Hybrid Heat Pump Design Strategies to Obtain Net-Zero Building

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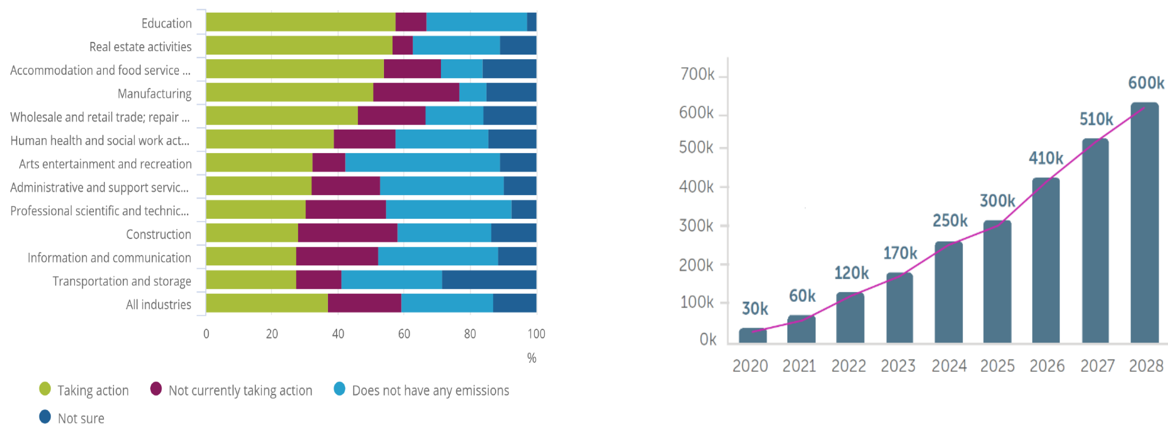
Abstract. All developed and developing countries seek to take action to avoid the increasingly evident catastrophic impacts of climate change and global warming. Geothermal energy has great potential for heating to obtain "Energy efficient buildings "and "Net Zero Energy Building" concepts as defined by the European Union. Heat pump applications have significantly improved recently with their commitment to net-zero buildings. They present a huge potential for hybrid energy-efficient applications in the world. This study profoundly examines the investigated large-scale heat pump (HP) systems and their hybrid design approaches assisted by gas boilers. Although the various design concepts for the HPs are available today, it isn't easy to find comprehensive information on large-scale HPs and their hybrid designs. Therefore, in this study, a performance study has been carried out for the hybrid Ground Source Heat Pumps (GSHPs) system in the UK. The actual hybrid GSHP system design is presented. The results suggest that hybrid heating saves a considerable amount of GHG emissions depending on the GSHP size and improves the unit's efficiency compared to the conventional heat pump. The savings of CO2 emissions of the GSHP heating system are determined as 4.37 tons/year savings for gas and 3.52 tons/year savings for electricity under validated conditions. This work can provide theoretical support and technical guidance for future research and engineering applications of the hybrid GSHP system. Moreover, further work is needed to understand the role hybrid heat pumps play in each building such as energy-efficient residential, public sector, institutional, and agricultural structures in the UK.

INTRODUCTION

Classification and general rules in the business sector show that the most concerning air pollutants from industrial buildings are CO2. The UK has aimed to reduce GHG emissions by approximately 80% by 2050, based on the carbon policy outlined from 2010 to 2015 [1]. Between 2020 and 2021, the business sector's regional carbon dioxide emissions increased by 5.9% (3.6 Mt) while it was public 6.3% (0.5 Mt) in the industry. Both have been due to the easing of pandemic restrictions on businesses and offices during the pandemic and terrible weather conditions, respectively.[2]. There is increasing standardization in regulatory specifications for the emission of CO2 released from such facilities. Businesses have become more interested in decarbonizing their buildings. Figure 1a shows that 38% of companies have installed at least one renewable energy generation application in the UK. Moreover, 24% of the businesses are proposing to act next year. According to the latest report in early October, the reasons why companies are not working on net zero action are mainly stated as being because of the 'Cost of implementing change' (20%) [3]. The National Grid Gas Winter Outlook report shows that the total gas demand in 2022 is projected to be higher when compared to the last five winters. Gas from the United Kingdom Continental Shelf (UKCS) and Norway remains the primary supply source to the UK. Liquefied Natural Gas (LNG) Storage and the European connections provide flexible supply to meet aggregate demand. Exactly what type of supply will emerge on any given day is difficult to predict [4].



