During storage mode performance, re-heat set-point was set at 65 °C means whenever tank temperature drops below it, heat pumps charges the tank and bring temperature to 75 °C. This temperature was sensed by temperature at bottom of the tank. During storage mode, two COPs come into role, first heat pump COP and second overall COP which includes tank heat losses too.

In combined mode, storage at night time was set at 2 a.m. where heat pump starts and charges tank (if temperature is lower than set point). Once temperature at bottom of the tank reaches 60 °C, it stops charging. In discharge, set point was set at 45 °C on controller. This means whenever house calls for heat, if temperature in tank is above discharge set point then it provides heat to the house and stops when temperature drops below set point. After that, heat pump takes over to meet house heating demand as in direct mode.

III. RESULTS AND DISCUSSION

During five months operation period of heat pump, house heat demand varied mainly due to weather conditions and occupancy. Fig. 7 shows heating demand variation between 21/11/2014 to 26/04/2015. Over this period average heat demand was about 94 kWh with maximum of 144 kWh to minimum of 40 kWh. Higher heat demand is mainly due to low air temperature and in some cases higher occupancy.

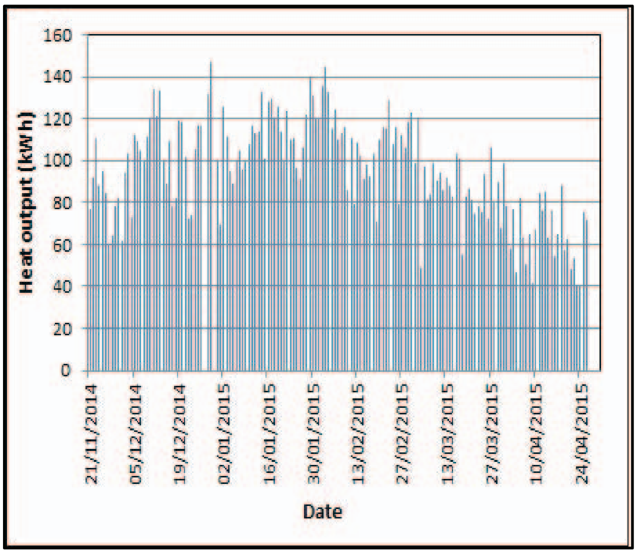

Fig. 7 House heat demand over test periods

Over this period heat pump performance tested in three different modes as mentioned above. Hence, heat pump COP varies too. However, just to analyse all three mode performance together, overall final COP values have been put together for better comparison purposes. Fig. 8 shows variation in overall COP during all three test modes combined for comparison purposes. It is clear that the COP is higher during direct mode performance compared to storage mode or combined mode.

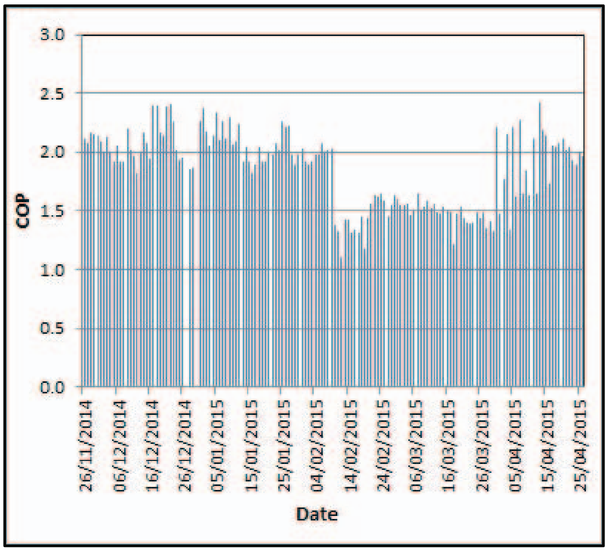

Fig. 8 COP variations over test periods

III.1 Direct mode performance

Direct mode performance occurred during winter period (from 26/11/2014 to 10/02/2015) which included coldest days of the year too. During this period COP varied in a range 1.82 to 2.38 with an average of 2.07. From field trial, it was found that when air temperature drops below 2 °C, heat pump struggles to maintain thermal comfort. This occurs due to increased heat loss from the house at lower ambient temperature and defrosts mode operation of heat pump due to low temperature and humidity.

