Carbon Neutral County Durham: A Review of County Durham's Low Carbon Sustainable Resource Base in Order to Become Carbon Neutral by 2050

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Carbon Neutral County Durham:
A Review of County Durham's Low Carbon Sustainable Resource Base in Order to Become Carbon Neutral by 2050

Robert James Mawson

Abstract

In February 2019, Durham County Council declared a climate emergency in recognition that without action, global warming will continue on its current trajectory of 3°C warming, causing disastrous effects. The target was agreed that County Durham would become carbon neutral by the year 2050. Aside from energy saving, carbon removal and offset measures, this project details the technical potential low carbon, sustainable resource base that County Durham has in order to meet the county's current energy demand of ~10,500 GWh/yr. This resource base includes; mine water, deep geothermal, photovoltaics, solar thermal, wind, biomass, waste, hydrogen, hydropower and tidal energy. Analysis of these resources covers how the resource works, what the resource depends upon, the energy potential in County Durham, possible limitations, land use, economics and the learnings taken from relevant case studies.

This study found that County Durham has an uneven low carbon sustainable energy mix, which favours the production of electricity and heat rather than alternative transport fuels. To decarbonise the heating sector, County Durham has a large mine water energy resource that has the potential to heat up to the equivalent of 91% of the homes in the county. If County Durham initially invested in mine water energy with other resources such as domestic solar thermal systems and heat pumps, this would allow time for the current gas networks to be repurposed for a hybrid hydrogen network. This hybrid network would remove mine water's limitation of proximity to the source. Due to land constraints there is no realistic alternative to transport fuels available from low carbon resources in County Durham whilst hydrogen, remains within its infancy as a major transport fuel energy source. Transport is therefore likely to require electrification which matches the UK's current plans. To produce enough electricity to decarbonise the electricity and transport sector, a mixture of offshore/onshore wind energy, photovoltaics, domestic energy projects and a biorefinery would be required. The proportion of this mixture depends upon if land and/or economic investment is prioritised.

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Chapter 1 - County Durham Background

County Durham is located in the North East of England, bordering Northumberland to the North, North Yorkshire to the South and Cumbria to the West. With an area of 2,226 km^2, County Durham is the seventh largest county in terms of land area, in the UK (ONS 2019).

With a population of ~530,000 County Durham is the eighth most populated district in the UK, with a population density of 238 people per km^2 (ONS 2019).

Historically, County Durham is known for its coal mining history. The county was one of the largest coal mining regions within the UK. Between 1877 through to 1956, 30 million t of coal were extracted on an annual basis (Gluyas, Personal Communication, 2020)

In 2017, tourism accounted for £867 million of Durham's economy (Hill, 2018). The county possesses some of the finest Norman architecture, the epicentre being Durham Cathedral and the UNESCO world heritage site of Durham Castle.

It is important to first gain an understanding of County Durham's background in terms of geology, geography and energy. This is because when reviewing each low carbon sustainable resource, these factors are important to understand and consider as they can impact their potential within County Durham.

1.1 Geology

Understanding the natural environment of County Durham both past and present is integral as it includes information that underpins the potential for low-carbon sustainable technologies in County Durham. This section and Figure 1.1 shows a summary of County Durham's geology.

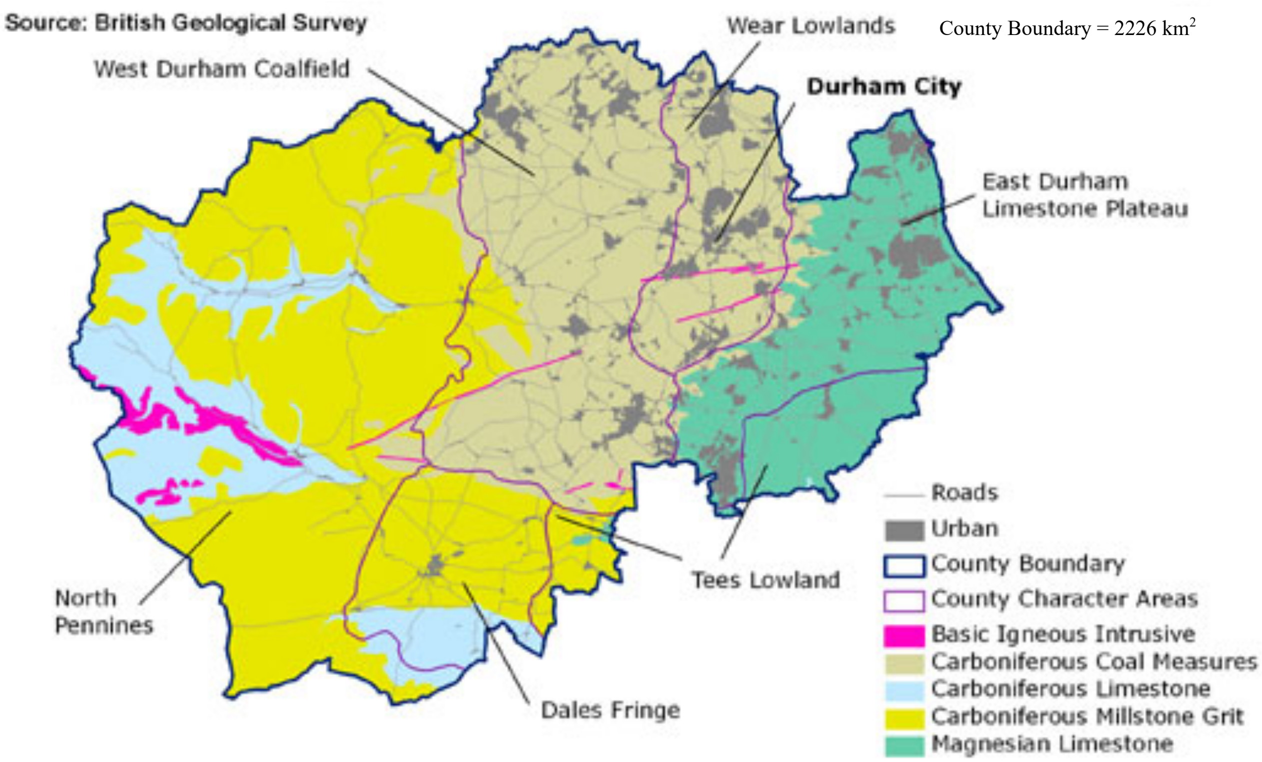


Figure 1.1 – A Geological map of the North East of England. Source – British Geological Survey 2020

1.1.1 Ordovician

During the Ordovician period, Britain was split into two halves (Laurentia & Avalonia) by an ancient ocean named Iapetus (Scrutton 1944; Figure 1.2) At its peak, Iapetus was 5000 km wide (Torsvik & Trench 1991; Figure 1.2). What is now County Durham is thought to have been positioned at the tip of the landmass Avalonia during this time (Scrutton 1994).

Ordovician aged strata are the oldest rocks that outcrop in County Durham (Gluyas et al 2020). They are exposed as two inliers (Cross fell and Cronkley Spar) both of which are located in Upper Teesdale. The lithology of these Ordovician strata is Skiddaw Slate mixed with some minor intrusions (Burgess and Wadge 1974). These lithologies have also been found underneath Carboniferous rocks at Roddymore and Allenhead boreholes (Dunham & Wilson 1990).