(a) (b)

FIGURE 1. (a) Business action by Industry, UK [3] (b) UK heat pump deployment [5] - Contains public sector information licensed under the Open Government License v3.0.

In the UK, most (62%) of the 32,000 heat pumps sold in 2019 were retrofit applications, and the remaining (38%) were used in new buildings. There are approximately 260,000 HP units in the UK. This amount is less than 1% of all installed heating systems. Despite an 11% increase compared to 2019, it accounts for a tiny proportion of new space heating systems, with around 36,000 established in 2020. The government is urging the HP Industry to increase its annual sales by 17 times in 7 years (see Figure 1b), and some key challenges exist in growing the market to this size in such a short time. The BUS scheme is expected to deliver 600,000 heat pumps annually by 2028 to meet government targets. It is estimated that 400,000 HPs will be retrofitted into existing residential or commercial buildings out of the 600,000 HP target [5]. Supply chain constraints, installer constraints, inconsistent training, network implications, low consumer awareness, and high heat pump system costs. Air Source Heat Pump (ASHP)s contribute a considerable market share and are expected to grow gradually between 2022 and 2028 to meet consumer demand [6].

In businesses like poultry farms, the replacement of natural gas use by large-scale heat pumps could significantly reduce carbon emissions. However, there are well-known disadvantages of large-scale heat pumps. While large-scale HPs are the most common application in the electrification of buildings in Europe, there are far-reaching and severe technical challenges, particularly in cold climates [7]. Even if government subsidies minimize installation costs, there are wide-ranging and many significant technical problems, as mentioned in cold temperatures. Although the results show that HP technologies have great potential to save energy, there are some main challenges for building applications: Low efficiency under cold climate conditions, Frost issues outside of ASHP, and performance gap & large-scale uncertainty.

Hybrid heat pump systems can eliminate the disadvantages of large-scale heat pumps used in businesses. Hybrid heat pumps (HHP) can use HP, boiler, or both to meet building demand. The system can switch between natural gas (NG) use and electricity use and use both at specific rates. The parameters to be considered during the design phase are the outdoor temperature, gas flow temperature, and heat pump available source temperature, and the priority will be to design the heat pump most efficiently. At the same time, the price of gas and electricity and whether electricity produced with renewable energy is used determines the design strategy. Table 1 shows numerical studies on HP applications and gas boiler technologies to evaluate the recent developments and studies on hybrid heating applications.

TABLE 1. Model samples on recent hybrid heating systems.

Method	Temperature /refrigerant	Aim	Application	Results	
TRNSYS model	55°C Temperature	Air Source Heat Pump (ASHP) with Condensing Gas Boiler (CGB)	21.5 kW Condensing gas boiler; 14.7 KW ASHP	HP seasonal efficiency increased by 66 and %22.⇧	[8]
Modelica Model	55°C/45°C/ 20°C Temperature	Configurations of ASHP, CGB PV and TES: tank with three scenarios	ASHP, CGB PV and TES: Combi tank	Heating power ~40% ⇩ and heat demand ~48% ⇩ oil consumption ~0.72 Mbbl/year ⇩	[9]
TRNSYS model	55°C temperature	Comparison of a hybrid system (HP and GB) and a Stirling micro CHP unit.	11 and 14 KW ASHP with various logic	Reducing the primary energy demand of the building examined,	[10]
Mathema tical model	30°C temperature, 410 A	The combination of a heat pump and a gas-fired water heater	23 kW heat pump and 7 kW gas-fired water heater	Reducing the heater energy demand	[11]

