Department of Mechanical and Aerospace Engineering

To Investigate Possibilities for Decarbonizing Glasgow Heating Systems

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A thesis submitted in partial fulfilment for the requirement of degree in

Master of Science in Sustainable Eng: Renewable Energy Systems and the Environment

2021

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Abstract

In colder climates, heating accounts for the overwhelming bulk of the energy used. The importance of increasing the long-term sustainability of net energy consumption has lately risen in significance. The involvement of the government, rising fossil fuel costs, and the increased availability of renewable energy sources have all contributed to the present trend of decarbonisation of the electric grid.

Despite this, the heating sector has not yet achieved the same degree of sustainability. This thesis shows the outcomes of a range of technologies that could potentially decarbonize Glasgow's heating system. The Glasgow City Council has estimated that Glasgow consumes 5,145,200 MWh per annum of natural gas [1], which means Glasgow city natural gas consumption is 587.35 MWh per hour. This thesis aims to discover whether currently available technologies can decarbonise heating in the city of Glasgow and freeing it from its dependence on natural gas.

Based on the literature review, in 2020, 97.4% [2] of Scotland's total electricity intake was from renewable sources; this year was a record high for renewable energy generation, 31.8 TWh. The net exports of electricity in 2020 was their highest to date at 19.3 TWh [3], a 21% increase compared to 2019 [3]. Scotland's electricity exports had an estimated wholesale market value of £0.76 billion. In the United Kingdom, Scotland became the first country to legislate on the establishment of heat networks in March 2020, establishing legislation governing the provision of thermal energy via a heat network and its construction and operation. As part of Government Policy on Heat Networks is the Renewable Heat Incentive (RHI), it is a government-sponsored financial incentive designed to promote the use of renewable energy [4]. The eligible heating systems are biomass boilers [4] and pellet compatible stoves, ground source heat pumps, air-source heat pumps, evacuated tube solar thermal panels and flat plate thermal panel [4].

The reason behind the government commitment toward the use of renewable energy and phasing out fossil fuels is carbon emission since Carbon Dioxide (CO2) [5][6] is the main greenhouse gas responsible for most of Scotland's carbon footprint [5]. In 2017, it accounted for 77.3% [5] of Scotland's total carbon footprint. Three distinct emission categories (scopes) [7] can be considered:

- Scope 1 This category includes the Green House Gas (GHG) emissions produced directly by a business, such as when its boilers and cars are used [7].
- Scope 2 These are the emissions generated indirectly by a business, such as when the power or energy it purchases to heat and cool buildings is generated on its behalf. [7].
- Scope 3 This is the point at which things get complicated. This category includes all emissions not directly attributable to the business, but which are indirectly attributable to the organisation along its value chain, for instance, via purchases from suppliers and by the usage of its goods [7].

These scopes will assist any organisation in quantifying their carbon emissions in order to report them to the government and measure the progress towards sustainability yearly goals.

Hydrogen generation technology, waste heat technologies, and heat pump technologies were all carefully analysed in terms of their limitations and advantages; this analysis enabled the thesis to develop two scenarios: one involving hydrogen generation via electrolysis and another involving the collection of heat pump technologies to electrify heating in Glasgow.

Scenario 1 aimed to decarbonize Glasgow's heating system by replacing natural gas [1] with hydrogen. Since the government are trying to generate hydrogen from renewable sources, which is possible., this research has found that it is achievable to fulfil the hydrogen demands based on the current technologies available. However, it will require enormous energy to be consumed by electrolysers units.

A 62% efficient 20 MW electrolyser [8] unit would produce 0.3721 tonnes/hr of hydrogen and use 3.3249 tonnes/hr of water, resulting in a requirement of 47 electrolyser units to match Glasgow's natural gas energy demands. The amount of hydrogen required for heating is 17.6 tonnes per hour. To power an electrolyser unit that will deliver 20 MW of energy, 19 wind turbines are needed; each wind turbine produces 3 MW with a capacity factor of 36.3%, resulting in a requirement for 893 wind turbines [9] (Vestas V 112/ 3000) to produce the adequate amount of energy to supply the electrolysers units (940 MWh per hour).

Scenario 2 aimed to decarbonize Glasgow's heating system by replacing natural gas with an electrified heating system such as heat pumps and waste heat recovery.

- Considering the potential of using heat pumps, six water source heat pump units would be allocated on the River Clyde [10], which would provide an area of 28 km^2 with 90

MWh per hour of heat. However, due to the high quantity of river water consumption, this potential project would be subject to complex licencing from the Scottish Environment Protection Agency (SEPA) [11].

- Waste heat recovery could benefit Glasgow, as based on the Geographic Information System (GIS) division database, Glasgow can produce 5,000 MWh per annum of heat waste, which implies that the city can provide 0.6 MWh of heat per hour [12].
- A Water Source Heat Pump (WSHP) installation at Glasgow's Underground Station (COP) of 2.5 and generate 0.7 MWh per hour [13].
- There are three different types of underground geothermal heat resources available in Glasgow[14], each with varying temperature levels. There are hot aquifers (low and potentially relatively high temperature) [14][15], hot sedimentary rocks (low and high temperature), and hot dry rocks / petrothermal sources in Scotland's mined regions that may provide approximately two and half megawatts per kilometre square (MW/km^2). When two and half megawatts is multiplied by the value of square kilometres in the mined region (2.5 x 15 km^2) [14], a rough estimate of the available heat of 37.5 MWh per hour .
- Each air source heat pump (ASHP) has a coefficient of performance of two and a heat capacity of 0.7 MWh per hour [16], while the ground source heat pumps have a coefficient of performance of three and a heat capacity of 0.091 MWh per hour [17]. Therefore, 511 air source heat pumps and 1099 ground source heat pumps are required to generate 458.55 MWh of heat per hour.

According to scenario 2, the combined collection of technologies will be able to offer Glasgow a maximum of 587.35 MWh of heating each hour, which is the precise amount of energy required. The currently available technologies are sufficient to replace natural gas use in Glasgow, although heat pumps require 255.3 MWh of electricity per hour which is generated by 234.4 wind turbines (3 MW wind turbine with capacity factor 36.3%) [9].

Both H2 and Heat pumps require backup energy generation technologies during periods of low renewable energy output (wind and solar), but this issue is outside the scope of this thesis, and these low generation gaps will be handled by the electrical grid.

Additionally, intermittency/storage must be addressed. However, the aim of this thesis is to study demand/delivery and the intermittency/storage issue that exists in both situations but is not addressed, and it is deemed to be outside of the scope of this thesis. However, it is discussed in greater detail in the discussion and recommendations.

It is recommended to use backup solutions to alleviate the problem of intermittency during low renewable energy generation times is recommended (wind and solar).

Green generation storage in battery farms at 90% efficiency, green H2 storage at large scale green H2 Combined Cycle Gas Turbine (CCGT) plants, flexible operation nuclear reactors [18], and distributed storage (battery, H2, thermal), these are among the backup solutions mentioned in this thesis.

If all of the buildings in Glasgow were to be converted or modified to comply with the Passivhaus standard [19], this would have a significant effect on the amount of electricity consumed for heating and could achieve a reduction of up to 80% [19] on energy used for heating in Glasgow. It is therefore recommended to retrofit buildings in Glasgow with excellent levels of insulation and minimal thermal bridges. The buildings must have high levels of airtightness and have excellent indoor air quality, as well as great solar gain from passive solar energy.

Acknowledgements

Thanks are due to Dr Paul Tuohy for his supervision, continuous advice, and support during this thesis.

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Nomenclature

Symbol	**Description**	**Units**
MWh	Megawatt hour	MWh
MW	Megawatt	MW
km^2	A kilometre square is a unit to measure the area	km^2
TWh	Tera Watt-hour	TWh
GWh	Giga Watt-hour	GWh
kWh	Kilowatt Hour	kWh
MtCO2e	Metric Ton CO2 Equivalent	MtCO2e
mW m-2	Milliwatt Per Square Metre	mW m-2
°C	The degree Celsius	°C
Q	Represents The Heat Content of The Substance	J
V	Volumetric Flowrate of The Substance	m^3/s
ρ	Density Of the Substance	kg/m^3
C_p	Specific Heat of The Matter	J/kg.K
Delta T	The Difference in Substance Temperature	K
	Watts Per Meter-Kelvin	W/mK
T_c	Lower Average Heat Rejection Temperature	K
T_b	Greater Average Heat Addition Temperature	K

1.0 Introduction

In colder regions, the vast majority of the energy used is for heating. Increasing the sustainability of the net energy consumed has recently gained new prominence. Direct governmental involvement, increasing fossil fuel prices, and easier availability of renewable energy have all contributed to the current trend of decarbonisation of the electric grid. Despite this, the same level of sustainability in the heating industry has not yet been reached.

This study is significant because it focuses on finding solutions to decarbonize Glasgow's heating systems, which currently use natural gas as a fuel source, resulting in massive amounts of carbon emissions, the equivalent of 951,862 tonnes of CO2 each year (it is calculated by using Defra’s conversion factor), which contributes negatively to climate change. Scotland is committed under the Climate Change Act 2019 [20] to achieving net-zero emissions of all greenhouse gases by 2045 [20]. This is more difficult than a net-zero [20]. carbon objective, which commits solely to carbon neutrality. A zero-emission building emits no greenhouse emissions [20].

Hydrogen generation technology, waste heat technology, and heat pump technologies would be carbon-free technologies if they were supplied by a renewable energy source. Therefore, during this thesis, all these technologies were thoroughly examined in terms of their designs, limitations, and benefits. Based on these findings, two scenarios were developed: one involving hydrogen generation via electrolysis and the other involving the collection of heat pump technologies to electrify heating in Glasgow, as illustrated in Figure 1.

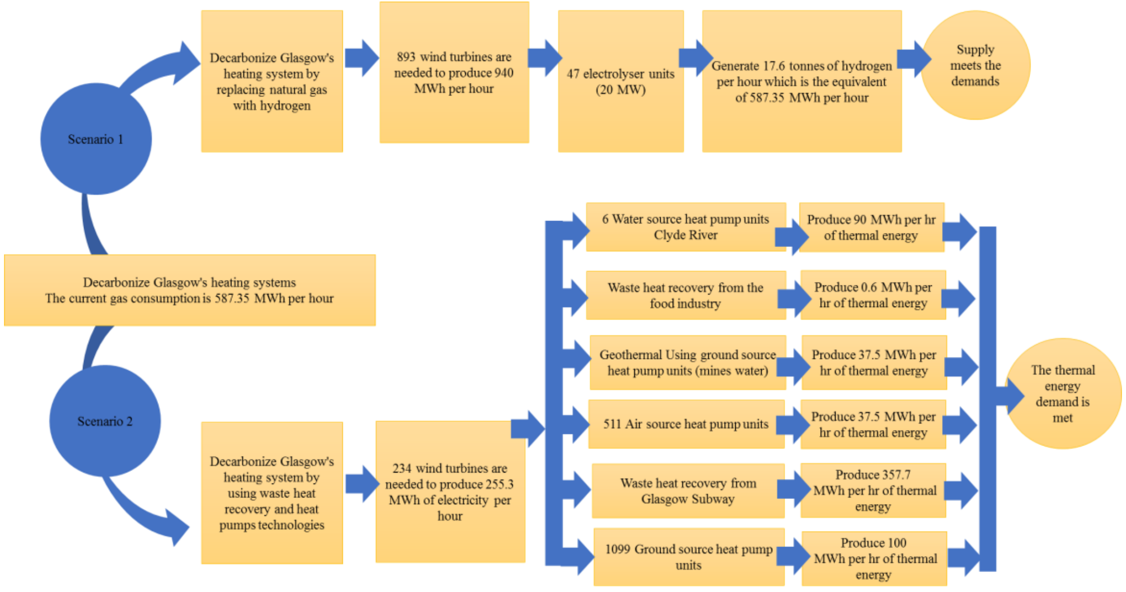


Figure 1 Decarbonize Glasgow's heating systems Scenario 1 and 2

The literature review section discussed a huge amount of data, statistics, and information that helped lay the groundwork for this thesis to decarbonizing Glasgow's heating systems and form scenarios 1 and 2. The purpose of each section is covered in the methodology section; however, the below illustration (Figure 2) shows a short description of the literature review.

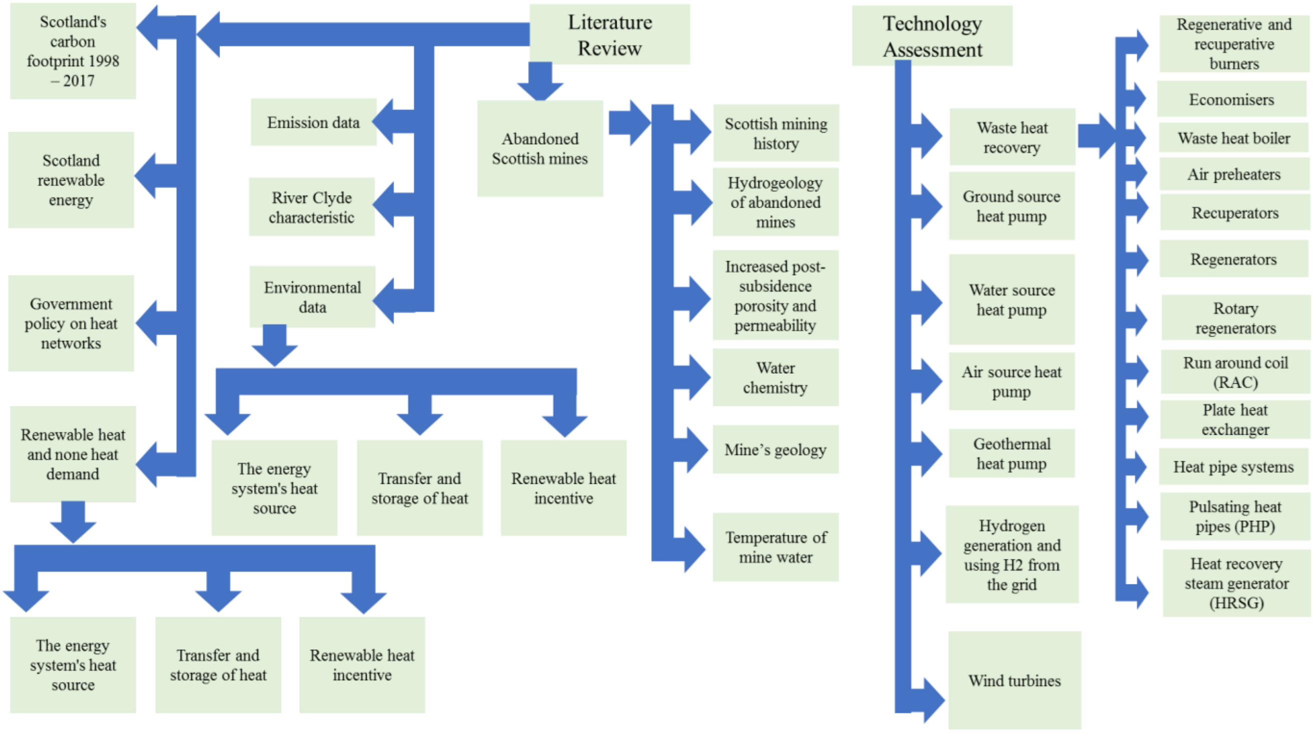


Figure 2 literature review and technology assessment map

1.1 Thesis's Aim

The principal aims of this thesis are as follows:

- Identify the peak heating demand for Glasgow city and the required thermal energy to meet the heating demand.
- To analyse how successfully the government supports renewable energy for heating through incentives.
- To investigate the River Clyde capability to supply water to the water source heat pump.
- To investigate the options to decarbonise the heating system for the city of Glasgow by analysing and selecting the best available technology.
- To size the electrolyser unit for hydrogen generation in order to use the hydrogen as a fuel source rather than natural gas for building heating.
- To calculate the electricity demand for the heat pumps and electrolysers units.

- To find out the adequate number of wind turbines to supply heat pumps and electrolysers units with the renewable energy source.
- To investigate the enrgyPRO tool for the modelling and simulation of heating networks.

1.2 Methodology

The methodology of research refers to the particular processes or methods used to identify, select, process, and analyse data pertaining to a subject., these principles were implemented in this thesis. Figure 3 demonstrate a summary of the methodology.

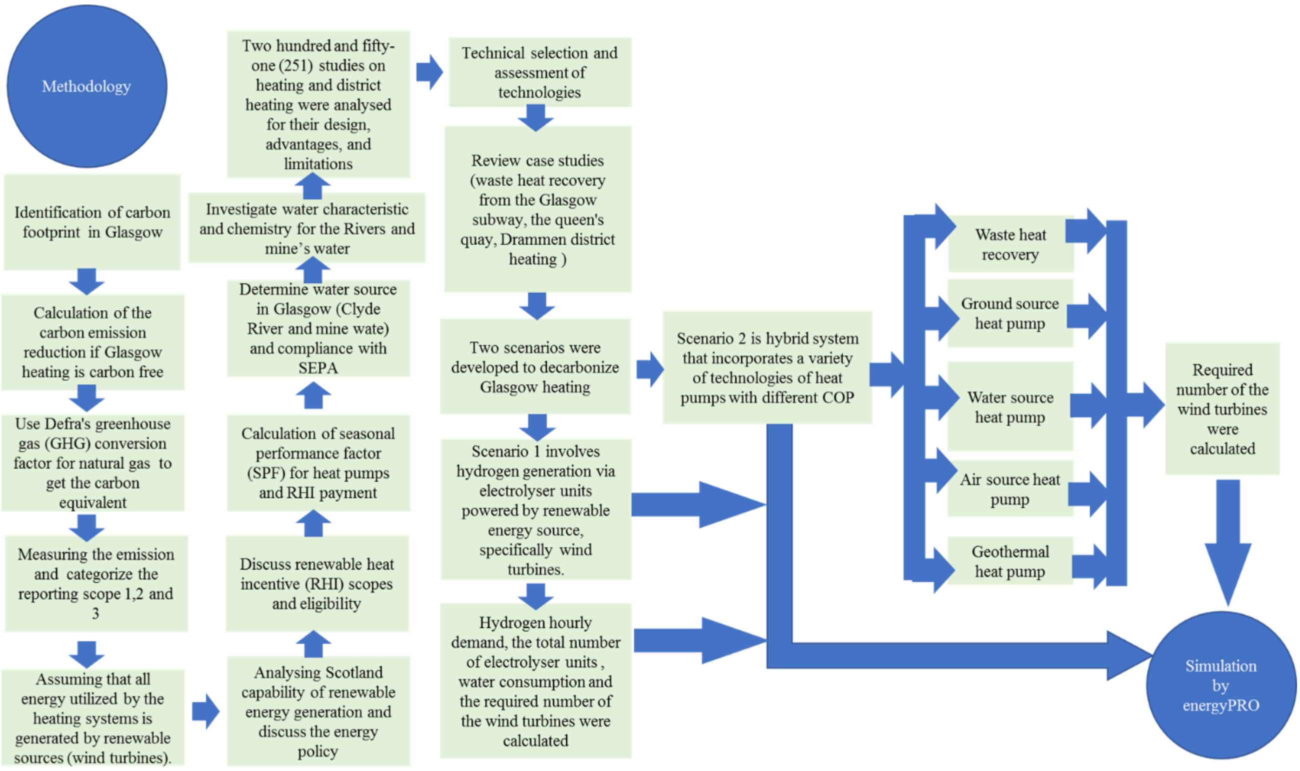


Figure 3 Methodology's summary

Carbon footprint and emission data must be the starting point for any methodology aimed at decarbonizing heating in Glasgow city in order to gain a comprehensive understanding of the impact of climate change and to achieve carbon-neutral heating in Glasgow city. Carbon Dioxide (CO2) is the primary greenhouse gas in Scotland, accounting for the majority of the country's carbon footprint. It accounted for 77.3% [5]of Scotland's total carbon footprint in 2017, a significant increase from 71.1% in 1998 [5].

The following step is to calculate the carbon emissions savings associated with carbon-free heating in Glasgow. Each type of fuel has a carbon emission equivalent to kilogrammes or tonnes. To convert a quantity of fuel or its energy equivalent to a carbon equivalent, it is necessary to multiply it by the conversion factor.

According to Defra's Greenhouse Gas (GHG) guidelines, the conversion factor for natural gas is 0.185 kg / kWh, which is the amount of Carbon Dioxide (CO2) generated by natural gas combustion [21].

The conversion process is demonstrated in the following Equation 1.

$$\begin{aligned} &Combustion\ thermal\ energy\ generated\ by\ Natrual\ gas\ (kWh) \\ &\quad * Defra\ converstion\ factor\ for\ natrual\ gas\ \frac{kg}{kWh} \\ &\quad = (CO2)\ kggenerated\ by\ natural\ gas\ combustion \end{aligned}$$

Equation 1

With the help of Equation 1, the Carbon Dioxide reduction can be measured. Three distinct emission categories (scopes) can be considered:

- Scope 1 this category includes the Green House Gas (GHG) emissions produced directly by a business, such as when its boilers and cars are used [7].
- Scope 2 these are the emissions generated indirectly by a business, such as when the power or energy it purchases to heat and cool buildings is generated on its behalf [7].
- Scope 3 this is the point at which things get complicated. This category includes all emissions not directly attributable to the business but which are indirectly attributable to the organisation along its value chain, for instance, via purchases from suppliers and by the usage of its goods [7].

The carbon emission target for Glasgow heating is zero-emission (set up by this thesis), assuming that all energy utilized by the heating systems is generated by renewable sources (Wind and Sun).however renewable energy sources, such as Wind and Sun, face the same problem: when there are gaps in the generation, backup technologies are required [6] As a result, the following set of assumptions were developed for this thesis as follow:

- Assume that the electrical grid is supplied by backup technologies.
- Assume that any gaps in the generation of renewable energy (wind and sun) are compensated for by other technologies.

- Assume that the electrical grid is carbon neutral as a result of the use of carbon capture technology and green generation storage in battery farms at 90% efficiency.

As noted, before both H2 and HP options require backup technologies during periods of low renewable energy generation (wind and solar), but this issue is outside the scope of this thesis, and it will be handled by the electrical grid.

The other issue that needs to be considered is intermittency/storage. However, the scope of this thesis is to examine demand/delivery, and the intermittency/storage issue that applies in both cases but is not addressed here was deemed to be outside the scope of this work. However, it is addressed further in the discussion and recommendation.

The second step of the methodology is analysing Scotland capability of renewable energy generation. It is assumed in this thesis that all energy utilized by the heating systems in Glasgow is generated by wind turbines. Renewable Heat umbrella covers several technologies such as biomass boilers and pellet compatible stoves, ground source heat [4] pumps, air-source heat pumps, evacuated tube solar thermal panels and flat plate thermal panels. These technologies are covered by the Renewable Heat Incentive (RHI) [4], a government-backed financial incentive designed to promote the use of renewable energy.

Seasonal Performance Factor (SPF) [4] must be calculated to qualify for the Renewable Heat Incentive (RHI) for the heat pump. The calculation process is demonstrated in the following Equations:

SPF is calculated as follows [4]:

$$SPF = \frac{Total\ heat\ energy\ output\ per\ annum(\ kWh)}{Total\ input\ electricity\ per\ annum\ (kWh)}$$

Equation 2

The SPF is considered when calculating payments using the following formula [4]:

$$Payments = \ Estimated\ annual\ renewable\ heat\ load\ (total\ heat\ demand\ x\ (1-\ 1/SPF))\ x\ tariff\ rate$$

Equation 3

Annual renewable heat load is calculated with the equation below [4]:

$$Annual\ renewable\ heat\ load =$$

$$(total\ energy\ demand\ x\ (1\ - \left(\frac{1}{Seasonal\ Performance\ Factor}\right)$$

Equation 4

The calculated heat load is used to determine the amount of the RHI payment as demonstrated in the below equation[4]:

$$Total\ annual\ Domestic\ RHI\ payment$$
$$= \ (tariff\ x\ estimated\ annual\ heat\ load)$$

Equation 5

The methodology’s third step is to determine the source of water in Glasgow, as water source heat pumps [22] use a large amount of water. If the utilized water is more than 2000 m3 per day, the project owner is subjected to complex licencing requirements by the Scottish Environment Protection Agency (SEPA) [11].

The River Clyde and abandoned mine water have been identified as major water sources for heat pumps in Glasgow; in this thesis, the river/mine water chemistry and characteristics have been carefully analysed in relation to the water source heat pump requirements for meeting part of the city's heating demands. Extensive site visits were carried out to all of Glasgow City Council's postcode areas, assessing the topographical and geological aspects of the locations. These site visits aided in acquiring a wealth of information and performing appropriate site mapping.

The methodology's fourth step is to conduct an in-depth technology assessment. Two hundred and fifty-one (251) studies on heating and district heating were analysed for their design, advantages, and limitations. This in-depth analysis steered the thesis's technical selection of technologies such as geothermal, heat pumps, and waste heat recovery. These technologies were selected using a selection matrix that considers efficiency, demand availability, risk of system failure, constraints, energy, and fuel consumption.

The fifth step of the methodology involved developing two scenarios as a result of the assessment of heating technologies. The first scenario involves hydrogen generation via electrolyser units powered by renewable energy sources, specifically wind turbines.

The following series of equations will calculate Glasgow's hydrogen requirements.:

$$\text{Hydrogen demand} = \left(\frac{\text{total Gas Energy kWh}*\text{conversion value from kWh to Mj}}{\text{LHV for H2}}\right)$$

Equation 6

For Glasgow, the hydrogen demand equivalent of the total gas consumption can be calculated as shown in Equation

$$= \left(\frac{5145.2 * 10^6 * 3.6}{119.96}\right)$$

$$= 154407469.2 \frac{kg}{year} \; of \; hydrogen = 154407.469 . \frac{Tonne}{year} \; of \; hydrogen$$

This means Glasgow hydrogen demands per hour is 17.6 tonnes/hour.

Equation 7

Calculation of Number of Electrolyser Units:

A 20 MW Electrolyser unit at 62% precent efficiency will generate 0.372 Tonne/hr and consume 3.3249 Tonne/hr of water, refer to Equations below:

$$The \; number \; of \; electrolyser \; units = \frac{Total \; hydrogen \; demands \; per \; hour}{Hydrogen \; production \; by \; electrolyzer \; unit}$$

Equation 8

As previously stated, each electrolyser unit consumes 3.3249 tonnes of water per hour. The below equation calculate the water consumption of 47 electrolyser units:

$$\begin{aligned} &The\ water\ demands\ to\ generate\ hydrogen \\ &\qquad = the\ number\ electrolyser\ unit * water\ demand\ per\ hr \end{aligned}$$

Equation 9

As per the Glasgow City Council’s website, Glasgow has 295,761 households [23], and water consumption per household is 0.0187 m^3 per hour [24].

As previously stated, the electrolyser units are powered by wind turbines; consequently, a wind turbine database was analysed to determine the appropriate size of wind turbine plants to supply the electrolyser units with the required renewable energy supply. Nineteen wind turbines (Vestas V112 / 3000 capacity factor 36.3%) would be required to supply a single 20 MW electrolyser unit with electricity, where each wind turbine would generate 3 MW. The following equation will determine the number of wind turbines required to supply the required power to the electrolyser units.

$$\begin{aligned} &The\ required\ wind\ turbines \\ &\qquad = number\ of\ electrolyser\ units\ *\ 19\ wind\ turbines \end{aligned}$$

Equation 10

After analysing all the calculated data, the advantages and disadvantages were concluded.

The second scenario is about Glasgow Heating Systems Potential is a hybrid system that incorporates a variety of technologies involving water source heat pumps, air-source heat pumps, ground-source heat pumps, and waste heat recovery. According to the assessment of heating technologies as mentioned earlier in the methodology, focusing exclusively on one technology will not suffice to decarbonize Glasgow's heating systems; thus, a hybrid system must be implemented, this hybrid system will be powered by wind turbines. The impact of the seasonal fluctuations in temperature on heat pumps was carefully analysed, graphical analysis was created to illustrate the variation of COP against delta mean temperature seasonal variation.

Several case studies, including waste heat recovery from the Glasgow subway, the Queen's Quay, Drammen district heating, Air, and ground source heat pumps, were simulated in Glasgow to meet heating demand and eliminate the city's reliance on natural gas as a fuel source for the existing heating system., the renewable energy demand was calculated[25], and the adequate number of wind turbines were determined. Successful heating system case studies were researched. These were then replicated in Glasgow using the simulation software 'energyPRO' and manual calculations to create a comparable situation and achieve decarbonization of Glasgow heating systems.

1.2.1 Thesis’s Structure

In Section 1, the introduction guides the reader from a broad field of study to a specific research area by summarising current knowledge and background information, stating the purpose of the work in the form of the hypothesis, question, and study area, briefly explaining the rationale, methodological approach and determining the possible outcomes revealed by this thesis.

The literature review in Section 2 demonstrates the author's knowledge and comprehension of the academic literature on decarbonizing Glasgow heating systems. Additionally, the literature review entails a critical assessment of the content. Each sub-Section of the literature review is logically linked to the following sub-Section.

Section 3 provides a thorough analysis of the heating systems. This analysis includes design, thermodynamic advantage, and limitations. The technology will be chosen based on efficiency, demand availability, system failure risk, constraints, energy, fuel type, and energy consumption.

Section 4 covers scenarios to decarbonise Glasgow heating systems. Hydrogen generation technology, waste heat technology, and heat pump technologies would be carbon-free technologies if they were supplied by a renewable energy source. Therefore, during this thesis, all these technologies were thoroughly examined in terms of their designs, limitations, and benefits. Based on these findings, two scenarios were developed: one involving hydrogen generation via electrolysis and the other involving the collection of heat pump technologies to electrify heating in Glasgow.

Section 5 included a thorough explanation of the results of the calculated data and literature review and the technology assessments, which led to the conclusion of the outcomes of scenarios one and two, recommendations and future work.

Section 6 covers all the references, and Section 7 contains the Appendices, which are wind turbine models database, modelling by using energyPRO and the simulation. Table 1 holds the purposes of the section.

Table 1 Purposes of sections.

Section	Title	Purpose
1.0	Introduction	The introduction guides the individual who research the subject to a specific research area. By summarising current knowledge and background information, declaring the purpose of the thesis in the form of the theory, and study area, in brief describing the rationale, practical approach and determining the possible outcomes revealed by this thesis.
1.1	Project Aim	The primary focus of the thesis.
1.2	Methodology	The methodology of this thesis refers to the procedures used to identify, choose, process, and analyse data pertaining to the subject decarbonizing Glasgow heating systems. These principles were implemented in this thesis.
2.0	Literature Review	The literature review demonstrates the author's knowledge and comprehension of the academic literature on decarbonizing Glasgow heating systems. Additionally, the literature review entails a critical assessment of the content. Each sub-section of the literature review is logically linked to the following sub-section.
2.1	Scotland's Carbon Footprint 1998 – 2017	To demonstrate the present amount of carbon emissions and to identify the primary source of this emission.
2.2	Scotland Renewable Energy	to have a thorough knowledge of the renewable energy potential and capability of Scotland. For renewable energy generation.

2.3	Government Policy on Heat Networks	to have a thorough understanding of government policy relating to energy distribution networks.
2.4	Renewable Heat and None Heat Demand	to have a great understanding of heat storage and renewable heat incentive’s scope and eligibility.
2.5	Environmental Data	Environmental data is primarily used to provide emissions data and to ensure compliance with applicable laws and regulations, as well as to mitigate the risks of harmful effects on the natural ecosystem and human wellbeing.
2.6	Emission Data	To explain the five key points about scope 1, 2 and 3.
2.7	River Clyde	To investigate the River Clyde's water characteristics.
2.8	Abandoned Scottish Mines	To gain an understanding of the history and geology of the mines beneath Glasgow.
3.0	Technology Assessment	To perform technical selection and assessment of heating technologies.
3.1	Waste Heat Recovery	To evaluate and distribute knowledge about twelve waste heat recovery technologies.
3.2	Ground, Water, Air Heat Pumps	To evaluate and distribute knowledge about Ground, Water, Air Heat Pumps technologies.
4.0	Scenarios to decarbonise Glasgow heating systems	To exemplify the outcome of the technology evaluation.
4.1	Scenario one, H2 from the grid	To have a thorough understanding of the calculations involved in generating hydrogen and sizing the required wind turbine power plants.
4.2	Scenario-two Glasgow Heating Network Potential	To possess an in-depth understanding of the calculations entailed in waste heat recovery and heat pumps[26], as well as the sizing of wind turbine power plants

2.0 Literature Review

This literature review demonstrates the author's knowledge and comprehension of the academic literature on decarbonizing Glasgow heating systems. Additionally, this literature review entails a critical assessment of the content. Each sub-section of this literature review is logically linked to the following sub-section, as illustrated in Figure 4.

