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Cost- and Carbon-Effectiveness Analysis of Renewable Energy Options for Delivering Net-Zero Housing in the United Kingdom †

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Abstract: The UK government has legal binding objectives under the "climate change act 2008" to accomplish net-zero carbon emissions by the year 2050. The government has implemented a variety of measures across many different sectors of the UK economy that are accountable for the emissions. The aim of this research was to evaluate and compare some existing renewable energy technologies. It discusses the advantages and disadvantages of installing these technologies into homes across the UK and the impact it has on the "net-zero housing" scheme. A series of results were produced using the SAP rating, deploying an existing dwelling located in Bradford, UK, fitted with a gas boiler and comparing the results to those obtained for an air source heat pump (ASHP) and a mechanical ventilation with heat recovery system (MVHR). The three systems were analysed in terms of cost-effectiveness, carbon footprint and energy savings. The study found that the installation of a gas boiler costs less than that of the other systems, whilst ASHPs involve high upfront costs. However, the latter showed higher energy savings, with an efficiency of 4.0 compared to 0.75 and 0.95 for the gas boiler and MVHR, respectively. The SAP rating showed that the ASHP had a carbon footprint of 2396.3 kg/year for the studied flat of 65.72 m^2, whilst carbon footprints of 3406.92 CO_2 kg/year and 7143.45 kg/year were determined for the gas boiler and the MVHR system, respectively. The study concluded that ASHPs work better than the other systems for most of the existing UK housing, unless a whole building fabric improvement is considered, in which case, some other renewable options could be a choice.

Keywords: renewable heating systems; carbon- and cost-effectiveness; net-zero carbon; UK housing

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1. Background

The UK government set a target of building all new homes according to net-zero standards by 2025 and of reaching net-zero energy for all existing homes by 2050 [1]. Currently, heating, and conditioning buildings account for almost 40% of UK total energy consumption, whilst the new regulation states that new homes' emissions must be lower than 30% of the current rates to help the country move towards net-zero carbon. The UK government introduced policies and initiatives to promote the delivery of net-zero housing, which include Green Home Grants (GHGs) in 2020, the Energy Company Obligation (ECO) and the Future Homes Standard (FHS). The GHG initiative launched in 2020 provides homeowners with grants to upgrade their homes' energy efficiency under the eligibility terms and conditions. The ECO government funding programme, whose latest version is the ECO 4 scheme, provides incentives to help lowering the energy bills and supports the fuel poverty act [2]. These schemes are just a few of the practises to achieve net-zero housing within the UK.

1.1. Air Source Heat Pump (ASHP)

What is an air source heat pump, and how does it operate? EDF Energy [3] defined the ASHP as a type of low-carbon heating technology that uses the principles of thermodynamics to transform heat energy from the outside air to heat energy for conditioning a building, even when the outdoor temperatures are below the freezing levels. The ASHP system utilises the building ambient air to extract thermal energy, which can be used for both space and water heating. Thermal energy is gathered from outside and is absorbed into a loop through a refrigerant fluid [4].

The system consists of three main components: the evaporator (outdoor unit), the refrigerant (a substance used to carry heat from one source to another) and the condenser (indoor unit). The refrigerant shifts the heat as it flows between the outdoor and the indoor units. The outdoor unit of an air source heat pump contains a fan, a compressor, a heat exchanger, and a refrigerant. The fan spins to draw air in from outside. This air contains thermal energy; so, even in the winter, at low temperatures, the system can provide heat energy. The heat exchanger then takes the heat energy and transfers it to the refrigerant. The refrigerant is in a liquid form but once it is in contact with heat, it turns into a low-pressure gaseous state. The compressor compresses the refrigerant, which in turn raises its temperature even further [5].

The indoor unit contains a second heat exchanger; this exchanger takes the heated refrigerant from the outdoor unit and passes it over pipes surrounded by cooler water. The water is heated by this process and is then circulated through a network of pipes around the property to provide hot water and heating to rooms. It can also provide heat for underfloor heating. The expansion valve opens and lowers the pressure of the refrigerant turning it into a liquid, and the cycle can begin all over again [6].