HYBRID GROUND SOURCE HEAT PUMPS: SIZING AND MODEL

A hybrid system was designed to provide the heating demand of a poultry house's annual energy demand to evaluate the novel hybrid system performance under the actual site condition. The peak load is calculated based on the recommended design temperature for Nottingham, UK, which is -4.7°C for the system sizing. The main calculations on the peak load are the heat losses through the walls and roof, heat exchange with the slab floor, ventilation heat losses, heat gains from the birds, and heat gains from electrical sources The minimum ventilation management is the key to the HVAC failure and the uncomfortable environmental conditions of the chickens[12], [13].

A heat pump (HP) was designed to provide part load of the poultry house's annual energy demand. A simplified thermodynamic/physical approach for the heat pump model has been taken to characterize the operation of the brine-to-water heat pump. The heat pump has four main components: An evaporator, compressor, expansion valve, and condenser. The evaporator is a heat exchanger that transfers the collected heat from the sources, which are solar and soil in this study, into the heat pump. This system has brought a new perspective to the analysis of hybrid systems and the use of innovative copper vertical ground heat exchangers.

The evaporation is an isobaric process. COP_{HP} is the coefficient of performance of the heat pump. The electricity consumed by the compressor, including the internal water pump of the HP, is W_{HP} and heat Q_{HP} is the following equation, then gives the heat provided by HP The COPHP of the HP.

$$COP_{HP} = \frac{Q_{HP}}{W_{HP}} \tag{1}$$

This study considers the part load of the space heating for the poultry house, and a 300L buffer vessel is chosen for the analysis. An energy balance equation can be written in control volume considering the heat loss to the environment. Solving the energy balance equations can determine the temperature on average inside the tank. Space temperature is assumed to be 20oC. There is a surface area between water and the ambient. U is the overall tank heat loss coefficient.

$$m_{tan} \cdot c_{w,tank} \cdot \frac{dT_{tank}}{dt} = Q_{HP} - Q_{store} - UA \cdot (T_{tank} - T_{plant}) \quad (2)$$

Where Q_{HP} is the heat gain from HP to the storage, $Qstore$ is the heat remaining after Fan Coil use, U is the heat transfer coefficient, and A is the tank surface area.

The heat loads of the boiler, the efficiency and power of the gas boiler, and the calorific value of the gas are the basic parameters that determine the efficiency of the gas boiler. The building load analyses were completed, and the heat loads of the GHEs were selected in the heat pump designed to meet the part loads. The cumulative heat loads given are determined by the following equarion

$$Q_n = m_f \cdot c_{p,f} \cdot (T_{g,o} - T_{g,i}) \quad (3)$$

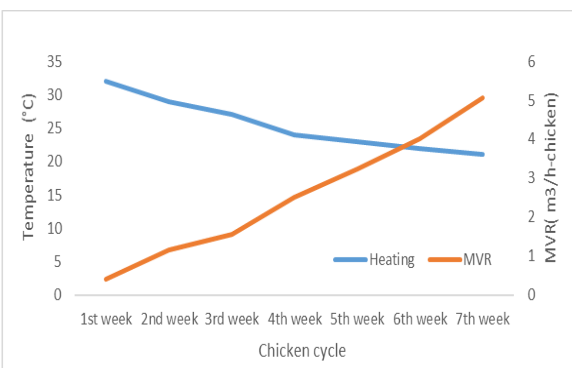
Where mf is the mass flow of the fluid flow through the boiler, kg/h; Cpf is the constant pressure specific heat capacity, kJ/kg*K. Tg,o is the temperature at which the boiler is left, ºC; Tg, i is the temperature at which the boiler enters, ºC. Gas boiler efficiency is considered as 0.85.