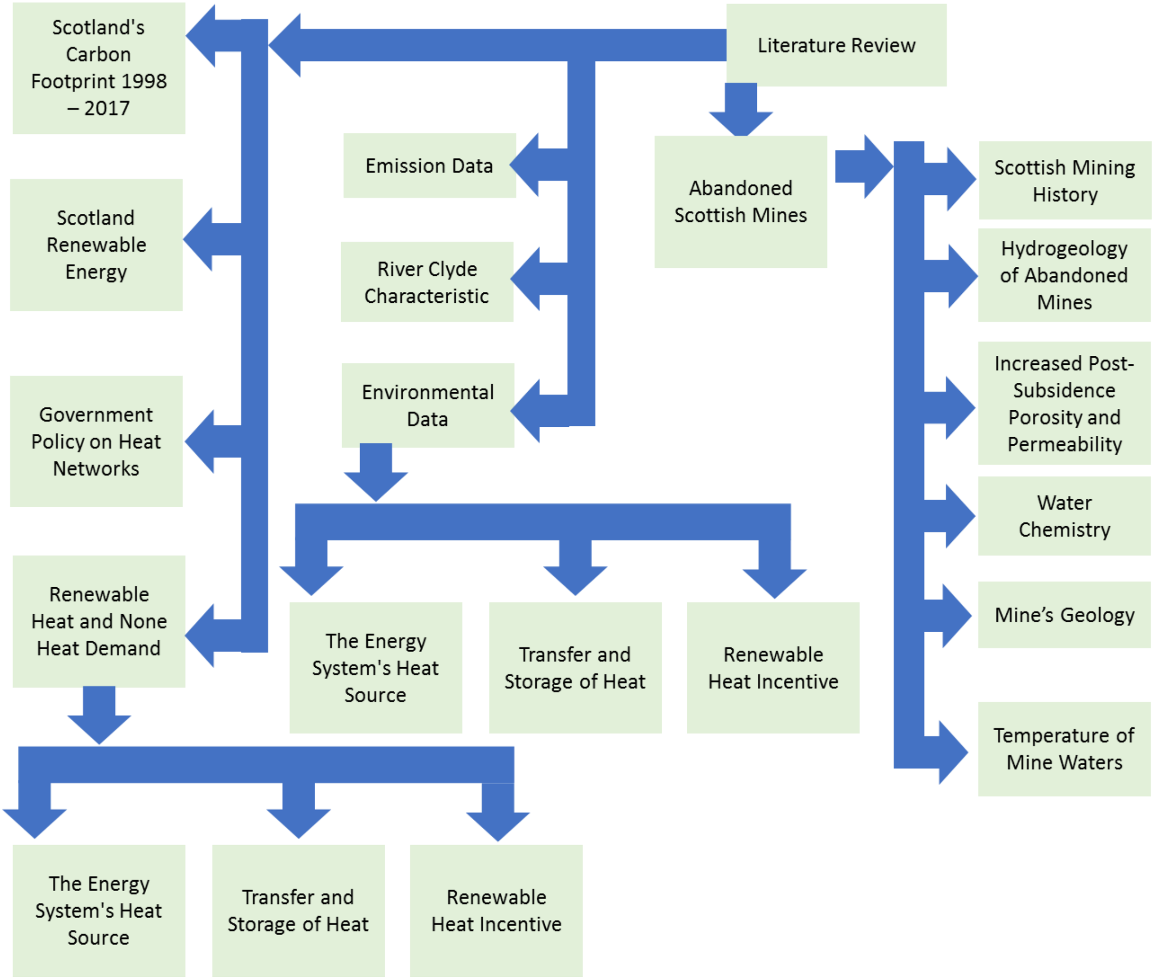
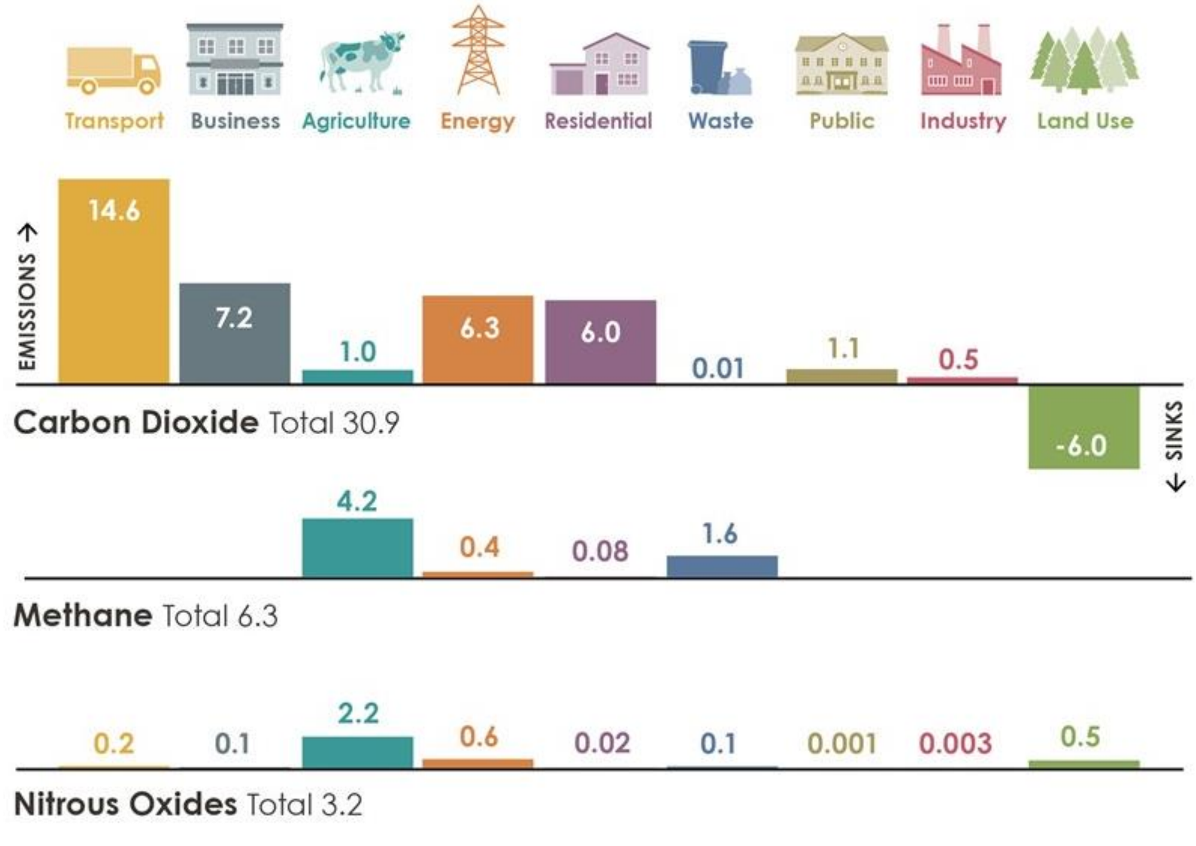


Figure 4 Literature Review logic flow

2.1 Scotland's Carbon Footprint 1998 – 2017

Carbon Dioxide (CO_2) [5] is the main greenhouse gas responsible for most of Scotland's carbon footprint [5]. In 2017, it accounted for 77.3% [5] of Scotland's total carbon footprint, up from 71.1% in 1998. Between 2016 and 2017, Scotland's overall carbon footprint decreased by 3.5% [5]. The ‘carbon footprint’ refers to calculations of greenhouse gas emissions on a Scottish consumption basis such as heating, industries. Fuel etc., the baseline set by the Scottish Government is the year 1998. The below figure illustrates the breakdown of carbon emissions in 1998 in Scotland [5] as illustrated in Figure 5.



Values in million tonnes of CO_2 equivalent ($MtCO_2e$)

Figure 5 Scotland greenhouse gases emission 2018 [27].

2.2 Scotland Renewable Energy

In 2020, 97.4% [3] of Scotland's total electricity intake was from renewable sources; this year was a record high for renewable energy generation, 31.8 TWh [3]. The net exports of electricity in 2020 was their highest to date at 19.3 TWh, a 21% [3] increase compared to 2019. Scotland's electricity exports had an estimated wholesale market value of £0.76 billion. Figure 6 is illustrating the net exports [3].

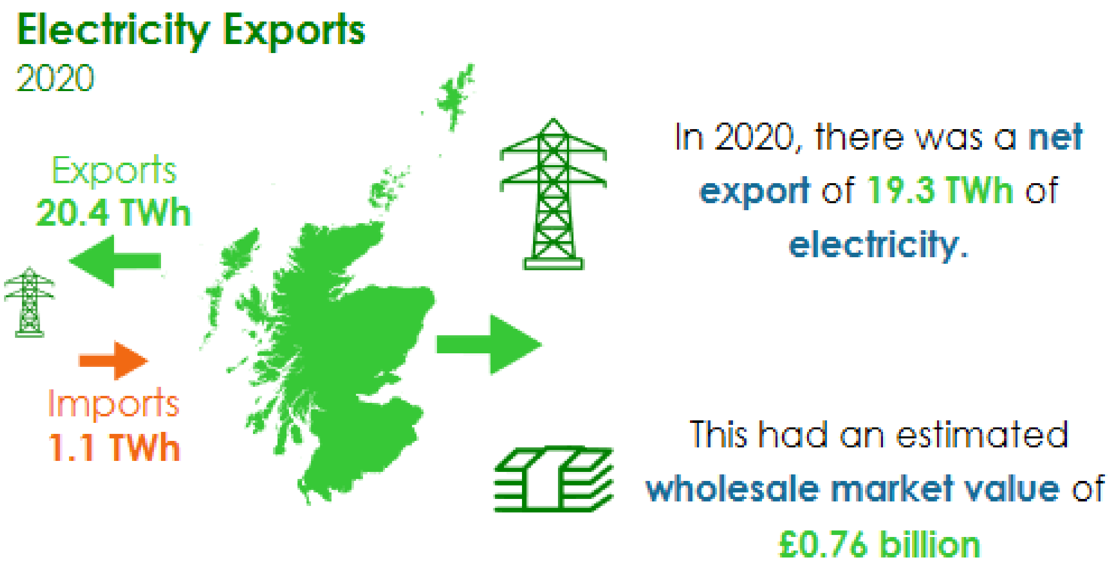


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Figure 6 Net Export, Export Minus Import [3].

Wind energy generates the majority of Scotland's renewable electricity (23.2 TWh), the offshore wind-generated 3.5 TWh in the year 2020, Figure 2 summarises the renewable electricity generation by source from 2000 to 2020, and the below Figure 7&8 are the illustration of the energy target [3].

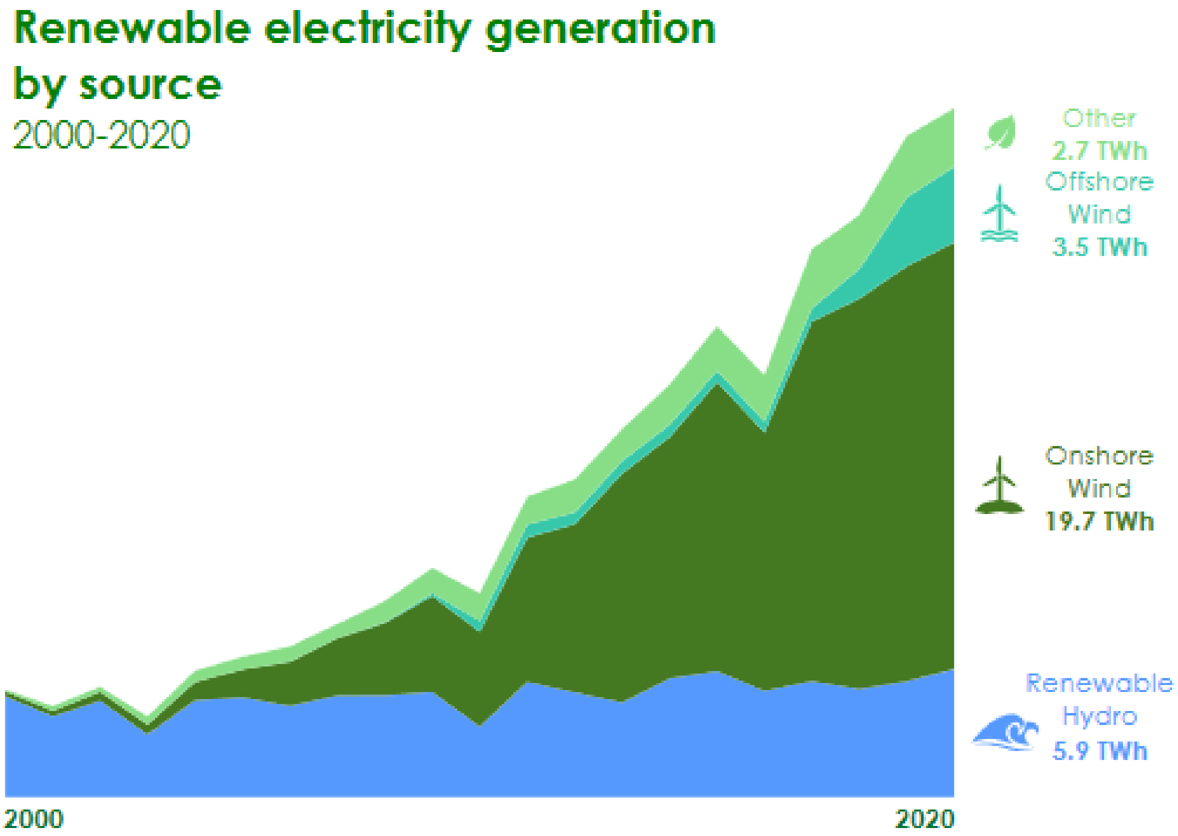
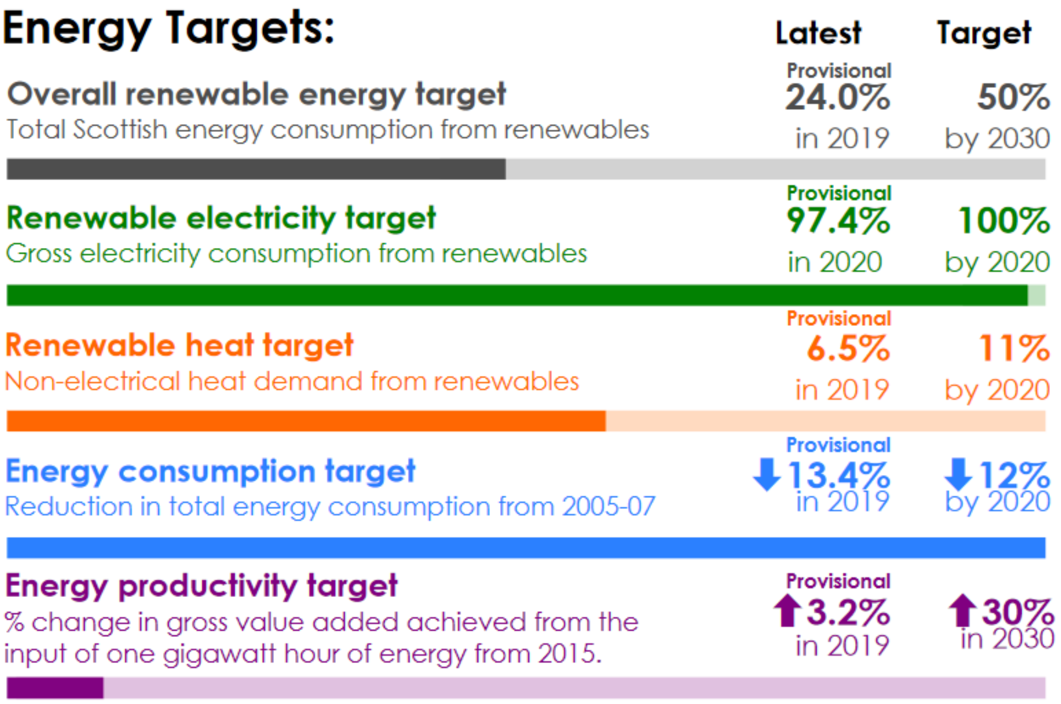


Figure 7 Renewable electricity generation [3].



Energy Targets:

	Latest	Target
Overall renewable energy target Total Scottish energy consumption from renewables	Provisional **24.0%** in 2019	**50%** by 2030
Renewable electricity target Gross electricity consumption from renewables	Provisional **97.4%** in 2020	**100%** by 2020
Renewable heat target Non-electrical heat demand from renewables	Provisional **6.5%** in 2019	**11%** by 2020
Energy consumption target Reduction in total energy consumption from 2005-07	Provisional ⬇**13.4%** in 2019	⬇**12%** by 2020
Energy productivity target % change in gross value added achieved from the input of one gigawatt hour of energy from 2015.	Provisional ⬆**3.2%** in 2019	⬆**30%** in 2030

Figure 8 Scotland energy target [3].

2.3 Government Policy on Heat Networks

The government established the Heat Networks Delivery Unit (HNDU) in 2013 as part of the Department for Energy and Climate Change[28]. The Department of Business, Energy & Industrial Strategy (BEIS) is now in charge of the unit, which is presently taking applications for its tenth financing cycle [15].

The HNDU has previously provided funds to one hundred and sixty-two (162) Local Authorities for heat networks totalling at least £22,488,700. HNDU assists Local Authorities in the United Kingdom (UK) in going through the developmental stages. HNDU financing can cover up to 67% of the expenses of development studies outsourced out by Local Authorities to third parties [15].

In the UK, heat networks come in a variety of configurations and sizes. Biomass, trash, sewage, combined heat and power, geothermal, and other heat pumps are used to heat water. These projects range in size from modest (10MW) to large (>50MW) [15].

Scotland became the United Kingdom's first country. to legislate on the establishment of heat networks in March 2020, establishing legislation governing the provision of thermal energy via a heat network and its construction and operation [15]. There are already over 830 heat networks functioning in Scotland, and the government has set a goal of delivering 1.5 TWh of heat by 2020 [29]. Scotland administers the District Heating Loan Fund to solve financial and technical impediments to district heating projects, thereby avoiding the challenges associated with commercial borrowing. Scotland's heat networks incorporate various technologies, including biomass boilers, ground heat pumps and combined heat and power (CHP). What is apparent is that the UK government is making a concerted effort to decarbonize heating across the UK, which demonstrates a solid commitment to the installation of district heating schemes and other heat reuse technologies that may help reduce heating-related emissions.

2.4 Renewable Heat and None Heat Demand

Scotland generated 5,205 GWh per annum of renewable heat in 2019, equivalent to the energy required to supply 380,000 Scottish homes with gas for 365 days [30].

A target was set by the Renewable Heat Action Plan in 2009 to meet 11% [30] of Scotland's non-electric heat demand through renewable energy sources by 2020 [30]. The renewable heat generated in 2019 in Scotland was 6.5% of fuels consumed for heat, up from 6.2% in 2018. In 2019 the renewable heat output was 26% due to increased biomethane output [30]. Figure 9 is illustrating the share of renewable heat of non-electrical heat demand in Scotland, 2008 – 2019 [30].

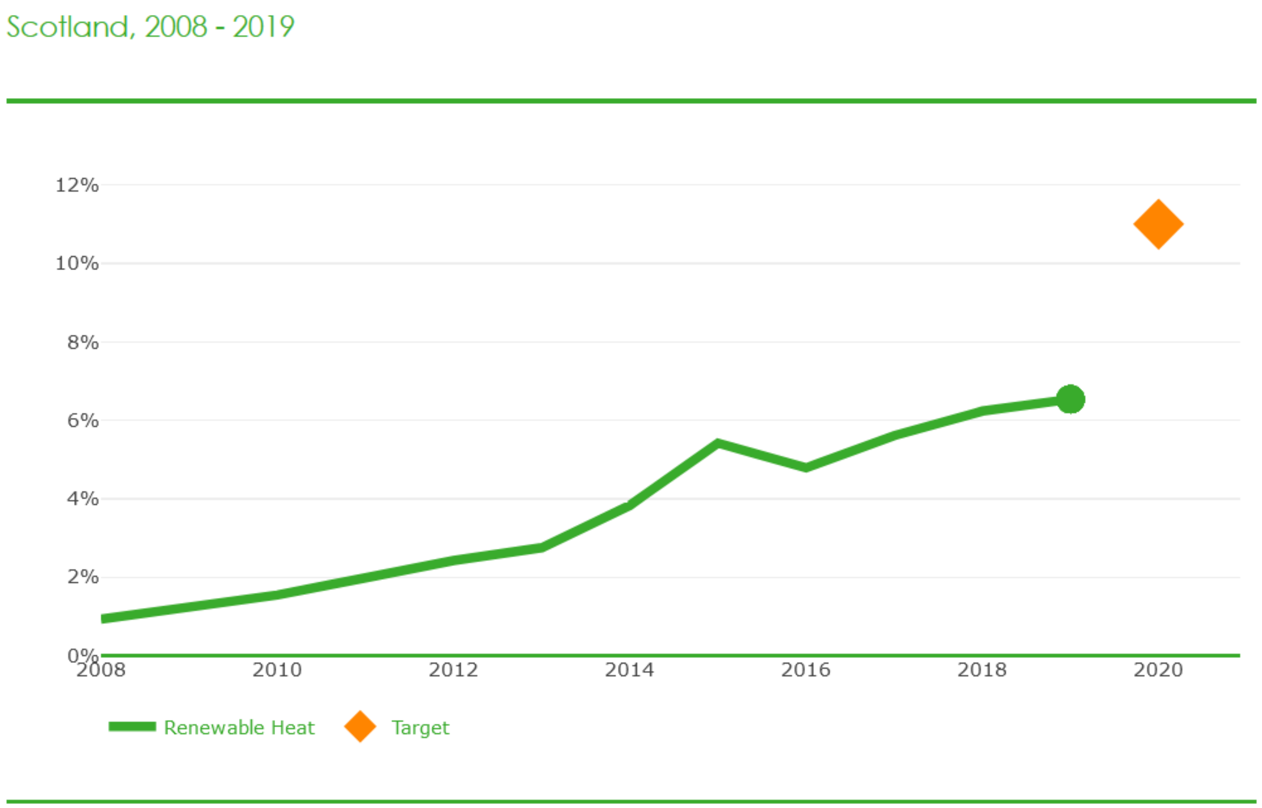


Figure 9 Share of renewable heat of non-electrical heat demand Scotland, 2008 – 2019 [30].

2.4.1 The Energy System's Heat Source

Scotland's energy system is based on heat. It accounts for the majority of our energy consumption (more than 55%) and is the primary source of our emissions (47%) [15]. Scotland spends £2.6 billion [15] per year on heating and cooling homes and businesses [15]. Scotland's renewable heat sector is expanding, with projected revenue of £2.7 billion by the end of 2020 [15]. The Scottish Government is dedicated to decarbonising the energy system by 2050 while maintaining and developing secure energy supplies at an affordable price for consumers [15]. The Scottish Government has already taken significant steps to reduce heat demand, which this Statement builds on [15].

Since 2007, the Government has invested and recycled over £45 million to assist Scottish households, businesses, and organisations in financing the implementation of energy efficiency and renewable energy measures, as well as the development of district heating schemes, resulting in over £65 million in loans to over 4,000 applicants [15].

Since 2009, the Scottish Government has invested around half a billion pounds [15] in a range of fuel poverty and energy efficiency [15] initiatives, which have already resulted in hundreds of thousands of homes becoming warmer and more affordable to heat [15].

Nearly one-third of all households (over 700,000) have now received assistance with energy efficiency [15]. Each of these facets of the heating system is addressed by three distinct objectives outlined in the Scottish Government's Heat Hierarchy [15]: reducing the need for heat, supplying heat efficiently and at the lowest possible cost to consumers, and utilising renewable and low-carbon [15] energy sources — Scottish government policy [15].

2.4.2 Transfer and Storage of Heat

Scotland's ambition was to meet 1.5 TWh [15] of Scotland's heat demand through district or communal heating by 2020 and connect 40,000 homes [15]. Between 2014 and 2016, Scotland supported projects through the District Heating Loan scheme by committing an additional £8 million [15], bringing the total to more than £11 million.

2.4.3 Renewable Heat Incentive

The Renewable Heat Incentive (RHI) is a financial incentive provided by the Government to encourage the use of renewable energy. The eligible heating systems are biomass boilers and pellet compatible stoves, ground source heat pumps, air-source heat pumps, evacuated tube solar thermal panels and flat plate thermal panels [4].

2.4.3.1 Renewable Heat Incentive for biomass boiler

2.4.3.1.1 Eligibility Requirements

The following is a list of eligibility requirements:

- Should use a liquid to heat a space (e.g., a room) [4].
- Must be designed in a way that solid biomass fuel can be used.
- Must adhere to Air Quality requirements, which establish obligations for plants accredited on or after 24 September 2013. The owner must operate their plant under the manufacturer's emissions instructions and their RHI emissions certificate [4].

2.4.3.1.2 Eligible uses

The subsequent is a list of eligible uses:

- Space heating (SH) is used exclusively to refer to the process of heating individual rooms within a structure [4].
- Space heating should be accomplished using a liquid medium.
- Heat is distributed throughout the building via heat emitters, including radiators or underfloor heating [4].

2.4.3.1.3 Ineligible uses

The subsequent is a list of ineligible uses:

- Systems designed to generate heat to cook food.
- Space heating (including heat dumps) and swimming pool heating are not included in domestic hot water (DHW). Domestic hot water refers to water heated by an accredited Domestic RHI plant and used in an eligible property (e.g., water taps, shower).

  Domestic hot water is distinct from space heating (which includes heat dumps) and swimming pool heating [4]. Biomass systems [4] are not required to provide domestic water heating but may do so.

2.4.3.2 Biomass Stove

2.4.3.2.1 Eligibility requirements

The following is a list of eligibility requirements:

- Must be explicitly designed for the use of wood pellets. (Non-eligible are wood-burning stoves.)
- Must incorporate a liquid-filled heat exchanger within the system [4] .
- Must adhere to air quality regulations [4].

2.4.3.2.2 Eligible uses

The subsequent is a list of eligible uses:

- Space heating (SH) only, or both space and Domestic hot water (DHW) heating [4].
- Biomass systems don't have to provide domestic water heating to be eligible but may do so.

2.4.3.2.3 Ineligible uses

The subsequent is a list of ineligible uses [4]:

- Systems intended primarily to generate heat to cook food.
- Space heating (including heat dumps) and swimming pool heating are not included in domestic hot water (DHW).

2.4.3.3 Air Source Heat Pump

2.4.3.3.1 Eligibility requirements

The following is a list of eligibility requirements:

- Should use a compressor driven by electricity [4].
- Should use a liquid to provide space (e.g., room), heating [4].

- Should have a minimum seasonal performance factor (SPF) of 2.5 [4].

Seasonal Performance Factor (SPF) is a term that is only applicable to heat pumps. It is a metric used to determine the efficiency with which your heat pump operates. Simply put, the higher the SPF value of your system, the more energy-efficient it is. SPF is a metric that shows how well an electric heat pump heating system performs over a year. It is the ratio of heat delivered to total electrical energy produced during a year.

From 25 March 2016, the SPF will be calculated by the installer using the value from the MCS website [4]. This number will be directly entered [4]into the MCS database upon registration of the renewable technology and will be used to calculate RHI payments [4].

SPF is calculated as follows [4]:

$$SPF = \frac{Total\ heat\ energy\ output\ per\ annum(\ kWh)}{Total\ input\ electricity\ per\ annum\ (kWh)}$$

Equation 11

Therefore, a heat pump with an SPF of 2.5 [4] will typically produce 2.5 kWh [4] of heat for every single 1 kWh [4] of electricity consumed. Electricity is required to run the heat pump as it powers the compressors. To maximise the heat pump's efficiency and keep electricity bills low, the property should be well insulated and designed with a low-temperature heating system, such as underfloor heating or low-temperature radiators [4].

The lower the temperature and the larger the surface area of your radiators, the less energy the heat pump will use and the higher its SPF [4].

2.4.3.3.2 Why is the SPF so critical?

The SPF is used to determine how much of the heat pump's heat output is renewable. According to the regulations, we must deduct the electricity used to power the heat pump from the heat it produces. Payments can be calculated using only the renewable portion of the heat generated by your heat pump. All heat pumps must have an SPF rating of at least 2.5 to be eligible.

The SPF is considered when calculating payments using the following formula [4]:

$$Payments = Estimated\ annual\ renewable\ heat\ load\ (total\ heat\ demand\ x\ (1–1/SPF))\ x\ tariff\ rate$$

Equation 12

Worked example for SPF calculation:

- The total heat demand is 15,000 kWh
- SPF is 2.7 (unitless)
- An example for ground source heat pump tariff price is 19.86p/kWh [4].

$$SPF\ calculation = \left(1-\frac{1}{SPF}\right) = \ (1-\frac{1}{2.7})\ =\ 0.63$$

Equation 13

Annual renewable heat load [4].

= (total energy demand x (1 - 1/ Seasonal Performance Factor)

$$= 15{,}000kWh\ x\ 0.63\ =\ 9{,}444kWh$$

Equation 14

$$Total\ annual\ Domestic\ RHI\ payment$$

$$= (tariff\ x\ estimated\ annual\ heat\ load)$$

$$= £1{,}875.67$$

Equation 15

$$Quarterly\ Domestic\ RHI\ payment$$

$$= \left(\frac{total\ annual\ Domestic\ RHI\ payment}{4}\right)$$

$$=£468.9$$

Equation 16

2.4.3.3.3 What if the system is metered quarterly payments?

If the system had been metered for payment, the quarterly payments are founded on actual meter readings where the electricity used is subtracted from the heat output. The quarterly payments will be calculated based on the metered output, but the owner will not be paid more than a pre-determined payment amount [4]..

The payment cap is calculated using the SPF and the estimated annual renewable heat load of the property. The SPF will determine the maximum amount that can be paid to the owner per year, as demonstrated in the following worked example.:

Using the worked examples below [4]:

Annual Payment Cap = tariff x estimated annual renewable heat load:

19.86p/kWh x 9,444kWh = £1,875.67

Equation 17

2.4.3.3.4 Eligible uses

The subsequent is a list of eligible uses:

- Heat pumps are not required to provide domestic water heating to qualify[28] , but they may. (They may also offer water cooling).
- Heating systems for domestic hot water.
- Space heating only or both space and Domestic hot water (DHW) heating.

2.4.3.3.5 Ineligible uses

The subsequent is a list of ineligible uses:

- Designed to use heat from air expelled from an appliance or building when generating heat.
- Domestic hot water (DHW).

2.4.3.4 Ground source heat pump

2.4.3.4.1 Eligibility requirements

The following is a list of eligibility requirements:

- Should use a compressor driven by electricity.
- Should use a liquid to provide space heating.
- Should have a minimum seasonal performance factor (SPF) of 2.5.

2.4.3.4.2 Eligible uses

The subsequent is a list of eligible uses:

- Spacing heating (SH) only or both space and Domestic hot water (DHW) heating.
- Heat pumps do not have to provide domestic water heating to be eligible but may do so. (They may also provide water cooling.).

2.4.3.4.3 Ineligible uses

The subsequent is a list of ineligible uses:

- Having a ground loop array that is shared with heat pumps in other eligible properties.
- Domestic hot water (DHW) that does not include space heating (including heat dumps) or swimming pool heating.

2.4.3.5 Solar thermal

2.4.3.5.1 Eligibility requirements

The following is a list of eligibility requirements:

- Should be a flat plate filled with liquid or an evacuated tube.

2.4.3.5.2 Eligible uses

The subsequent is a list of eligible uses:

- Domestic hot water (DHW) heating only.

2.4.3.5.3 Ineligible uses

The subsequent is a list of ineligible uses:

- Thermal stores are supplying space heating (SH).
- Any usage which is not domestic hot water heating by generating electricity.
- Space heating (SH) (including heat dumps) or heating a swimming pool.

2.5 Environmental Data

2.5.1 Water Environment Regulations

The Water Environment (Controlled Activities) (Scotland) Regulations 2011 – more commonly referred to as the Controlled Activity Regulations (CAR) [11] and subsequent amendments in 2013 and 2017 impose regulatory controls on activities that may have an adverse effect on Scotland's water environment [11]. This legislation was enacted in response to the European Community's (EC) [11] Water Framework Directive (WFD) becoming law in Scotland in 2003 as the Water Environment and Water Services (Scotland) Act 2003. (WEWS Act) [11].

2.5.2 Scottish Environment Protection Agency (SEPA) Guidelines

SEPA is a tough, fair, and effective regulator committed to listening to businesses and the public and assisting in the improvement and protection of Scotland's environment. SEPA's mission [11] is to provide Scotland with an efficient and integrated environmental protection system [11], one that improves the environment while also contributing to the Scottish Government's overall goal of ensuring long-term sustainable economic growth. SEPA adheres to sound regulatory principles and works to continuously improve their services to ensure that Scotland has the best possible environment while encouraging economic growth.

The required licences and subsistence charges are the two critical areas of the regulations that apply to water source heat pumps. If the scheme abstracts more than 2,000 m^3 of water per day [11], a 'Complex License' is required. This requires a fee of £2,934 [11] and a four-month application process. A separate 'Engineering Licence' would be necessary for the pipework and heat pump structure in addition to the 'Complex Licence'. This would cost £2,000. Subsistence charges can be avoided if the heat pump extracts and returns the water it extracts to one of fifty locations around Scotland listed by SEPA [11].

2.5.3 Water Engineering Authorisations

Engineering projects can degrade habitat [11] in rivers, lochs, and wetlands, affecting invertebrates, plants, birds [11], and mammal populations. Additionally, engineering projects can obstruct the passage of migrating fish and degrade spawning habitats during critical times. Certain species of fish are a significant economic resource in many parts of Scotland.

When SEPA is considering an application for authorisation under the Controlled Activity Regulations (CAR), they will consider all of these factors and work to mitigate any adverse effects to the greatest extent possible [11]. Where significant potential impacts exist, they will only authorise works if they are outweighed by the constructive contributions the works [11] make to the economy, society, or environment.

The level of authorisation required is contingent upon the activity's impact on the aquatic environment. General binding rules (GBRs) apply to activities deemed to pose a low risk to the environment. The engineering consultancy will not be required to contact SEPA or pay any fees, but will be expected to follow a set of regualtions[11].

There are two types of activities as follows:

- Registration activities [11]

  Activities that cause a low individual risk but have the potential to have a negative impact on the environment in combination will require registration, which will require an application to SEPA and incur a fee. However, there will not be an annual subsistence fee [11].

- Licence activities

  Activities that cause a moderate to high risk to the environment will either be granted a simple licence or a complex licence, depending on the complexity of the environmental assessment required [11].

  A licence is contingent upon the identification of a responsible person who is responsible for ensuring compliance with the licence's terms and conditions.

  In both cases [11], an application fee will be assessed, and the activity may also be assessed as requiring an annual subsistence fee.

2.5.3.1 Engineering work requiring SEPA approval:

If the engineering work entails any of the following, the engineering work will require SEPA approval:

- The removal of sediment from rivers [11], lochs, and wetlands.[11]
- The construction of bank protection, embankments, or floodwalls; the construction of new bridges, fords, and culverts.
- The construction of any new structures on the bed of a river, burn, or loch, river diversions.
- Restoration works, including the removal of structures and any other activity that may create a risk.
- Construction Site Licenses (run-off permits)

Serious environmental harm could occur because of a variety of construction activities, including excessive siltation from run-off, impeding fish migration, or affecting fish spawning. Construction activities can include a wide range of activities that may require authorisation from SEPA. These activities include discharge of run-off from the construction area, construction of bridges and culverts, riverbank work, diversion and realignment of rivers and streams, installation of cofferdams and dewatering excavations.

To avoid harm, all developers and contractors should assess proposed activities and ensure that adequate mitigation measures are planned and that all regulatory permissions required by SEPA are obtained prior to beginning work.

2.6 Emission Data

2.6.1 Scottish Greenhouse Gas Emissions 2018

Scopes were introduced in the 2001 [7] Green House Gas Protocol and are now the foundation for obligatory Green House Gas (GHG) reporting in the United Kingdom.

2.6.1.1 Emission categories:

Three distinct emission categories (scopes) can be considered:

- Scope 1 - This category includes the Green House Gas (GHG) emissions produced directly by a business, such as when its boilers and cars are used [7].

- Scope 2 These are the emissions generated indirectly by a business, such as when the power or energy it purchases to heat and cool buildings is generated on its behalf [7].

- Scope 3 This is the point at which things get complicated. This category includes all emissions not directly attributable to the business but which are indirectly attributable to the organisation along its value chain, for instance, via purchases from suppliers and by the usage of its goods [7].

  Scope 3 is usually the highest in terms of emissions. The below Figure 6 illustrate the emission statistic for the year 1990 and year 2018

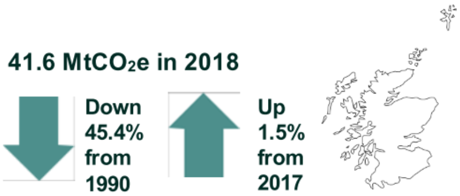


Figure 10 Scottish CO2 metric statistic at the years 1990 and 2018 [21].

2.6.2 Five Key Points About Scope 1, 2 and 3

Five key points about Scope 1, 2 and 3 are as follows:

1) Scopes 1 and 2 are often the most under control of an organisation. Businesses typically have the source data necessary to convert direct purchases of gas and electricity to a value in tonnes of GHGs [7]. This data may be held by procurement, finance, estates management, or a sustainability department.

2) In some circumstances, net-zero [7] emissions for Scope 1 and 2 emissions are possible; for instance, an organisation can get renewable power or natural gas, electrify its heat requirement, or move to electric vehicles.

3) Frequently, Scope 3 is where the impact occurs [7]. Scope 3 emissions account for more than 70% of the carbon footprint of many firms. For example, a business that manufactures items will frequently generate considerable amounts of carbon dioxide during the extraction, production, and [7] processing of raw materials.

4) Additionally, businesses have less say over how Scope 3 emissions are treated. The organisation can propose to engage with current suppliers on emission-reduction strategies or discuss reorganising the company supply chain. However, suppliers will have a significant impact on how emissions are lowered in the majority of regions through their purchasing [7] strategies and product design [7].