This system can extract thermal energy from air at a temperature as low as −25 degrees Celsius, providing heat and hot water all year round [6]. The only non-renewable energy the system uses is electricity. It is used to power and run the compressor, the fan, and the circulating pump. However, it can be powered by a renewable energy source such as solar panels. In addition to providing heat, some air source heat pumps can be used to cool down houses in the summer. This is done by reversing the flow of the refrigerant. In this case, the air source heat pump removes thermal energy from the inside of the property and releases it outside. Ground source heat pumps are out of this research scope, as retrofitting scheme funds are mostly supporting ASHPs, which are suitable for most UK housing. However, according to GreenMatch and other sources, there two common types of ASHPs in the UK, and the main distinction between them is the way heat is distributed, i.e., either via air or via water.

1.1.1. Efficiency

It was reported by Josh Jackman from 'The Eco Experts' that the "air source heat pump has an efficiency rate of 300%; there are reports of higher ratings for the more expensive high-end pumps". The above statement shows that, generally, for every unit of electric energy used by an air source heat pump, three units of energy are produced by the pump. To put this into an energy perspective, an average UK home uses just over 12,000 kWh per annum for heating, and an air source heat pump can provide an amount of heat about of about 4000 kWh [7]. As a rough example, if electricity is priced at GBP 0.14 per unit, the total yearly costs will be estimated at GBP 560.

1.1.2. Cost

There are around half a dozen major brands who are currently manufacturing air source heat pumps, for example, Samsung, Panasonic, Vaillant and Mitsubishi Electric. The prices vary from around GBP 2500 to GBP 20,000 depending on the brand, size and model that is purchased. There are cheaper systems, which, however, supply heat only for underfloor heating or are completely different, being air-to-air heat pumps. This report is focused on heat pumps to replace existing boilers and, so, on air source heat pumps to heat radiators and supply heated water [8].

The government officials are now offering grants of up to GBP 5000 to property owners who replace their gas central heating and hot water system with a heat pump. This research focused on the systems provided by two major companies who sell and install air source heat pumps, whose prices were used to obtain an average price that was compared to that of a heat recovery system. We will supply information on the property that was considered in our case study to obtain an accurate pricing for these systems.

One of the companies is Daikin Airconditioning Ltd founded in 2002 in Weybridge UK, which provides indoor climate management solutions for industrial, commercial, and residential customers. It is a subsidiary company of Daikin Europe NV. The Daikin heat pump calculator estimated a price for the specific property under study of GBP 10,970.00 using the Diakin Altherma 3 H HT High-Capacity Heat Pump (14–18 Class) Integrated Indoor (R32) system. This price included setting up the system, which amounted to a cost of GBP 1950.00, plus the material cost at GBP 576.00. This system is powered by single-phase electricity. This selected solution is supplied with an indoor standing unit and an outdoor unit.

This system will produce a heating capacity of 10.18 kW, which should compensate the property's heat loss to guarantee comfort in the worst weather conditions. This air source heat pump will generate 5674 kWh/y and has an annual heating energy demand of 100,097.23 kWh and a SCOP (seasonal coefficient of performance) rating of 4.51.

By only using the heat pump, the outdoor unit delivers a leaving water temperature of 70 degrees Celsius at an outside temperature of −15 degrees Celsius. At −15 degrees Celsius, this outdoor unit limits the heating capacity loss. It can also extract thermal energy at −28 degrees Celsius though. In the standard operation mode, it produces a sound pressure of 38 dBA at a 3 m distance and in the ultra-low sound mode, it produces a sound pressure of 35 dBA at the same distance. Also, this model is equipped with the R-32 refrigerant. This specific product reduces the environmental footprint by 68% compared to the R-410A refrigerant. Using the R-32 refrigerant directly leads to lower energy consumption due to its high energy efficiency and a 30% lower refrigerant charge.