Electrical emission factors can be varied, and the assumptions used in the environmental assessment are the same as those presented in the economic evaluation in the previous section. The emission factors of natural gas and electricity are taken from the latest UK government announcement. The emission factors used are presented below: Gas emission factor: 0.2. kg.CO2 [14].

RESULTS AND DISCUSSION

Building Loads with Climatic Data

A selected poultry farm located in the UK is theoretically investigated regarding the thermal regulation energy demand and internal air quality temperature of 24°C and 2.5 m3/h minimum ventilation rate per chicken. Figure 2a presents the heating load of the poultry house under the various temperatures and airflow rate conditions for the entire winter PC. The model involves the different internal gains from the chickens, changing with their mass and age.



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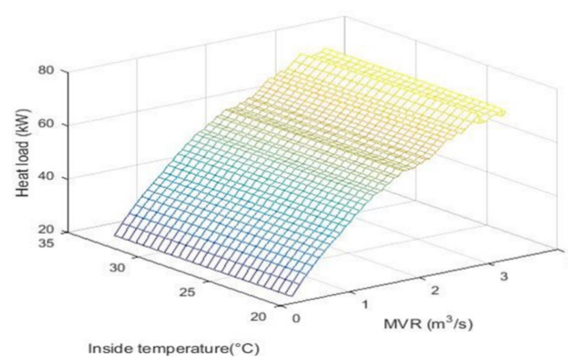

(b)

FIGURE 2. (a) Average temperatures and minimum ventilation rates (MVR) for the entire 7-week PC (b)Annual energy requirement in the poultry house

With the development of the chicken PC, the validated results showed that the annual heating energy requirement is 39.3 MWh. The heating load in the building during the year is presented in Figure 2b. The Production Cycles (PC) were analyzed to estimate the annual energy requirements of the facility by calculating the total energy requirement based on the number of PCs completed annually. The results are subsequently used to size the output of the HVAC systems ready to be designed and installed for validation in the poultry facility during the year.

Hybrid Heating System

Considering the heating backup requirement, the new heating system in the chicken house required two 65-70 kW heater units., and 15 kW HP was selected, considering the existing heat extracted from available sources. The design consists of 15 kW HP attached with a novel Polyethylene heat exchanger (PHE) underneath the PV panel and a novel copper vertical ground heat exchanger (VGHE) attached to the heat pump (Figure 3). The system performance data under natural conditions ranged between 10.61 kW and 18.6 kW on average heat pump capacity, with a PVt array and vertical copper ground heat exchanger with long-term stable performance. Gas boiler efficiency is considered as 0.85.