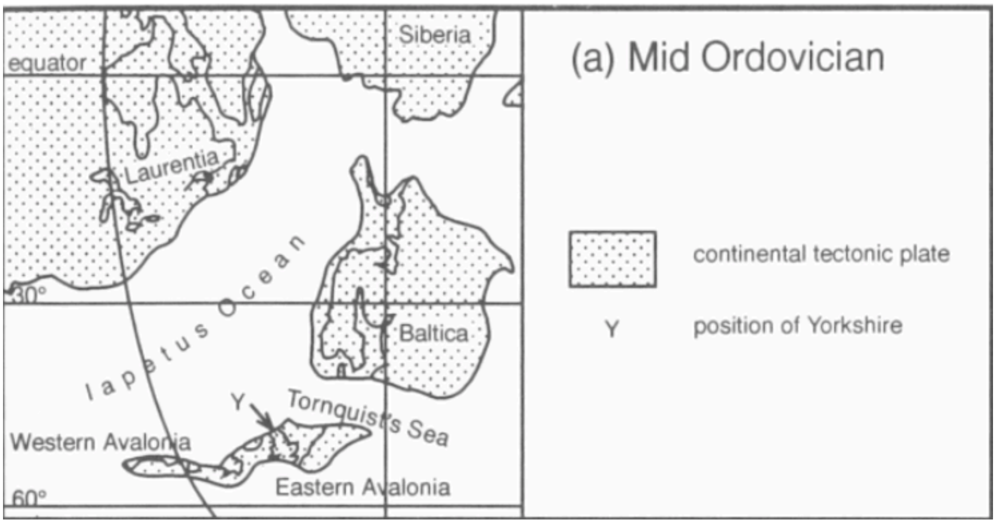


Figure 1.2 – Tectonic reconstruction of the Mid Ordovician period. Source – Scrutton 1994

1.1.2 Devonian

The Devonian period marked the time in which the Weardale Granite was emplaced (Gluyas et al 2020). The Weardale Granite is not exposed at the surface within County Durham (Gluyas et al 2020). However, it has been shown to exist through gravity surveys and boreholes taken at Rookhope and Eastgate (Bott & Smith 2017). The granite is now known to be made up of five contiguous plutons, with the largest (labelled A on Figure 1.3) being referred to as the Weardale Granite (Kimbell et al 2010).

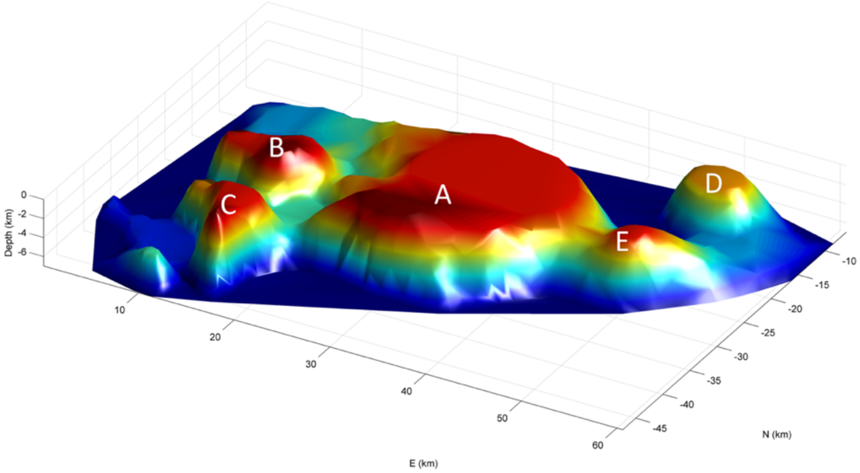


Figure 1.3 – 3D thermal model of the North Pennine Batholith formally known as the Weardale Granite suite. Colours used represent different depth ranges where red is the shallowest depth ranging to blue which represents the deepest sections - Source - Kimbell et al 2010.

Boreholes drilled at Rookhope shows the granite is typically white/pale grey and consists of quartz, muscovite, biotite, albitic feldspar, potassium feldspar with accessory monazite, zircon and magnetite ilmenite (Kimbell et al 2010). Texturally the granite is non-porphyritic (Gluyas et al 2020). Radioactive isotopes potassium, uranium and thorium are abundant within the Weardale Granite, during decay, these radioactive isotopes release heat energy allowing the Weardale to still be a significant heat source beneath the county (Gluyas et al 2020). This heat source will be explored as a low carbon, sustainable resource in the deep geothermal section of this thesis (Section 2.2).

1.1.3 Carboniferous

The Variscan orogeny dominated the tectonics of the Carboniferous period (Gluyas et al 2016). This orogenous event was the outcome caused through the collision of two land masses, Gondwana and Laurussia (Gluyas et al 2016).

During the Carboniferous, Britain was divided into five major provinces by large structural features such as the Southern Uplands high (Gluyas et al 2016). County Durham was situated within the Pennine province (Figure 1.4; Woodcock & Strachan 2002).

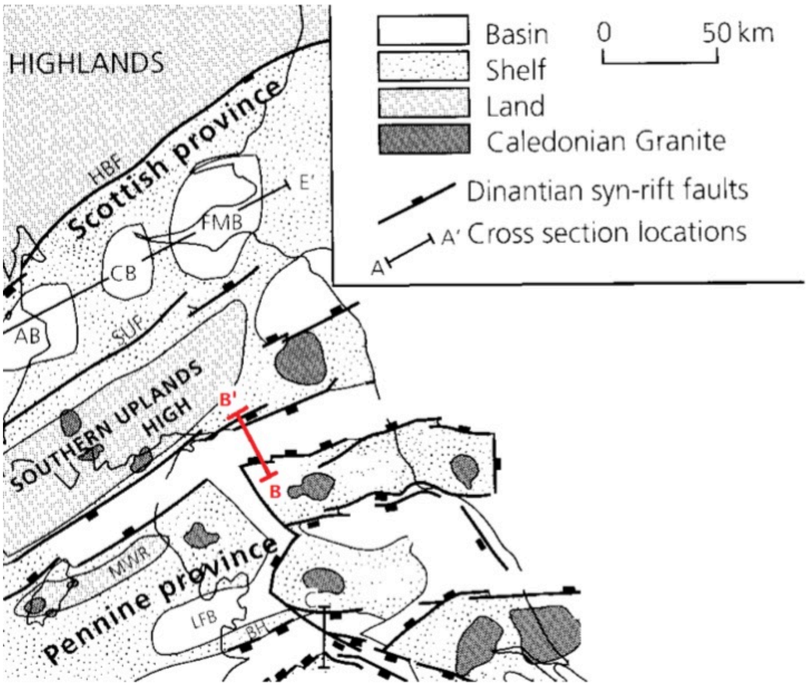


Figure 1.4 – Mississippian paleogeography of Northern England
Source – Woodcock & Strachan 2002

County Durham itself and much of North East England can be divided structurally into three main areas. Positioned to the north there is the Northumberland Trough. Located in the south is the Stainmore Trough and situated in the middle is the Alston Block (Gluyas et al 2016; Figure 1.5). Separating the three sections are two major east/west trending fault systems (Gluyas et al 2020). Named the *'Ninety Fathom Fault'* sometimes also known as the '*Stublick Ninety Fathom Fault'* is found in the north of the county, and the *'Butterknowle Fault'* found in the South (Gluyas et al 2020). These fault systems will be examined if they can serve potential for geothermal fluid flow in County Durham.

These half-graben blocks, troughs and fault systems were formed as a result of the back-arc extension during the Lower Carboniferous in a north south direction (Gluyas et al 2016).

The sediments deposited in the Northumberland Trough are approximately 4 km thick, compared to 6 km for the Stainmore (Gluyas et al 2020). The Alston Block has a sediment thickness of 500 m sitting on top of the Weardale granite (Gluyas et al 2020; Figure 1.5).

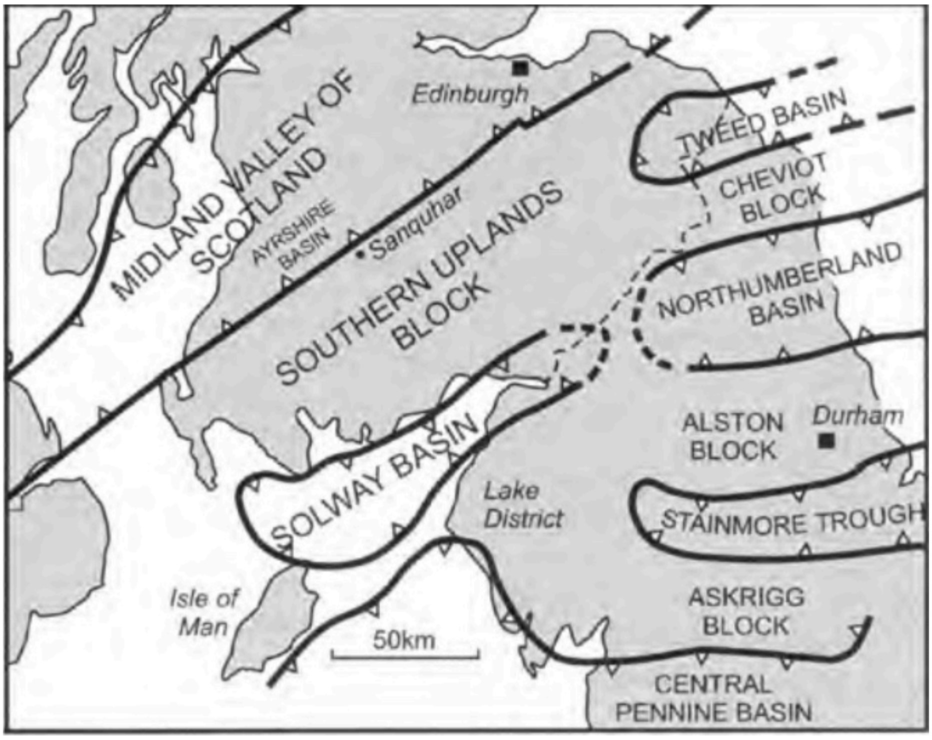


Figure 1.5 – Map of Northern Britain divided into associated blocks and troughs. Durham is located for reference. Thick black lines depict the extent of the geological feature. Source – Tucker 2003