5) Committing to net zero emissions [7] requires addressing the Scope 3 emissions. Although definitions of net-zero ambition can be ambiguous, firms committed to best practice will include Scope 3 emissions in their goals. Mapping client's emissions footprint according to scale and the degree of control they have over the source is a smart place to start. Additionally, they will have simple access to pollution hotspots.

2.6.3 CO2 Metrics

The abbreviation MtCO2e stands for million tonnes of carbon dioxide equivalent. This is a standardised method for determining the greenhouse gas contribution to global warming.

Carbon dioxide, methane, and nitrous oxide were measured in 1990 [21]; hydrofluorocarbons, perfluorocarbons, sulphur hexafluoride, and nitrogen trifluoride were measured in 1995.

In 2018, Scottish sources were predicted to have emitted 41.6 million tonnes of carbon dioxide equivalent to a basket of seven greenhouse gases (MtCO2e). This is a 1.5 % rise above the 41.0 MtCO2e number for 2017; a 0.6 MtCO2e increase [31].

Between 2017 and 2018, the primary driver of this increase was an increase in Energy Supply emissions (0.8 MtCO2e; 13.4%) [21]. This increase was nearly entirely the result of higher emissions from power plants. Between 1990 and 2018, estimated emissions decreased by 45.4%, or 34.6 MtCO2e.

The following points played a significant role in this total reduction:

- Emissions from the Energy Supply have decreased (such as power stations) -70.1% reduction; -15.9 MtCO2e

- The land use, land-use change, and forestry (LULUCF) [21] have become a larger sink, offsetting an additional 5.1 MtCO2e of emissions.
- Reduced waste management emissions (from landfills, for example) (-4.4 MtCO2e; a 72.2% reduction) [21].
- Emissions from business decrease (-4.0 MtCO2e; a 32.2% reduction)

'Transport (excluding international)' is the main factor impeding the overall reduction. This industry contributed the most CO2e in 2018 (12.9 MtCO2e) but has decreased by just 4.9% since 1990 [21], compared to the overall trend of 45.4% [21]. The most recent year's calculation of the GHG account can be summarised as shown in Figure 11 [21].

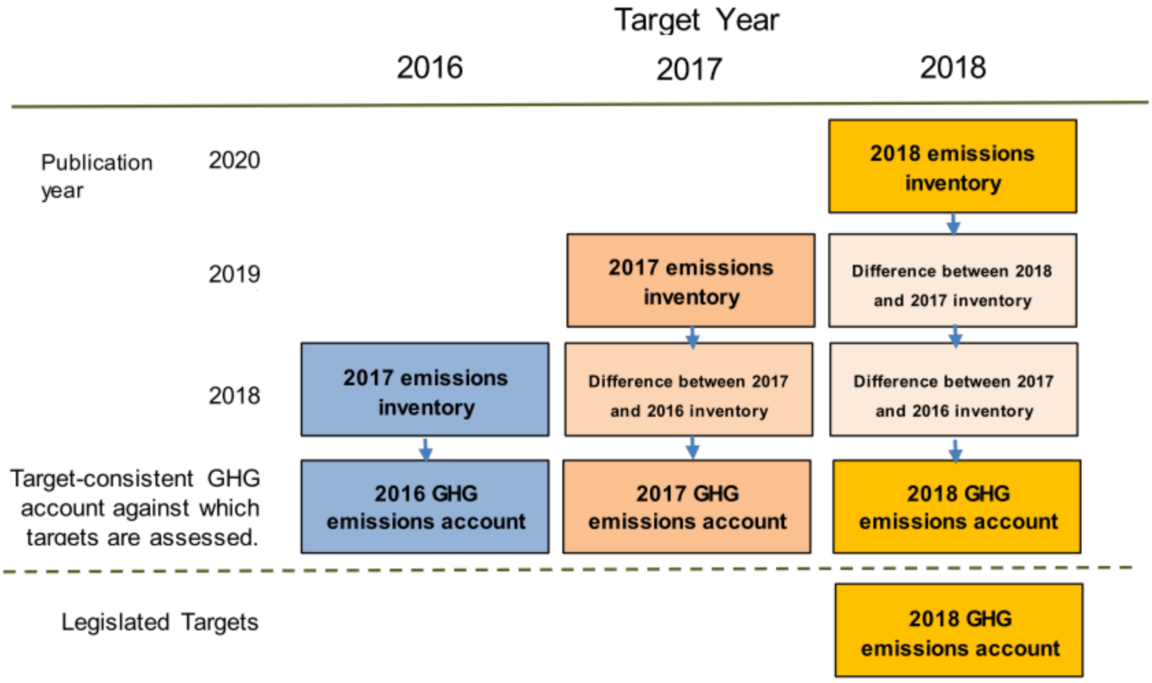


Figure 11 Summary of GHG calculation for the most recent years [21].

2.7 River Clyde

When determining the viability of installing a heat pump in a particular river, the two most critical variables are the water temperature and river flow rates. Where accessible, this data may be acquired through local environmental government organisations. However, this data is often collected in data centres located far from the proposed heat pump site on the river.

River flow rates are dependent on the morphology of the river bed, although the difference may be insignificant [32] in high volume rivers. The temperature of the water is dependent on the depth of the probe, with the temperature being more constant (less reliant on-air temperatures) at lower depths. This increases the feasibility of heat pumps that operate at shallower water depths. Independent measurements should be performed to ensure the analysis's correctness. Both flow rates and water temperature are influenced by tides.

The River Clyde, or the Clyde Estuary more precisely, offers considerable potential as a source of heat. The downstream flow rate is about 50 m3/s. Reduce the temperature of the river by 3°C, and river heat pumps will be able to extract 188.1 MW of heat. Due to the average efficiency of river heat pumps of 3.0 [32], the heat delivered is 1.5 [32] times that of the river component. As a consequence, the estuary has the potential to generate 282 MW of heat. Typically, industrial heat pumps provide heat at a temperature of 80°C.

2.7.1 The Queen's Quay Water Source Heat Pump

The Queen's Quay, a residential neighbourhood in West Dunbartonshire, Scotland, had a river source heat pump system installed in the year 2020. This was the first 80°C heat pump system installed in the UK [33].

Star Refrigeration Ltd provided the heat pumps, which were built at their Glasgow plant. Vital Energi was responsible for the project delivery. The same design principle will be implemented in this thesis.

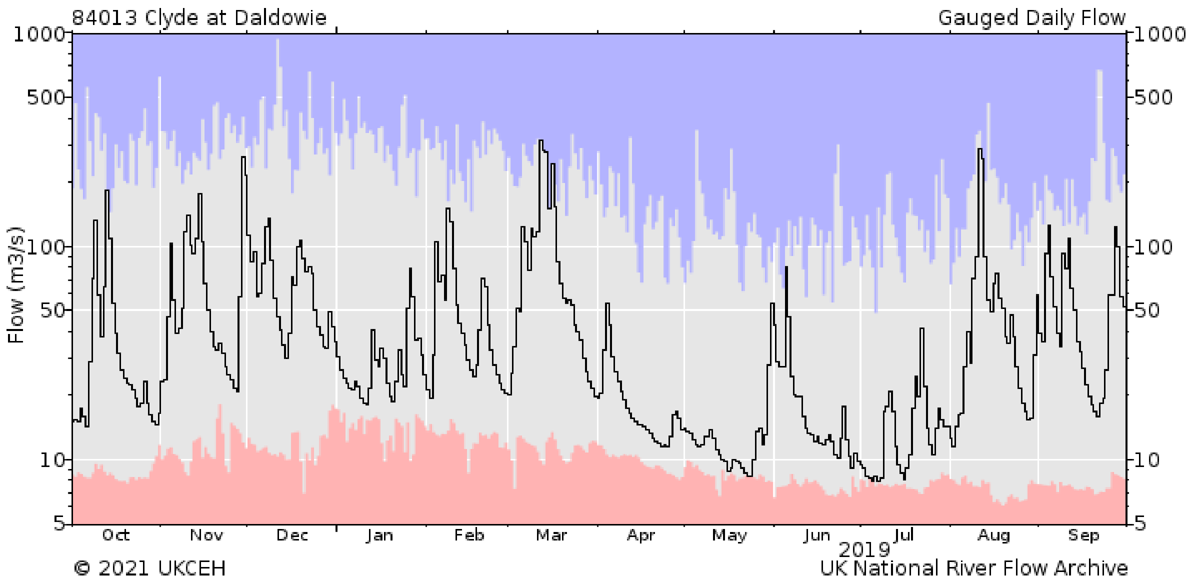


Figure 12 River Clyde annual hydrograph [32].

Key: Red and blue envelopes represent the lowest and highest flows on each day over the period of record [32].

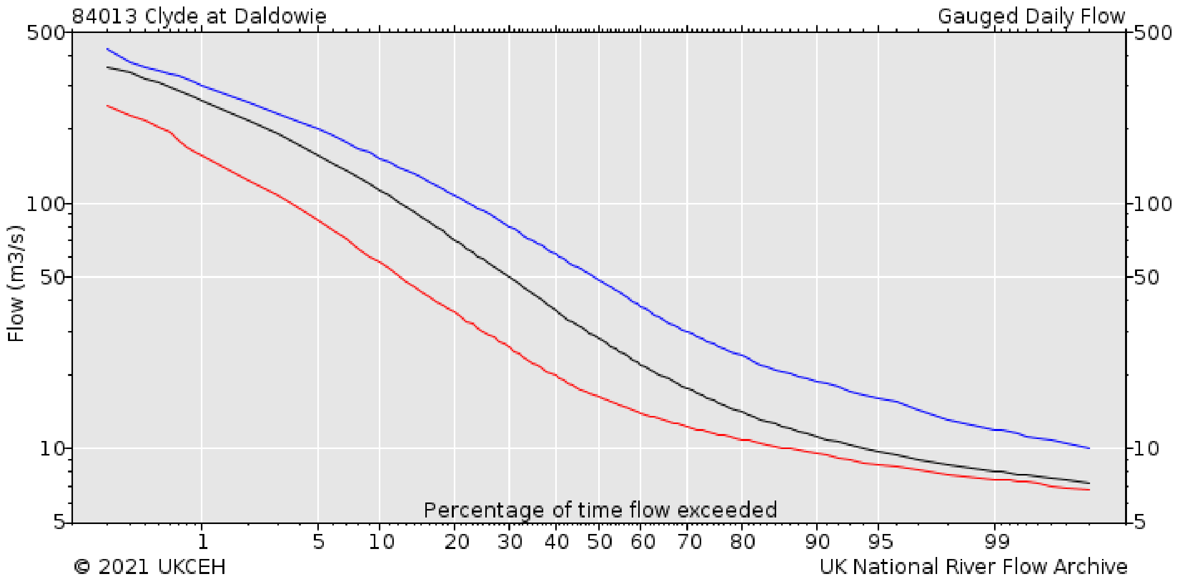


Figure 13 Clyde flow duration curve [32].

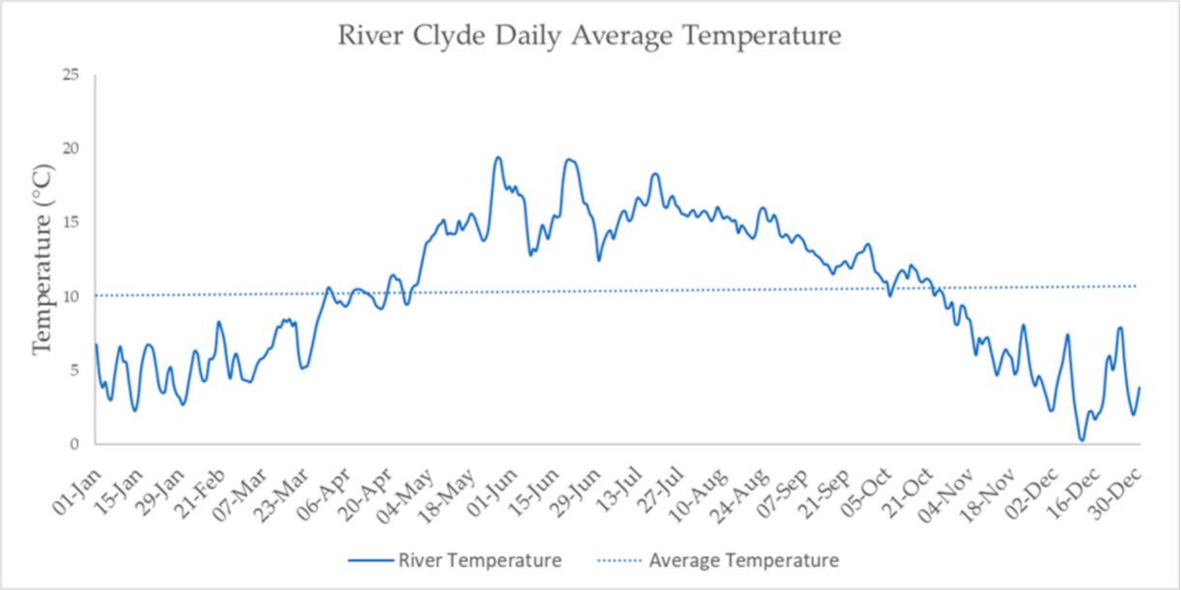


Figure 14 River Clyde average temperature [32].

The River Clyde's minimum temperature is 1°C [32], and its maximum temperature is 20°C, as seen in Figure 14.

2.8 Abandoned Scottish Mines

2.8.1 Scottish Mining History

For many millennia, coal mining was a significant part of the Scottish economy, owing to the abundance of coal-bearing strata and variety of coal types. Coal production in Scotland dates back at least to the 12th Century, though its scale of mining remained quite small until the late 16th Century [34]. The earliest underground workings were shallow and were either be completely dry or gravity-drained [8].

Such drains are likely to remain in place today, and as a result, the workings may remain dry. Production rose exponentially in the late 18th century with the invention of pumping machinery, most notably James Watt's improved steam engine.

Drainage mines allowed mining in much deeper workings by pumping to lower the water table. The longwall method of extraction has been widely used since the 1950s for underground mining. Two parallel access roads serve as roads through which coal seams are accessed in longwall mining [34].

When coal from the roadway next to the panel travels to the other side, the drum shearer breaks it up. The roof supports located around the coal face act as moving boundaries for the coal and safeguard the area directly adjacent to the coal face, but as the shearer progresses or descends, based on the system, the roof collapses coal panels of between 100 to 250 m wide separate the roadways.

Longannet Colliery was the last deep mine in Scotland to close.

Pumping in the majority of mines stopped when abandonment began, resulting in water levels rapidly regaining or remaining the same. Some of the mines still pump to avoid or reduce surface water contamination.

2.8.2 Hydrogeology of Abandoned Mines

Mining has a major impact on the hydrogeology of affected areas, though the extent of the effect varies according to variables such as the method of mining and the number and thickness of mined seams [34].

2.8.3 Increased Post-Subsidence Porosity and Permeability

Stoop and room mining accounted for a relatively small proportion of total mining in the Glasgow region, according to detailed modelling and analysis.

The roof is supported in stoop and room mining by rock pillars (stoops) that are left in place during mining operations. After mining is complete and assuming no collapse occurs, the voids (rooms) occupy approximately 50% of the mining volume.

2.8.4 Water Chemistry

As a result of its chemical makeup, abandoned mine water is frequently of low quality, and it can result in a variety of environmental concerns when discharged.

The Environment Bureau, the Scottish Environment Protection Agency, and the Coal Authority have collaborated on a study titled "Abandoned mines and the aquatic environment," which provides a detailed overview of the different concerns and their occurrences throughout the United Kingdom. Low oxygen levels, acidic waters, and large quantities of dissolved metals such as iron, which precipitate out when exposed to oxygen when the water is brought to the surface, are all potential issues [34].

Iron oxide flocculants have negative consequences, such as making it more difficult to re-inject water because the particles plug the spaces in the subsurface, lowering permeability and making re-injection harder. Because of available technology, these difficulties do not have to preclude water from being utilised for Ground Source Heat Pumps (GSHP); nevertheless, the water chemistry must be evaluated and any problems taken into consideration during the system's design [34].

Following heat extraction and before re-insertion, there is the possibility of treating the water used in the process. The Coal Authority maintains a pilot treatment and re-insertion system at Dawdon in County Durham, England, and difficulties related to treatment and re-insertion have been addressed at the Heerlen scheme in the Netherlands, among other locations.

Longwall mining entails the sequential removal of coal strips and subsequent collapse of the worked strips. When a structure collapses, the voids are filled with broken overburden, resulting in surface subsidence. Around 20% of the mined void is expected to stay after longwall mining-induced subsidence occurs. Subsidence caused by longwall mining results in well-studied stresses in the overlying strata.

Compression and extension will have an effect on the thinner zones above this. The mined horizon is likely to stay in the extremely permeable zone, despite the fact that it contains broken goaf following subsidence. It was suggested that this would have a porosity similar to gravel, around 0.3, or 30%. Figure 11 is illustrating the zones of extraction-related subsidence above a recently worked longwall pane.

The goaf horizon will be dictated by intergranular flow, whereas the disturbed zone above will be dominated by fracture flow. Multiple seams at varying depths are frequently mined, resulting in a club sandwich effect of layers with varying degrees and types of permeability. Fracture flow is likely to dominate in the aggregate. The major benefit is to make the upper strata more permeable, enabling better groundwater extraction, as illustrated in Figure 15.

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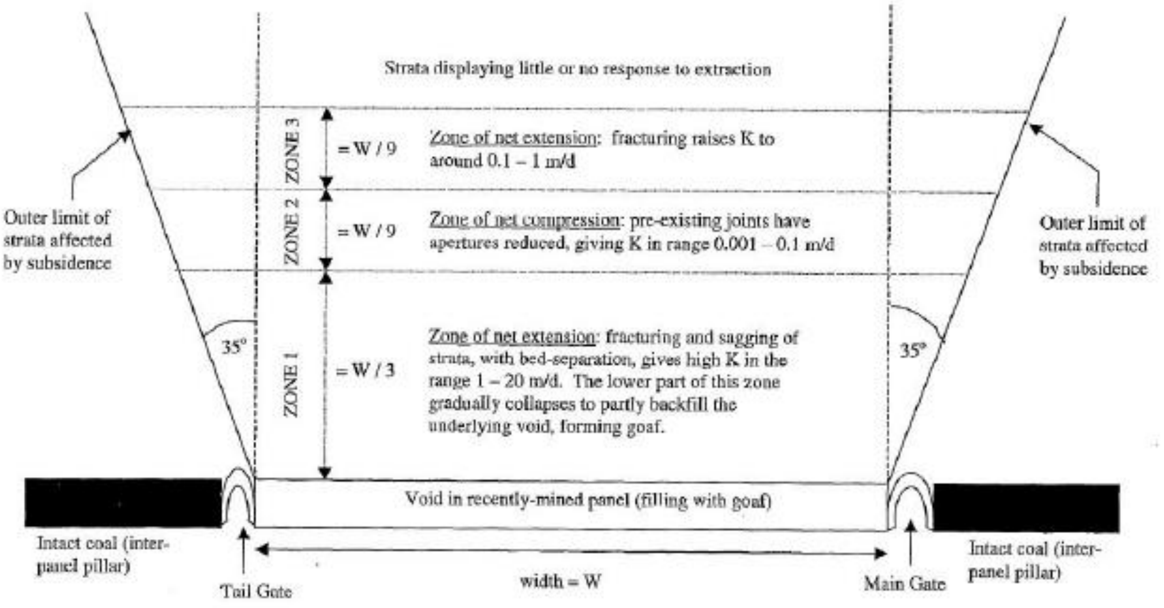


Figure 15 Schematic diagram of the zones of extraction-related subsidence above a recently worked longwall panel [34].

One benefit of these mining-enhanced aquifers [34] multi-layered structures is the ability to extract water from one depth interval and re-inject it at a lower temperature into a different horizon [34].

This is advantageous because obtaining consent to discharge mine water [34] to the surface or sewers is likely to be difficult, and additionally, this type of circulating system maintains water levels in the subsurface while acting as a hydraulic and thermal barrier (by intervening low permeability strata), extending the time required for thermal breakthrough (thermal "short-circuiting") to occur [34]. This is how the Shettleston project in Glasgow was developed [34].

2.8.5 Mine’s Geology

Although Scotland is located on a geologically [14] stable section of the Earth's crust, it lacks any of the readily apparent characteristics, such as hot springs or volcanic activity, that would suggest the existence of a significant heat resource in easily accessible areas of the subsurface. This is lower than the mean of 35 heat flow estimates recorded for Scotland (65 mW m-2) [34]and it is considerably lower than the values often associated with usable supplies of deep geothermal energy (which are typically higher than 56 mW m-2) [34].

It is necessary to measure the geothermal gradient in a borehole in order to determine the heat flow value. The geothermal gradient is the percentage at which temperature rises with depth in the Earth's crust.

Researchers have discovered that warming of the ground surface [34] since the last period of widespread glaciation has caused the geothermal gradient within the top 2 km of the crust to be perturbed, with the result that measured geothermal gradient values and, as a result of the reduction in heat flow values, has decreased.

Due to the fact that Scotland was severely impacted by the Ice Age glaciations, current heat flow measurements in Scotland are likely to be substantially underestimated in terms of the actual magnitude of the heat resource that lies underneath the climate-affected zone [34].

In specific regions of northern Europe and North America, published research suggests that recent climatic changes could have resulted in a 60% reduction in near-surface heat flux in some areas. According to preliminary, unpublished research by the British Geological Survey, heat flow [34] measurements in the East Grampians area of Scotland may be reduced by as much as 29% in certain cases. Heat flow below the climate-affected zone in Scotland (which may extend to a depth of about 2 km) seems to be considerably higher than previously thought, according to these results.

In addition to surface temperature data collected from boreholes, temperature data collected from boreholes provides the best presently known alternate method of determining the amount and distribution of the heat resource beneath Scotland.

When displayed as temperature versus depth, data from 133 boreholes ranging in depth from a few hundred metres to five kilometres and representing both onshore and offshore areas of Scotland reveal a clearly defined pattern. Given the geographic scope of the data and the stability of the trend across the whole depth range, it is reasonable to speculate that the trend represents a regional temperature gradient [34] in Scotland. The gradient is somewhat curved and rises with depth, increasing from 30.5°C/km in the shallowest third to 46.7°C/km in the deepest third, with the shallowest third being the shallowest.

Based on these results, which correspond to temperatures of 100°C and 150°C [34] at depths of about 3.0 and 4.0 km [34], respectively, it seems that there is a much greater heat resource at accessible depths under Scotland than had previously been believed.

However, since the data used to define the trend are mostly from offshore boreholes in sedimentary rocks, care should be used when projecting the same gradient to deep depths onshore, especially in crystalline formations, as the trend suggests.

It will need more study to confirm this finding; nevertheless, the borehole temperature trend indicates that the temperature differential in the crust underneath Scotland may be much larger and more constant regionally than has previously been recognised.

Geothermal activity under Scotland's surface continues to be poorly understood at the regional scale.

Before choices can be made on the location and design of more thorough, site-specific research, it is necessary to get a better knowledge of the regional distribution of heat in shallow parts of the crust, both laterally and vertically.

A significant quantity of data has been digitised for use in Geographic Information Systems (GIS) by the Coal Authority, which has the complete data documenting the mining history of Scotland. Subterranean working polygons with depth, date, and seam extraction data in five seams are included, as well 2,785 likely unrecorded working polygons and related depth, and 11,637 spine roads, underground roadways linking coal, uranium, and other workings. The project does not have the resources to deal with such a huge amount of spatial data.

The British Geological Survey (BGS) also has a wealth of information about mines; for example, the Environmental Geology Map (EGM) series from the 1980s covers the Midland Valley of Scotland at a scale of 1:10,000. There are known adits and shafts in mined regions that are included in this series.

In addition to georeferenced, scanned pictures, the EGMs are also accessible as digitised information, except in the Glasgow region, which allows them to be used fully in a Geographic Information System (GIS).

The Coal Authority's polygon indicating where a more thorough search of mine plans should be undertaken when contemplating development was judged to be the most suitable data for this study's areal extent of mining in Scotland, and thus it was used. Figure 16 shows Mineshafts in the Midland Valley.

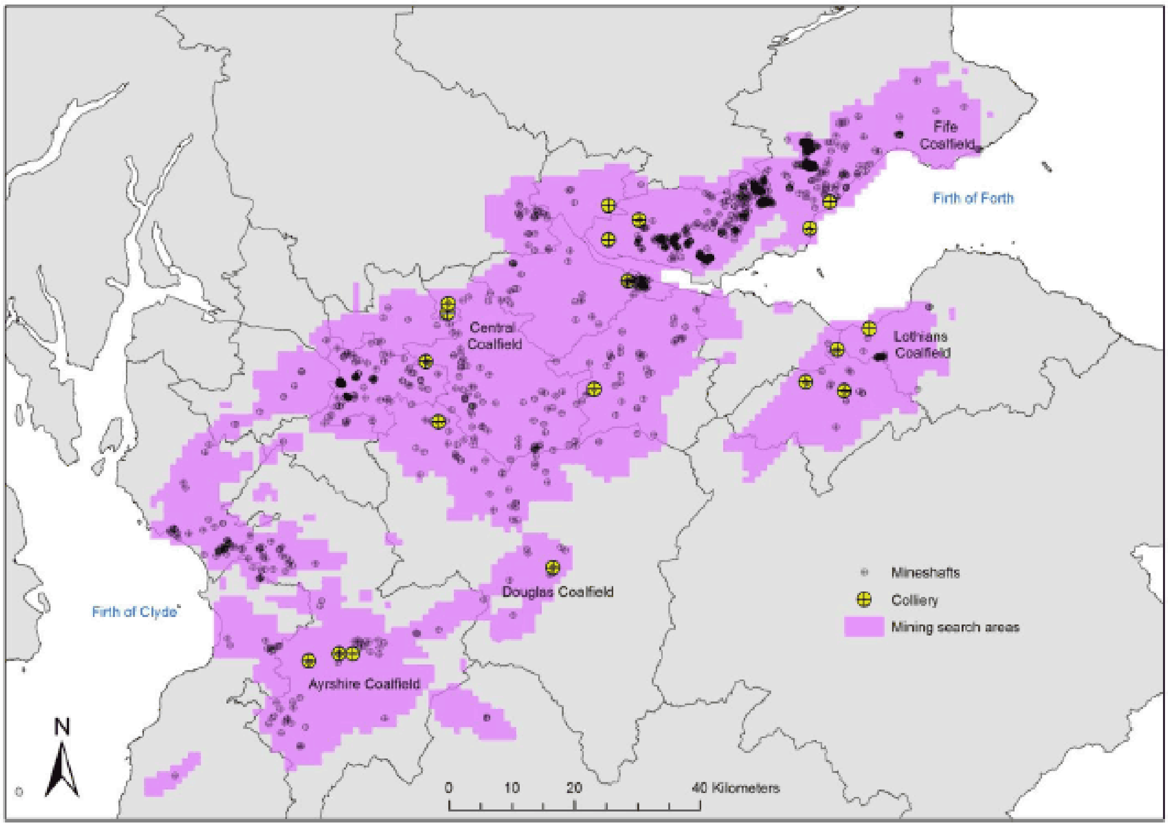


Figure 16 Mineshafts in the Midland Valley [34].

When creating a surface showing the depth of mine workings throughout the Midland Valley, it was possible to determine the vertical [9] (depth) extent of mining in Scotland.

Using a dataset of all entries in the BGS [9] Single Onshore Borehole Index (SOBI) that included the words 'shaft' or 'pit', this was produced. The dataset may be seen at:

(http://www.bgs.ac.uk/products/onshore/SOBI html) [34]

Once the data had been processed, it was filtered to exclude any entries that began at the height of zero, borehole lengths of zero, or entries that started below ground level.

In the GOCAD® programme, the surface was generated via interpolation, as shown in Figure 17.

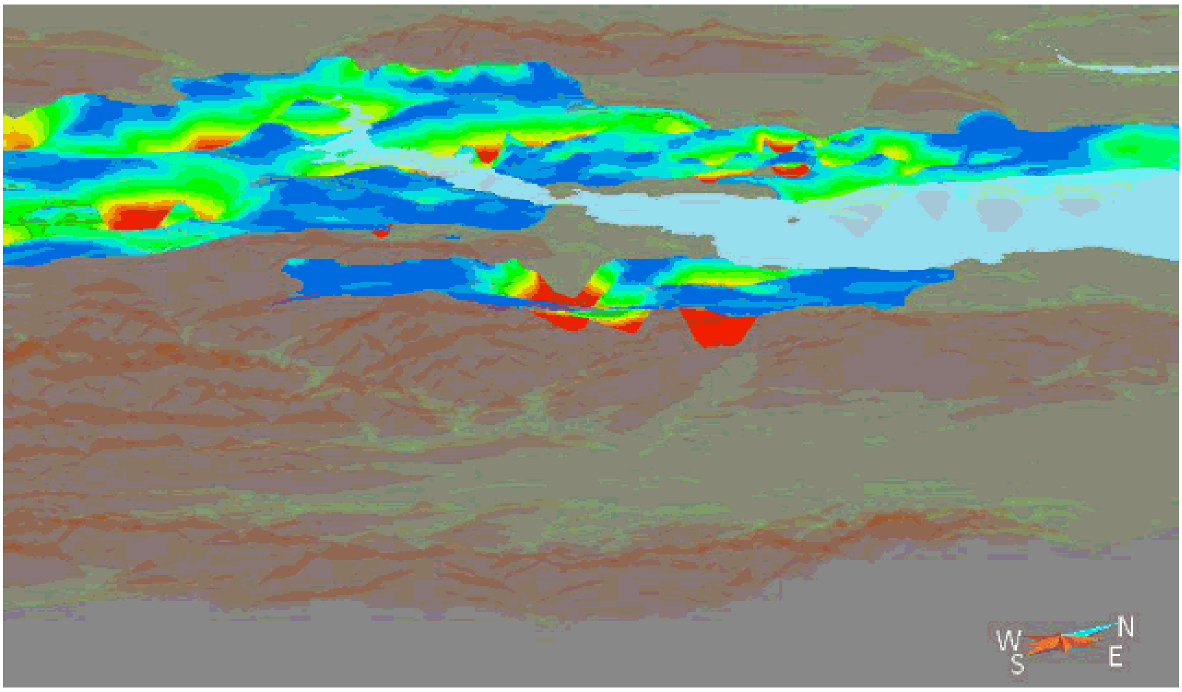


Figure 17 Depth of mine workings in the Lothians, Fife and Central coalfields, viewed in GOCAD program (©Paradigm) 3D modelling software and showing deepest workings in orange and red.[14].

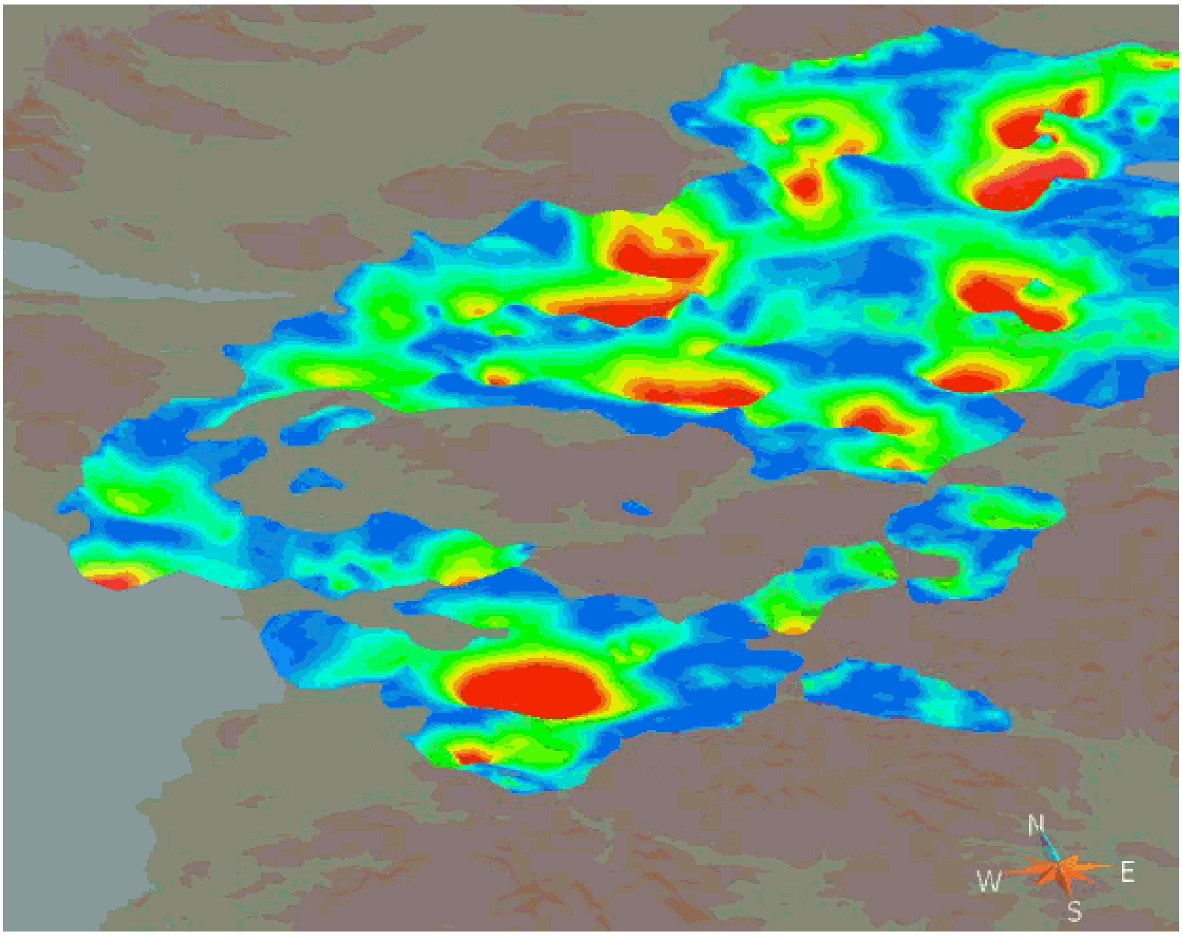


Figure 18 Depth of mine workings in the Ayrshire, Douglas and Central coalfields, viewed in GOCAD program, it is a 3D modelling software and showing deepest workings in orange and red [14].