A case of heat pump performance has been presented when heat pump COP was the lowest (1.82). However, ambient temperature was not lowest on that day. It was found that heat pump operation time and heat demand plays important role on COP along with air temperature and humidity. Fig. 9 shows flow/return temperature and room temperature on lowest COP day. Once heat pump started in the morning, it ran continuously until it achieved given set point in the room. Hence, it took long time to reach set point compared to gas boiler operation. This could be due to lower heat output by heat pump in a range of 15 kW compared to 21 kW by gas boiler. Fig. 10 shows heat pump heat output on that day where maximum heat output remains about 15 kW with frequent drops due to defrost cycle operation which contributed in longer heat pump operation.

In addition, heat pump was working in its full capacity means power consumption was also highest. Fig. 11 shows variation in power consumption during the day. Full power varies between 6 to 9 kW with peak of 8.8 kW. If vast penetration of such heat pump is carried out then such power consumption scenario should be considered in order to find limitation and adverse impact of low-voltage network [8] [9].

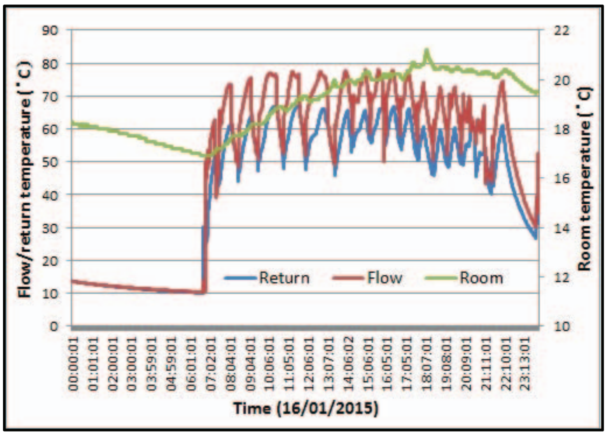

Fig. 9 Heat pump flow/return temperature and room temperature

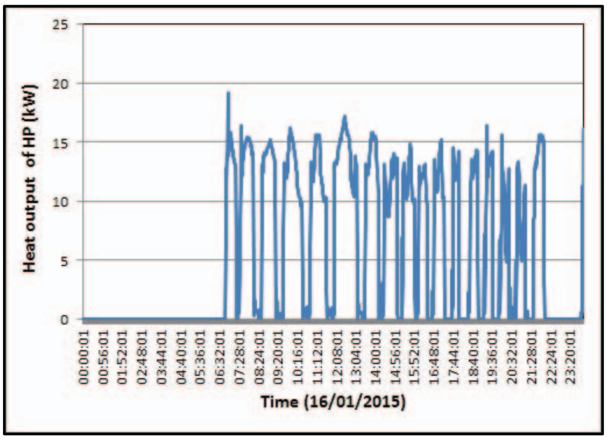

Fig. 10 Heat output by heat pump a lowest efficiency operation day

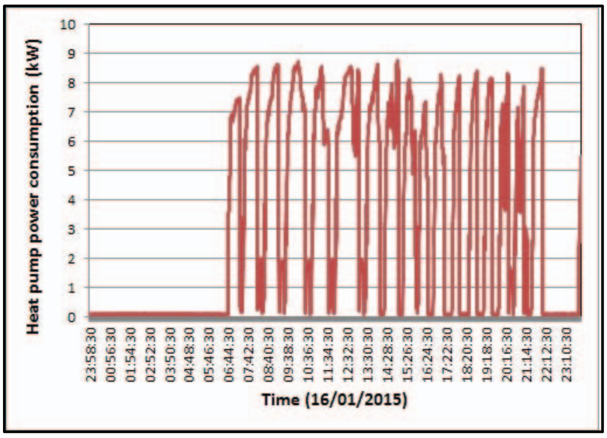

Fig. 11 Heat pump power consumption at lowest efficiency operation day

III.2 Storage mode performance

As mentioned previously, in storage mode, house heat demand is met by storage tank and heat pump gives heat to storage tank. During this process, significant heat losses occurs from storage tank due to energy stored at high temperature which results in lower COP (overall) compared to direct mode. During storage mode (from 11/02/2015 to 01/04/2015), COP varied in range of 1.11 to 2.21 with average of 1.48. Another reason behind lower COP is requirement of high flow temperature (above 75˚C) to charge the tank and longer running hour due to set-point and simultaneous charging/discharging of tank.