In addition, the Daikin Altherma 3 Heat pump's indoor unit is supplied with a built-in domestic hot water tank which can store up to 180 L of water, which is sufficient for common hot water usage, including showers and use by domestic appliances. The indoor unit is supplied with all the necessary hydraulic components, meaning that no third-party components are required. A benefit of using this system is that it does not require the homeowner to buy new radiators, as the Diakin Altherma can be connected to the radiators' inlet and outlet pipes and works in the same way as a boiler would. Gas connection is not required for installing this system, as it will produce heat using renewable energy and will use electricity to generate the power required for the fan and the pump [9].

The outdoor unit is a smaller-size machine that is positioned outside the dwelling; it can be placed on the ground away from the building, on the ground against the wall or on the roof. The homeowner would have to take into consideration the material needed when fixing the outdoor unit outside. A pipe is installed between the two units, which will increase the material cost depending on its length.

The system also includes a thermostat, and the buyer can choose between a single-room thermostat and a multi-room thermostat. The single-room thermostat is a master controller which manages the temperature of the whole house from one of the rooms. The multi-room thermostat is an optional extra with a multi-zone control that can change the climate zones of each room individually.

1.2. Heat Recovery System

1.2.1. What Is an MV with Heat Recovery System and How Does It Work?

A mechanical ventilation heat recovery system, also known as heat recovery system, is a whole-house ventilation system designed to recover heat generated by various processes in a property.

The system consists of a heat recovery unit, a network of ducts, which are placed in each room, supply air diffusers and an extract air grille. The heat recovery unit is typically positioned in an insulated loft or in a utility room. Different rooms in the house create different amounts of heat; for example, the kitchen and the bathroom are hotter rooms as they generate additional heat from cooking and showers. Here is where the extractor ducts would be placed, in addition to a few other rooms.

The system works by continuously extracting heat from warm stale air through these extractor ducts; at the same time, through a separate duct, fresh air is drawn in from outside and filtered. The fan that draws fresh air from outside, filters it to clean it from pollutants and airborne allergens. The stale air is then expelled from the property. Heat is captured from the stale air and is passed over a heat-exchange matrix, which sits inside the heat recovery unit. The heat is then transferred to the incoming fresh air from the intake ducts. The warm, fresh air is then pumped through the ducting outlets around the house.

The transfer of heat is used to either pre-heat or pre-cool the drawn-in air, depending on the season. This lowers the energy needed to condition the air to area comfortable warmth or coolness. This indicates that less energy will be necessary to heat or chill the building, which can result in significant energy savings over time.

Heat recovery systems have become significantly popular over the last few years for newly built houses. Airtightness is a key aspect in achieving thermally efficient houses. Airtightness stops cold from entering the house (in the form of draughts) and stops heat from escaping the house. Building regulations have been updated to improve airtightness and heat conservation within homes. The improved airtightness of new homes leads to homeowners opting to buy a heat recovery system, as their new homes will have stuffy rooms, and the heat recovery system can prevent this by pumping fresh filtered air into them. To install such a system, a house needs to be airtight, as mentioned above. Any poor insulation or leaks in the house will result in heat loss [10].

1.2.2. Cost

The price for a heat recovery system varies depending on the property size, the size of the unit required, the amount of ducting required and the installation and commissioning costs. On average, a basic heat recovery system can cost from GBP 3000 to GBP 5000 for a small residential property. However, larger properties or those with more complex layouts may require more advanced systems that can cost up to GBP 10,000. Rega Ventilation, a company that has been manufacturing heat recovery systems for 40 years, has two variants of the heat recovery system's main unit. The heat recovery unit can be either a wall-mounted unit or a loft-mounted unit. Depending on the size of the dwelling and the space available, the homeowner will choose the most convenient unit. Both units have an airflow capacity of up to 130 L per second, with a single unit being able to service a 350 m^2 floor area and to operate at various fan powers, as low as 0.51 w/l/s. The heat recovery unit has two types of duct systems—branched and radial—as well as three types of vents supplied from Rega Ventilation, a roof terminal, wall-mounted grilles, and internal vents [11].