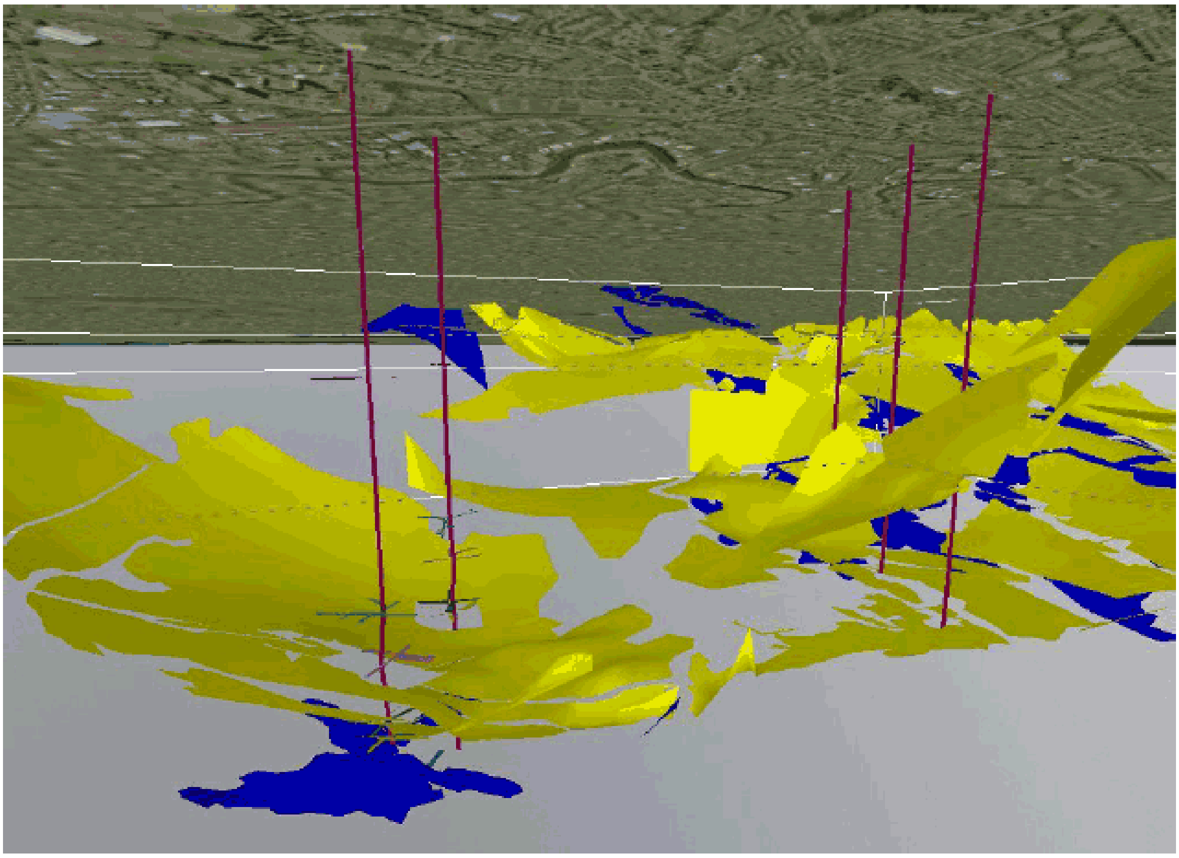


Figure 19 3D model of mined coal seams (yellow color and blue color surfaces), mine shafts (red color sticks) and mine roadways (green, light blue and pink) beneath Glasgow's East End. Viewed in Virtalis/ BGS GeoVisionary software [14].

Therefore, it is projected that the total volume of the mined area (i.e., from the bottom of the mine workings to the surface of the land) is 6 x 10 11 m^3, or 600 km^3[14].

Further research would need information on the quantity and thickness of seams that have been mined, as well as the locations of shafts and roads that are in the area. For Glasgow, the British Geological Survey (BGS) has previously collected most of this data. [14].

For data on other areas of the Midland Valley, the Coal Authority can be contacted to provide digital data or BGS for paper or scanned image data.

2.8.6 Temperature of Mine Water**.** [14]

In general, the temperature of mine waters rises with depth in accordance with the geothermal gradient; nevertheless, it is difficult to estimate the temperature of water pumped from a borehole since the water of varying temperatures may be entering the borehole at various depths.

Even while groundwater exchanges heat with the rocks that it runs through, the degree to which this equilibration takes place will be determined by the pace at which groundwater flows through the aquifer.

Table 2 displays the results of a compilation of mine water temperatures for boreholes in the Midland Valley, which reveals a very limited range of temperatures, as shown.

Table 2 Mine water temperatures for boreholes in the Midland Valley [14].

Borehole name. [14]	Grid reference	Depth (m)	Temperature (deg C)
Douglas Colliery	NS 830 300	239	12.2
Bogside Colliery	NS 9564 8778	334	17
Solsgirth Colliery	NS 9777 9329	387	21.5
Barony Colliery	NS 5105 1971	411	17
Highhouse Colliery	NS 5321 7202	436	18
Polkemmet Colliery	NS 9190 6278	549	17
Killoch Colliery	NS 4883 2130	655	17
Bilston Glen Colliery	NT 2996 6320	670	15
Lady Victoria Colliery	NT 3294 6666	768	18

Even though the data [14] in the table has been sorted by depth, there is no connection between the depth and the measured water temperature. The temperature of mine water ranges from 12 to 21 degrees Celsius, with a mean of 17 degrees Celsius [14].

3.0 Technology Assessment

This Section's purpose is to provide a thorough analysis of the heating systems. This analysis includes design, thermodynamic advantage, and limitations. The technology will be chosen based on efficiency, demand availability, system failure risk, constraints, energy, fuel type, and energy consumption (Figure 20).

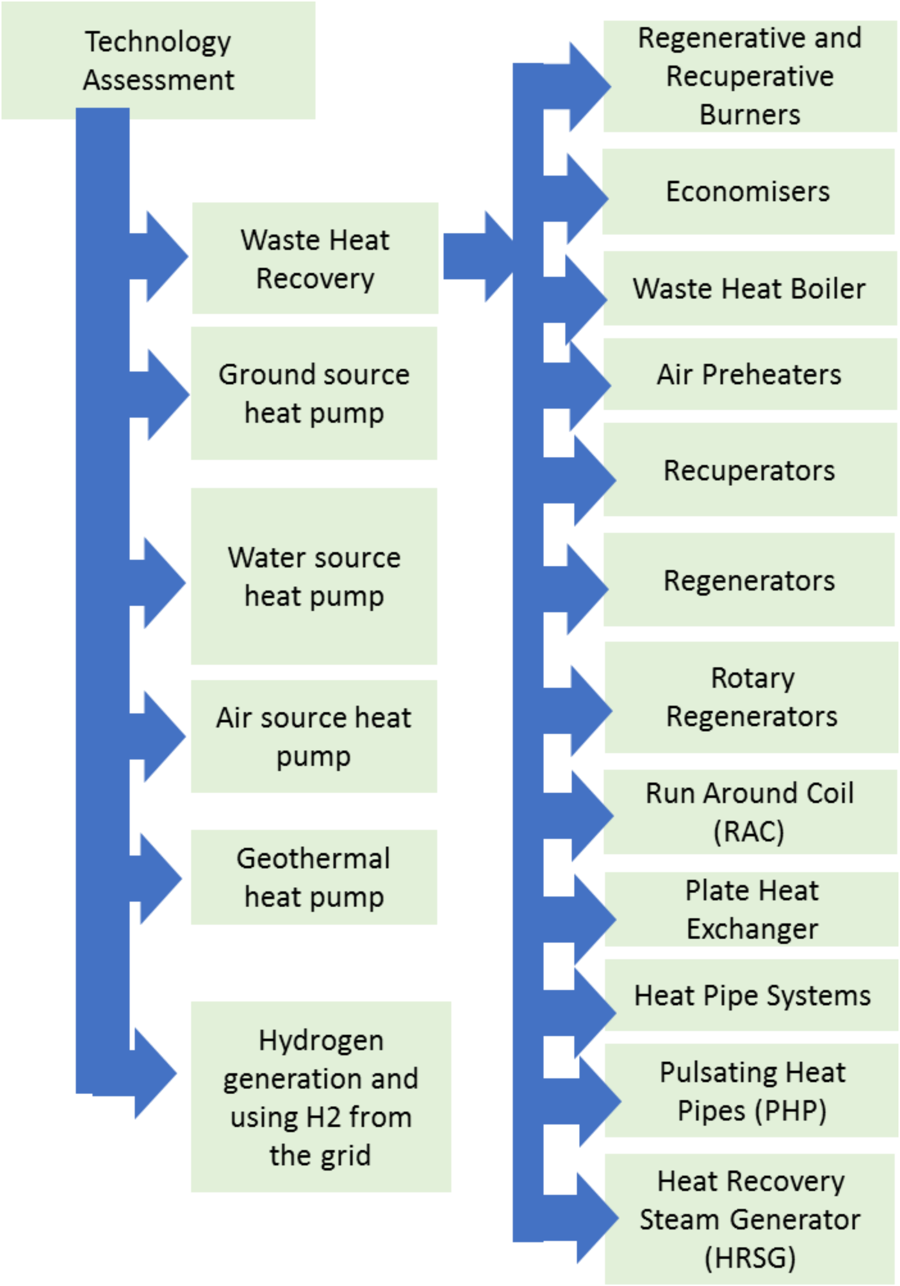


Figure 20 Technology assessment map

3.1 Waste Heat Recovery

In light of the increasing trend in fuel costs over the last several decades, together with the growing concern about global warming, the engineering industry is confronted with the job of decreasing greenhouse gas emissions [35] while simultaneously enhancing the efficiency of their facilities. It has been shown in this respect that the use of waste heat recovery systems in industrial processes has been a crucial component in the development of important research fields for reducing fuel consumption, lowering hazardous emissions, and increasing production efficiency [35].

It is the energy [35] produced in industrial operations that are not put to any practical use and instead are squandered or thrown into the environment that is called industrial waste heat. The most common sources of waste heat include heat loss [35] from industrial goods, equipment, and processes that is transmitted via conduction, convection, and radiation, as well as heat released from combustion operations.

It is possible to categorise heat loss into three categories: high-temperature loss, medium temperature loss, and low-temperature loss. Each kind of waste heat is assigned to a Waste Heat Recovery (WHR) system, allowing for the most efficient waste heat recovery to be achieved at the highest possible efficiency.

Waste heat recovery (WHR) is the process of recovering waste heat at temperatures higher than 400 degrees Celsius; the middle-temperature range is 100–400 degrees Celsius [36] [37], and the low-temperature range in temperatures less than 100 degrees Celsius [36].

Typically, the majority of waste heat in the high-temperature range comes from direct combustion processes [37], the majority of waste heat in the medium temperature range comes from the exhaust of combustion units, and the majority of waste heat in the low-temperature range comes from the parts, products, and equipment of process units. It is estimated that the industrial sector in the United Kingdom uses up to 17% [37] of the total energy consumption of the country's economy and produces about 32% of the country's heat-related CO2 emissions. According to this figure and as shown in Figure 16, 72% of the industrial demand in the United Kingdom is met by [37] industrial thermal processes, of which 31% is classified as low-temperature process heat and nearly 20% of that, or 40 TWh/yr, is estimated to have the potential for industrial waste heat recovery [37] (Figure 21).

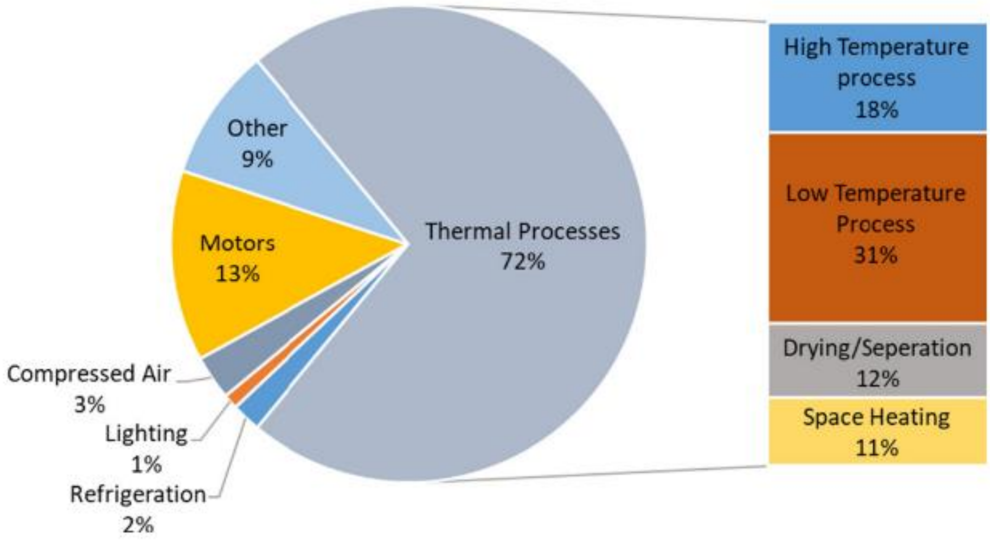


Figure 21 Energy consumption in the UK manufacturing industry [37].

The cement, ceramic, iron and steel [37], refineries, glass manufacturing, chemicals, paper and pulp, and food and beverage sectors are considered to be the most energy-intensive businesses in the UK. These sectors together provide about £50 billion [37] per year to the economy of the UK. This implies that progress is being made. Energy efficiency, achieved via waste heat recovery methods, may assist UK companies in lowering their operating costs, increasing the energy efficiency of their facilities, and lowering the country's industrial CO2 emissions [37].

Waste heat recovery methods [37] include collecting and transporting waste heat from a process involving gas or liquid back to the system as a further energy source, as well as other techniques. The energy source [37] may be utilised to produce extra heat, as well as electrical and mechanical power, depending on its configuration.

In theory, waste heat may be rejected at any temperature; nevertheless, common wisdom holds that higher temperatures produce better waste heat and allow for more straightforward optimization of the waste heat recovery process. For this purpose, it is critical to determine the largest quantity of recovered heat with the greatest potential from a process and to guarantee that the best possible efficiency is achieved from a waste heat recovery system [37].

The quantity of available waste heat can be calculated with the help of Equation 8 given below.

$$Q = V * \rho * C_p * \ \Delta T$$

Equation 18

In this equation, Q (J) [37] represents the heat content of the substance, V represents the flow rate of the substance (m3/s), represents the density of flue gas (kg/m3), Cp represents the specific heat of the matter (J/kg.K), and T represents the difference in substance temperature (K) between the final highest temperature at the outlet (Tout) and the initial temperature at the inlet (Tin) [37].

It is necessary to examine the quantity and grade of heat that can be recovered from the process depending on the kind and source of waste heat, as well as to justify the use of a particular waste heat recovery system in order to determine which system may be employed.

For the purpose of collecting and recovering waste heat, a wide [37] range of heat recovery technologies is available. The most common kind is the waste heat recovery unit, which is comprised mostly of energy-saving heat exchangers and other heat recovery components.

Common waste heat recovery systems [37], for example, air preheaters with recuperators, regenerators with furnace regenerators and heat wheels or heat wheels and run around the coil, regenerative and recuperative boilers, heat pipe heat exchangers, plate heat exchanger, economisers, waste heat boilers, and direct electrical conversion devices, are included in this category.

In order to collect, recover, and exchange heat in a process with potential energy content, all of these units operate on the same basic concept.

3.1.1 Regenerative and Recuperative Burners

Energy-efficient burners, such as regenerative and recuperative [38] burners, maximise energy efficiency by integrating heat exchanger surfaces that collect and utilise waste heat from the hot flue gas produced during the combustion process.

A regenerative device is typically composed of two burners [38] with independent control valves that are linked to the furnace and by turns heat the combustion air entering the furnace, as shown in the illustration [38]. The device works [38] by directing the exhaust gases from the furnace into a container containing refractory material such as aluminium oxide. It is a simple but effective design.

The exhaust gas [38] warms up the aluminium oxide media, and the heat energy from the exhaust is recovered and stored in the aluminium oxide media as well. When the media has reached its maximum temperature, the direction [38] of the flue gas is switched to the reverse direction, with the stored heat being transferred to the intake air entering the burner and the burner with hot media starting to burn again. Once the hot media has been heated up by combustion air, the colder media may be heated up, and the process can begin again.

Figure 22 illustrates how the regenerative burner [38] may save the fuel required to heat the air, thus improving the efficiency of combustion.

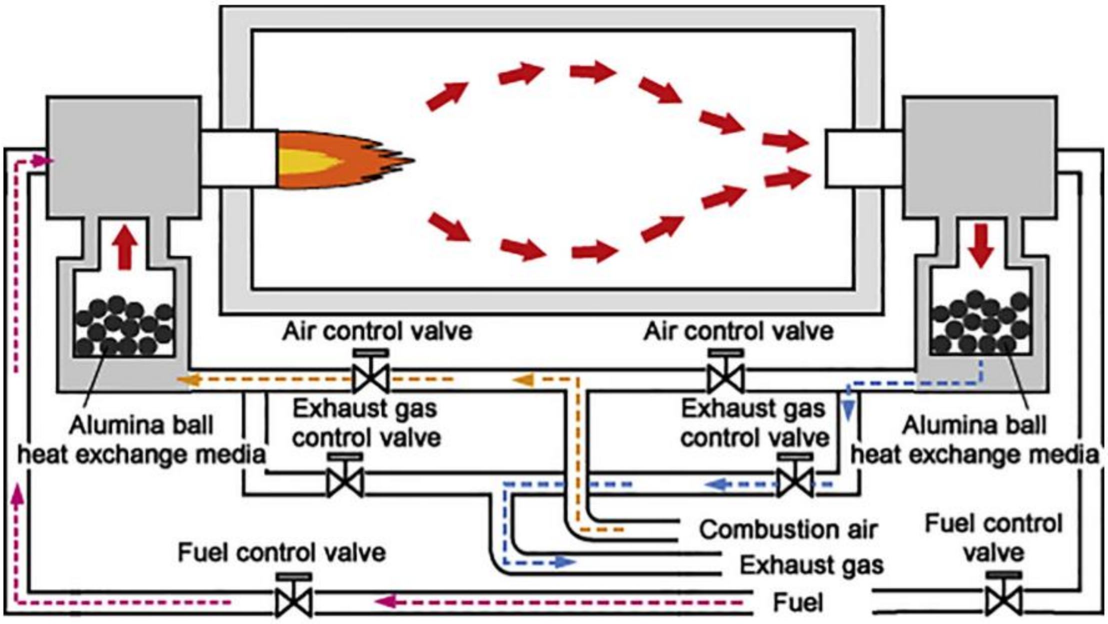


Figure 22 Regenerative burner mechanism [39].

The usage of burners with recuperative systems is also widespread in the commercial sector. A recuperative burner incorporates heat exchanger surfaces into the burner design, which collect energy from the hot gas that travels through the body of the burner and returns it to the system.

The burner takes advantage of the energy contained in waste gas from the exhaust to pre-heat the combustion air before it is added into the combustion chamber. In order to create thermal contact between the waste exhaust gases and the combustion air that comes from the supply pipe, the burners are equipped with an internal heat exchanger that has a variety of characteristics such as grooves, counter-current flow, and fins, among others. To function, the design collects both the exhaust gas and waste heat from the body of the burner nozzle and then uses both of them to transmit heat into the combustion air.

This preheating of the air leads to increased combustion efficiency, and, as a consequence, more heat is emitted from the nozzle. Notably, the burner and nozzle are both placed inside the furnace body, and the waste heat is delivered to the burner via convection from the exhaust gases, as previously stated. When using a furnace with a temperature of 1000 degrees Celsius, Osaka Gas shows that the air may be warmed to at least 500 degrees Celsius, resulting in a significant increase in thermal efficiency see Figure 23.

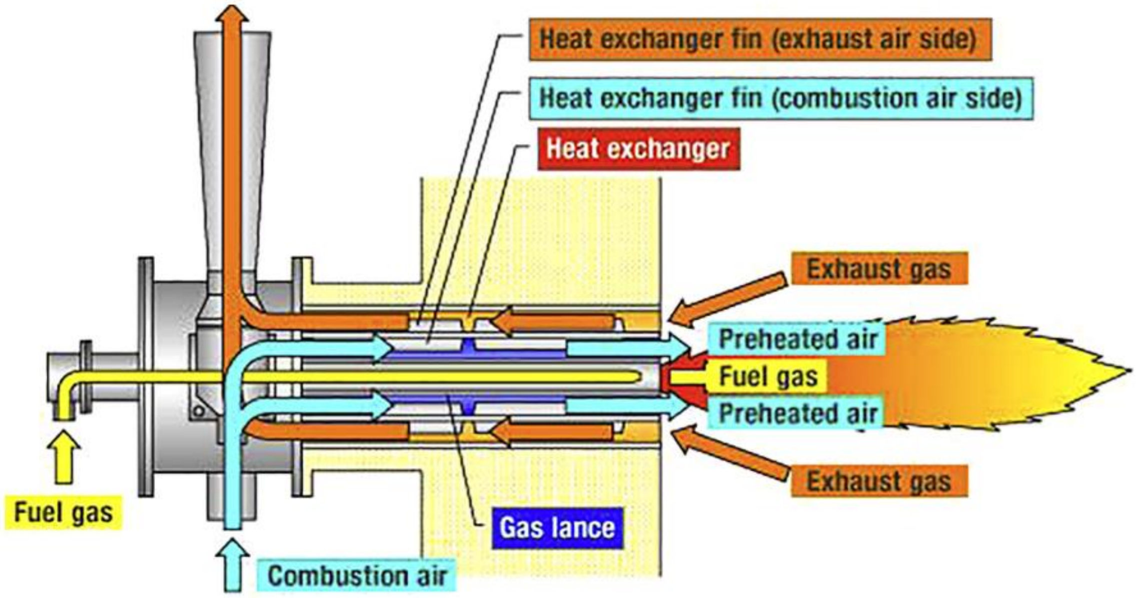


Figure 23 Recuperative burner structure [39].

3.1.2 Economisers

Economisers, also known as finned tube heat exchangers [40], are devices that recover low to medium-level waste heat and are mostly used for the heating of liquids. System components include tubes that are coated with metallic fins in order to increase the surface area of heat absorption and the pace at which heat transfers [40].

When installed in the ductwork that transports the gases leaving the exhaust, the system absorbs waste heat by allowing the hot gases to pass through various portions that are covered with finned tubes. The liquid is transported through the tubes, where it absorbs the heat emitted by the finned tubes. The heated liquid is then recycled back into the system, increasing the thermal efficiency to its maximum potential [41].

According to research performed by Spirax Sarco [42], the installation of an economiser in a boiler system may improve the efficiency of the system by 1% for every 5 degrees Celsius decrease in flue gas temperature. Based on this, it is possible to decrease the system's fuel usage by 5–10% [41] with a payback period time of fewer than 2 years[43]. By preheating a fluid in a system, such as the feedwater in a steam generator or the boiler water in a boiler, an economiser may recover waste heat and increase the efficiency of a system. This lowers the quantity of energy required to get a system up to a boiling point.

According to research conducted by Maxxtec [43], if the temperature of the flue gas is lowered by 140 degrees Celsius, the fuel consumption may be reduced by 7%, regardless of the system's design. Several different kinds of economisers are available for various purposes, but they all perform the same functions, according to the findings of the investigation.

Finned tubes [44], coiled tubes, non-condensing, and condensing economisers are some of the types available today. Generally speaking, condensing and non-condensing kinds of boilers are used to increase the efficiency of boiler systems, while the other types of boilers are frequently found in thermal power plants and big processing units to recover waste heat of the flue gas [44].

In light of the foregoing, Vandagriff investigated [45] the availability of economisers that are used for low-temperature heat recovery, namely as deep economisers, that are constructed of advanced materials such as Teflon, carbon, and stainless-steel tubes and are capable of withstanding the deposition of acidic condensate on the surface of the heat exchanger [46]. On the other hand, glass-tubed economisers are utilised for gas-to-gas heat recovery as well as for low to medium temperature applications [46].

3.1.3 Waste Heat Boiler

Waste heat boilers are made up of a number of water tubes that are arranged in a parallel fashion and in the direction in which the heat is being removed from the system [47]. The system is intended to recover heat from medium-to-high-temperature exhaust gases, which is then utilised to produce steam as a by-product. The steam may subsequently be utilised to generate [47] electricity or recycled back into the system, depending on the needs of the system. For instance, consider a coal-fired power plant [47], the heat produced by the combustion process after it exits the combustion chamber may reach temperatures of up to 1000 degrees Celsius [47].

Waste heat boilers are utilised in this situation to recover and repurpose the heat from flue gases, which is then converted into steam, which may then be used to generate electricity via turbines and generators, as shown in the diagram below. Steam production pressure and rate are mostly determined by the temperature of the waste heat used in the process [47].

The addition of an extra burner unit [47] or an afterburner in the exhaust gases may be used to reimburse for the fact that the waste heat is not adequate to generate the necessary quantity of steam in the system. Waste heat boilers may also be used in conjunction with other waste heat recovery equipment such as afterburners, preheaters, and finned-tubed evaporators to increase efficiency by preheating the feed water and producing superheated steam if necessary (see Figure 24) [48].

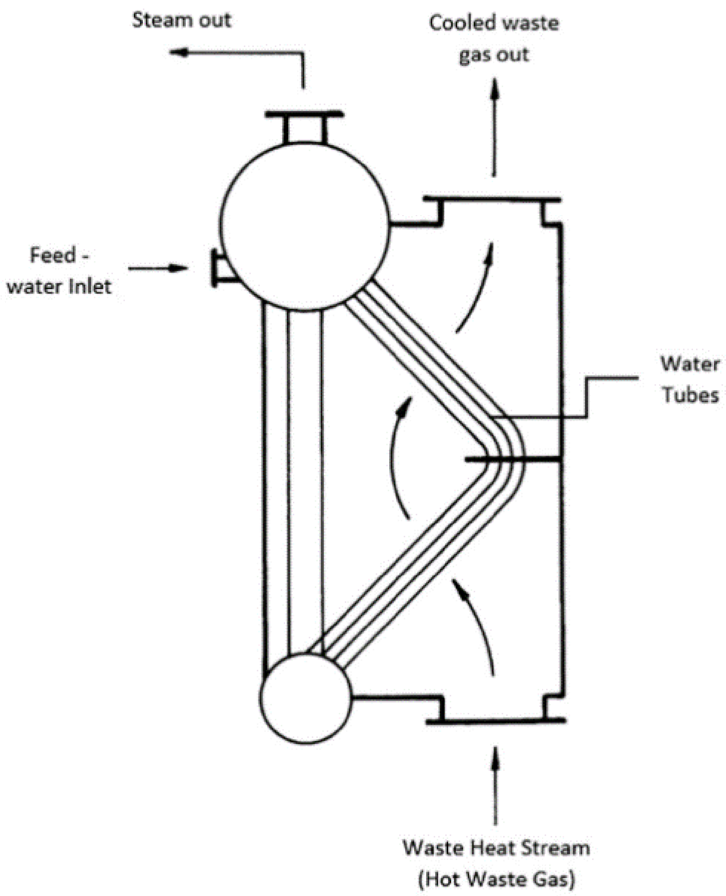


Figure 24 Schematic of a waste heat boiler incorporating parallel water tubes [48] .

3.1.4 Air Preheaters

Heat recovery from the exhaust to air is the primary [40] use for air preheaters, which are often utilised in lower and mid-temperature applications. This method is especially helpful when it is necessary to avoid cross-contamination during the manufacturing process[49].

Applications such as gas turbine exhausts and heat recovery from furnaces [49], ovens, and steam boilers are examples of this kind of technology. Plate type and heat pipe type air preheating are the two types of designs that may be used for air preheating [49] as described below:

- Plate type [49] is comprised of parallel plates that are positioned perpendicular to the incoming cold air intake, resulting in a closed system. It is injected into the channels between the plates, imparting heat to the plates and establishing hot channels through which cold air is forced to circulate.

- Heat pipe type - For the heat pipe type, a bundle of many sealed pipes [49] is arranged in parallel to one another in a container and sealed together with tape. The container is divided into two parts, each of which accommodates cold and hot air, as well as an input and an exit. Working fluid is contained inside the container by means of pipes. When the working fluid comes into contact with hot waste gas at one end of the pipes [49], it evaporates and travels towards the other end of the pipe, where cool air is flowing.

  Thus, heat is absorbed in the hot part of the pipe and transmitted to the cold segment, where it is heated as it travels across and through them. Working fluid condenses and flows toward [49] the hot portion of the pipe, where the cycle is repeated.

Nicholson explains that there are three kinds of air preheaters that are categorised as regenerators that are frequently utilised; these include rotary regenerators, run around coil regenerators, and recuperative regenerators [50].

Despite the fact that all of these technologies operate on the same basic concept as air preheaters, they have a variety of configurations and are used for a variety of applications (see Figure 25) [50].

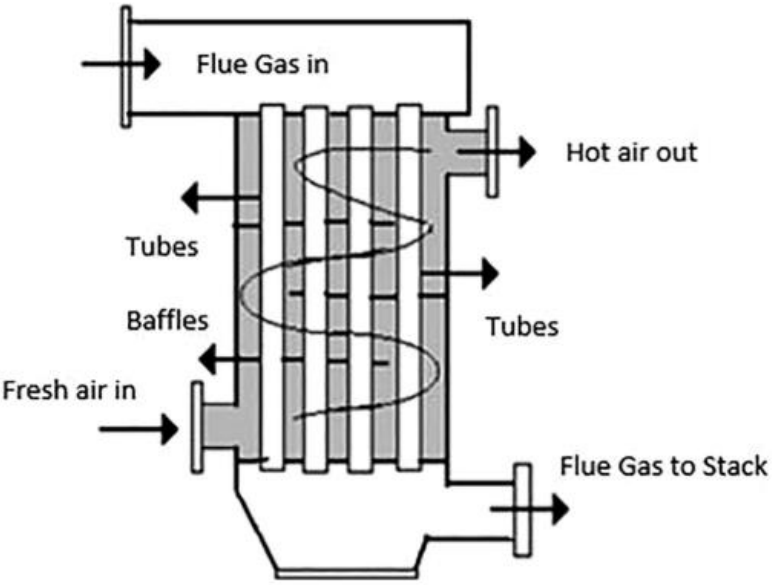


Figure 25 Air preheater layout showing air movement [50].

3.1.5 Recuperators

The term "recuperator" refers to a type of heat exchanger unit that is typically made of metallic or ceramic materials [51], depending on the application, and that is used to recover waste exhaust gases at temperatures ranging from medium to high. As part of this process, the hot exhaust gases are routed through a series of metal tubes or ducts that also serve to transport inlet air from the surrounding atmosphere [51].

As a result, the recuperator pre-heats the inlet gas before recycling it into the system. The energy that is now available in the system can be described as the energy that does not need to be supplied by the fuel, resulting in a reduction in energy demand and production costs.

Metallic recuperators are used in low- to moderate-temperature applications., whereas ceramic recuperators are better suited for applications with high temperatures. Recuperators can be said to transfer heat to the inlet gas primarily through convection, radiation, or a combination of radiation and convection, depending on their design. A radiation recuperator is made up of metallic tubes [51] that wrap around the inner shelf, through which hot exhaust gases pass.

Figure 26 shows how the cold incoming air is fed into the tubes surrounding the hot shelf, where heat is radiated to the tubes' walls.[52]

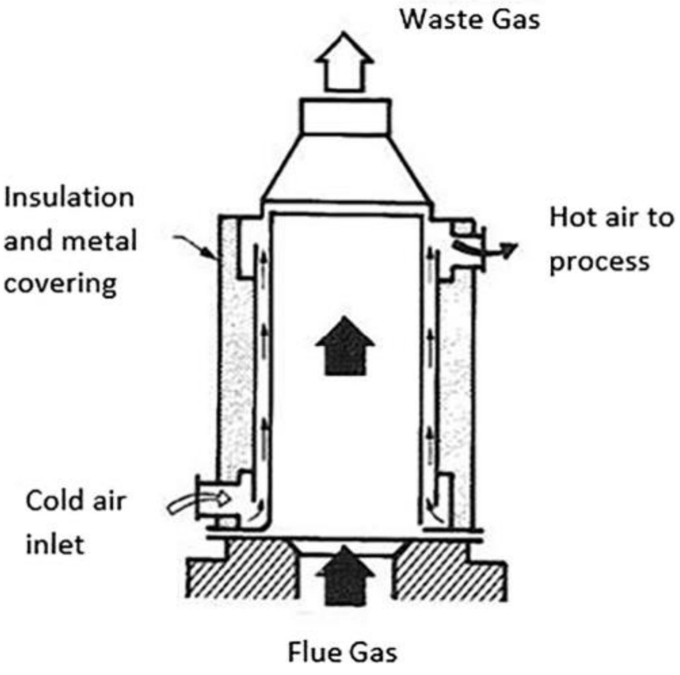


Figure 26 Diagram of metallic recuperator [52].

Thermal transfer occurs through the tubes, which heats the cold air, which is then delivered to the furnace burners. The convective recuperator, on the other hand, exchanges heat by passing hot exhaust gases through tubes with relatively small diameters that are placed on a larger shelf.

It is passed through the large shelf [53], where it absorbs heat from the small hot tubes within the shelf, which is heated by the waste gas. A combination of radiant and convective recuperators offers yet another option for increasing the efficiency of heat transfer [53].

The hot exhaust gas is fed into a larger shelf, which is then divided into smaller diameter tubes. As a result of the introduction of cold air into and around the shelf, a quantitative [53] improvement in heat transfer is achieved see Figure 27 [53].

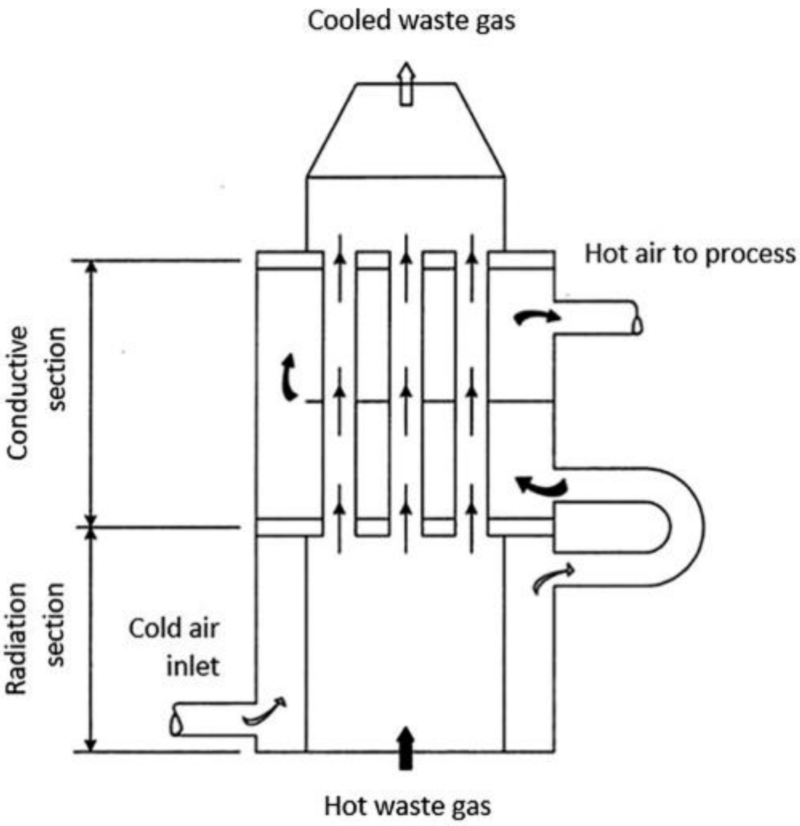


Figure 27 Combined radiation and convective type recuperator [53].

3.1.6 Regenerators

Regenerators transfer heat from the hot gas duct to the cold gas duct by storing waste heat in a material with a high heat capacity in order to transfer heat from one to the other. The system is comprised of a chamber that serves as a link between [48] the hot air duct and the cold air duct, transferring heat energy from the hot side to the cold side and storing it in the chamber.

For example, regenerative furnaces are made up of two brick chambers [48] in which hot and cold air exchange heat with one another. Heating occurs as hot combustion gases pass through the brick chamber. The heat from the hot flue gas is captured and stored in the brick chamber before being transferred to the cold airflow [48] as it passes through the brick chamber [48].

As a result, the preheated gas is injected into the flow [48] of gas going to the combustion chamber, which reduces the amount of energy required to heat the entire system. Two chambers are used, with one transferring heat to the flow entering the system and the other absorbing heat from the flow entering the system.[48]

The direction of the inlet flow [48] is changed on a regular basis in order to maintain a constant heat transfer rate. For high-temperature applications such as glass furnaces and coke ovens, regenerators are well-suited. In the past, they have also been used [48] in open-hearth steel furnaces.