From the middle of the Carboniferous period, Yoredale Cycles dominate the deposition throughout County Durham (Gluyas et al 2016). They range between 5-50 m in thickness and consist of marine limestone (transgressional systems tract), coarsening upwards pro-delta mudstone and a deltaic distal mouth-bar sandstone succession (high stand systems tract) that is capped by coal and a paleosoil (Tucker et al 2003; Figure 1.6).

The cycles were caused by glaciation on Gondwana in the southern hemisphere that created a glacioeustatic sea-level change in northern Britain (Tucker et al 2003).

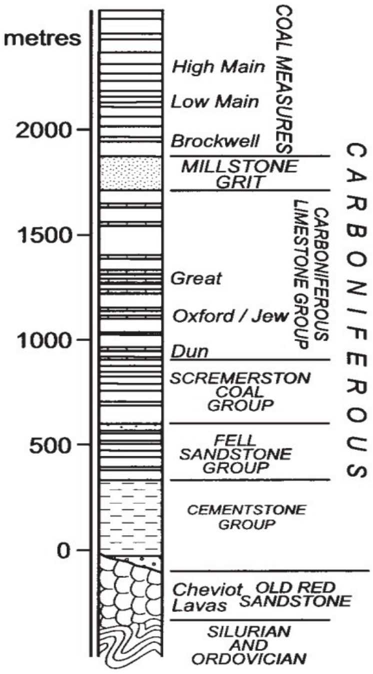


Figure 1.6 – Log of a typical Yoredale cycle. Depth increasing downwards (m).
Source - Tucker 2003

Due to the now shallow marine setting with delta plains and back swamps post Yoredale cycles, thick coal measures developed across County Durham (Gluyas et al 2016). The resulting *Durham Coalfield* can be divided into Lower, Middle and Upper coal measures (Gluyas et al 2016). Between the 13th and 20th century, the coal formed during the Carboniferous was excavated and burned for energy during the industrial revolution, leaving behind abandoned mines (Banks et al 2004). Later I will examine the possible low carbon, sustainable energy potential from these abandoned coal mines.

1.1.4 Permian

Permian aged strata deposited throughout County Durham lie unconformably on Carboniferous deposits (Gluyas et al 2016). Due to Variscan associated uplift, simultaneous glacioeustatic low stand, and that NE England lay within the centre of the supercontinent Pangea, the Permian lacked marine deposition (Gluyas et al 2016). Deserts formed across England, which is shown by oxidised coal measures and major deposition of sandstones via aeolian and ephemeral fluvial processes (Gluyas et al 2020). Permian strata is exposed as a strip in South Shields that widens to 20 km at its southernly extent of Hartlepool.

During the late Permian, repeated connections to the Tethys ocean re-established a large marine presence located across the Pennine province, which marked the start of the Zechstein cycles (Gluyas et al 2016; Figure 1.7). The Zechstein cycles were cycles of marine sedimentation in the Zechstein Sea that spanned from the East of England to Northern Poland (The Geological Society of London 2020). This sedimentation included mudstone, limestone, dolomitic limestone, evaporites and marl slate, all in varying quantities and thickness (Tucker 1991). These Zechstein associated evaporite deposits will be explored as possible hydrogen storage facilities (Section 2.8).

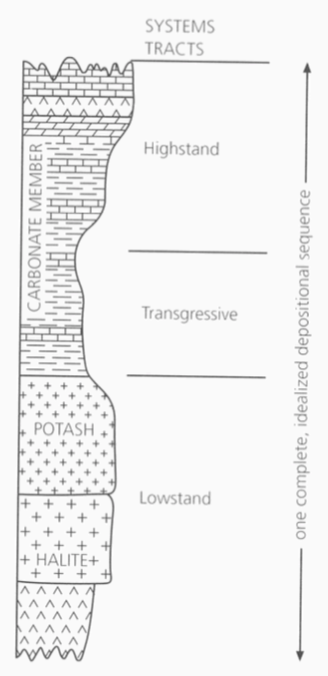


Figure 1.7 – Sequence stratigraphic understanding of a typical Zechstein Cycle Source – Tucker, 1991

The area now occupied by County Durham was heavily affected by the quartz-doleritic magmatism that occurred at the Carboniferous-Permian boundary (Westaway et al 2019). The product of this magmatism is the Whin Sill (Gluyas et al 2020). This concordant igneous intrusion is absent from Permian strata but intrudes into Carboniferous strata (Gluyas et al

2020). The Whin Sill ranges from 30-70 m in thickness (Westaway et al 2019; Figure 1.8). This previous magmatism could prove helpful when assessing heat flow within County Durham.

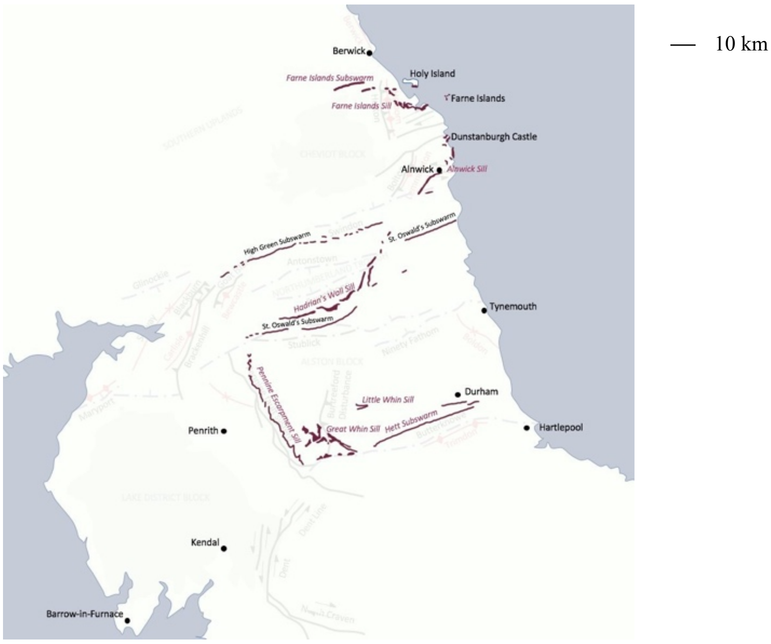


Figure 1.8 – Map of Northern Britain showing the location of the Whin Sill igneous intrusion complex. Red lines depict the location and extent of different sill complexes. Source – Geology North 2020

1.1.5 Triassic

There are a small number of Triassic strata exposures in County Durham. The exposures that do exist tend to be conglomerate or sandstone, such as the Sherwood Sandstone, both typically were deposited in braided rivers (Gluyas et al 2016).

1.1.6 Jurassic

The Jurassic period saw the break-up of the Pangea supercontinent (Gluyas et al 2016). This breakup and associated rifting caused environments of deposition to support a greater marine dominance once again within the areas now occupied by County Durham and Britain. The marine environments now mixed with a more humid climate resulted in coal and organic-rich shale being deposited (Gluyas et al 2016).

1.1.7 Summary

A general understanding of the geology of County Durham is necessary as it is important to refer back to throughout relevant low carbon, sustainable resources. Particular areas of interest which will be investigated further include the geothermal potential of the Weardale Granite and its associated fluid flow via associated fault systems. Secondly, the geological storage potential of hydrogen within the Zechstein evaporite deposits via dissolution caves will be explored. Finally, the potential for mine water energy using the abandoned coal mines in County Durham will also be explored.