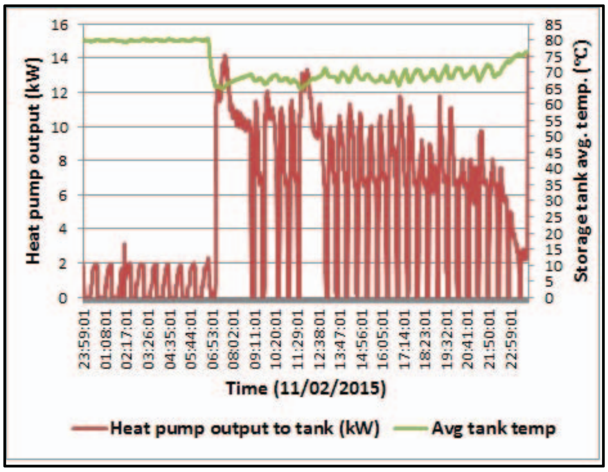

Fig. 12 Storage mode: Heat pump output with respect to tank temperature during charging

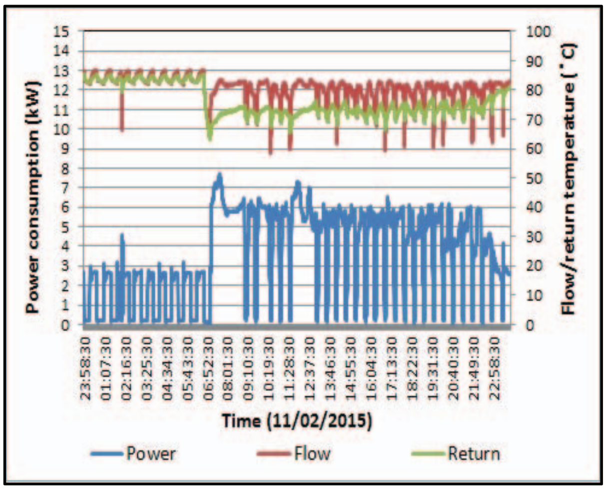

Fig. 13 Storage mode: Heat pump flow/return temperature and power consumption

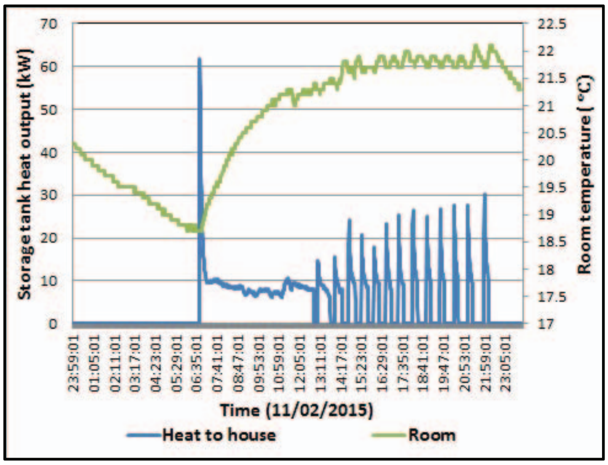

Fig. 14 Storage mode: Heat output from storage tank and room temperature

Fig. 12 shows heat output of heat pump in re-heating mode with respect to storage tank temperature. It was found that heat pump output reduces as storage temperature decrease and above 75˚C it acts as immersion heater by giving heat output in a range of 2kW. Heat pump heat output increases as temperatures drops (around 65˚C) and it remains around 8kW. Fig. 13 shows flow/returns temperature from heat pump and power consumption during storage mode. It was found that heat pump operates mostly around 80˚C flow temperature that reduces COP too. Power consumption during storage mode remains around 2.5 kW during low heat output and after that it remains around 6-7 kW. However, heat pump runs almost all time due to stratification of tank which sense lower temperature at bottom and higher temperature in middle and top. Fig. 14 shows heat output from tank based on house demand and room temperature inside the house. Due to stored energy in the tank, it provides higher heat output during start which favours to reach thermal comfort earlier and gives similar performance to gas boiler.