However, they can be very large in size and have very high capital costs, which are both disadvantages of this technology. Regenerators are particularly well suited for applications with dirty exhausts.

3.1.7 Rotary Regenerators

Rotary regenerators function in a similar way to fixed regenerators; however, in this technology, heat is transferred between the hot and cold flows through a porous thermal wheel [53].

Essentially, two parallel ducts [53] carrying hot and cold flows [53] are placed across a rotating disc or heat wheel made of a high thermal capacity material [53] and connected by a rotary shaft. When a flow passes through the hot duct, the heat wheel absorbs and stores the heat, then rotates and transfers it to the flow that passes through the cold duct[53].

Rotary regenerators are used for low to medium-temperature applications and have the potential to provide extremely high overall heat transfer efficiency if designed properly (see Figure 28) [53].

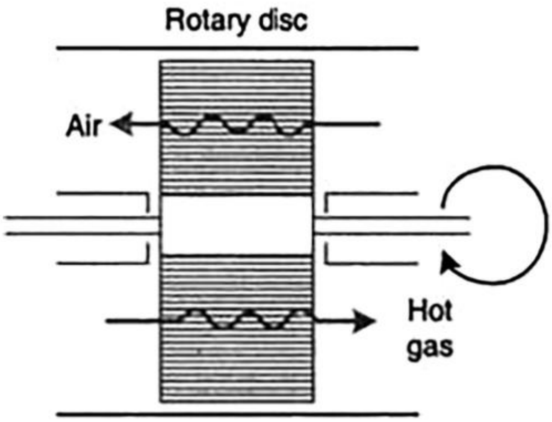


Figure 28 Schematic diagram of heat wheel [53].

Due to the structural [53] stresses and the possibility of large expansion and deformations that can be caused by temperature differences between the two ducts, heat wheels are not recommended for use in high-temperature applications, and they are not suitable for use in such applications.

Heat wheels made of ceramic materials, on the other hand, [53] can be used for high-temperature applications, as previously stated.

Cross-contamination cannot be prevented because heat wheels are primarily made of porous materials, and therefore cannot be avoided. This has the possibility to be a significant disadvantage, particularly when it comes to preventing cross-contamination between the two ducts [53]. As a result, it has been demonstrated to be advantageous in applications where the recovery of moisture and humidity from the outlet duct is necessary.

3.1.8 Run Around Coil (RAC)

As seen in Figure 29 and as described by Toolan [54], this system is composed of two coiled heat exchangers connected by a run-around coil filled with a fluid such as water [26]., glycol, or a combination of the two [55][26].

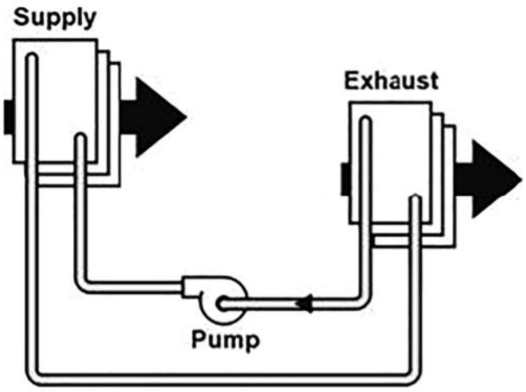


Figure 29 Schematic of run around coil system [55]

The liquid in the coil collects waste heat from a process's [26] exhaust gas and transfers it to the secondary recuperator, where it is mixed with supply air. The ability of the two air streams to exchange heat is enabled by the liquid round coil system, which is connected to each other through pumped pipework.

This machine is utilised when the heat sources are too far apart to employ a direct recuperator, and cross-contamination between the two flow sources is required owing to moisture, corrosive gases, poisonous and biological contaminants. This technique is shown to be significantly less effective than a direct recuperator and requires the operation of a pump, which requires [26] more energy input and maintenance. The efficacy and efficiency of this technology may be demonstrated through the use of a supplementary heat source, as seen in Figure 25 [26].

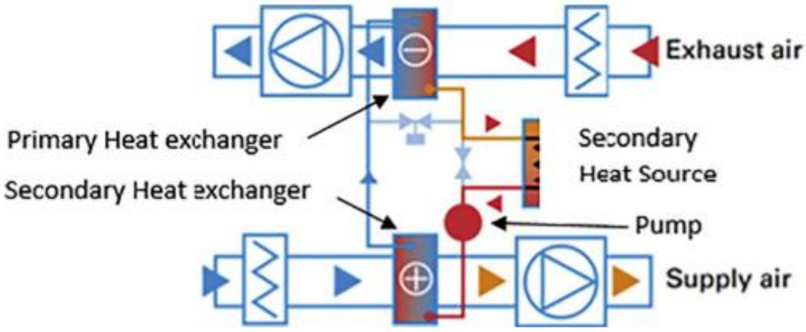


Figure 30 Run around coil system compromising a secondary heat source [26].

3.1.9 Plate Heat Exchanger

When cross-contamination must be avoided, plate heat exchangers are used to transfer heat from one fluid to another. A plate heat exchanger.[56] is constructed from a series of thin metal plates that are stacked or brazed in parallel and shaped into a hollow metallic shell.

Each plate is often composed of a variety of pressed patterns that are surrounded by gaskets to regulate the flow of fluid and create turbulence for improved heat transmission. The gaskets are placed in such a way that only one type of fluid flows through one gap while the other type of fluid flows through the next gap. As seen in Figure 31, a gap or channel has been created between each pair of successive plates to allow hot and cold fluids .[56] to flow along and through the plate plane [56].

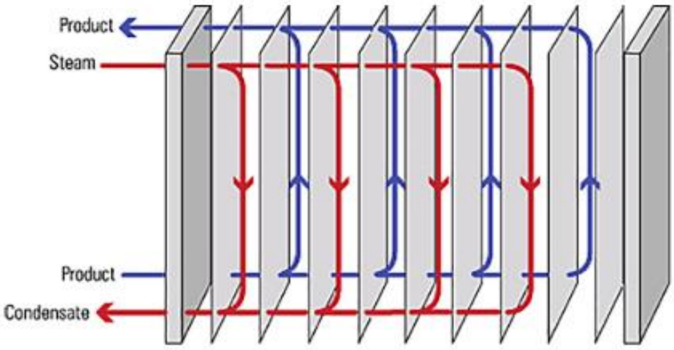


Figure 31 Schematic of a plate heat exchanger [56].

With this method, hot and cold fluids alternately travel over the front and rear of plates in each part of the heat exchanger, exchanging heat and avoiding contamination.

The additional benefit that plate heat exchangers have over comparable types of heat exchangers [57], such as traditional shell and tube heat exchangers, is that the hot and cold fluids are exposed to a greater surface area per unit volume and a higher heat transfer coefficient.

According to the manufacturer, there are primarily three types of plate heat exchangers [57], which are organised in single-pass or multi-pass [57] configurations, as seen in Figures 32 and 33 [57].

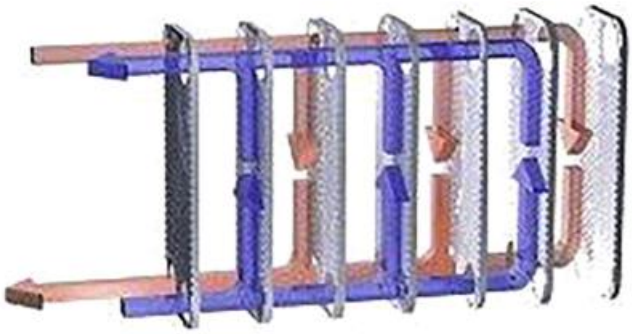


Figure 32 Single-pass configuration plate heat exchanger [57].

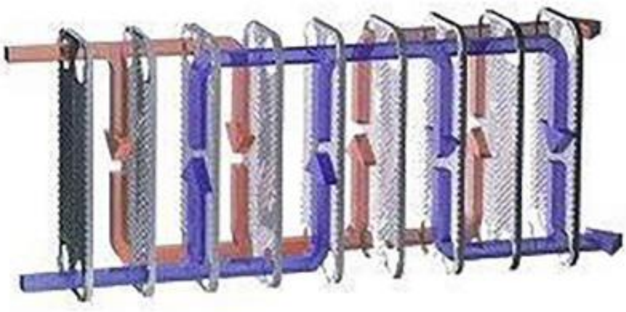


Figure 33 Multi-pass configuration plate heat exchanger [57].

Plate heat exchanger plates can be welded together, gasketed or brazed.

In a gasket plate heat exchanger [57], a formed polymer substance is sandwiched between the plates and acts as a seal and separator along the plates' edges [57]. Using tightening bolts and two thicker pressure plates on each side, the plates are positioned and fastened together in a frame.

As a result of the design, the heat exchanger [57] may be removed for maintenance. By cleaning or by relocating, or adding new plates, the capacity can be increased or decreased.

The use of gaskets in this design provides resilience to heat fatigue and abrupt pressure changes by allowing the plate pack to be flexible. This is excellent for applications that are frequently subjected to thermal cycling due to temperature changes.

Having said that, the usage of gaskets [57] is constrained by the cycle's operating temperature and pressure, which is inconvenient. Despite this, it has been demonstrated that gasket plate heat exchangers provide efficient and effective heat [57] transmission with a recovery rate of up to 90% [57].

All of the plates in a brazed plate heat exchanger are brazed together using copper or nickel in a vacuum furnace [57].

Unlike a gasket heat exchanger, this design is more resistant to increased pressure and temperature ranges and is very inexpensive to maintain. However, because it is brazed together, it cannot be disassembled, which creates complications when cleaning or changing the size is necessary.

Due to the circumstance that the design is more rigid than the gasket type [57], it is more vulnerable to thermal stress, and any abrupt or frequent change in temperature or load can result in fatigue and structural collapse. As a result, brazed heat exchangers are mostly utilised in applications with modest temperature variations and gradual thermal expansion, such as thermal oils.

In comparison to brazed heat exchangers, welded plate heat exchangers [57] are said to be more flexible and resistant to temperature cycling and pressure fluctuations. This advantage is accomplished [57] by the use of laser welding processes that create welded seams that keep the plate pack together.

This form of heat exchanger has been demonstrated to have greater temperature and pressure working limitations, making it ideal for heavy-duty applications [57]. Nonetheless, they, like brazed heat exchangers, cannot be disassembled or resized. However, when a plate heat exchanger is utilised [57] to superheat the system's working fluid, the performance of an evaporator employed in a heat recovery steam generator can be enhanced.

3.1.10 Heat Pipe Systems

As seen in Figure 34, a heat pipe is a device that uses the condensation and vaporisation [58] of a working fluid to transport heat from one location to another [58].

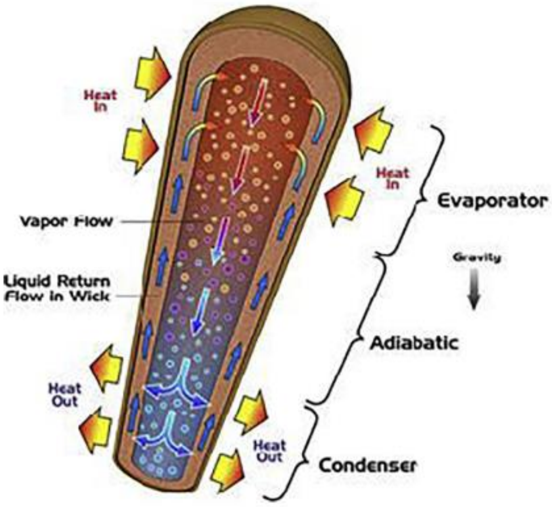


Figure 34 Schematic of a heat pipe [58].

A heat pipe is made up of a sealed container[58], a wick structure, and a tiny amount of working fluid such as water, acetone, methanol, ammonia, or sodium that is equilibrated with its own vapour. A heat pipe is composed of three distinct sections[58]: the evaporator, the adiabatic transport, and the condenser.

When one side of the pipe is heated, the heat is transmitted through the pipe wall and wick structure, evaporating the working fluid inside the pipe. As a result, vapour pressure is created, propelling the vapour through the adiabatic transit portion of the pipe to the other end. The vapour then condenses by transferring the latent heat of vaporisation to the heat sink via the wick structure and pipe wall [58]. The vapour becomes liquid and is absorbed by the wick structure. The capillary pressure generated by the menisci in the wick structure forces the liquid back to the pipe's heated end, where the cycle begins again.

Heat pipes have extremely high effective thermal conductivities [58], as can be demonstrated. Thermal conductivities of solid conductors such as aluminium, copper, graphite, and diamond range between 250 and 1500 W/mK, whereas heat pipes have effective thermal conductivities of 5000–200,000 W/mK[59]. Aluminium, copper, titanium, Monel, stainless steel, Inconel, and tungsten are all examples of materials used to create heat pipes.

The material used in heat pipes is primarily determined by the temperature range of the application and the material's compatibility with the working fluid.

As previously stated [60], the heat pipe wick construction facilitates the return of the working liquid from the condenser to the evaporator. The heat pipe wick structure may be constructed using a variety of materials and processes, although the screen/woven and sintered powder metal structures are the most popular [60].

Additionally, it is said that heat pipes referred to as thermosyphons are available; these lack a wick component and operate only by gravity. These heat pipes cannot be used horizontally and must be installed vertically.

Heat pipes with a wick construction are not restricted in this way and can function in both horizontal and vertical orientations [60].

As seen in Figure 35, wick structures with a screen mesh structure are typically composed of copper or stainless steel and are expanded against the pipe wall to produce the wick structure [60].

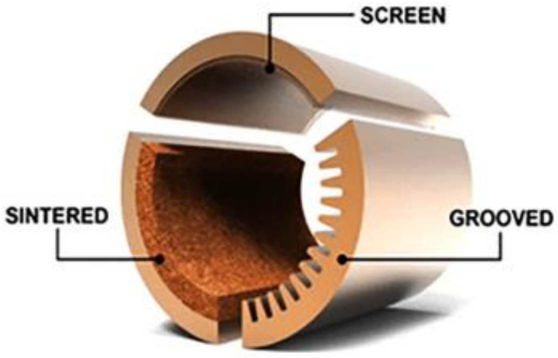


Figure 35 Common wick types of a heat pipe [60].

This construction enables heat pipes to transfer the working fluid horizontally and vertically, as well as against gravity at a minor inclination from the horizontal.

Grooved wick structures, on the other hand, are formed by elevated dents that are perpendicular to the pipe surface using extrusion or threading techniques [60]. They are often constructed of copper or aluminium.

Similar to screen wick systems, heat pipes constructed with this sort of construction may work in gravity-assisted and horizontal orientations and can carry liquid at a small inclination from horizontal.

The sintered copper powder structures are capable of vertically and horizontally conveying the working fluid against gravity with little restriction. Typically, this sort of wick structure is created by fusing copper powder particles together to produce a sintered wick structure.

The type of working fluid used in a heat pipe is highly dependent on the temperature range of the application. Ammonia, acetone [61], "Freon" refrigerants, and water are utilised in low-temperature applications between 200 and 550 K [61]. The majority of heat pipe applications lie within this temperature range, and water is considered to be the most often utilised fluid due to its low cost, strong thermophysical characteristics, and safety.

Heat pipes, in general, have a high thermal conductivity, which results in a low-temperature drop when transferring heat over long distances, a long life that requires no maintenance due to their passive operation and lack of wearable moving parts, and lower operating costs when compared to other types of heat exchangers [61].

3.1.11 Pulsating Heat Pipes (PHP)

PHPs are passive closed two-phase heat transfer devices that [62], like traditional heat pipes, are capable of transmitting heat without the need for extra electricity. As seen in Figure 36, the system comprises a long, thin tube filled with a working fluid [62].

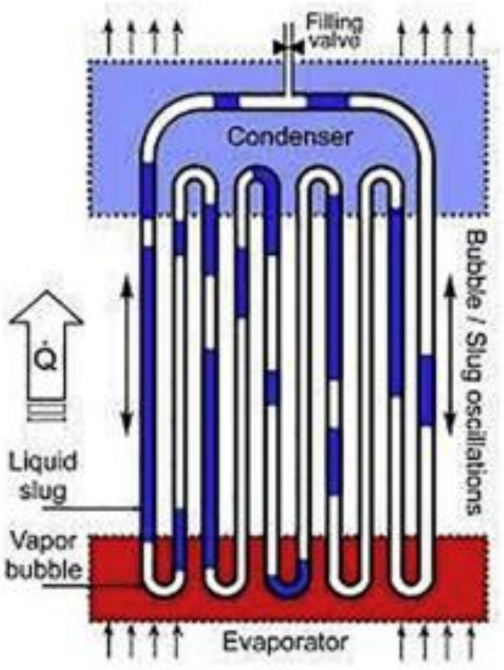


Figure 36 Schematic of a pulsating heat pipe [63].

The PHP may be configured as an open-loop or closed-loop system [63] and is powered by the oscillatory flow of liquid slugs and vapour plugs [63].

As seen in Figure 31, both ends of the tube are linked in the closed-loop configuration, whereas in the open-loop design [63], one end of the tube is welded and pinched off, while the other end is left open and connected to a charging valve .

The primary distinction between PHPs and heat pipes is the absence of a wick structure to transport condensate to the condenser, and heat transmission is solely accomplished by the oscillatory flow.

It was researched and demonstrated that by utilising a closed-loop oscillating heat pipe [63], the amount of fuel consumed in pottery kilns might be decreased, and energy conservation accomplished. A closed-loop oscillating heat pipe was constructed from a copper [63] capillary tube and filled with R123, and water was utilised in this experiment as a heat exchanger to recover waste heat from pottery kilns.

3.1.12 Heat Recovery Steam Generator (HRSG)

The heat recovery steam generator (HRSG) is a sophisticated device that is used to recover waste heat [64] from a power plant's exhaust. It is composed of many major heat recovery components, including an evaporator, a superheater, an economiser, and a steam drum.

By examining the layout of an HRSG in Figure 32, it is clear that the superheater is located upstream of the evaporator in the route of the hottest gas and the economiser [64] is located downstream of the evaporator in the path of the coolest gas.[64]

HRSGs are typically composed of a triple pressure system [64]: high pressure, reheat or intermediate pressure, and low pressure. Additionally, the system may recover waste heat from manufacturing processes' exhaust to increase overall efficiency by creating steam that can be utilised for industrial process heating or to drive a steam turbine to produce power.

It is stated that when HRSG is used to generate steam, a system efficiency of up to 75–85% may be obtained [64]. The system is comprised of an evaporator and a steam drum for the conversion of water to steam. The steam is then superheated by increasing its temperature over its saturation point [64].

As seen in Figure 37, the evaporator is sandwiched between the economiser and the secondary heater, with the steam drum on top. The evaporator generates the steam required for the turbine, which is subsequently supplied to the steam drum and superheater [64]. As seen in Figure 32, the steam drum separates the steam and water combination from the saturated steam during the feedwater delivery to the evaporator.

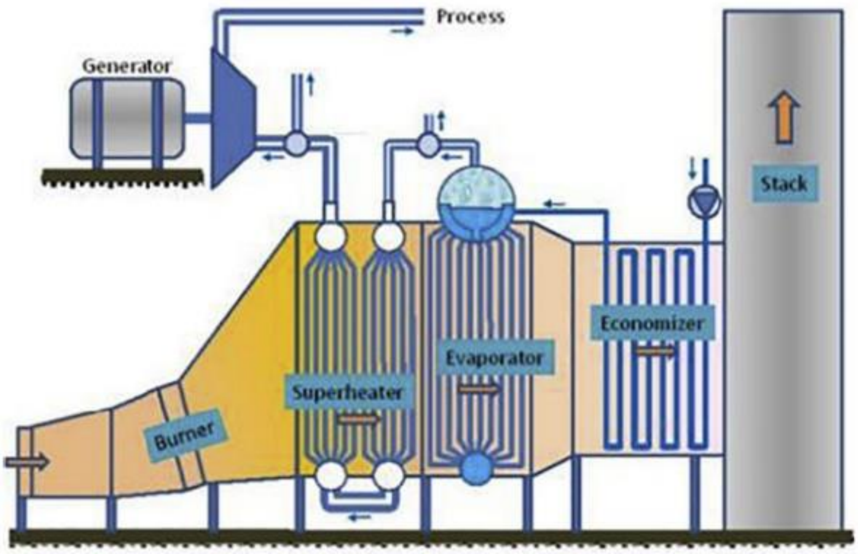


Figure 37 Heat Recovery Steam Generator (HRSG) [64].

Separation of the steam occurs in two stages, utilising a combination of the following:

- Before it reaches the superheater, it undergoes gravitational and mechanical effort. This raises the temperature of the steam over its saturation point, resulting in superheated steam [64].
- The economiser, on the other hand [64], pre-heats the feedwater to the evaporator, therefore increasing steam generation efficiency. The steam created during the operation is then routed through a thermodynamic cycle to generate electricity and increase the plant's efficiency.

3.1.13 Thermodynamic Cycles Used for Waste Heat Recovery

3.1.13.1 Organic Rankine Cycle

The Organic Rankine Cycle is a cycle [65] that is based on the Clausius-Rankine cycle [65], but instead of using water or steam as the working fluid, it utilises organic compounds with low boiling temperatures and high vapour pressures [66].

It has been demonstrated that by employing an organic fluid as the working fluid [66], the system is ideal for using low-grade waste heat and generating electricity using renewable energy sources such as geothermal, biomass, and solar.

The Clausius-Rankine Cycle, abbreviated CRC, is introduced as the ideal vapour power cycle and is defined as the fundamental operating cycle for all power plants that generate electricity using an operating fluid such as water [66]

A typical Rankine cycle is composed of the following components: a pump, a condenser [66], an evaporator, and a generator. The evaporator burns fuel and heats the water used as the working fluid to create superheated steam. This is then sent to the turbine, which generates electricity, and is finally transferred to the condenser, where it loses heat and reverts to a liquid form. After pumping the liquid water into the evaporator [66], the cycle is repeated.

In comparison to the CRC, an Organic Rankine cycle (ORC) system generally comprises of a heat exchanger connected to an evaporator and a preheater during the cycle, as well as a recuperator connected to a condenser [65].

When waste heat travels from the source and passes through the heat exchanger, it heats the intermediate fluid, which then circulates through the evaporator and preheater. The organic fluid is subsequently heated by the intermediate fluid, vaporising and converting to superheated vapour. The vaporised organic fluid then flows through the turbine with a high enthalpy, and the vapour expands, spinning the turbine and generating energy. The vapour then exits the turbine and travels past the recuperator [66], lowering the temperature and subsequently preheating the organic fluid. The organic vapour is condensed back into a fluid at the condenser using air or water from a cooling tower or the surrounding environment. Once the fluid reaches the pump, the system is pressurised to the appropriate pressure, and the fluid is returned to the recuperator [66], where it is warmed, and the cycle is restarted (see Figure 38).

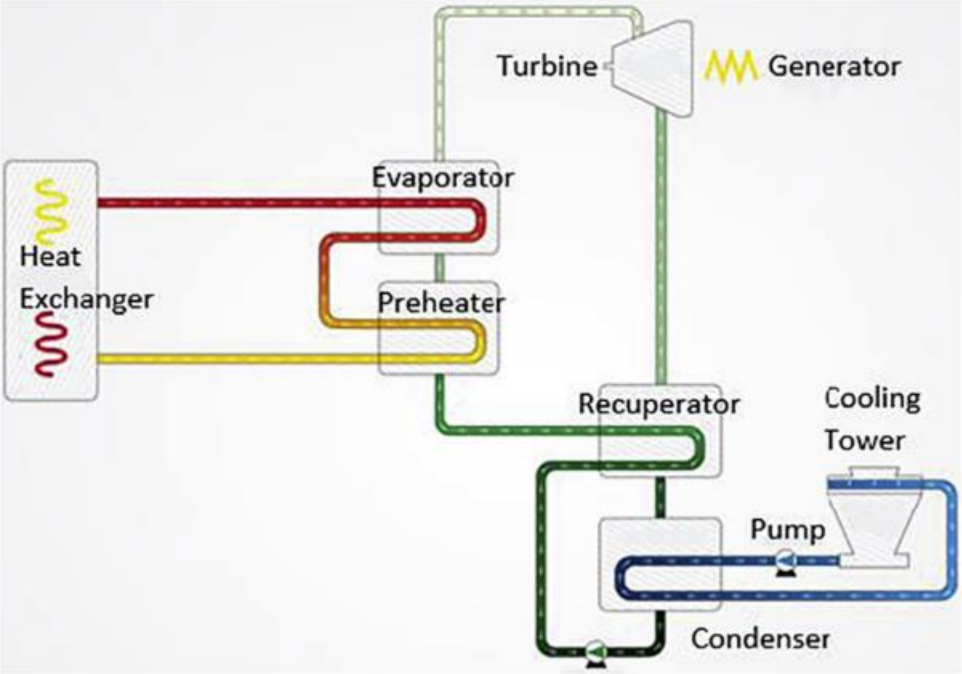


Figure 38 Schematic of a Typical Organic Rankine cycle [65].

Mamun demonstrated that an ORC has several benefits over a traditional steam turbine for waste heat recovery.

Combining an ORC with a waste heat recovery *steam* [65] generating unit, a net efficiency of about 22% may be obtained in a steel mill. However, the design and functioning of an ORC system are dependent on the choice of the working fluid and its thermodynamic, environmental, and safety characteristics

This demonstrates the critical nature of selecting the optimal working fluid when contemplating the usage of ORC for waste heat recovery operations. For example, Douvartzides and Karmalis [67] examined 37 different working fluid substances and found that by properly selecting the working fluid and cycle operation, a plant's total efficiency may be boosted by almost 6% while reducing fuel usage by 13%.

3.1.13.2 Kalina Cycle

Similar to the Organic Rankine cycle, the Kalina cycle is a variation [68] of the Rankine cycle that generates energy by using the working fluid in a closed cycle [68].

However, this system frequently utilises a combination of water and ammonia as the working fluid [68] in a process that typically includes a recuperator and separator in addition to other Rankine cycle components [68] to create steam and electricity (see Figure 39).

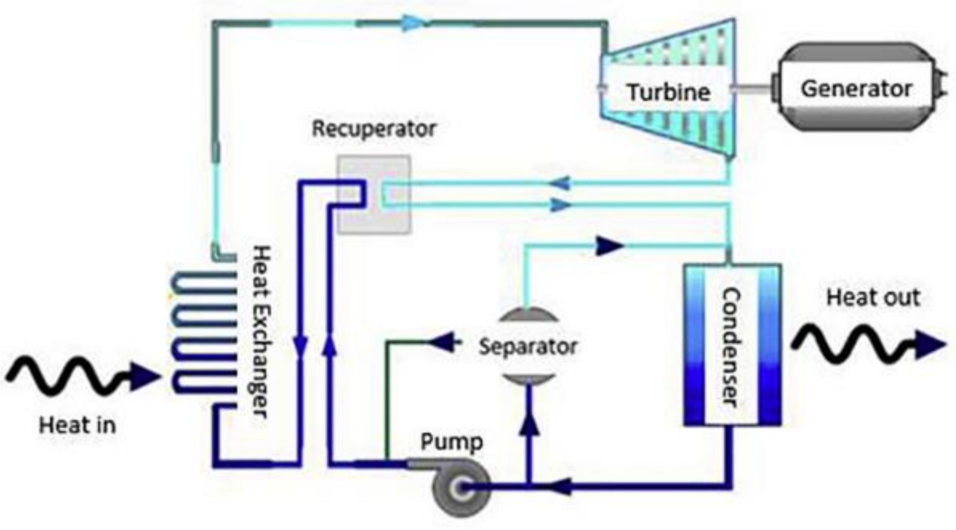


Figure 39 Configuration of a Kalina cycle consisting a Recuperator and Separator [68].

The difference between the Kalina cycle and cycles that work with a single fluid is that the temperature does not remain constant throughout boiling, which results in a higher cycle efficiency [69].

A single-fluid cycle heats the working fluid evenly to the evaporation temperature at which supercritical or superheated steam is created indefinitely [69].

However, when a binary combination of working fluids is used, such as in the Kalina cycle, each fluid's temperature is increased individually during evaporation due to each fluid's distinct boiling point [69]. This results in a better thermal match between the evaporator and condenser, as the source of the cooling medium is not required to meet the requirements of a particular process fluid [70] (see Figure 40).

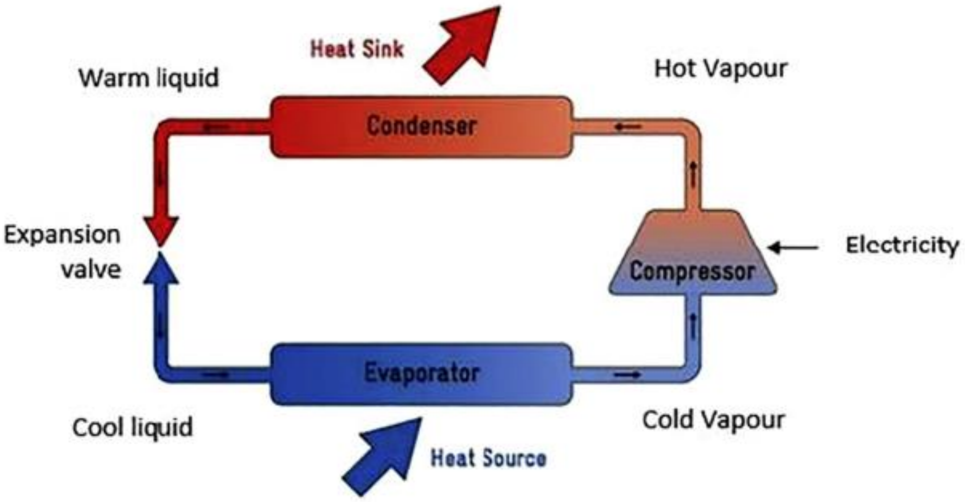


Figure 40 Heat pump working diagram [70].

The Kalina cycle [70] has a lower average heat rejection temperature (Tc) and a greater average heat addition temperature (Tb) when compared to the Rankine cycle. This, along with the Carnot efficiency (Carnot) obtained from Equation 9 below, results in a greater thermal efficiency [70].

$$\eta_{Carnnot} = 1 - T_c/T_b$$

Equation 19

Based on the above, Wang [71] proved that the Kalina cycle system outperforms the ORC by creating a mathematical model using waste heat recovered via a waste heat boiler [72].

On the other hand, Milewski [72] investigated the idea of Waste Heat Recovery (WHR) in the steel sector and discovered that the Kalina cycle performs better when the recovered heat is of medium-high quality. When the recovered heat was less than 200°C, the ORC outperformed the Kalina cycle in this research [72].

Table 3 Waste heat recovery technologies evaluation - Part A.

Technologies	Temperature Range	Advantage	Limitations
Regenerative Burners	High	By preheating the combustion air and increasing the efficiency of combustion, it will reduce the cost of fuel.	The system's operation is complicated since it requires extra components such as a pair of heat exchange medium and many control valves.
Recuperative Burners	High	Both exhaust gas and waste heat from the body of the burner nozzle are captured, resulting in increased heat generation from the nozzle.	The burner and nozzle must be placed into the furnace body, which may need the furnace to be installed and modified.
Economisers	Low –Medium	The system maximises a system's thermal efficiency by collecting low-medium temperature heat from waste flue gas and using it to heat/pre-heat liquids entering the system.	The system may require the use of advanced materials to withstand the deposition of acidic condensate, which can be costly.
Waste Heat Boilers	Medium-High	The system is intended to recover heat from exhaust gases with a medium-high temperature range and to generate steam as an output.	If the waste heat is insufficient to generate the required amount of steam, an additional unit such as an auxiliary burner or an afterburner may be required in the system.
Recuperators	Low –High	The technology is employed in low–high-temperature applications and is used to reduce energy consumption by	To maximise the system's heat transfer efficiency, more sophisticated designs may be required.

Technologies	Temperature Range	Advantage	Limitations
		preheating the incoming air into a system.	
Regenerators	Medium-High	The method is well suited for recovering waste heat from high-temperature applications such as furnaces and coke ovens, as well as applications with polluted exhaust.	The system's size and capital expenses may be quite big.
Rotary Regenerators	Low –Medium	Rotary regenerators are employed in low–medium temperature applications and have the potential to achieve extremely high heat transfer efficiency.	The system is not appropriate for high-temperature applications due to the structural stresses and deformations that can occur at elevated temperatures.

Table 4 Waste heat recovery technologies evaluation - Part B.

Technologies	Temperature Range	Advantage	Limitations
Run around the coil (RAC)	Medium-High	This unit is utilised when the heat sources are too far apart for a direct recuperator to be employed and when cross-contamination between the two flow sources must be avoided.	This technology is proven to be significantly less effective than a direct recuperator and requires the operation of a pump, which requires more

Technologies	Temperature Range	Advantage	Limitations
			energy input and maintenance.
Heat Recovery Steam Generator (HRSG)	High	The system can be utilised to recover waste heat from a power generation or manufacturing plant's exhaust in order to considerably increase overall efficiency by creating steam for process heating in the industry or power generation.	The system functions through the use of numerous components and may require an additional burner to improve the quality of the recovered waste heat. On the other hand, the system is quite large and requires construction on-site.
Plate Heat Exchanger	Medium-High	Plate heat exchangers operate at elevated temperatures and pressures and are used to transfer heat from one fluid to another in situations where cross-contamination must be avoided.	Parameters such as temperature and load variation must be investigated, and based on that, an appropriate heat exchanger design must be established to avoid the structure of the heat exchanger failing in the application.

Technologies	Temperature Range	Advantage	Limitations
Heat Pipe Systems	Medium-High	Heat pipes have extremely high effective thermal conductivities, which results in a low-temperature drop for long-distance heat transfer and long life that requires no maintenance due to their passive operation. They operate at a cheaper cost than other forms of heat exchangers.	To obtain the best performance from the heat exchanger, it is necessary to study and select an appropriate design, material, working fluid, and wick type based on the application and temperature range of the waste heat.

3.1.14 Waste Heat Distribution and Potential of Recovery:

The estimated total waste heat resource in the United Kingdom is 391,000 GWh [28].

This is an estimate, and while most of this heat can be recovered, some is either irrecoverable (such as heat generated during the welding of automobile bodies) or is already being retrieved (such as in the calcination preheating in cement production facilities).

Considering the total estimated waste heat of 391,000 GWh, approximately 46,000 GWh is estimated to be from industry, whereas waste heat from electricity generation is estimated to be approximately 345,000 GWh [28]. The distribution of total waste heat is primarily concentrated in the central part of the United Kingdom, particularly in the Midlands and the Northeast, see Figure 41.