1.2 Geography

Many low-carbon sustainable resources' energy potential depends upon various geographical and geomorphological features. It is therefore important to understand County Durham's geography so it can be referred back to when calculating resource potential.

1.2.1 Topography

County Durham varies in elevation between 73 m – 207 m (Durham Landscape 2010; Figure 1.9). Although, County Durham includes a large proportion of the North Pennines that typically ranges from 548 m to the highest point of 788 m at Mickel Fell. This undulating topography with areas of high elevation could increase the potential for resources dependant on gravitational potential energy and increased wind speeds, such as hydropower and wind energy, respectively.

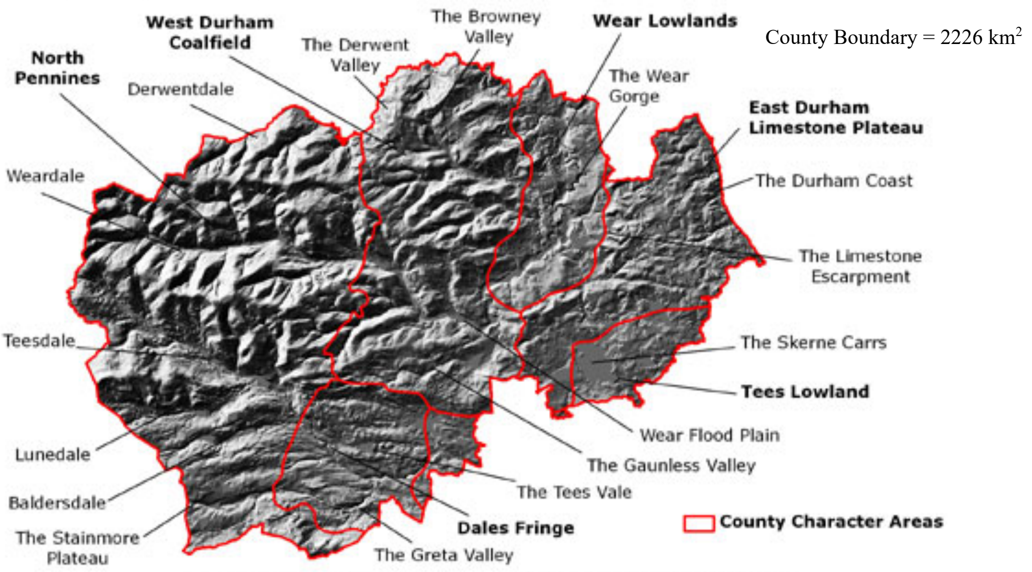


Figure 1.9 – Topography of County Durham. Source – Durham Landscape 2010

County Durham possesses a total of 17 rivers. The two longest rivers being the River Wear and Tees (Figure 1.10) with a combined length of ~235 km. Both rivers flow eastwards throughout the county until their end point at the North Sea. The rivers Tyne, Wear and Tees all have associated estuaries, which could be resources of tidal energy in County Durham.

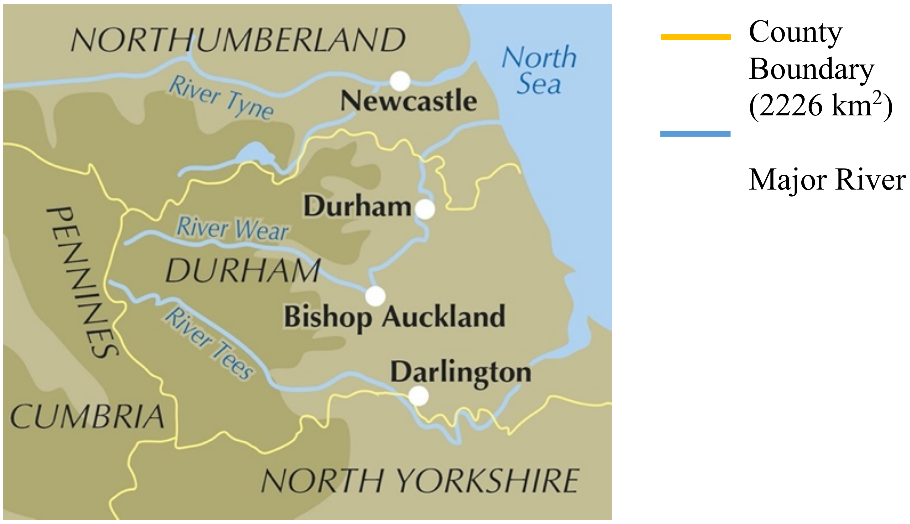


Figure 1.10 – Map of County Durham showing the routes of both the River Wear and River Tees. Source – Cicerone Press

1.2.2 Solar Insolation

Figure 1.11 highlights the total daily incident shortwave solar energy, including both visible light and ultraviolet radiation in County Durham.

The period between April 29th to August 14th represents the time of the year that receives the highest solar insolation values for the county, averaging 4.9 kWh/m^2 of solar energy (Weather Spark 2020). The peak of this period usually comes at the end of June with an average of 6 kWh/m^2 (Weather Spark 2020). In contrast to this, between October 22nd and February 21st represents the period that receives the lowest level of solar insolation for the county, with an average solar energy level of 1.5 kWh/m^2 (Weather Spark 2020). December 24th is usually the darkest day of the year registering 0.4 kWh/m^2.

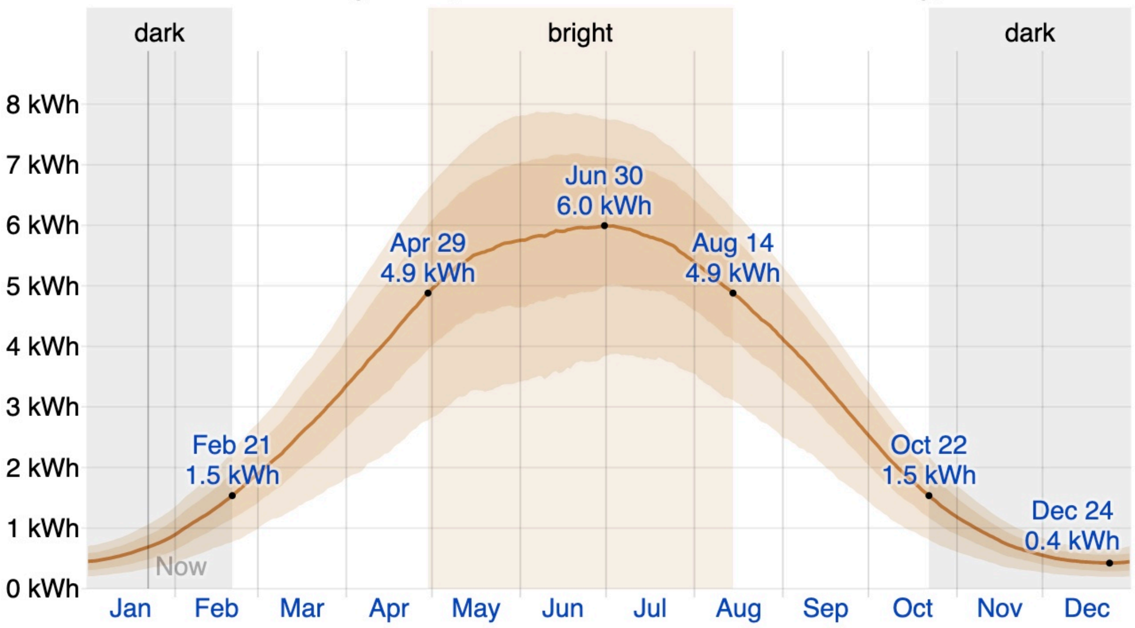


Figure 1.11 – Average Daily incident shortwave solar energy in County Durham in kWh. Source – Weather Spark 2020

1.2.3 Wind

The prevailing wind direction throughout the year in County Durham is from the West (WeatherSpark 2020). County Durham experiences seasonal changes in average wind strength Weather Spark 2020). Between October to March the wind speeds on average are at their highest, with recorded average wind speeds of 5.9 m/s (21.1 kph) (WeatherSpark 2020). Highest daily average wind speeds are usually recorded around January 24th with winds of 7.2 m/s (25.9 kph) (WeatherSpark 2020). Calmer periods throughout the year usually last for approximately 6.5 months between March and October, where wind speeds average approximately 5.4 m/s (19.44 kph) (WeatherSpark 2020). The calmest day is usually around July 26th with average wind speeds of 4.5 m/s (16.3 kph) (Weather Spark 2020). Recorded statistics are based upon measurements taken from 10 m above the ground (Weather Spark 2020; Figure 1.12).