The typical cost based on the Mitsubishi range of units in the UK ranges from GBP 2690.17 to GBP 4823.60. A system for an average home with a floor area size of 150 m^2, including a kitchen, a bathroom, a utility room, a W.C. and ensuite bathroom, three bedrooms, a living room, and a dining room, will cost around GBP 3092.45, excluding the installation cost and any home improvements needed to install the system.

2. Research Rational

The originality of this research is that the analysis and the data collected regarded a real case. All SAP input data were carefully selected and accurately inserted, so that the simulation reports reflected reliable outcomes, which were compared to the actual data. The heating systems were selected and sized based on the actual building's details and on information from providers based in the UK to obtain realistic estimations. The aim of this study is to provide homeowners with important details and information regarding renewable heating systems choices in the UK Moreover, this information will make homeowners aware of parameters like the carbon cost-effectiveness of heating systems rather than solely comparing their pricing, as community involvement is important to achieve net-zero carbon.

3. Research Methodology

This article discusses the viability of some options of energy heating systems considered by the ECO 4 scheme as renewable systems in terms of their carbon cost-effectiveness compared to conventional gas heating system. A detached bungalow house at 24 Abbey Lea, Allerton, Bradford city, owned by a friend, was studied. The house was recently converted into a two-storey detached house (all plans and details are provided later in this article). The main method used to study the carbon cost-effectiveness of this property was the SAP (standard assessment procedure) to generate a series of reports comparing three systems (gas boiler, air source heat pump and MVHR system). In addition, the SAP outputs were compared with the current EPC of the house and the actual energy bills.

4. Building Model and Simulation

4.1. Case Study

The property chosen for this study is a detached two-storey house, which was originally a detached bungalow house, located in Allerton, Bradford. The property is a bricked house with a cavity wall of 100 mm, filled with polystyrene beads (Thermabead insulation) and has an ACC block (autoclaved aerated concrete) on the inner side of the wall. The roof is a pitched roof with 270 mm of insulation sat in the loft. All internal walls have sound insulation and are layered with plywood, sat on the timber frame, with a plasterboard and a coat of plaster above it. All works were compliant with the specific building regulations.

The main heating source is a combi boiler controlled with a programmer, a room thermostat and TRVs. The hot water is supplied through the main heating source, and the floor is suspended, with 220 mm of earth wool insulation placed between the joists. All windows are double-glazed with a 12 mm air gap between the glasses.

Table 1 below reports the features of the house.

4.2. SAP Modelling; Findings and Discussion

Figure 1 shows the new plans for the converted two-storey house at 24 Abbey Lea as a full new floor extension added on the top. The calculated energy requirements of a dwelling were converted into primary energy demand figures by the SAP application using primary energy factors. This provided the final SAP rating and all emissions produced in the SAP worksheet. The total fabric heat loss for this property provided by the SAP report was 154.81 W/K.

Three different scenarios were created by inputting the data of the two-storey house into the SAP. In the first scenario, the house was simulated as it is, with a standard condensing combi boiler as the primary heat source. The measurements of the house as well as of any construction and structural elements were the same in all scenarios. Therefore, the first scenario data were used for the other two scenarios. The air source heat pump (ASHP) replaced the combi boiler in the second report, whilst a heat recovery system (MVHR) unit was selected for the third scenario.

Table 1. Construction details of the house at 24 Abbey Lea.

Element	Material	Construction Makeup	Insulation	Area in m^2
Walls	Brick Cavity wall, 100 mm ACC block	Brickwork outer leaf (102.5 m) Cavity wall filled with polystyrene beads (100 mm) Concrete ACC block (100 mm) Plasterboard dot on dab Plaster	Thermabead insulation in cavity wall	2×45.4526 2×30.848
Roof	Pitched–plaster board insulated at flat ceiling level	Concrete tiles Wooden hardwood timber joists Roof space Insulation roll Timber frame Softwood/plywood chipboard Plasterboard Plaster	300 mm insulation roll (earth wool)	65.72
Floor	Suspended timber floor on both ground floor and first floor	Unheated space/void Hardwood timber joists Insulation between joists Softwood chipboard carpet	Insulation rolls of 220 mm	65.72
Windows	PVC-U doubled-glazed	Window fixings Expanding foam Window sealant (outside) PVC trim	12 mm Air gap	Combined window area of 14.0922