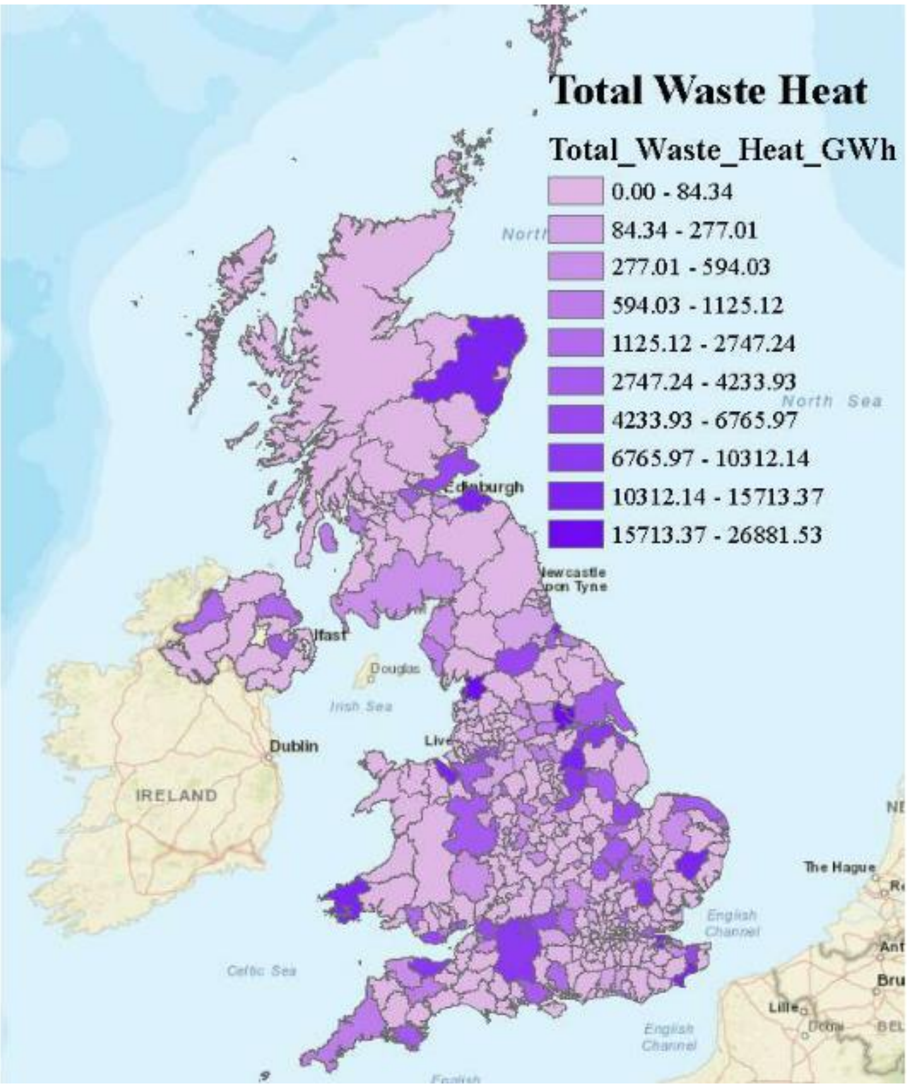


Figure 41 Distribution of estimated total waste heat in the UK [28].

The electricity production industry generates the bulk of waste heat, followed by the food and beverage, chemical, and mineral sectors, which all contribute much more. Metal processing and vehicle manufacture contribute far less (see Figure 42).

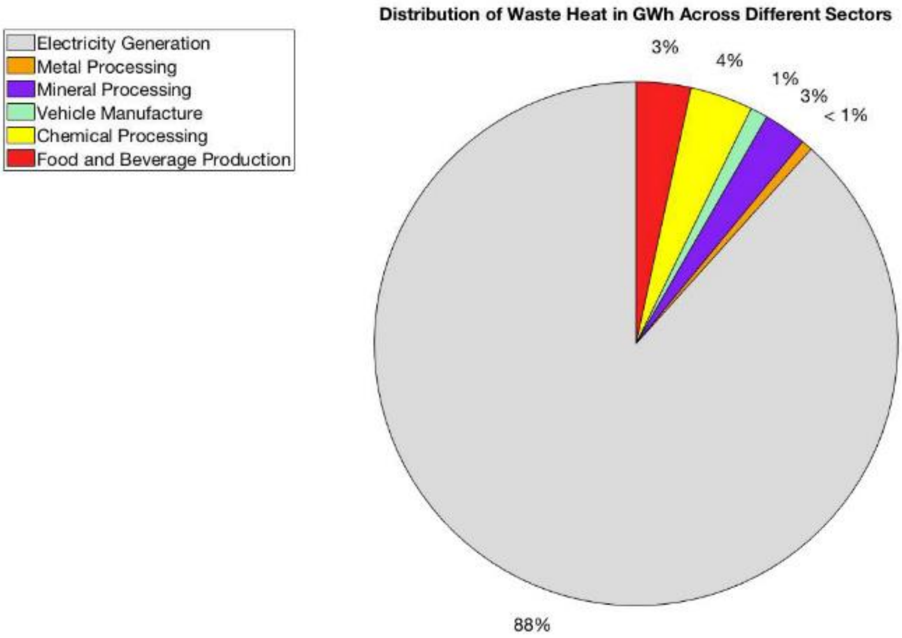


Figure 42 Distribution of estimated total waste heat [28].

3.1.14.1 Electricity Generation, 345,000 GWh

In the United Kingdom, the majority of waste heat is concentrated in Yorkshire and the Midlands, with additional concentrated high regions in other parts of the country, see Figure 43.

Areas with a high concentration of power plants, particularly those that constantly operate with a high load factor, generate a lot of waste heat. Numerous considerations, such as access to fuel and a good heat sink, might influence the site of a power plant.

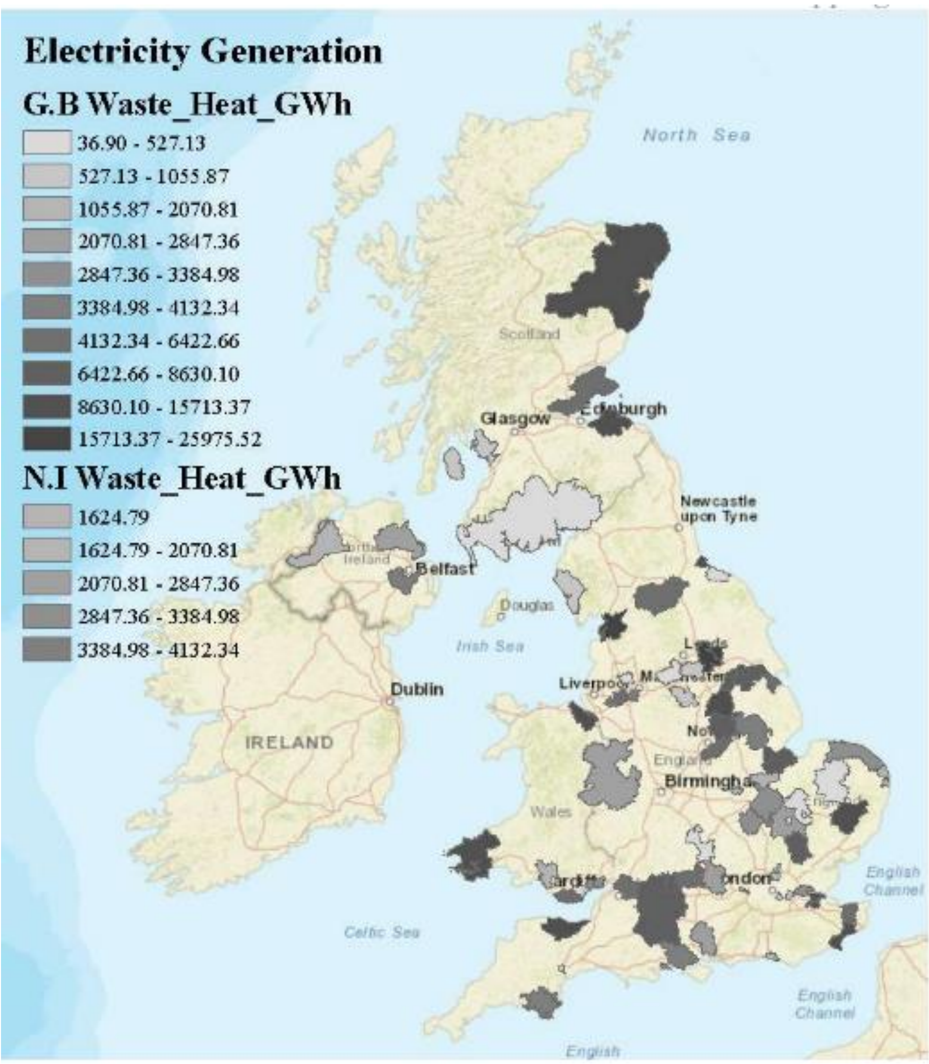


Figure 43 Distribution of estimated waste heat from electricity generation in the UK [28].

Historically, the construction of a power plant resulted in an increase in population density in the area since workers lived close to the plant. This could account for the roughly linear relationship between population density and waste heat from electricity generation depicted [28].

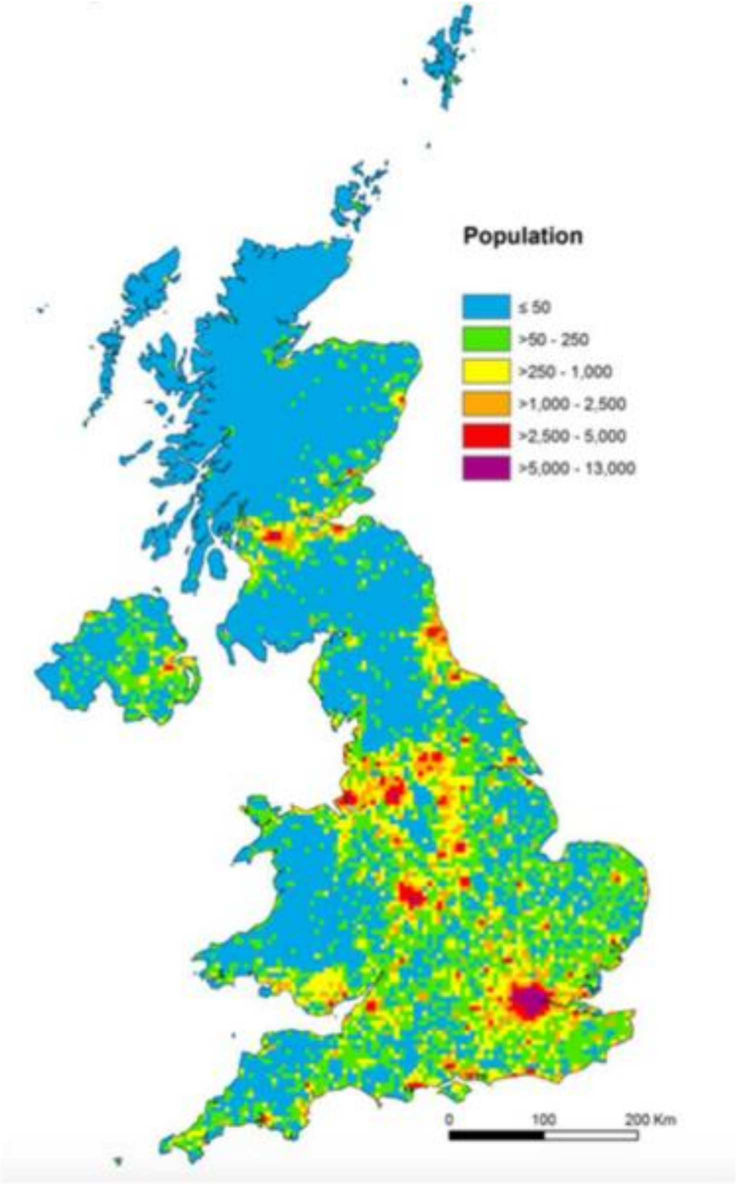


Figure 44 Population density in the UK [28].

However, the location of various types of power plants will be determined by a variety of circumstances. For example, natural gas power stations are concentrated along the coast, near gas pipelines, which may account for Aberdeenshire's and South Wales' high waste heat estimations. A detailed examination of the locations of each type of power station would exceed the scope of this report's time limits. The sector research findings on each form of energy generation and the associated waste heat are discussed.

3.1.14.2 Natural Gas

Since summer 2019, the UK has operated 61 natural gas-fired power plants. This category encompasses the following: Gas, Gas Oil, Gas Oil/Kerosene and CCGT.

CCGT power plants account for 38 of these plants, with an average efficiency of 49% and installed capacities ranging from 50 to 2,199 MW. CCGT power plants have a power load factor of 42.7%, showing that they operate at a higher rate of efficiency when compared to other types of power plants, which all have lower load factors with the exception of nuclear.

As a result, they contribute significantly to overall heat waste, around 120,000 GWh, see Figure 45 [28].

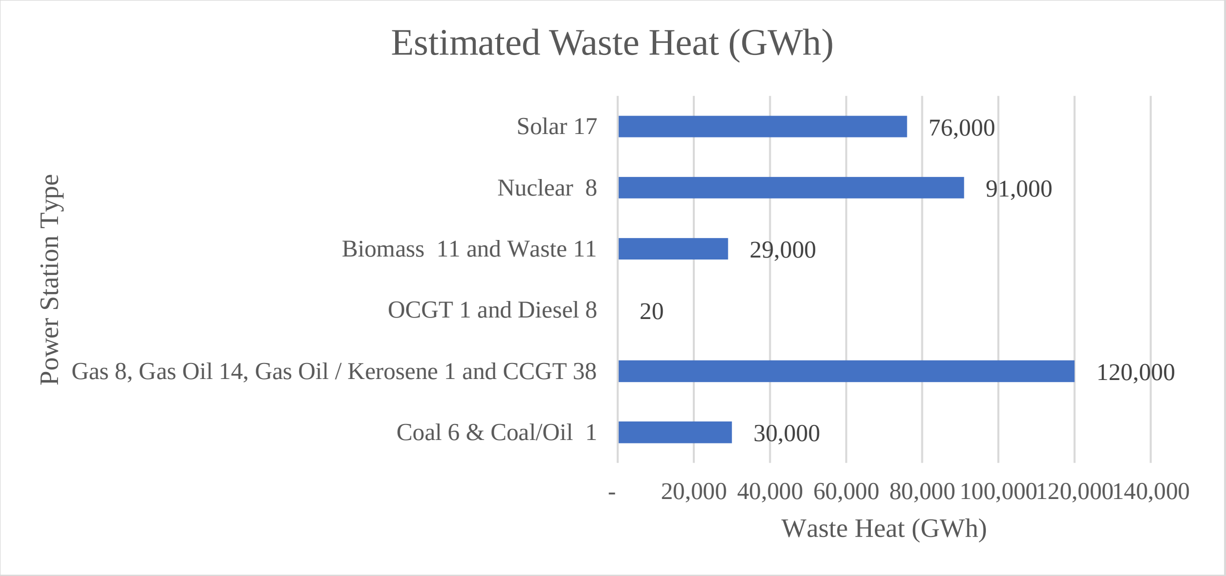


Figure 45 Estimated Waste Heat (GWh) [28].

3.1.14.3 Waste Heat Sources in the UK

The following are notable waste heat sources in the UK:

- Chemical Sector: Chemical energy consumption is 15,200 GWh and generates 3794.88 GWh waste heat, see Figure 46 [28].

Figure 46 Distribution of estimated waste heat from the chemical industry [28].

- Food and Beverage Sector: Food and Beverage energy consumption is 14,700 GWh and generates 1,131.13 GWh waste heat, see Figure 47

Figure 47 Distribution of estimated waste heat from the UK Food & Beverage sector [28].

- Minerals Sector: Mineral energy consumption is 10,400 GWh and generates 2,493.12 GWh waste heat, see Figure 48 [28].

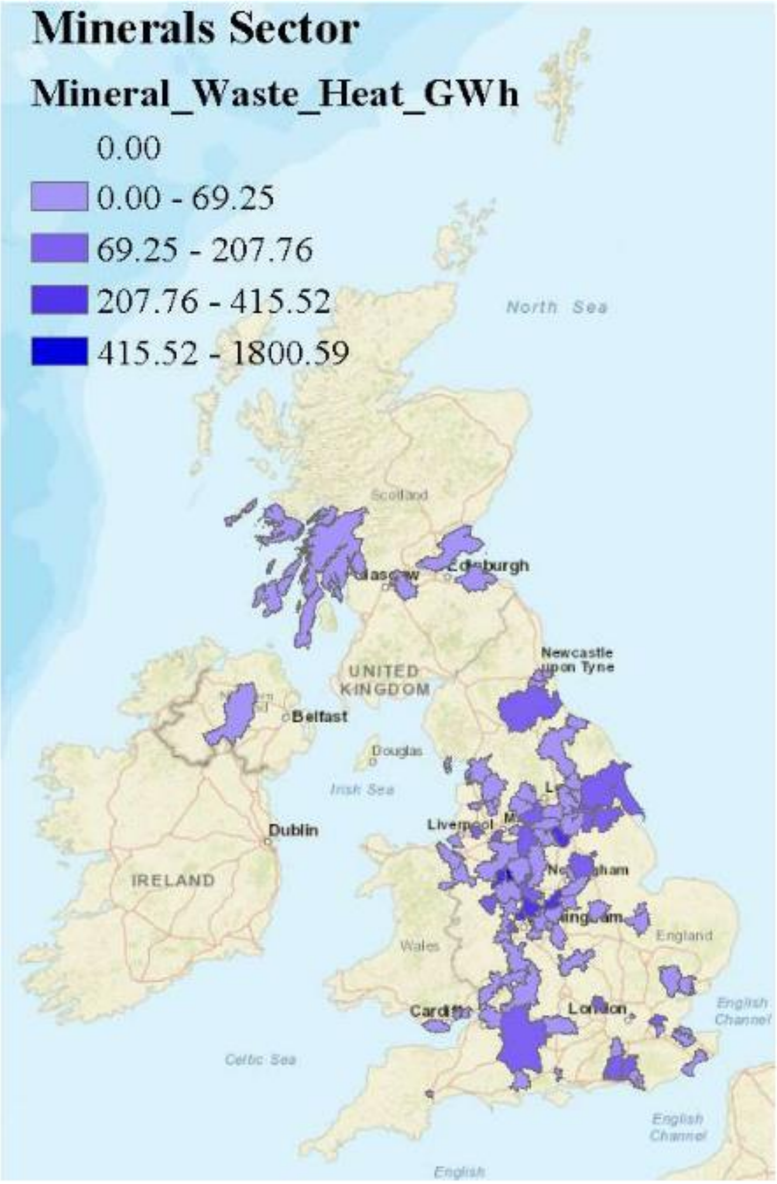


Figure 48 Distribution of estimated waste heat from the UK Minerals sector [28].

- Vehicle Sector: Vehicles energy consumption is 4,200 GWh and generates 414.32 GWh waste heat, see Figure 49 [28].

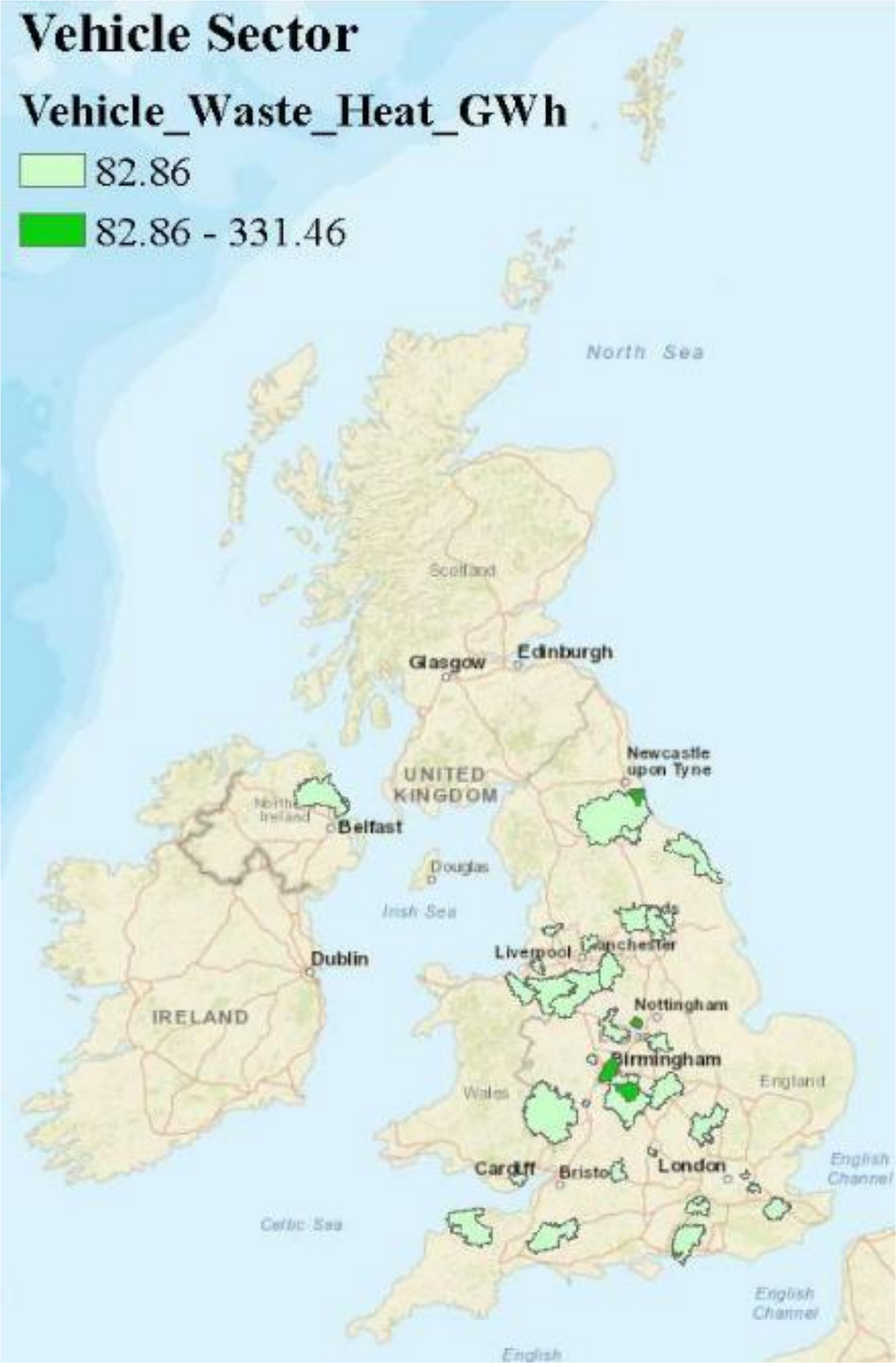


Figure 49 Distribution of estimated waste heat from the UK vehicle sector [28].

- Iron and Steel Sector: Iron and Steel energy consumption is 2,800 GWh and generates 805 GWh waste heat, see Figure 50 [28]

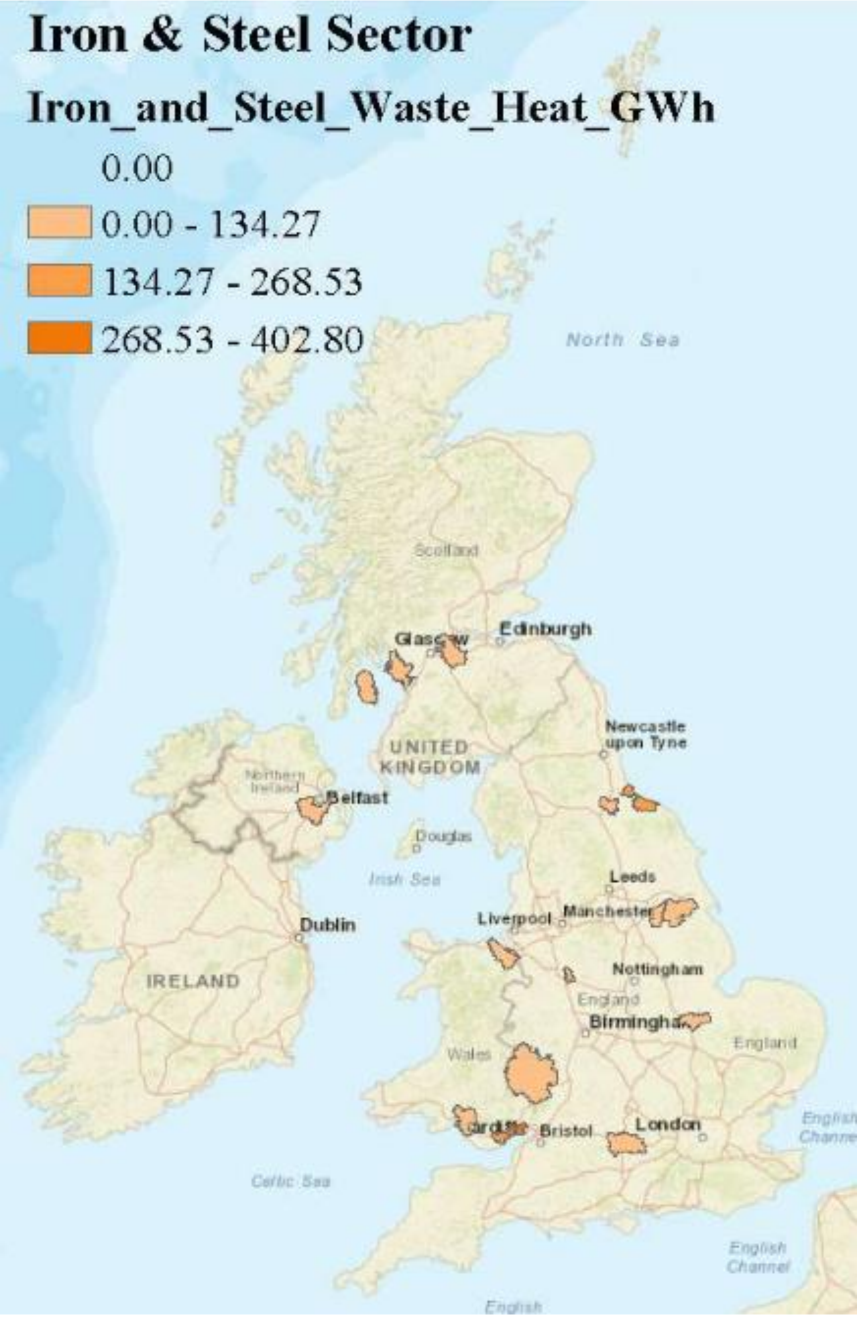


Figure 50 Distribution of estimated waste heat from the UK Iron & Steel sector [28].

3.2 Ground, Water, Air Heat Pumps

3.2.1 AIR Source Heat Pump (ASHP)

ASHPs derive their energy from the ambient air [73]. Air/water systems deliver heat via wall radiators or underfloor pipes [73] via a hydronic system. Heat energy is distributed throughout the building via ducts using air/air heat pumps. As ASHPs may be installed in high-density dwellings where ground source heat pumps cannot be installed, they provide great potential for retrofit schemes [73].

However, due to the exposed placement of the outside unit, they are susceptible to frost damage, especially in wet or cold areas. This risk can be reduced by situating the ASHP [73] in a protected or sunny location. Consideration should be given to the frosting problem and de- and anti-frosting methods [73] (Figure 51).

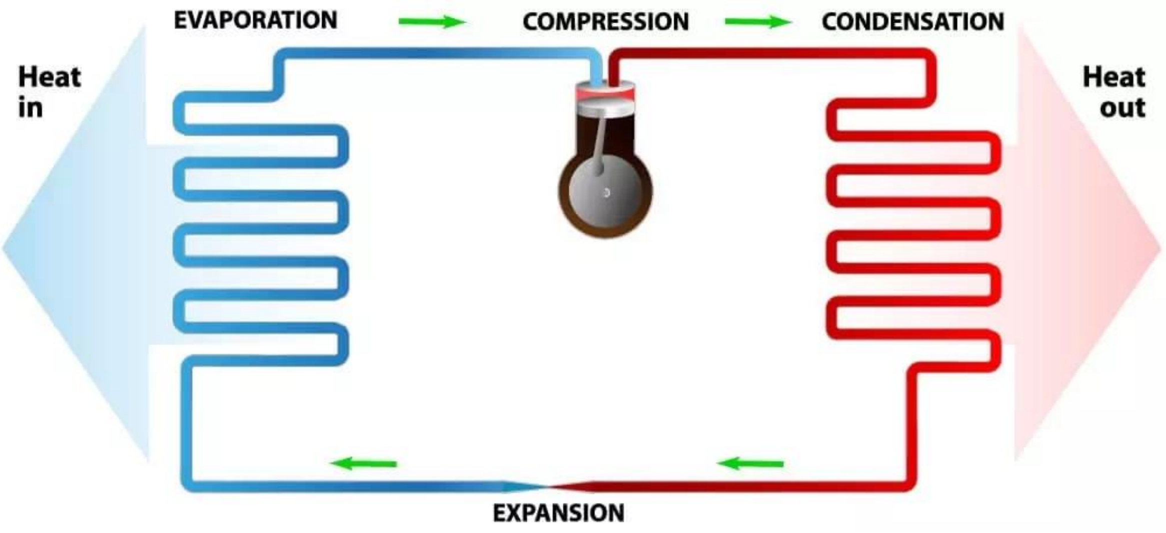


Figure 51 Air source heat pump process [73].

3.2.1.1 Limitation Of Air Source Heat Pump

Regrettably, the initial expense is almost certainly the primary downside of air source heat pumps. The majority of people just do not have or feel capable of paying the higher upfront expenditures.

The cost of air source heating is mostly determined by the cost of installing an air source heat pump [73]. Because renewable energy is a relatively new business, fewer people are familiar with it than with fossil fuel alternatives.

A significant disadvantage of air source heat pumps is that they do not produce the level of heat that some homeowners have grown accustomed to with the current technology.

In cold temperatures, air source heat pumps suffer from decreased efficiency and heat supply. When temperatures go below zero, air-source heat pumps must work harder and are therefore less cost-effective than they are in the summer.

3.2.2 Water Source Heat Pump (WSHP)

Water source heat pumps (WSHPs) are particularly efficient in transferring heat from a supply of water to your home[22], especially when the water temperature is between 5 and 8 degrees Celsius; there are various advantages to heat pump installation. Dependent on the type of heat pump, either water from a river or small stream or a particular refrigerant fluid is pushed through pipes laid in the body of water and is circulated through the heat pump.

While both types have their advantages, the latter requires less care and is easier to instal, making it a more affordable option [22].

Since the late 1940s [22], water source heat pumps have been in use. Rather than taking heat from the exterior air temperature[22], they use the relatively constant temperature of the water as an exchange medium. Thus, water source heat pumps may achieve relatively high efficiency (300–600%) even on the coldest winter nights, compared to 175–250% for air-source heat pumps on cool days. Water source heat pumps are extremely efficient because they use two kilowatts of free heat from the water and one kilowatt of energy to generate three kilowatts of heat [22].

This is accomplished through the passage of heat up the flue pipe. As a result, heat pumps have low operating expenses.

3.2.2.1 Limitation of Water Source Heat Pump

Open-loop water source heat pump systems face extra engineering issues associated with dealing with open water that may contain debris, have unstable pH values, or support biological growth, necessitating increased pumping loads.

Additionally, all but the smallest schemes will need to adhere to the Environmental Agency's abstraction standards.

The majority of these issues are avoidable by using a closed-loop system with heat exchangers immersed in the river or open water.

The primary disadvantage of employing a big body of water to achieve heat exchange with a generally constant temperature is that you cannot store summer heat in that body of water for the purpose of retrieving it during the winter.

3.2.3 Ground Source Heat Pumps (GSHP)

3.2.3.1 How does a GSHP function?

Ground Source Heat Pumps is a device that transports heat from the ground to homes. The sun's radiation heats the earth. The soil then stores the heat and maintains a temperature of roughly 10°C even in the winter, just two metres or so below the surface; the ground source heat pump taps into this regularly renewed heat store to heat buildings and provided hot water via a ground heat exchange loop.

The technology is comparable to that used in refrigerators. Similarly to how a refrigerator absorbs heat from food and distributes it to the kitchen, ground source heat pumps obtain heat from the ground and transfers it to a building, refer to Figure 52.

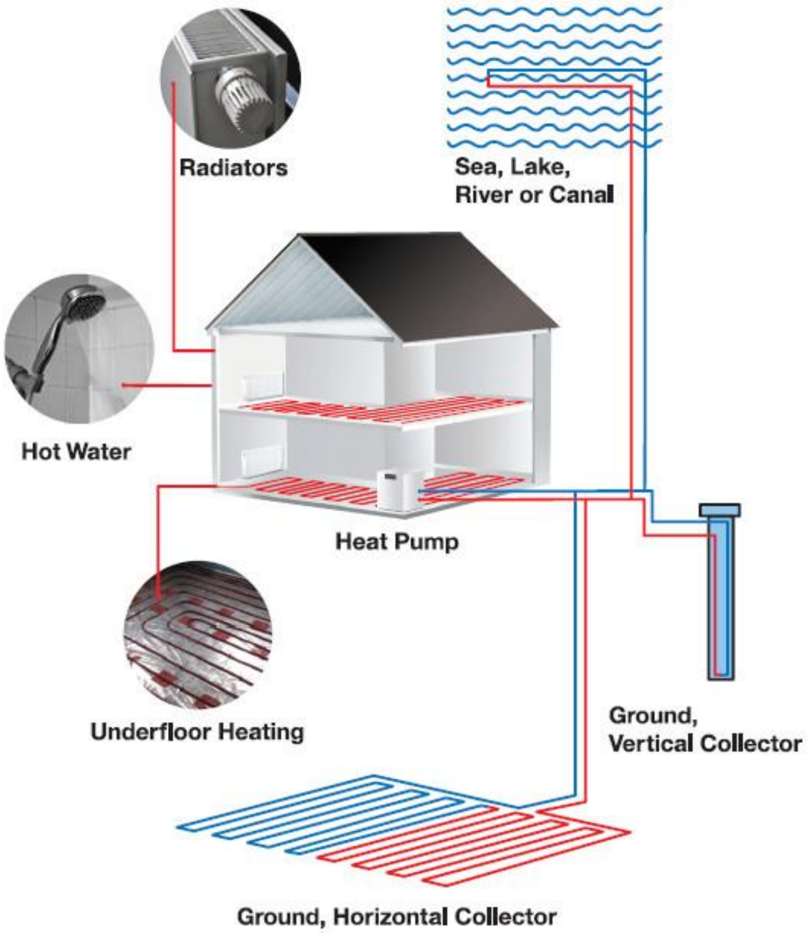


Figure 52 Ground source heat pump process [65].

Because groundwater is generally constant in temperature, the systems can attain a greater Coefficient of Performance (COP) than ASHPs.

A ground source heat pump system is composed of three fundamental components: a ground heat exchange loop, a heat pump that concentrates available ground heat, and a heat distribution system. The ground loop is a pipe that is buried underground, either horizontally or vertically, in a trench or borehole.

Two metres below ground level, horizontal trenches are dug and, while requiring more land than boreholes, are typically less expensive for smaller systems. Boreholes are created from 15 to 150 metres deep and may benefit from warmer ground temperatures than trenches [65].

There are several different styles of pipe that can be used in a trench rather than a straight one, increasing the quantity of heat taken from the ground and hence performance [57]. The amount of ground area required for trenches varies according to the location, the property, and the desired heat output. As a general reference, two trenches of 30-40 metres in length would normally be necessary for a newly constructed three-bedroom house of approximately 120 m2 with a heat loss of approximately 6kW.

The pipe is pumped with a mixture of water and antifreeze., absorbing heat from [57] the earth. The absorbed heat is then extracted and transferred to the heat pump via a heat exchanger. The third fundamental component of a ground source heat pump [57] is the heat distribution system, which might be low-temperature radiators or, more ideally, underfloor heating.

When asked to generate higher temperatures [65], as in a normal radiator circuit, the heat pump's efficiency decreases.

If the site has direct access to an aquifer [65], as is often the case in the Southeast of England, one alternative to a closed ground heat exchange loop is to build two open-loop boreholes to absorb heat directly from the aquifer. After installing a ground source heat pump, no exterior fans or equipment are visible. The system runs quietly, emits no pollutants, is extremely safe, and requires no maintenance.