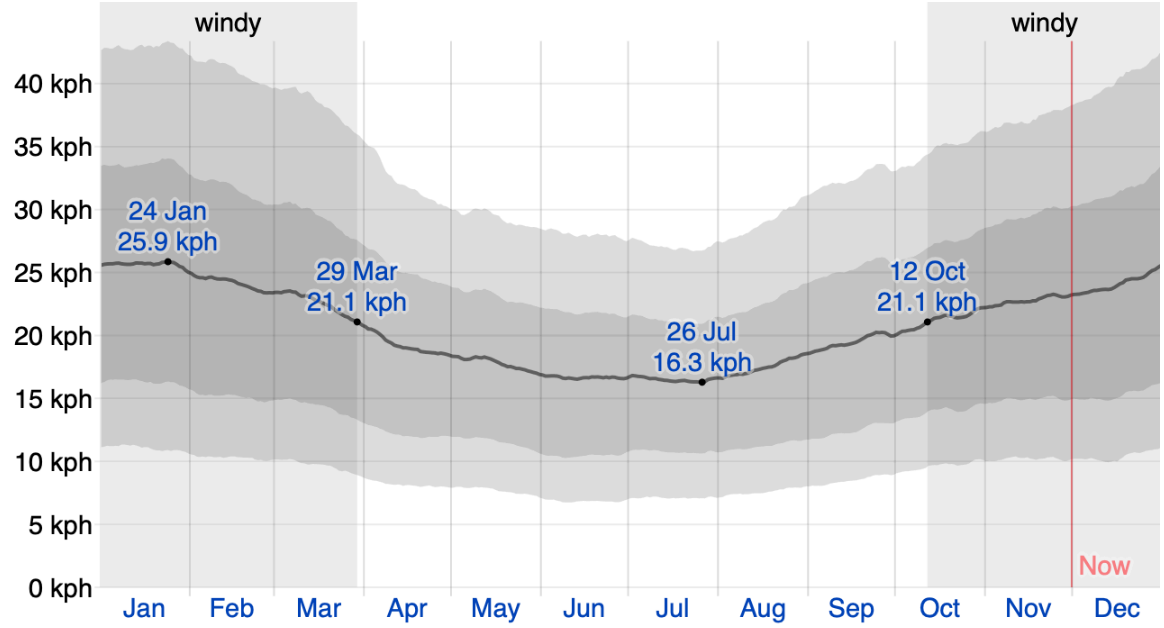


Figure 1.12 – Average mean hourly wind speed in County Durham with 10th, 25th, 75th, 90th percentile bands. Source – Weather Spark 2020

1.2.4 Rainfall

Rainfall records show County Durham has an average annual rainfall of 0.5 m compared to the UK average of 0.85 m (WeatherSpark 2020). August and October typically experience the highest rainfall throughout the county, with 0.05 m of rain compared to only 0.03 m that falls throughout February (WeatherSpark 2020; Figure 1.13).

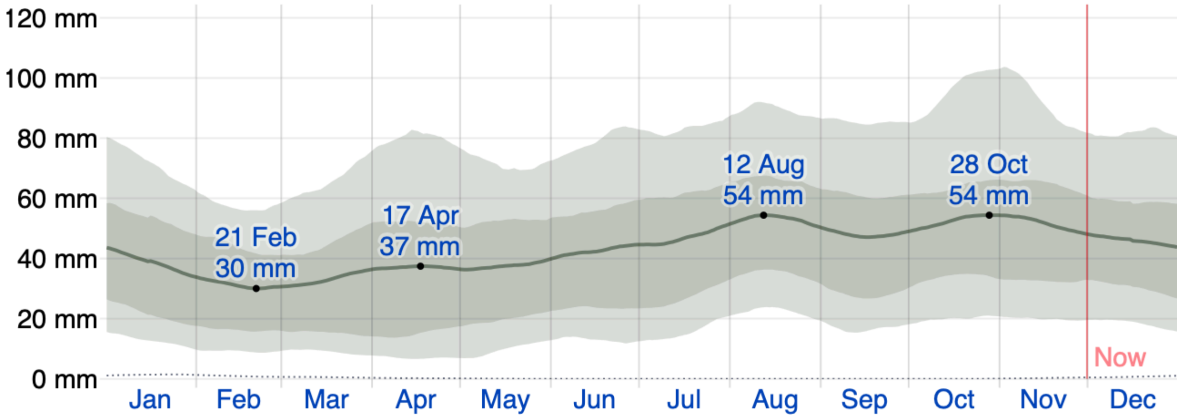


Figure 1.13 – Average monthly rainfall measured in inches over the course of an average year. Source - Weather Spark 2020

1.3 Energy

The energy demand and emission data for County Durham is important to understand when evaluating the potential of different low-carbon sustainable resources. It gives a point of reference as to how significant the resource could be to County Durham. Furthermore, different technologies supply energy in different ways (heat, electricity & fuel), therefore it is important to divide the energy demands of the County into the sectors of transport, electricity and gas.

1.3.1 Energy Demand

In 2015 County Durham recorded a total energy expenditure of 10,513 GWh (DCC 2019). This total value can be subdivided into three sectors, transport, electricity and gas. These divisions can be split further into both domestic and industrial consumption (Figure 1.14).

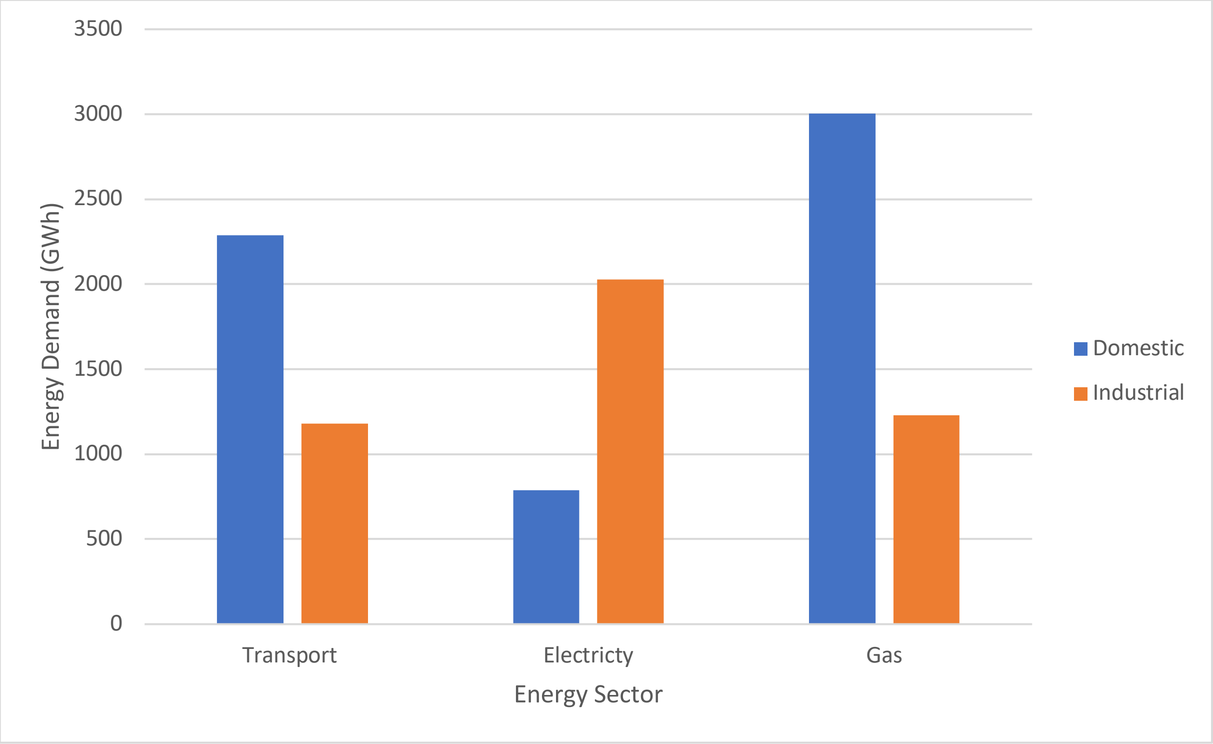


Figure 1.14 – Graph showing County Durham's energy demand for transport, electricity and gas in 2015. The graph shows two data series for domestic and industrial demand. Data Source – Durham County Council 2015

Sector	**Total (GWh)**	**Domestic (GWh)**	**Industrial (GWh)**
Transport	3465	2286.9	1178.1
Electricity	2816	788.48	2027.52
Gas	4232	3004.72	1227.28
Total	10513	6080.1	4432.9

Table 1.1 – Table of data supporting figure 1.14 of energy demand data for County Durham in 2015. Total energy expenditure is divided into Transport, Electricity and gas. Energy given as GWh's. Data Source – Durham County Council 2015

Figures 1.14 & Table 1.1 display the split for the transport sector was 66% domestic - 34% industrial. Electricity recorded 28% domestic - 72% industrial. Gas registered 71% domestic - 29% industrial.