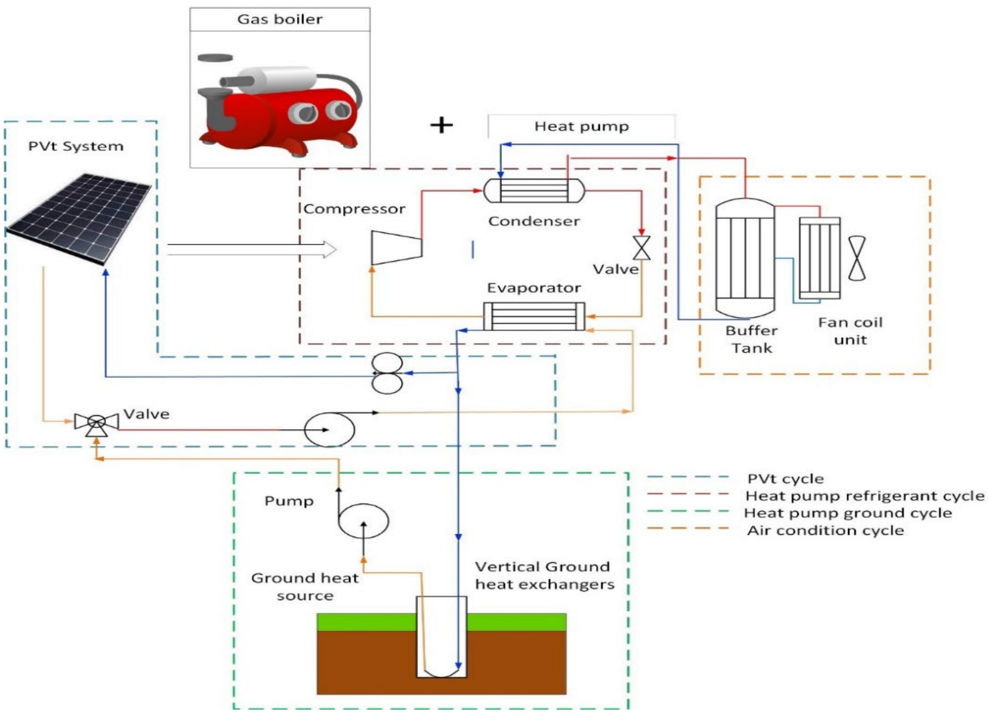

FIGURE 3. Gas Boiler and GSHP

During the experimental term, the external temperature ranged from 2-25°C, and the external relative humidity from 40-95%. The total thermal output from the heat pump was approximately 15 MWh per annum. The daily COP ranges between 2.05 and 5.17, with a maximum value of 5.17 in PC 4, while the minimum is 2.05 in PC1. Figure 4 presents the heat energy generation. The heating load of the building, the heat output of the heat pump, and the part load provided by the heat pump (Figure 4). The results of the seasonal experimental study revealed that 6165 kWh of heat and 1876 kWh of electricity energy were provided under autumn/winter weather conditions.

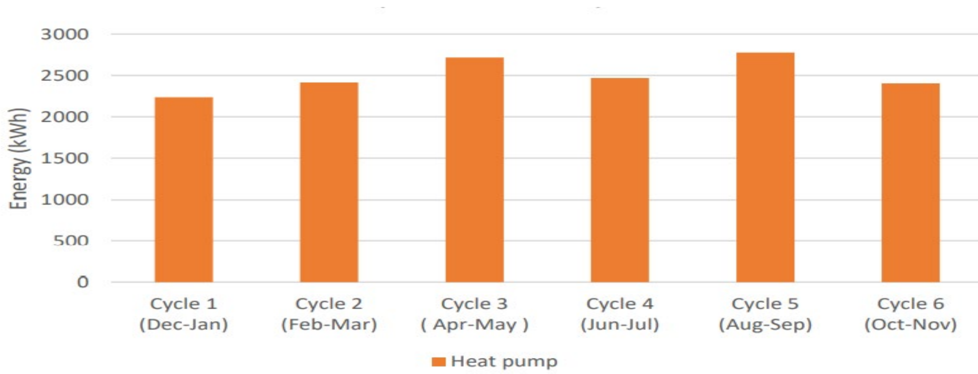

FIGURE 4. Annual heat pump part load during PCs on average

CONCLUSION

Businesses, including the agricultural sector, will require a large-scale heat pump depending on the heating needs of the building. However, there is a lack of information on case studies for large-scale HPs in the UK. Although there are limited large-scale applications commercially, ASHPs are still very efficient and cost-effective compared to the alternative conventional boiler. A hybrid heating system could be a solution for this gap, regardless of the type of heat pump. Therefore, in this study hybrid heat pump systems boilers are presented, and a real hybrid GSHP system design is discussed. In field measurements, the heat pump met part of the energy demand of the house as designed. The system can be improved with more operating modes in settings and component circuits. A control strategy is proposed to be used for future evaluations. HPs have some major problems due to low efficiency and freezing at low temperatures, mostly the efficiency of almost the whole system can be improved by using gas boiler and Heat pump season innovative art storage method. As the poultry farm is in rural area, it is difficult to provide heat pump control. For future consideration, a special design for agriculture industry is highly recommended, such as seasonal storage from PVT to soil with relatively high programmed hours for heat pump and gas boiler, and insertion path valve between PVT and soil.

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