3.2.3.2 Advantages of Ground Source Heat Pumps

A list of the advantages of GSHPs is as follows:

- GSHPs are cost-effective. Heat pumps are significantly less expensive to operate than direct electric heating systems.
- GSHPs are more cost-effective to operate than oil boilers, coal, LPG, or natural gas boilers. This is before RHI benefits are included, which total more than £3,000 per year for an ordinary four-bedroom detached house – more than any other technology covered by the RHI.
- Because heat pumps may be completely automated, they require significantly less maintenance than biomass boilers.
- Heat pumps are space-saving.

- There are no requirements for fuel storage.
- There is no requirement to manage fuel deliveries.
- There is no possibility of gasoline theft.
- Heat pumps are completely safe.
- There is no combustion and hence no release of potentially hazardous gases.
- There is no requirement for flues.
- GSHPs require less maintenance than conventional heating systems that use combustion.
- GSHPs have a greater life expectancy than combustion boilers.
- A ground source heat pump installation's ground heat exchanger element has a design life of more than 100 years.
- Heat pumps help to reduce carbon emissions.
- In comparison to burning oil, gas, LPG, or biomass, a heat pump emits no carbon dioxide on-site (and no carbon emissions at all if a renewable source of electricity is used to power them).
- GSHPs are safe, silent, unobtrusive, and out of sight; they do not require planning approval.
- Heat pumps can also be used to offer cooling in the summer and warmth in the winter.
- A well-designed ground source heat pump system will likely raise the value of a property when it comes time to sell.

3.2.3.3 Limitation of Ground Source Heat Pumps

Due to the requirement for a ground heat exchanger, GSHPs are more expensive to install than air-source heat pumps. However, it is this link to the earth that enables a GSHP to operate much more efficiently than an ASHP, notably during the coldest months of the year when heating is most needed.

Ground source heat pumps can cause problems if the installation is not properly built or matched to the building's heating requirements.

Effective ground source heating and cooling systems require a thorough understanding of how heat moves through the local geology, the ground, and the heating and cooling requirements of your facility. To reap the benefits of a well-designed system, an expert installer must be used. This raises the installation cost, but proper design and planning will result in significant savings during the system's life.

4.0 Scenarios To Decarbonise Glasgow Heating Systems

Hydrogen generation technology, waste heat technology, and heat pump technologies would be carbon-free technologies if they were supplied by a renewable energy source. Therefore, during this thesis, all these technologies were thoroughly examined in terms of their designs, limitations, and benefits. Based on these findings, two scenarios were developed: one involving hydrogen generation via electrolysis and the other involving the collection of heat pump technologies to electrify heating in Glasgow, as illustrated in Figure 53

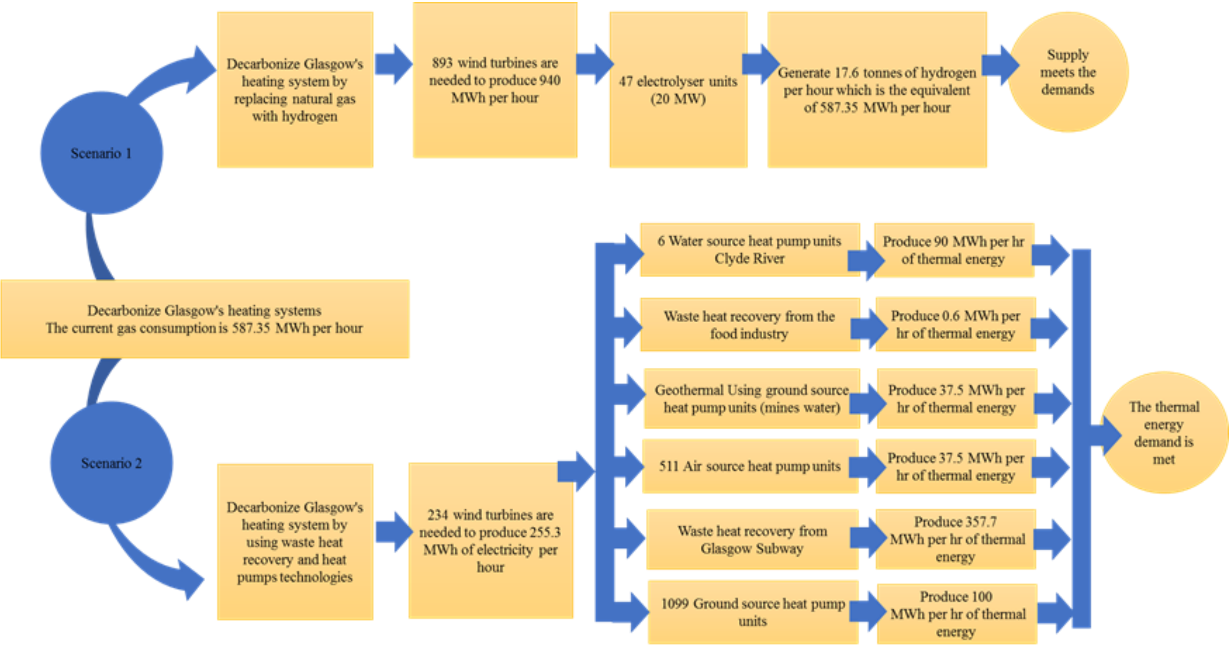


Figure 53 Decarbonize Glasgow's heating systems Scenario 1 and 2

4.1 Scenario one, H2 from the grid

The city of Glasgow consumes 5145.2 GWh per annum of gas, as illustrated in Figure 54 [23].

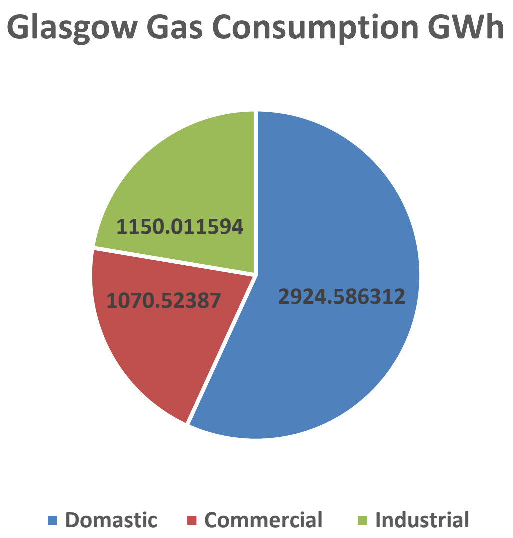


Figure 54 Glasgow gas consumption [23].

Equation 10 below calculates the hydrogen demand equivalent of the total gas consumption.

$$\text{Hydrogen demand} = \left(\frac{\text{total Gas Energy kWh} * \text{conversion value from kWh to Mj}}{\text{LHV for H2}}\right)$$

Equation 20

For Glasgow, the hydrogen demand equivalent of the total gas consumption can be calculated as shown in Equation 11.

Hydrogen demand equivalent $= \left(\frac{5145.2*10^6*3.6}{119.96}\right)$

$= 154407469.2\frac{kg}{year}\ of\ hydrogen = 154407.469.\frac{Tonne}{year}\ of\ hydrogen$

This means Glasgow hydrogen demands per hour is 17.6 tonnes/hour.

Equation 21

Therefore, to replace natural gas consumption with hydrogen gas in Glasgow, $17.6\frac{Tonnes}{hour}$ would be needed.

4.1.1 Calculation of Number of Electrolyser Units

A 20 MW Electrolyser unit at 62% precent efficiency will generate 0.372 Tonne/hr and consume 3.3249 Tonne/hr of water, refer to Equations 12 and 13 below.

$$The\ number\ of\ electrolyser\ units\ = \frac{Total\ hydrogen\ demands\ per\ hour}{Hydrogen\ production\ by\ electrolyzer\ unit}$$

$$The\ number\ of\ electrolyser\ units\ = \frac{17.6}{0.372} = 47\ Electrolyser\ unit$$

Equation 22

Therefore, the total number of electrolyser units that would be required to produce the quantity of hydrogen required is 47 Electrolyser units.

4.1.2 Calculation of the Required Water Consumption

The water consumption required to operate the 47 electrolyser units required is calculated in Equation 13 below.

$$\begin{aligned}&The\ water\ demands\ to\ generate\ hydrogen\\&\qquad = the\ number\ electrolyser\ unit * water\ demand\ per\ hr\end{aligned}$$

$$The\ water\ demands\ to\ generate\ hydrogen\ = 47 * 3.3249 = 156.27\ tonne/hr$$

Equation 23

The water consumption converted to the metric cube is 156.27 m^3/hr, which is the equivalent to 3% of the current water consumption of Glasgow when compared with the results of Equation 14 below.

As per the Glasgow City Council’s website, Glasgow has 295,761 households [23], and water consumption per household is 0.0187 m^3 per hour [24].

$$\begin{aligned}&Glasgow\ city\ water\ consumption\ calculation\\&= \ number\ of\ household * \ the\ water\ consumption\ in\ one\ house\ holds\end{aligned}$$

$$\begin{aligned}&Glasgow's\ water\ consumption\ per\ hr\ calculation\\&= \ 295761 * \ 0.0187 = approximatly\ 5530.7307\frac{m^3}{hr}\end{aligned}$$

Equation 24

4.1.3 Calculation of the Required Number of Wind Turbines

Based on the results of Equation 15 below, 19 wind turbines (Vestas V112/ 3000 capacity factor 36.3%) would be required to supply a single 20 MW electrolyser unit with electricity, where each wind turbine would generate 3 MW[74].

$$The\ required\ wind\ turbines\ = \ number\ of\ electrolyser\ units\ * \ 19\ wind\ turbines$$

$$The\ required\ wind\ turbine\ = \ 47\ * \ 19 = 893\ wind\ turbine$$

Equation 25

The overall number of wind turbines that would be required to supply the required number of electrolyser units (47 electrolyser units) with electricity is 893 wind turbines. Considering the UK currently has an estimated 10,000 wind turbines, this would be approximately 8.93% of the current number of wind turbines in the UK.

4.1.4 Limitation of Using Hydrogen from the Grid

The key limitations of using hydrogen from the grid as an alternative to natural gas for Glasgow are as follows:

- Hydrogen currently is incompatible with appliances, boilers, and infrastructure.
- The amount of water required to supply the number of electrolyser units required is equivalent to 3% of the current water consumption of Glasgow, as noted above.
- The needed number of wind turbines to power the number of electrolyser units required is approximately 8.93% of the current number of wind turbines in the UK, as noted above.

4.2 Scenario two Glasgow Heating Network Potential

The assessment of heating technologies discussed in earlier sections of this report indicates that focusing exclusively on one technology will not suffice to decarbonize Glasgow’s heating; therefore, a hybrid system must be implemented. According to Glasgow City Council, Glasgow is consuming around 5145.2 GWh of natural gas, and this energy must be matched by the designed hybrid heating systems.

4.2.1 Water Source Heat Pump (River Clyde)

4.2.1.1 Drammen District Heating

4.2.1.1.1 Drammen system overview

The on-site ammonia heat pump is comprised of three by two-stage Vilter single screw compressor units connected in series [75], each with a heating capacity of roughly 4.5 MW. Star Refrigeration Ltd, based in the United Kingdom, designed the installation and built the heat pumps[10]. The supply temperature of district heating water varies throughout the year based on the amount of heat required.

In the summer, while demand is low (less than 2 MW) [75], the supply water temperature is 75°C; when the ambient temperature drops and the heating demand increases, the supply water temperature rises to 120°C at peak load[75].

The temperature of the district heating loop's return water is relatively consistent throughout the year, ranging between 60°C and 65°C. When gas boilers are used, they operate on a steady flow with a temperature difference of 10°C between the entrance and outflow[10] . After mixing the water with district heating water, the appropriate outgoing temperature is achieved. To maximize the heat pump's effectiveness, it was critical to have a variable flow system that drew water directly from the district heating return line, as every degree of subcooling is critical, and any degree of overheating is a waste of energy. Seawater serves as the heat source for the heat pump.

Norway is renowned for its rugged coastline. The thermodynamic beauty of this area is found in the fact that the sea becomes extremely deep just off the coast.

When taking in water at a depth of 40 meters, the water temperature remains consistent between 8 and 9°C for the majority of the year.

At this level, fluctuations in air temperature from +30°C in the summer to -20°C in the winter have a negligible impact on water temperature. The water intake pipe extends 800 meters into Oslo Fjord [10], while the return pipes are 600 meters in length to prevent the 4°C output water from mixing with the inflow water.

The seawater pumps are located on land but at a lower elevation than the sea. Seawater is cooled directly in spray chillers [75], which spray ammonia through titanium pipes containing seawater.

4.2.1.1.2 Results

85% of Drammen's district heating heat demand is met by the installed heat pumps. The heat supplied by gas boilers is varied from 2 MW in the summer to 13.2 MW in the winter, with a peak of up to 15 MW [10].

Even with such a wide temperature differential between the seawater source and the district heating water loop, the heat pump installation can maintain a fairly constant coefficient of performance (COP) of 3.05 for water at 90°C throughout the year [75].

Table 5 The result of Drammen district heating [75].

	Summer	Winter
Heat capacity	2 MW	13 MW
Heat source	Seawater cooling from 8°C to 4°C	
Heat sink-water loop temperature	60°C to 80°C	60°C to 90°C
COP	2.80	3.05

Annual energy use averages 67 GWh. The whole amount of 200 GWh will be reached by the end of 2014. This is the carbon dioxide equivalent of driving 188 million kilometres in a car, except that Drammen has avoided it.

The entire cost of electricity for an ammonia heat pump installation would be approximately 659,000 € per year, compared to 3,350,000 € per year for a gas boiler installation. There is an expected annual savings of 2,690,000 Euros.

4.2.1.2 Glasgow Weather Versus Drammen Weather

Glasgow has a warm and temperate climate. Glasgow receives heavy rainfall throughout the year [76]. Even the driest month receives significant rainfall. Glasgow's yearly average temperature is 8.1°C. The annual rainfall totals 1228 mm, see Figure 55.

Drammen has a cold and temperate climate. Even in the driest month, Drammen receives plenty of rain. Drammen's average temperature is 5.4°C. The annual rainfall is approximately 1022mm [76] .

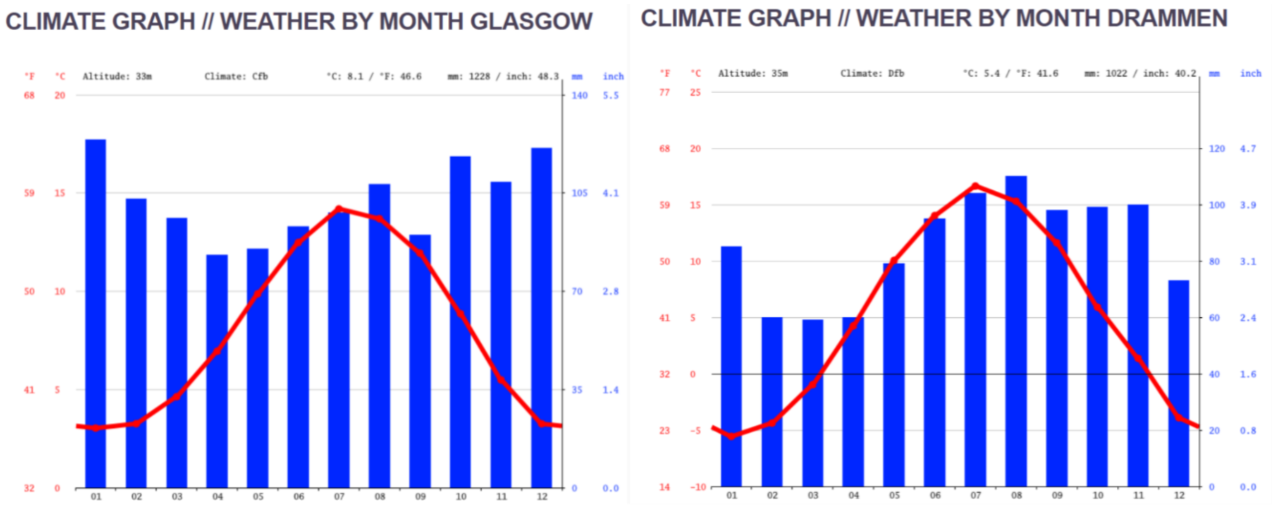


Figure 55 Glasgow weather versus Drammen weather [76].

4.2.1.3 Glasgow's Water Source Heat Pump District Heating Boundaries

According to Section 4.2.1.2, which compares Glasgow's weather with Drammen's weather, Glasgow is a few degrees warmer than Drammen, which will improve heat pump efficiency.

Only 6 heat pump units could be situated on the River Clyde's coast and are intended to serve 28 km^2 of Glasgow, refer to Figure 50; each unit is 15 MW with a 3.05 COP (refer to Table 6 below); nevertheless, this project only meets 90 MWh per hour (Figure 56).

Due to the extensive use of the River Clyde water, this project would require a complicated SEPA licence.

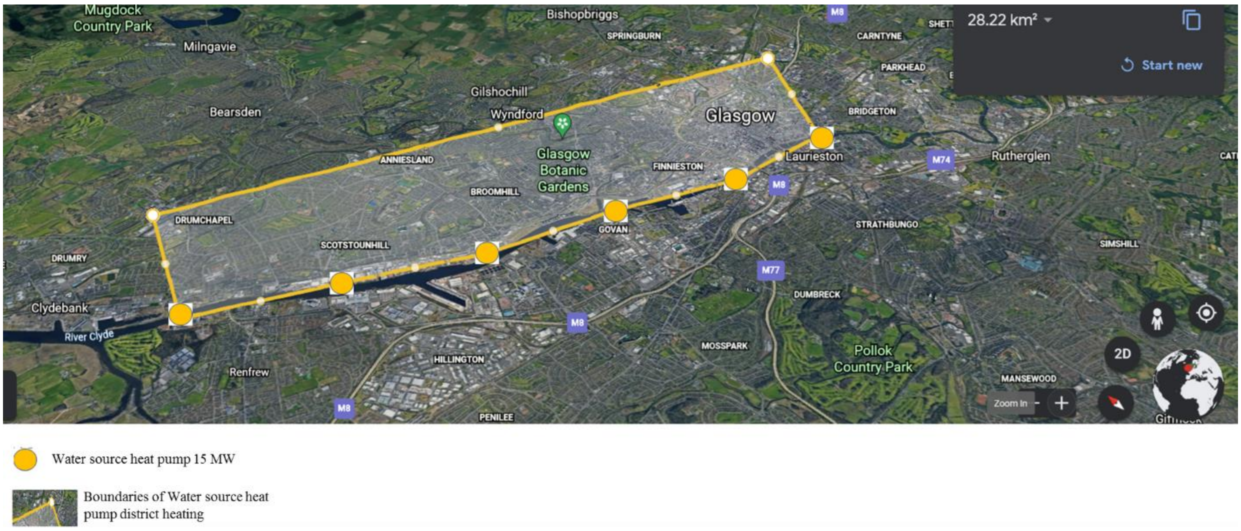


Figure 56 Water source heat pump map.

4.2.1.3.1 Model of seasonal fluctuation in COP

Seasonal variations in river temperature affect the heat pump's coefficient of performance (COP). The variance is assumed to be 4.6% of the intended COP per degree. This indicates that increasing the water temperature by one degree leads to a 4.6% rise in COP, whereas decreasing the water temperature by one-degree results in a 4.6% drop in COP Figure 57 and Table 6.

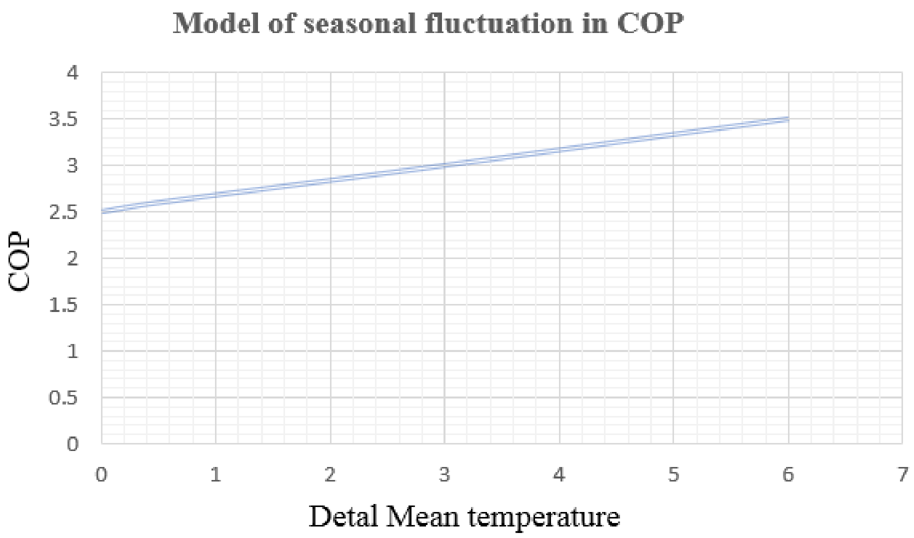


Figure 57 Model of seasonal Fluctuation in COP.

Table 6 The simulated result of the Glasgow heating network.

	Summer	Winter
Heat Capacity	2 MW	15 MW
COP	2.90	3.05

4.2.2 Heat Recovery from Food Industries

The distillery and waste-water treatment industries were estimated to have the highest waste heat potential. Significant quantities of heat may be re-used by implementing appropriate heat recovery technologies (e.g., water-to-water heat pumps). Bakeries and paper and pulp industries also have significant waste heat potential owing to their high energy usage [12].

In contrast to other industries, data centres, supermarkets and breweries have comparatively little waste heat potential. According to the GIS view of waste heat potential distribution (refer to Figure 58, Glasgow can generate 5000 MWh heat waste per year which means it generates 0.6 MWh for one hour).

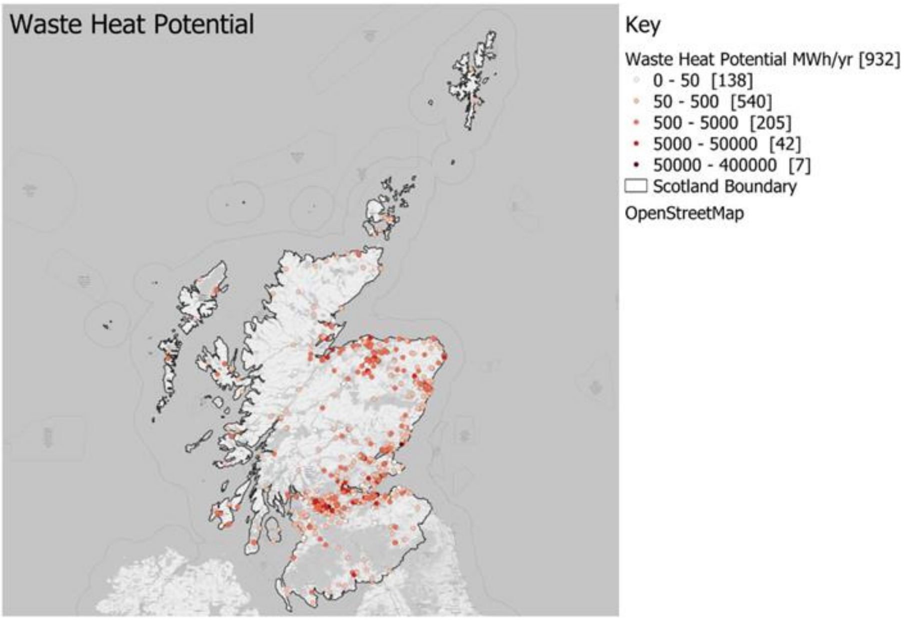


Figure 58 GIS view of waste heat potential distribution (number of sites in square brackets [12].

4.2.3 Heat Recovery from Glasgow Subway

4.2.3.1 Wastewater Temperature

A field experiment site was chosen based on four factors [77][25]: distance (from the "source" to the "sink"), water flow dependability, temperature, and water quality. Figure 59 shows the temperature variations for the subway tunnel (average temperature = 14.2 C).

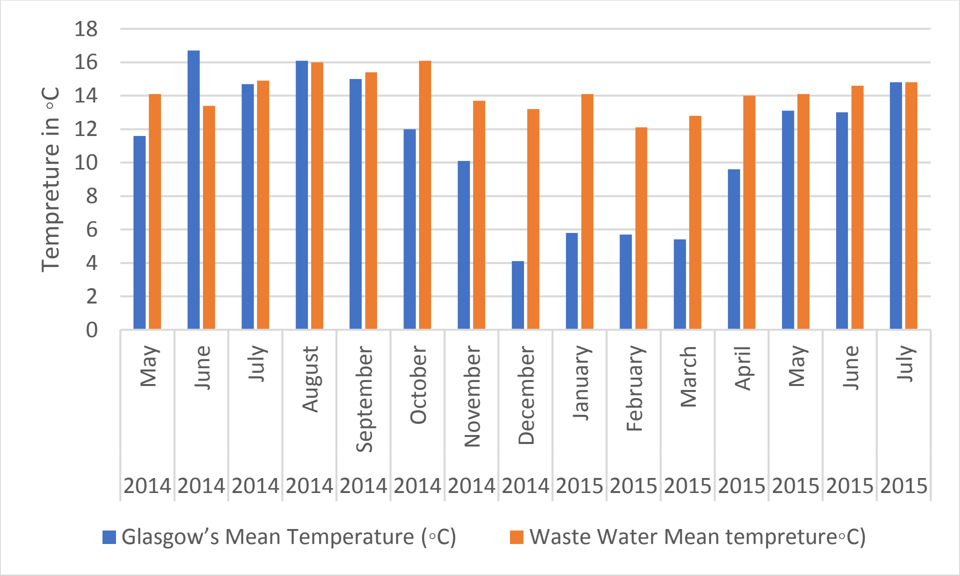


Figure 59 Glasgow and wastewater temperatures during the monitoring period [77].

A Water Source Heat Pump (WSHP) installation at Glasgow's Underground Station utilised subterranean wastewater intrusion to heat the office at St. George's Cross station. For a few months, the operation of the Glasgow Subway's new heating system was monitored. The real system's performance is shown by an average coefficient of performance (COP) of 2.5 and a 60% energy input reduction for the heating system based on the energy demand of the previous heating system (Figure 60).

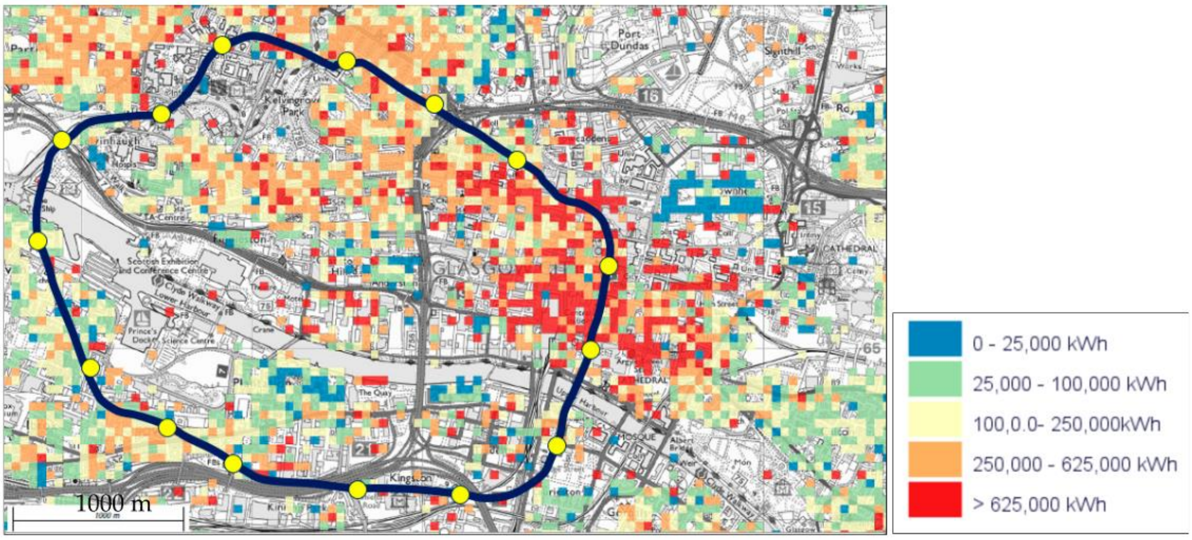


Figure 60 Superimposing the Glasgow Subway map onto Glasgow's Heat Map. Source: Scottish Heat Maps. Legend: Colour marking of heat demand in Glasgow.[77] [25].

The heat requirement for St George's Cross station was estimated to be 5.2 kW [25]. As a result, a 9 kW water source heat pump [25]was required to meet the heating and domestic hot water demands.

The main components of this experimental installation are outlined in a design schematic (Figure 61).

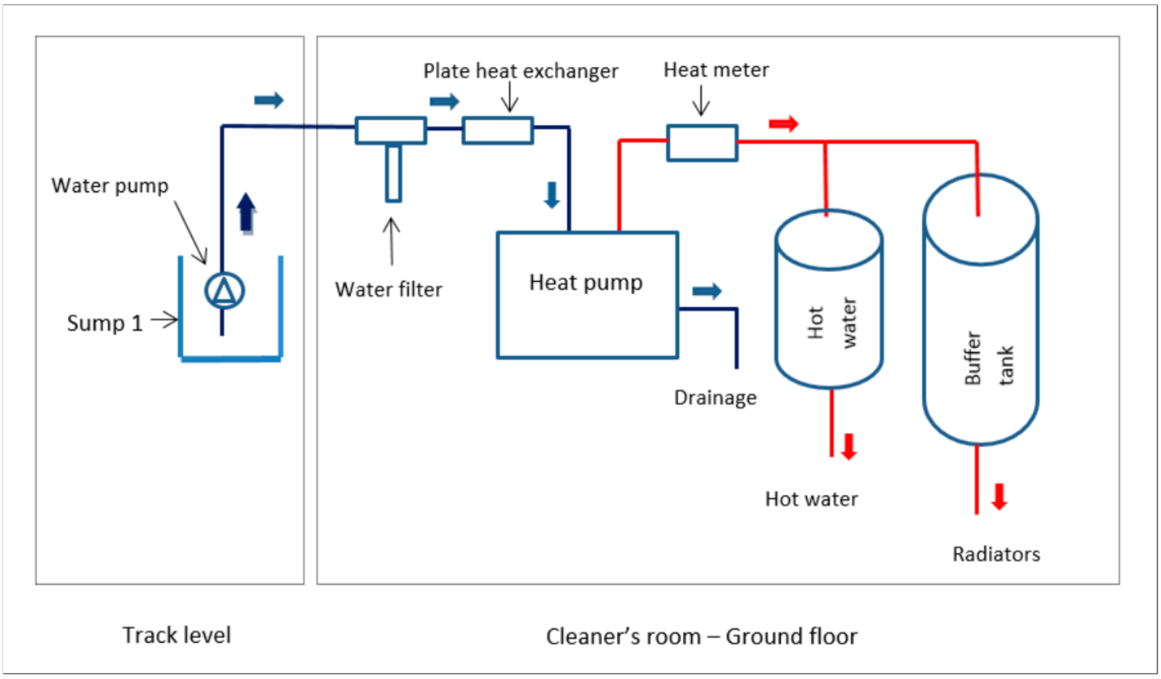


Figure 61 Station's diagram of the heating system [25].

The technology conformed with fire standards, which was essential given the trial's subterranean location [25]

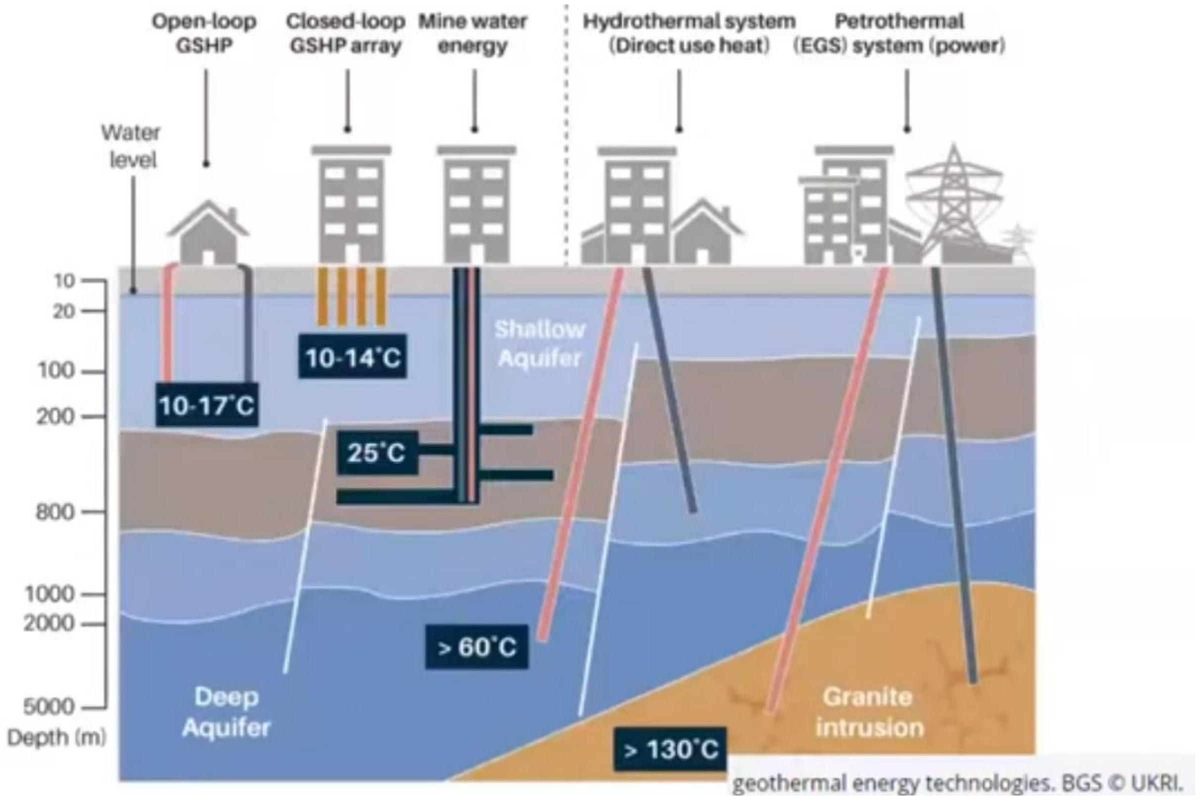
This trial's total installation cost was £44,000. This comprised the heat pump and its accompanying equipment, as well as pipework and labour.

The absence of boreholes, once the water was available at the trial location , was an advantage of this experiment, which kept the cost low when compared to a conventional WSHP arrangement .

The disadvantage was that all maintenance was done during non-operational Subway hours, which resulted in higher labour costs (from midnight to 5 a.m.); nevertheless, this project only generates 0.75 MWh per hour

4.2.4 Geothermal Ground Source Heat Pump

The geothermal heat resource underneath Glasgow is classified into three types: abandoned mine workings (low temperature)., hot sedimentary aquifers (low and potentially quite high temperature), and hot dry rocks / petrothermal sources (relatively high temperature) The below Figure 62 illustrates the geothermal temperature range.



geothermal energy technologies. BGS © UKRI.

Figure 62 Geothermal heat source under Glasgow

Figure 63 indicates mined areas located under Glasgow and the surrounding area.