Currently in order to meet energy demands, County Durham uses a mixture of energy sources, including the combustion of non-renewable fossil fuels that emit greenhouse gases into the atmosphere and consequently contribute to global climate change (DCC 2019).

This data being taken from 2015 shows one of the limitations of this study as energy demands, and emissions are likely to have changed since 2015. However, at the time of publication this was the most recent data available for study.

It is important to understand this energy demand, associated emissions and what their impact is on County Durham's climate so that we can understand the emissions reduction that is required as well as the aims and reasons for undertaking this project.

1.3.2 Emissions

Greenhouse gases (GHGs) are any compound found within the Earth's atmosphere that absorbs infrared radiation (EPA 2020). Greenhouse gases trap and retain heat within the atmosphere consequently warming the Earth (EPA 2020). GHGs are emitted primarily through the burning of fossil fuels, mainly oil, gas and coal to produce energy (EPA 2020). Different GHGs have the varying potential for absorbing infrared radiation (NOAA 2014). Although carbon dioxide is not the most absorbent GHG it is the most common and therefore is frequently used as an indicator of climate change (NOAA 2014). The amount of CO_2 being emitted by human activity in County Durham is decreasing, which can be seen in Figure 1.15.

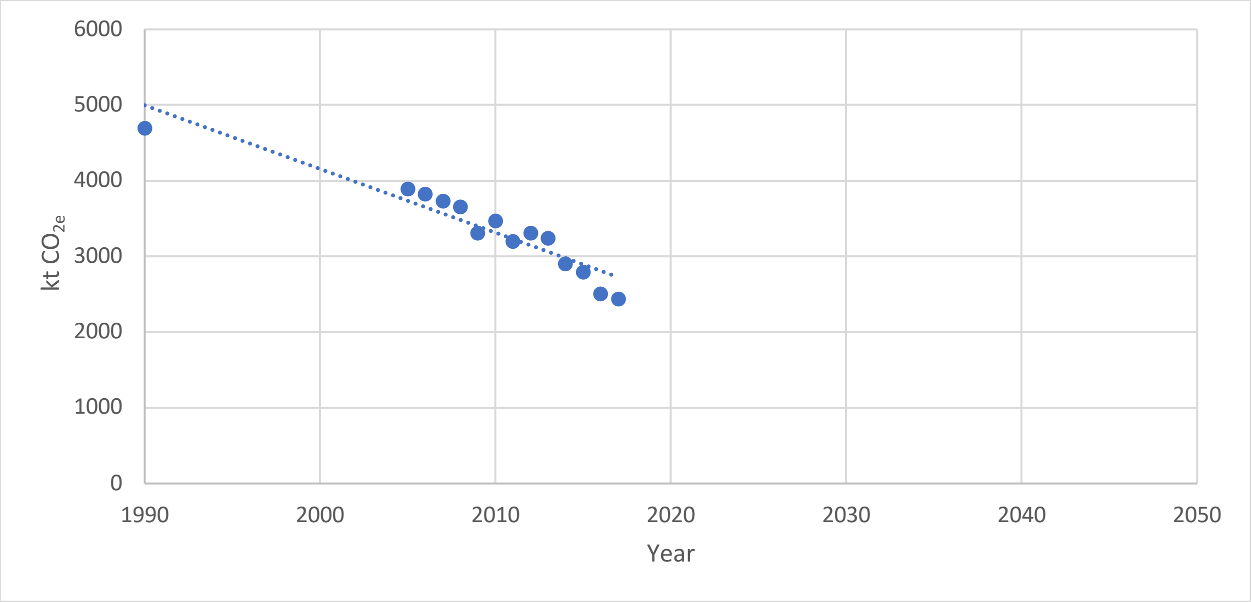


Figure 1.15 – Graph showing the total $ktCO_{2e}$ over time. First data point is 1990 level. The graph shows a negative correlation. Data Source – Durham County Council 2019

Post-industrial revolution, the impact of human population caused drastic changes to global climate, mainly through more GHGs being emitted into the atmosphere (IPCC 2007). Changing climates can increase meteorological risks and severe weather events, such as floods, droughts, wildfires etc (IPCC 2018). Other risks including human health, food security, water supply, human security, and loss of species, which can all also impact economic growth (IPCC 2007).

All consequences of climate change have been globally observed and monitored, including in County Durham (DCC 2019).

County Durham has consistently observed and experienced increased temperatures (DCC 2019; Figure 1.16), rising sea levels, and more recently, severe weather events such as flooding and moorland fires (DCC 2019). Figures 1.16 & 1.17 show how County Durham matches global temperature rise.

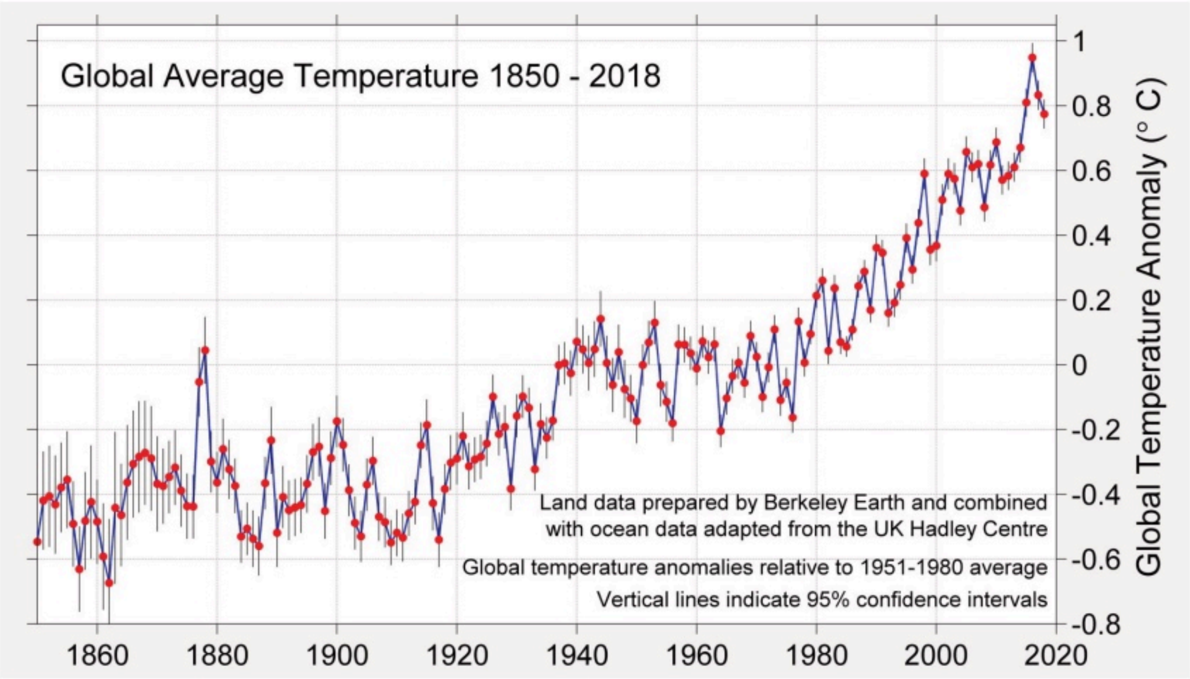


Figure 1.16 – Global average temperature from 1850 to 2020. Source – Berkeley Earth 2018