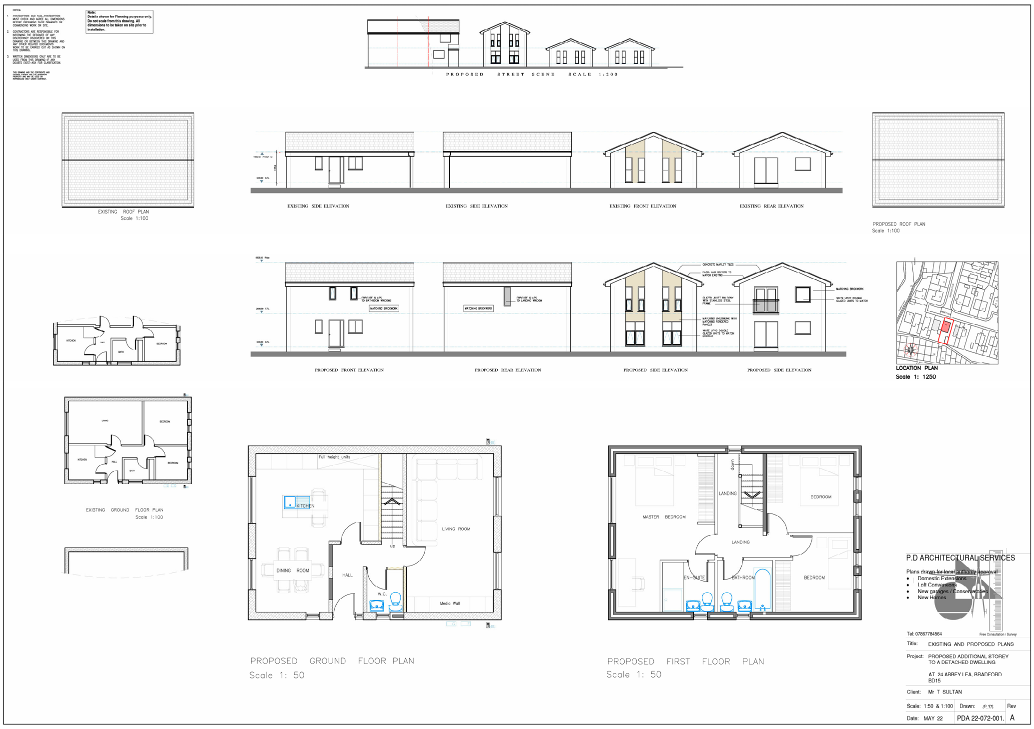

Figure 1. Previous and new design plans for the house at 24 Abbey Lea.

All non-renewable sources of energy are becoming limited. This has an impact on the energy prices and is currently causing an energy crisis in the UK This might have an impact on the SAP ratings as well. The SAP report set, by default, the efficiency of the three individual main heating systems at an average rate. It estimated the standard condensing combi boiler system with radiators to be 89.0% efficient, the ASHP system with radiators to be 170% efficient, and the heat recovery ventilation system to be 100% efficient.

4.2.1. Mains Gas Heating Source Report

It can be understood from the SAP worksheet for the mains gas heating source that a total of 3406.92 CO_2 kg/year was generated, corresponding to a CO_2 emission of 28.23 per m^2. The contributing factors (all included in SAP worksheet reports) were:

- Space heating (main system and secondary).
- Water heating.
- Electricity for lighting.
- Electricity for pumps, fans, and maintenance.

The report determined for this dwelling was SAP rating of 73.56 for this individual heating system. The dwelling with this heating source showed a predicted EPC of 74, which is low. This is an accurate rating, as the dwelling was constructed to achieve this rating.

4.2.2. Air Source Heating Pump Report

The SAP rating for the ASHP was 78.47. This rating was calculated based on the CO_2 emissions produced by the system. The total CO_2 emission produced was 2396.3 kg/year, and the CO_2 emission per m^2 was 19.85 kg/year. This showed approximately a 30% reduction in operating carbon emissions compared to the gas boiler system. However, this does not mean the whole system is more carbon cost-effective, as all carbon emissions over the lifespan of the system, including production and maintenance, must be considered.