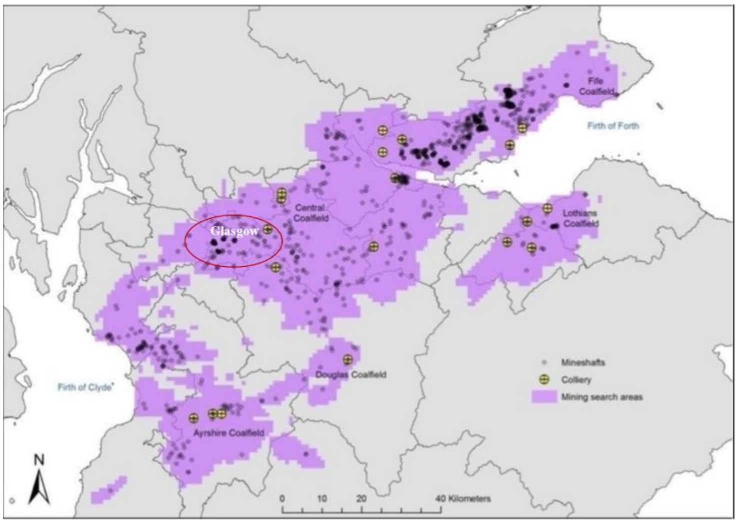


Figure 63 Mines area under Glasgow [78].

It is predicted that open-loop ground source heat systems [78]. in Scotland's mined regions may provide approximately 2.5 megawatts per kilometre square (MW/km^2).

[78]. When this value is multiplied by the number of square kilometres in the mined region (2.5 x 15 km^2), a rough estimate of the available heat of 37.5 MW has obtained [78].

4.2.5 Air source heat pump and ground source heat pumps

The yellow boxes indicate the coverage area of air source heat pumps (ASHPs) in Glasgow; each ASHP has a coefficient of performance of two and a heat capacity of 0.7 MWh per hour. The red boxes are the GSHP units; each unit has a coefficient of performance of three and a heat capacity of 0.091 MWh per hour (Figure 64) both technologies from star refrigeration [16] [17] .

- 511 Air source heat pumps are needed to generate 358 MWh of heat per hour
- 1099 Ground source heat pumps are needed to generate 100 MWh of heat per hour

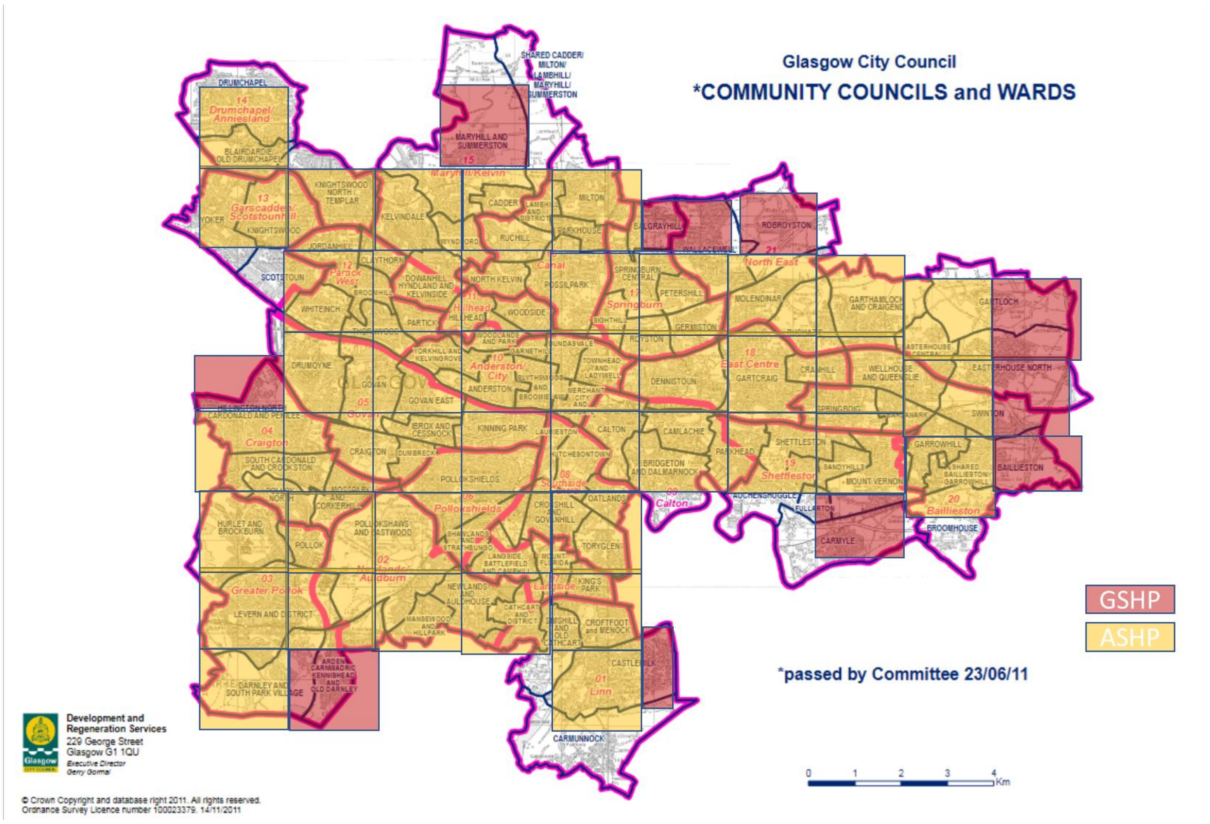


Figure 64 Air source heat pumps and ground source heat pumps' potential locations.

4.2.6 Electricity demand calculation for the heat pumps

The relation between the coefficient of performance and the electricity consumption for any heat pump technology is directly proportional. For example, a 1 MW heat pump with a coefficient of performance of 3 will consume $\left(\frac{COP}{Heat\ energy\ output}\right)$

$= 0.33\text{MWh}$ of electricity.

Table 7 Electricity demand calculation for the heat pumps.

	Heat energy output (MWh)	COP	Electricity consumption (MWh) (COP/Heat energy output)	Number of 3 MW wind turbine with capacity factor 36.3%
Waste heat recovery from food industries	0.6	3	0.2	1
Water source heat pump (Clyde River)	90.0	3	30.0	28
Heat recovery from Glasgow subway	0.7	3	0.2	0
Heat recovery from Glasgow mines	37.5	3	12.5	11
Air source heat pumps	358	2	179	164
Ground source heat pumps	100	3	33.3	31
		Total	255.3	234.4

5.0 Discussion and Conclusions

According to the Glasgow City Council’s database, Glasgow uses 5,145,200 MWh of natural gas per annum, which means 587.35 MWh per hour. The goal of this thesis is to decide if existing technology can decarbonize a potential Glasgow’s heating scheme and liberate it from its reliance on natural gas.

This thesis covers several options for decarbonizing Glasgow’s heating to declare independence from the use of natural gas for heating. However, as previously stated, the gas energy consumption data provided by Glasgow City Council is extremely high; Figure 65 illustrates the variations in the data.

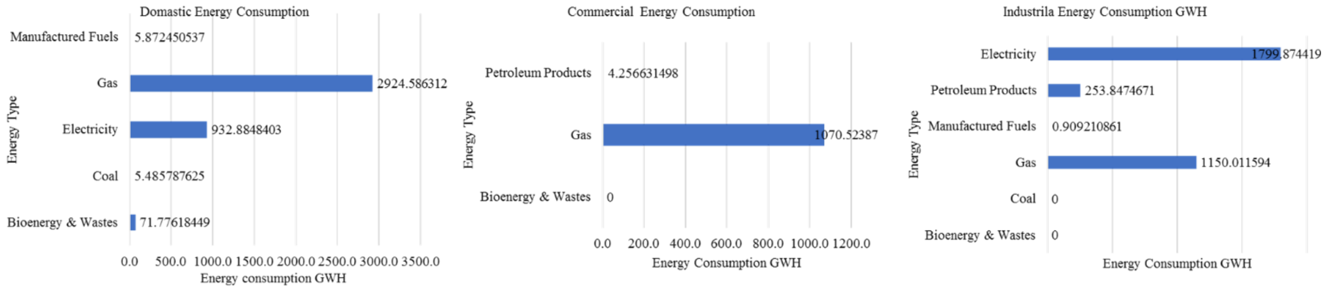


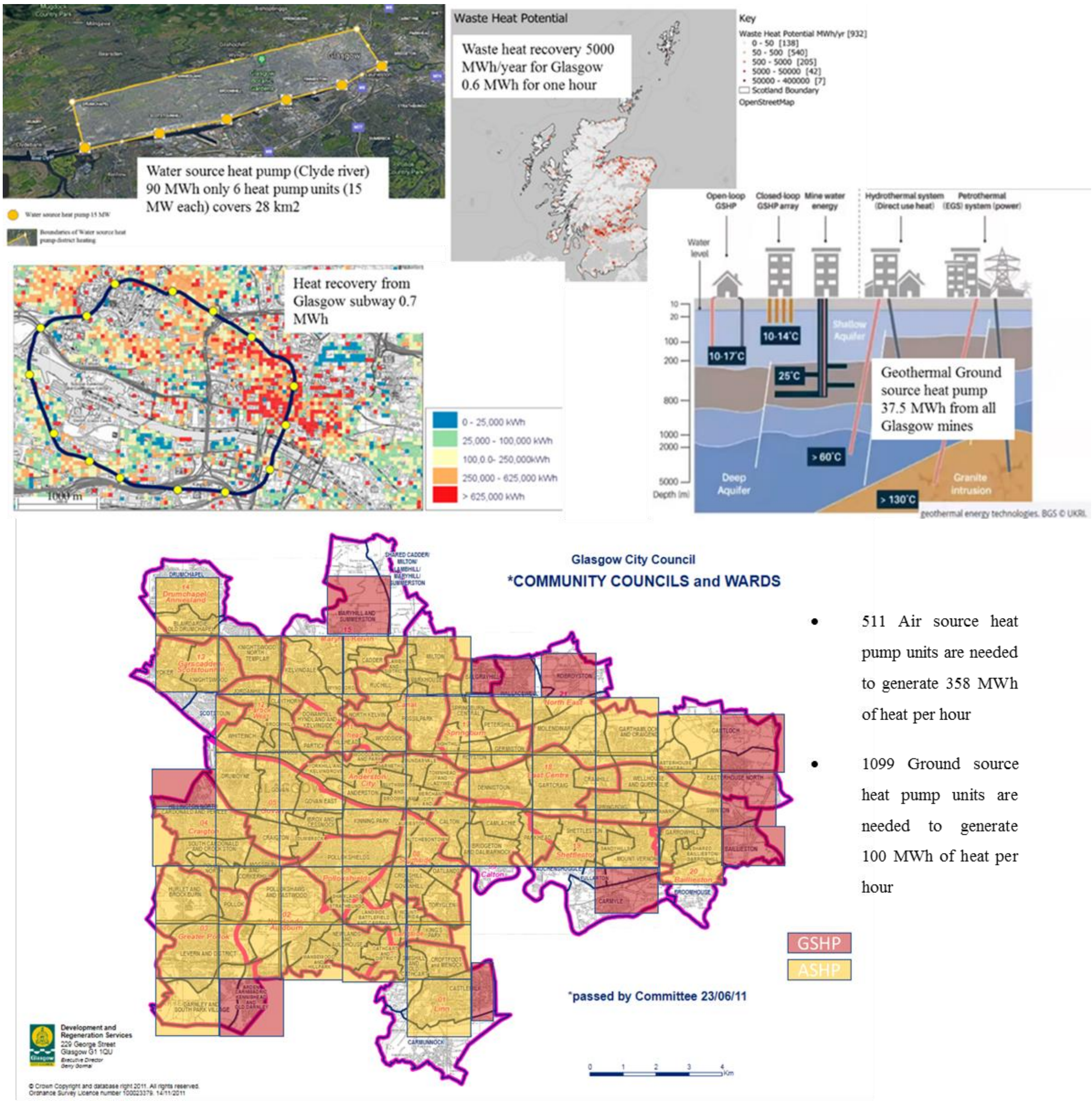
Figure 65 Domestic, commercial and industrial energy consumption provide by Glasgow city council [1].

Globally governments are now extremely determined to utilise hydrogen instead of natural gas and are aiming to produce hydrogen from renewable sources, which is feasible with limitations, as described in section 4.1 Scenario one, H2 from the grid, which involves H2 generation from the electrolyser units

In Scenario 1 at 62% efficiency, a 20 MW electrolyser unit will generate 0.3721 tonnes/hr of hydrogen and consume 3.3249 tonnes/hr of water, implying that Glasgow requires 47 electrolyser units to generate the equivalent demands of natural gas, and the water consumption in the metric cube is 156.27 m3/hr, which is the equivalent of 3% Glasgow's current water consumption.

It has been calculated that 19 wind turbines would be required to provide energy to supply a single 20 MW electrolyser unit. As each wind turbine generates 3 MW with a capacity factor of 36.3%, a total of 893 wind turbines would be needed to produce the necessary electricity to feed the electrolyser units, which is 8.93% of the current number of wind turbines in the United Kingdom.

Scenario 2, successful case studies for several heating technologies were analysed, and if the same methodology was to be implemented in the city of Glasgow, the result would be as shown in Figure 66.


Water source heat pump (Clyde river) 90 MWh only 6 heat pump units (15 MW each) covers 28 km2

Waste heat recovery 5000 MWh/year for Glasgow 0.6 MWh for one hour

Heat recovery from Glasgow subway 0.7 MWh

Geothermal Ground source heat pump 37.5 MWh from all Glasgow mines

- 511 Air source heat pump units are needed to generate 358 MWh of heat per hour
- 1099 Ground source heat pump units are needed to generate 100 MWh of heat per hour

Figure 66 Summary of scenario two waste heat recovery and heat pump technologies.

As shown in Figure 66, only six water source heat pump units may be placed in the area considered along the River Clyde, covering a 28 km^2 area. The project would be subject to a complicated licence from the Scottish Environment Protection Agency (SEPA) since it uses a large amount of river water. The estimated heat production if this project is to be implemented would be 90 MWh per hour.

According to a GIS view of waste heat potential distribution, Glasgow can generate 5000 MWh heat waste per annum, which means it generates 0.6 MWh per hour

The geothermal heat resource underneath Glasgow is classified into three types: abandoned mine workings (low temperature), hot sedimentary aquifers (low and potentially quite high temperature), and hot dry rocks / petrothermal sources. The heat that could be generated using all of Glasgow's underground mines is 37.5 MWh.

Each air source heat pumps have a coefficient of performance of two and a heat capacity of 0.7 MWh. And the ground source heat pumps have a coefficient of performance of three and a heat capacity of 0.091 MWh. 511 Air source heat pump &1099 Ground source heat pump are needed to generate a total of 458.55 MWh of heat per hour

Based on scenario 2, this whole collection of technologies will only be able to provide a maximum of 587.35 MWh per hour of heating for Glasgow, which is the exact amount of energy required. The current technologies available are sufficient to replace natural gas use in Glasgow; however, heat pumps require. 255.3 MWh per hour of electricity, this electricity is generated from 234.4 wind turbines (3 MW wind turbine with capacity factor 36.3%)

Both H2 and Heat pumps require backup energy generation technologies during periods of low renewable energy output (wind and solar), but this issue can be solved by implementing intermittency/storage technologies.

Overlooking Monterey Bay, the Moss Landing Power Plant tower became the world's biggest battery, storing surplus energy generated by solar panels and wind farms and sending it back into the grid, which is a successful case study to overcome the issue of intermittency of renewable power generation. A 300-megawatt lithium-ion battery is prepared for operation inside a huge turbine building, with another 100-megawatt battery scheduled to come online by the end of the year 2021 [79].

They will be able to generate enough electricity to power about 300,000 California households for four hours during nights, heat waves, and other times when energy demand exceeds supply, according to project developer Vistra Energy [79].

Another solution for intermittency is the flexible operation of nuclear plants. While nuclear reactors are well-known for their capacity to supply continuous electricity, their output may also be adjusted to meet specific grid demands. Operators can restrict output by reducing the quantity of steam that passes through a turbine to generate energy or by using control devices to reduce the rate of nuclear fusion in the nuclear reactors. France is practising this process to satisfy daily and seasonal energy demands, while reactors in the United States and Canada operate flexibly in the spring to accommodate more hydroelectric capacity on the grid [18]. Thermal storage and H2 storage can be a solution for intermittency with smart controls flexible tariffs.

Both scenarios 1 and 2 are successful in decarbonizing Glasgow heating units; however, scenario 1 required 893 wind turbines to supply 47 electrolysers since the electrolyser has 62% efficiency, which means 38% will be energy loss and the technology of hydrogen 8 MW boilers are not widely available. Scenario 2, on the other hand, require 234.4 wind turbines to supply the heat pump units and the technologies are available in the market

5.1 Recommendations

The recommendations of this thesis are as follows:

- It is recommended to retrofit buildings in Glasgow with excellent levels of insulation with minimum thermal bridges, and the airtightness must be at a good level; the buildings must have excellent indoor air quality and must have great solar gain from passive solar energy. If all buildings in Glasgow are converted or modified to comply with passive-house standards, this will have a large impact on the quantity of electricity consumed for heating, and it can reach up to 80% reduction of energy used for heating.

- It is recommended to use backup technologies to solve the problem of intermittency during periods of low renewable energy generation (wind and solar). These backup technologies, according to this thesis, are green generation storage in battery farms at 90% efficiency, green H2 storage at large scale green H2 (CCGT) plants, flexible nuclear plants, and distributed storage (battery, H2, thermal).

5.2 Future work to be considered

Based on this thesis, future work to be considered is as follows:

- Environment impact assessment.
- Financial analysis.
- Glasgow’s electrical grid limitations.
- Research alternative solutions to generate hydrogen.
- Thermal storage.
- Green generation storage in battery farms at 90% efficiency.
- Carbon capture units and carbon recycling.
- Energy from the flexible operation of nuclear power plants.
- Green generation storage in battery farms at 90% efficiency.

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7.0 Appendices

7.1 Wind Turbine Models Database

Figures 59, 60 and 61 detail the current wind turbine models, production data and the diameters associated with them. The graphs on the left show wind turbine models versus power (kW), and the graphs on the right show wind turbine models versus diameter (m) [9].

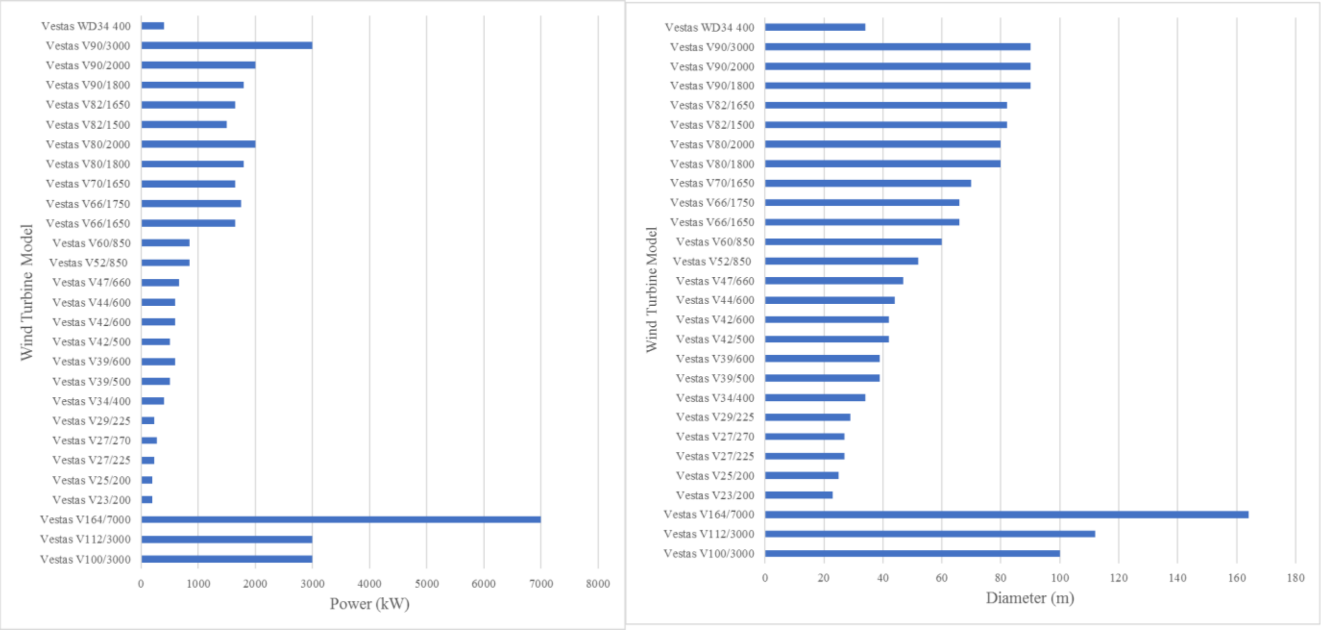

Figure 67 Wind Turbine Models Details-Part A [9].

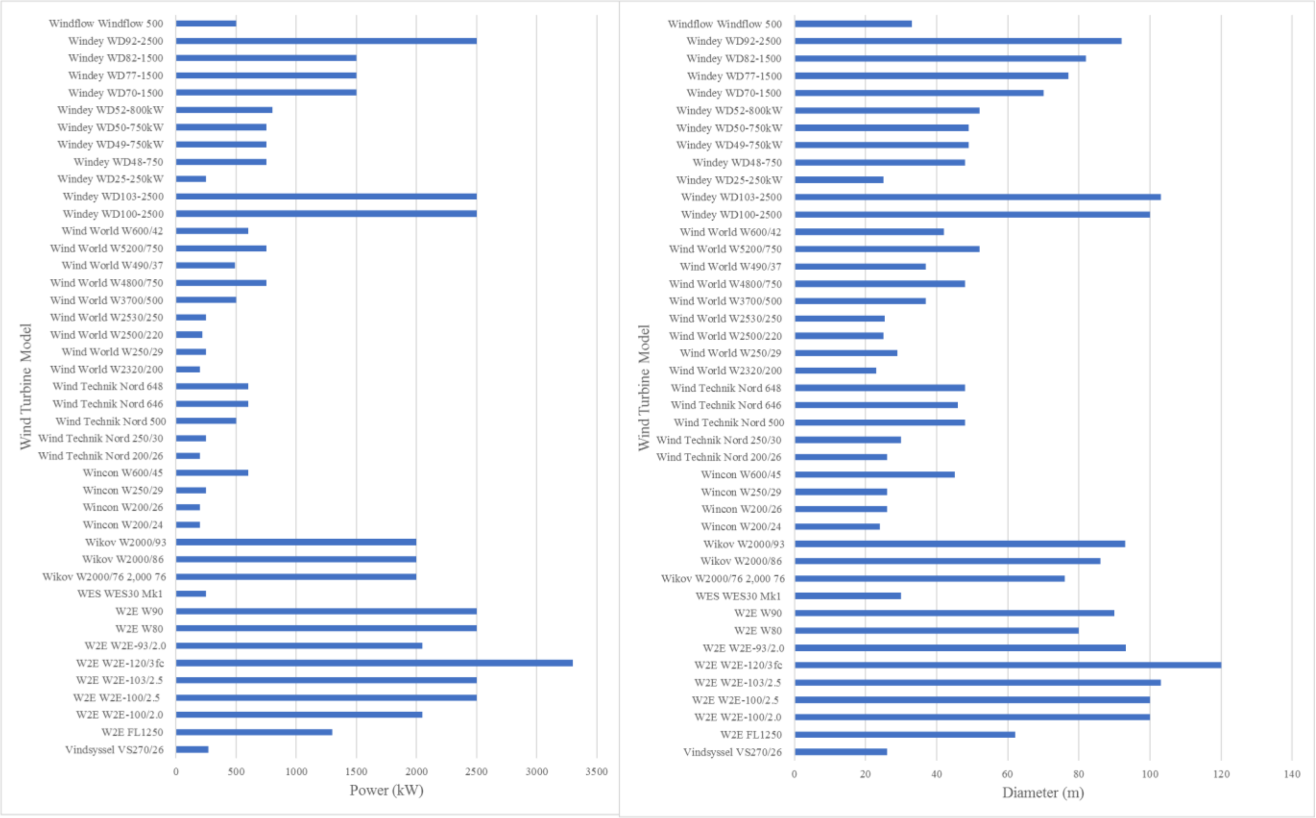

Figure 68 Wind Turbine Models Details-Part B [9].

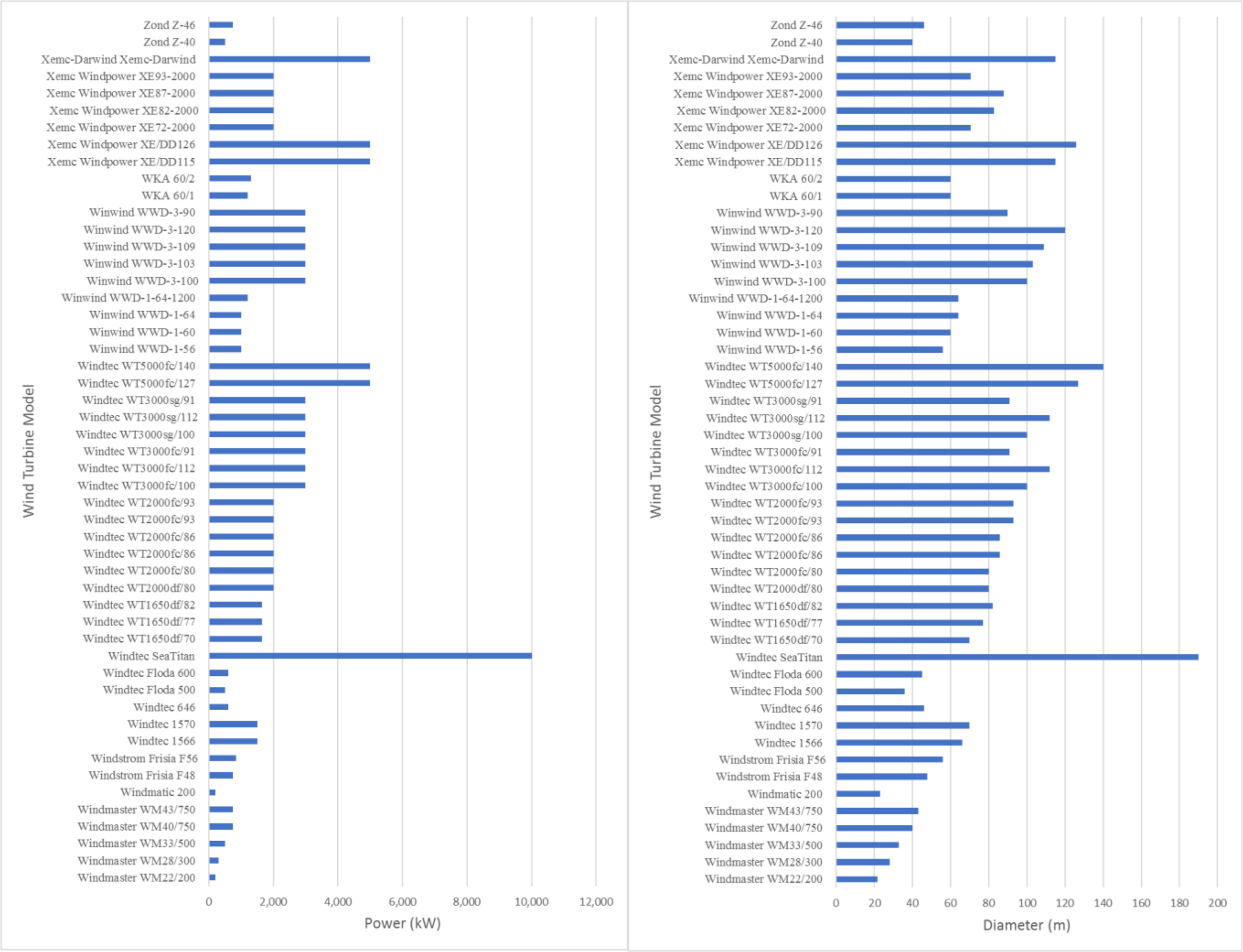

Figure 69 Wind Turbine Models Details-Part C [9].

7.2 Modelling

7.2.1 energyPRO

energyPRO is used for comprehensive technical and financial analysis of both current and new energy projects in a highly user-friendly interface that provides a clear picture of the project. The programme delivers a wide variety of technical and economic data, as well as a graphical representation of the simulated operation, providing an overview and in-depth knowledge of the dynamics in a complex energy system[80].

The calculations take into account all project circumstances and provide accurate findings in a printed format approved by the World Bank and other investment institutions. energyPRO's flexible and modular framework allows it to simulate any kind of energy facility.

7.2.2 Simulation

As illustrated in Figures 62, 63, 64, and 64, the case studies have been simulated by a software called energyPRO.

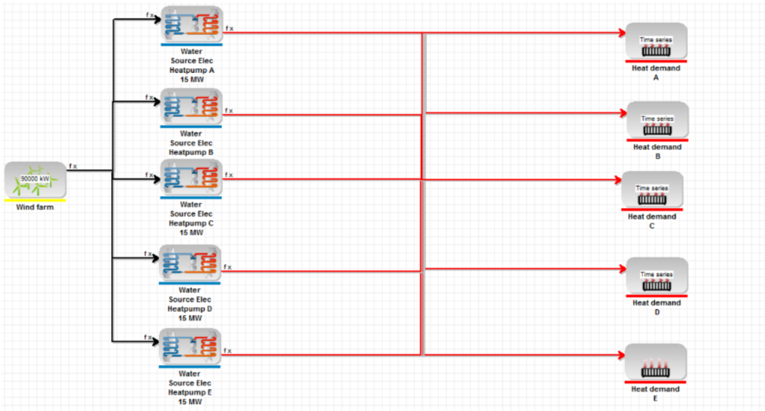

Figure 70 Simulation of water heat pump water source is river Clyde.

Six water source heat pump units were modelled along the River Clyde in the region selected, spanning a 28 km^2 area as shown in Figure 62. Each unit has the power of 15 MW with a 3.05 COP. 90 MWh of heat per hour would be produced if this project were to be completed.

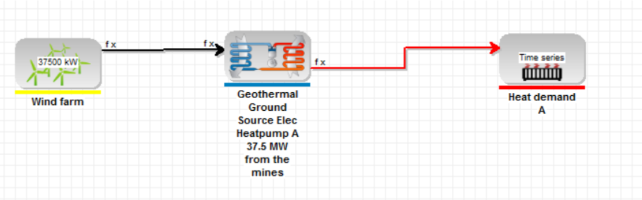

Figure 71 Geothermal ground source heat pump water source is mines water.

Open-loop ground source heat systems are expected to produce about 2.5 megawatts per kilometre square (MW/km^2) in Scotland's mining areas. When this value is multiplied by the area of the mined zone (2.5 x 15 km^2), an approximate estimate of 37.5 MWh per hour of accessible heat is produced. This project fulfils just 37.5 MWh per hour of Glasgow's heating requirements, as shown in Figure 63.

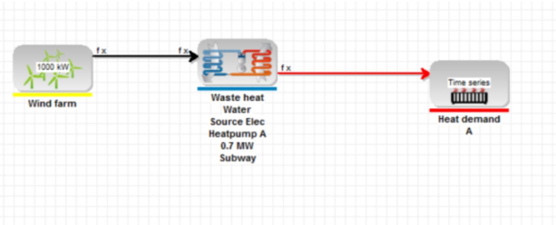

Figure 72 Simulation of waste heat recovery from the Glasgow subway.

The waste heat generated from the Glasgow subway is recovered, and the heat energy is 0.7 MWh per hour.

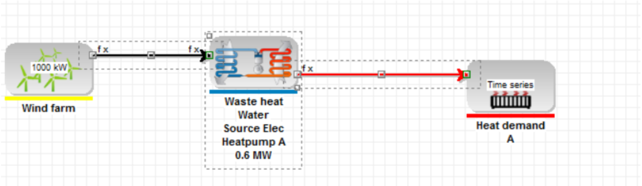

Figure 73 Simulation of waste heat recovery from Glasgow industries.

Glasgow can generate 5000 MWh heat waste per year which means it generates 0.6 MWh for one hour.

Wind energy generated at a wind power plant is used in all of the case studies demonstrated in Figures 62, 63, 64, and 65, and it is the same source of renewable energy used in all of them, as indicated in Figure 66. In addition, the same peak heat demand of 15 MW was selected since it was experienced from 8 to 9 in the month of January[81]

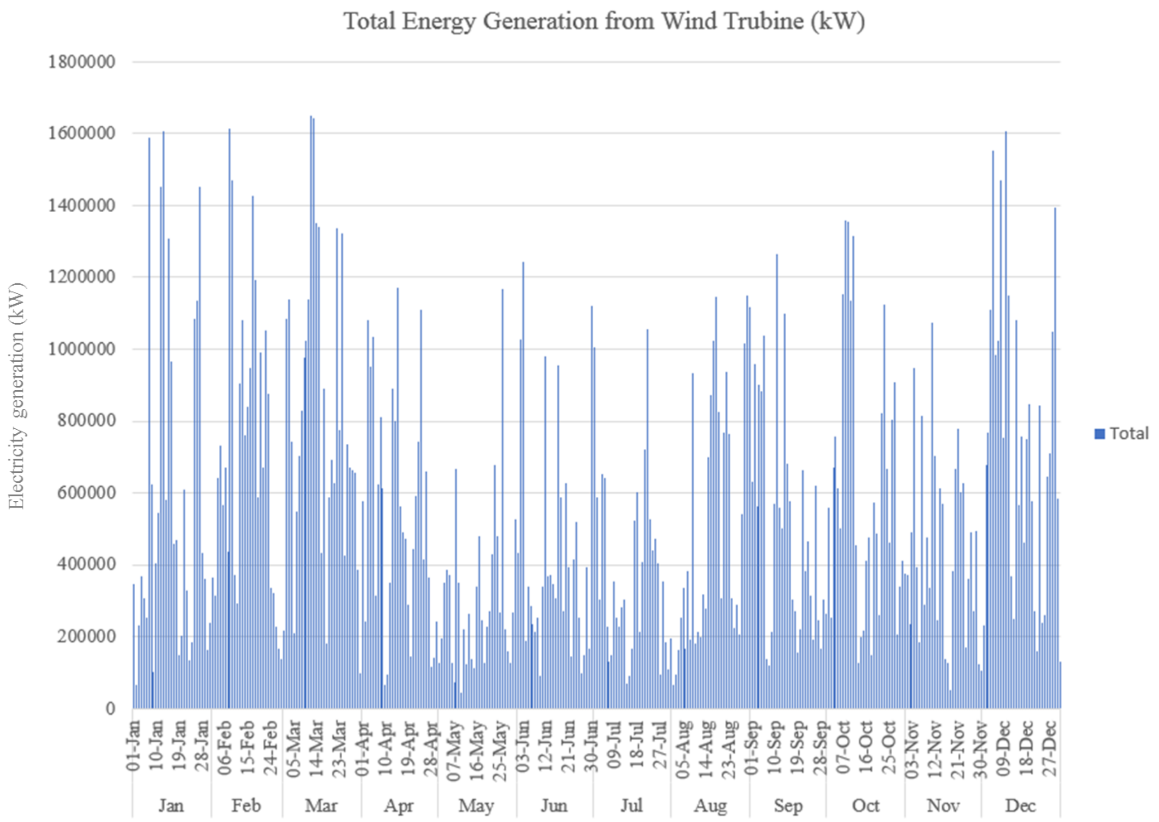

Figure 74 Wind turbine energy generation data.