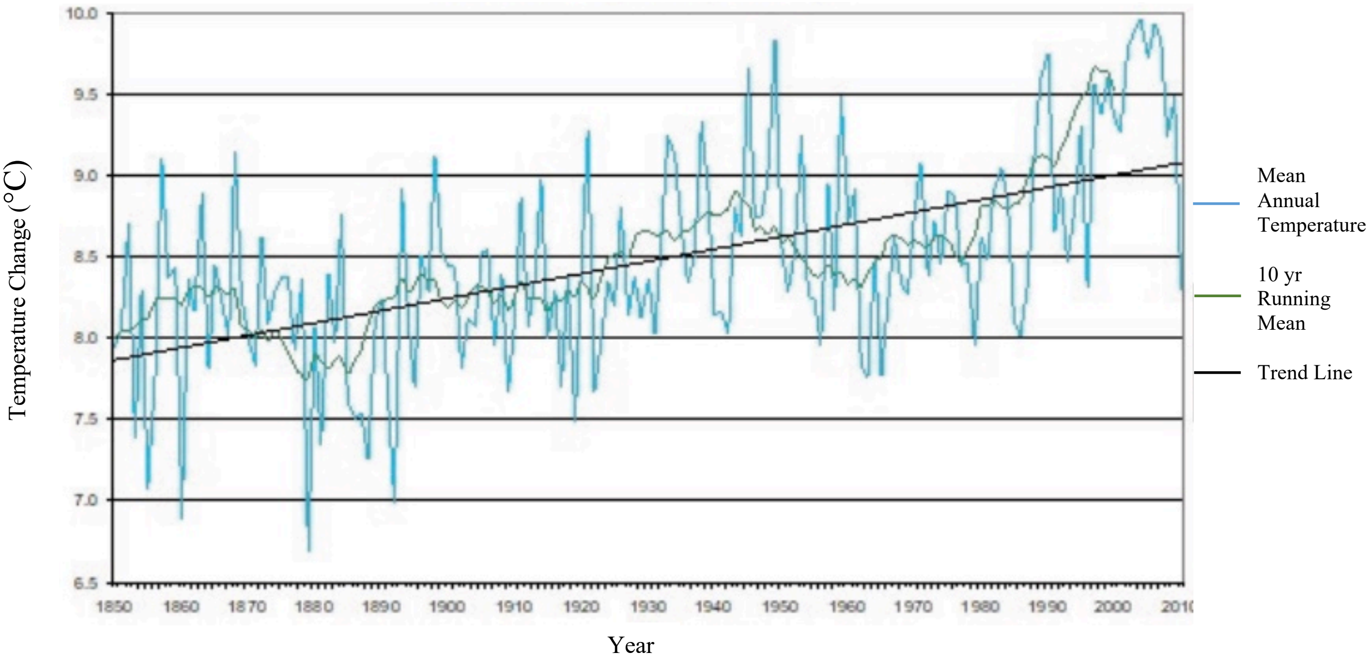


Figure 1.17 – Mean annual temperature change for County Durham from 1850 to 2010. This graph matches the global temperature increase in Figure 1.16. Source - Telford 2011

The consequences and aftereffects of climate change will continue to increase in severity, as the world moves towards 1.5-2 °C of warming, above pre-industrial levels (IPCC 2018). The IPCC (2018) reported current greenhouse gas emission trajectory predicts unless emergency action is taken within the next 12 years, global warming will increase to 3 °C above preindustrial levels.

In February 2019 Durham County Council declared a climate emergency. It entailed reducing the council's emissions by 60% by 2030 and making the county as a whole carbon neutral by 2050 (DCC 2019). To summarise, the county will need to reduce emissions by 2,442 kt of CO_{2e} in 30 years, equating to 81 kt/yr, whilst also meeting its energy demands of 10,513 GWh. However, energy demand is likely to change, for example, in sectors such as transport, energy demand is increasing (DCC 2019; Figure 1.18).

Figure 1.18 – Graph to show the ktCO_{2e} emitted for industry, domestic and transport over time. Data source - Durham County Council 2019

Overall emissions in County Durham decreased by 52% from 1990 levels, 9% higher than the national average (DCC 2019). One possible reason for the decline is the decarbonisation of the National Grid (DCC 2019).

County Durham has decreased its coal dependency, and started generating more energy through low carbon resources, which is demonstrated within Figure 1.19.

In 2014 the UK carbon factor of grid electrcity was 495 gCO_{2e}/kWh of electrcity generated (ICAX, Unknown). In 2017, this carbon factor dropped to 212 gCO_{2e}/kWh, and is expected to decrease to 66 gCO_{2e}/kWh, by 2035 (ICAX Unknown).

The National Grid ESO (2020), states four future scenarios for the UK's energy systems. Three scenarios predict the UK reaching its net-zero target on or ahead of the 2050 deadline. One report claims that by 2050, the power sector could sequester 62 million t of CO_{2e}. In another scenario, the transport sector energy demand will fall by 75%, between 2019-2050.Tthe average homes energy consumption will fall to 25% of the current levels (National Grid ESO 2020). For reduced emissions to be realised, 80% of households will be required to posses an electric vehicle (EV) charger. Vehicle-to-grid networks will have to reach 5.5 million vehicles. Eight million hybrid heat pumps will need installing, and eight million homes will need to be fitted with thermal storage and load shifting technologies. At the same time, there will be a requirement to introduce policy legislation to phase out oil and natural gas fired boilers (National Grid ESO 2020).

These scenarios have faced criticism levelling the net-zero stratergies for being over-relient on biomass which has negative land consequences and carbon capture and storage which may not mature and upscale rapidly enough (Edie 2020).

If emissions do follow the trends outlined, the emissions targets the county is aiming to ahcieve, including those targets set out within this thesis, are likely to decrease rapidly. Consequently, continual trend analysis will need to be taken, as this may change the invetment strategy of low carbon, sustainable resources.

1.3.3 Current Low Carbon Energy Production

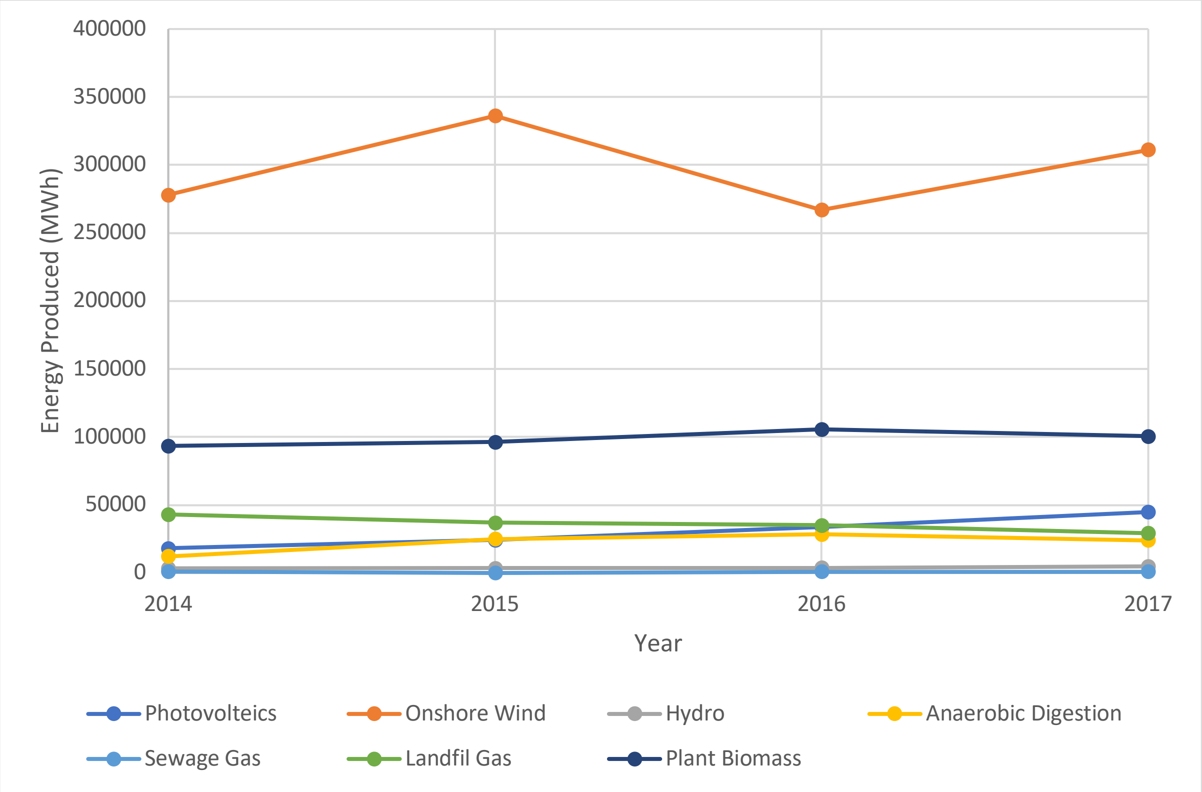


Figure 1.19 – Graph shows the trend of different renewable energy sources and how much energy they have produced in County Durham from 2014 – 2017 in MWh. Data Source – DCC 2017

Since 2014, County Durham has used low carbon sustainable energy resources, consisting of onshore wind, photovoltaics, biomass energy, and hydroelectric power (DCC 2017). Onshore wind (311,214 MWh) is the dominant method of low carbon energy supply into the county, followed by biomass (154,748 MWh) and photovoltaics (44,826 MWh).