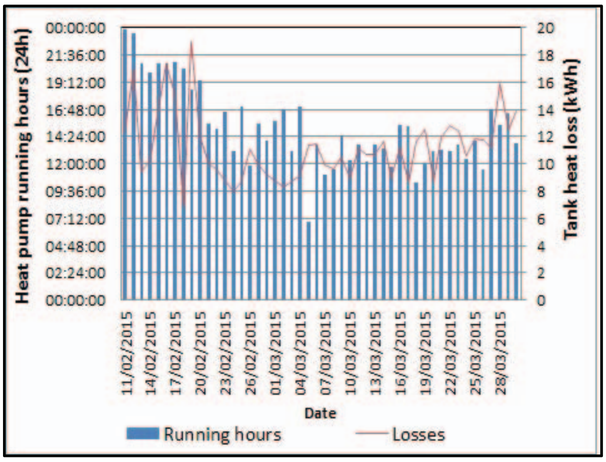

Fig. 15 Storage mode: Heat pump running hours with de-stat pump off and de-stat pump on

During storage mode, operation with de-stat pump off (from 11/02/2015 to 20/02/2015) and de-stat pump on (from 21/02/2015 to 30/03/2015) also analysed. Fig. 15 shows benefit of de-stat pump operation in terms of reduced heat pump operating hours due to more uniform temperature inside the tank. In addition, heat loss from the tank remains around 11 kWh that reduces efficiency of overall system.

However, storage mode gives good performance in terms of meeting house heat demand faster than direct mode performance. Fig. 16 shows comparison of gas boiler, direct mode and storage mode heat output during first 30 min of operation. As gas boiler mostly reaches desired flow temperature around first 30min from cold start in the morning, heat output in first 30 min has been considered to compare other performances too. Gas boiler gives about 9-10 kWh during first 30 min whereas heat pump in direct mode gives about 6 kWh, hence it takes longer time to reach thermal comfort/ set point. Storage mode with de-stat pump off gives heat output in a range of 8-10 kWh which is very comparable to gas boiler performance.

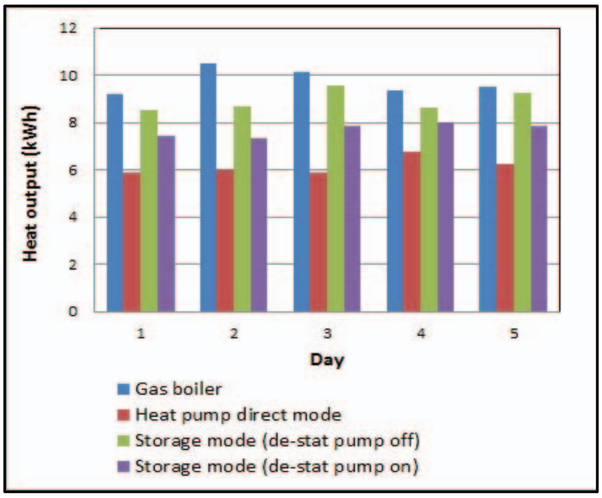

Fig. 16 Heat output comparison during first 30 min of house heat demand

III.3 Combined mode performance

Performance in this mode helps to take advantages of high heat output in storage mode and cheap electricity tariff during night time with higher COP operation in direct mode. Test was started on 16/04/2015 and still ongoing. However, data obtained till 26/04/2015 shows that an average COP is 2 which is still lower than direct mode performance.