The air source heating pump simulation showed this system to be very efficient, as most of the other results indicated higher CO_2 emissions. This showed that the chosen dwelling was built according to a high standard. However, the air source heat pump is widely accepted to be efficient in providing thermal energy for space heating. The predicted EPC was 78, indicating a band C rating. It showed that the air source heat pump, despite running on electricity only, is a good choice for its thermal efficiency.

4.2.3. Heat Recovery Ventilation System Report

The SAP worksheet report calculated a total CO_2 emission of 7143.45 kg/year and a total CO_2 emission per m^2 of 59.18. The SAP rating for this system was 36.79, which is relatively low compared to the ratings of the other two heating systems. Although this system is deemed to be very efficient and uses renewable energy, the SAP programme considered the electricity necessary to run this renewable source.

The carbon footprint was determined based on the electricity used for the system, which is much worse than natural gas, leading to a lower rating and an alleged higher carbon footprint if the system is not fed by PV solar panels.

The SAP programme calculated these figures and considered that electricity is more expensive than gas. Other factors to consider are the loss of electricity during its transfer from the source of production and the primary energy calculation to determine the CO_2 emissions. To put this into perspective, the primary energy factor is 1.22 for gas and 3.07 for electricity, i.e., more than 2 times higher; hence, the lower rating for this system. Depending on where the electricity is supplied from, the SAP calculation estimates how the electricity is produced and the conversion process to obtain it.

The SAP processes all these factors and creates a rating based on them; hence, a low rating for the MVHR system. The EPC for the dwelling with a heat recovery system installed was 38, corresponding to a low E/high F rating. This was predictable, as the system relies on electric energy. In addition, the hot water system is powered by an electric immersion heater, which also contributes towards a lower rating.

5. Conclusions

In conclusion, both energy technologies (air source heat pump and heat recovery system) are efficient in producing heat generated by renewable sources. However, the air source heat pump is a better option to achieve the net-zero housing scheme. The air source heat pump has a higher efficiency output and is simple to install. The existing boilers in dwellings around the UK can easily be replaced with this system and, unlike the heat recovery system, the ASHP can provide both heating to the property and hot water around the house. It can also be installed into properties that do not have any mains gas. The heat supplied from this system can be transferred to radiators and underfloor heating. The air source heat pump can be paired with PV panels to create a net-zero carbon home, providing the most effective way to reach the net-zero target set by the UK government for 2050. The GBP 5000 government incentive is a good reason to opt for this system and will spur homeowners to install it; it will also allow cuts on energy bills. Since we are in an energy crisis, this initiative will motivate homeowners to instal these systems.

The study believes the heat recovery systems should be installed into commercial buildings, as it can be installed during the construction phase which would be a better alternative to commercial boilers, in addition to reducing the CO_2 emissions of an infrastructure. Heat recovery systems can be constructed to use energy from PV panels, which would create carbon-neutral heating systems; however, the downfall of the heat recovery systems is the difficulty of installing them into existing dwellings. This would require exposing all partitions in a dwelling to install the ducting for the system, resulting in extra expenses for the homeowner, in addition to the overall cost of the heat recovery ventilation system.

The study would propose to the UK government to encourage the installation of an air source heat pump in all existing dwellings and a heat recovery system in all new buildings. In doing so, the target of net-zero housing will be achieved at a quicker rate.

Both systems have their downfalls, but they are efficient in reducing bills and creating lower carbon emissions. Their choice depends on the property type, the amount of money homeowners is willing to spend and their energy improvement targets. In general, the air source heat pump appears to be the best solution for achieving net-zero housing in the UK This study has limitations, as only few energy heating systems were examined, due to time and budget restrictions. We recommend comparing the simulation results to the actual performance of each system in longer monitoring periods. Further study on ground source heat pumps and combined heat and power systems might be useful to draw wider conclusions and recommendations.

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