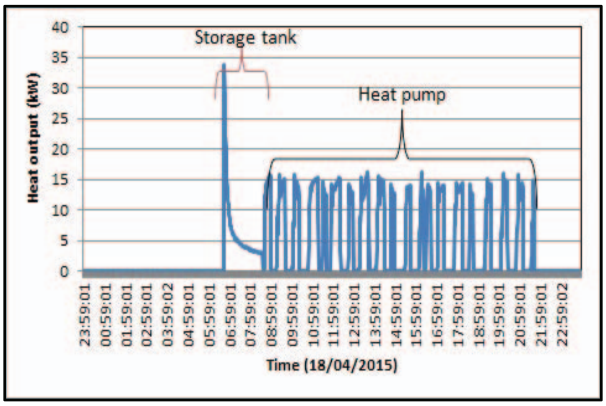

Fig. 17 Combined mode: heat output to house in by storage tank and heat pump

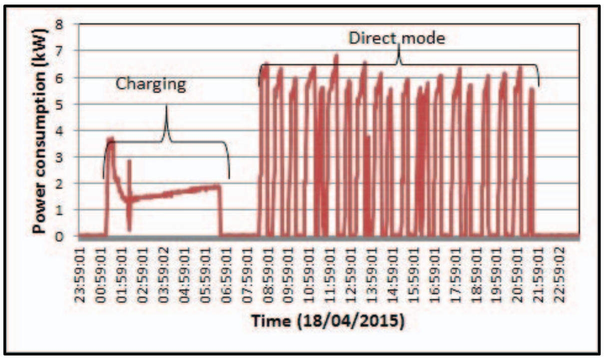

Fig. 18 Combined mode: Heat pump power consumption during charging and direct mode

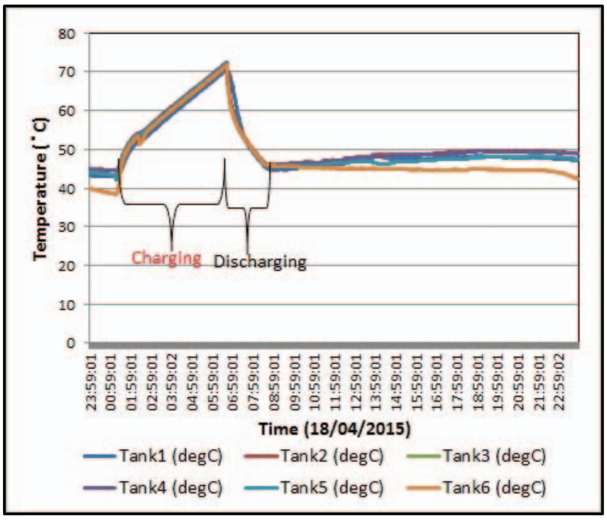

Fig. 19 Combined mode: Tank temperature during charging and discharging

Main reason behind lower COP is again high flow temperature during charging time where sometimes stored energy in the tank did not discharge at all due to set-point. Fig. 17 shows heat output to house in combined mode. Stored energy in tank helps to deliver high amount of heat that helps to reduce time required to reach set point in the house. Fig. 18 shows power consumption during charging mode and direct mode which shows during charging mode power consumption varies between 2 to 4 kW which is far lower than standard operation. Thus, lower power demand could help electricity grid to handle vast deployment/operation of such heat pump during night time. Fig. 19 shows tank temperature variation during charging and discharging. Once tank temperature drops to 45˚C, discharging stops and heat pump takes over as in direct mode. There are still more test underway to find best suitable conditions in order to reduce charging time, set-point and improve COP.

IV. CONCLUSION

Field trial of high temperature pump as retrofit technology showed some promising results. It was found that such kind of heat pump can be easily installed in domestic building in weak gas/electricity network area without need of further insulation, replacing existing radiators or controller system which reduces overall cost. From field trial, it was clear that heat pump should be properly sized, comparable to gas boiler in capacity in order to reach thermal comfort in same time as gas boiler. Heat pump oversizing factor should be also considered in order to address issue of defrost and running hours.

Heat pump COP in direct mode remains around 2.38 during winter operation and it is expected that operation during summer time could improve COP further in order to bring seasonal COP of 2.5 for renewable heat incentive considerations. Heat pump operation in storage mode does not give any benefits in terms of COP. However, it is able to delivery higher heat output which helps to reach thermal comfort faster than direct mode. Heat pump operation in combined mode shows promising results in terms of COP, electricity consumption, heat output. It is better to store energy at low temperature by use of phase change material with improved heat exchange design that would help to reduce flow temperature during charging and hence improve overall COP.

Power consumption variation during direct mode gives useful information for electricity grid point of view. However, combined mode, night time charging shows promising result to divert peaks of electricity demand and reduced power consumption during that time. Such system could help electricity generated from renewables to avoid their curtailment (e.g. wind) without much need of large-scale storage.

In addition, smart controller technology is essential which predicts and/or gets real time data of electricity market price, wind speed, weather conditions etc., and decide right operation time considering optimum efficiency and cost conditions. Such controller is in development and it will be tested with existing heat pump system to see real potential and benefits.

V. ACKNOWLEDGEMENT

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