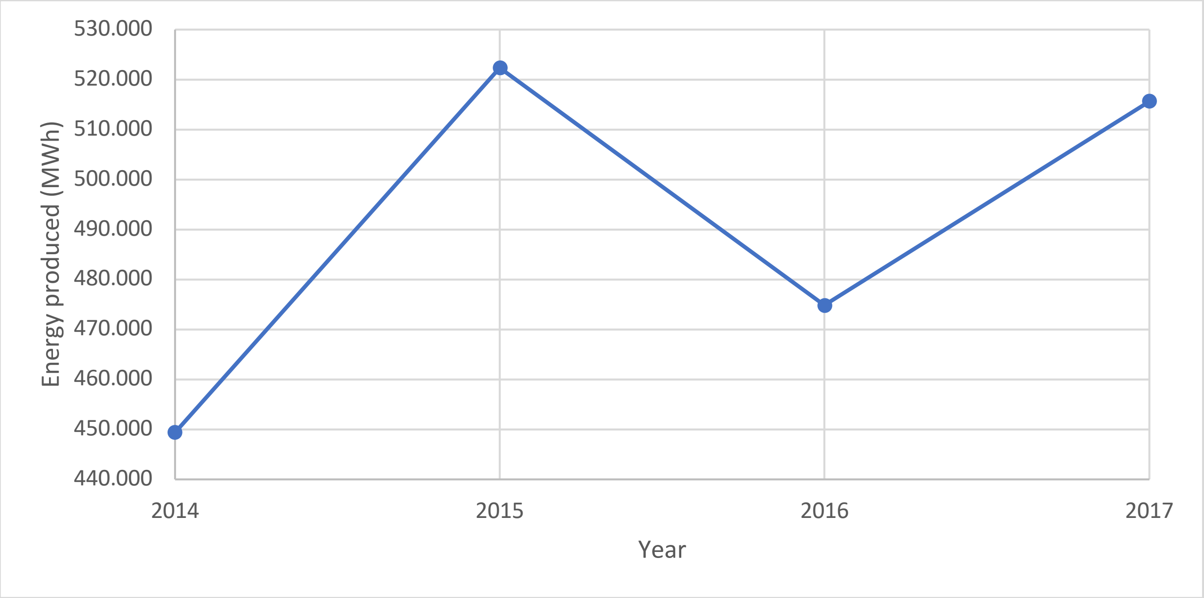


Figure 1.20– Graph showing the total energy produced from renewable sources in County Durham from 2014-2017. Data Source – DCC 2019

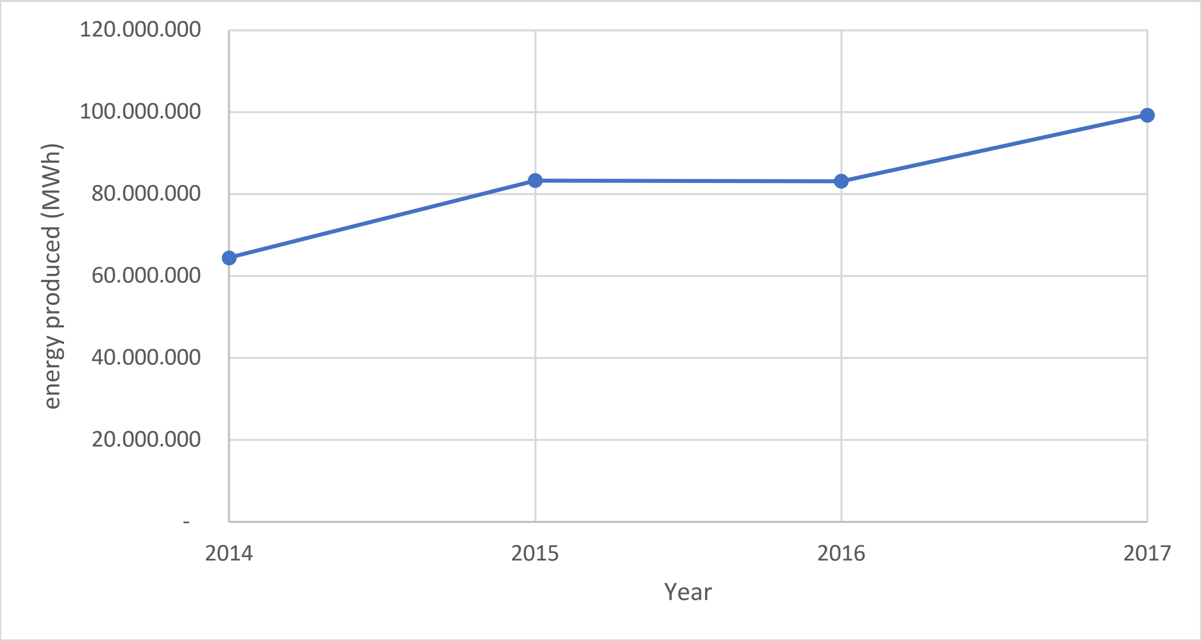


Figure 1.21 – Total energy produced in the UK from renewable sources from 2014-2017. Graph shows a steady increase and positive correlation. Data Source – DCC 2019

Figure 1.20 shows that in 2017, County Durham produced 515,681 MWh of energy, through low carbon sustainable resources, which is equivalent to 67% of the county's domestic electricity bill. County Durham matches the UK renewable energy production trend, excluding 2016, which the cause seems to be a reduction in onshore wind production (Figure 1.19 & 1.21).

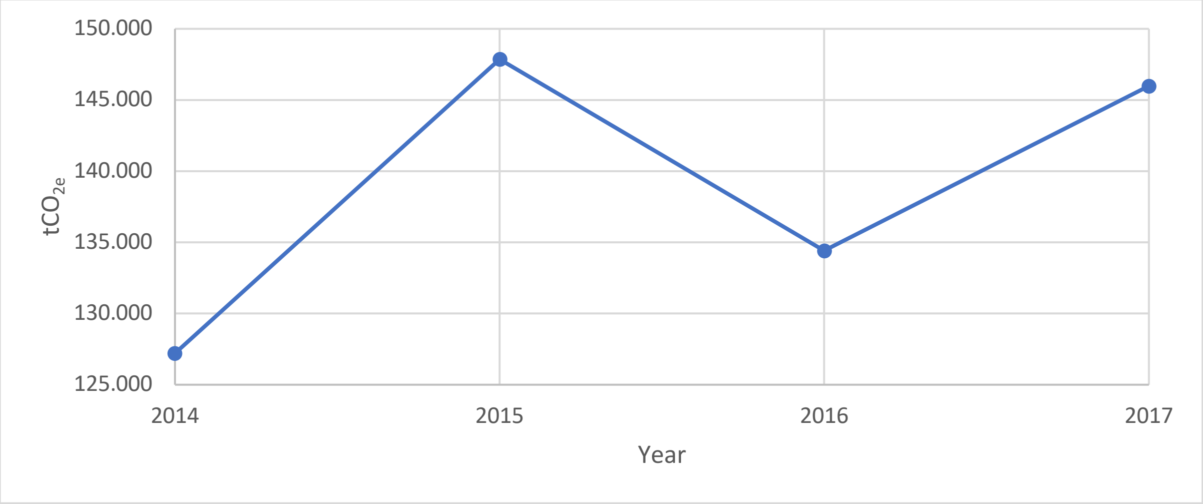


Figure 1.22 – Graph showing the amount of carbon the UK has saved from entering the atmosphere from 2014-2017. Data Source – DCC 2019

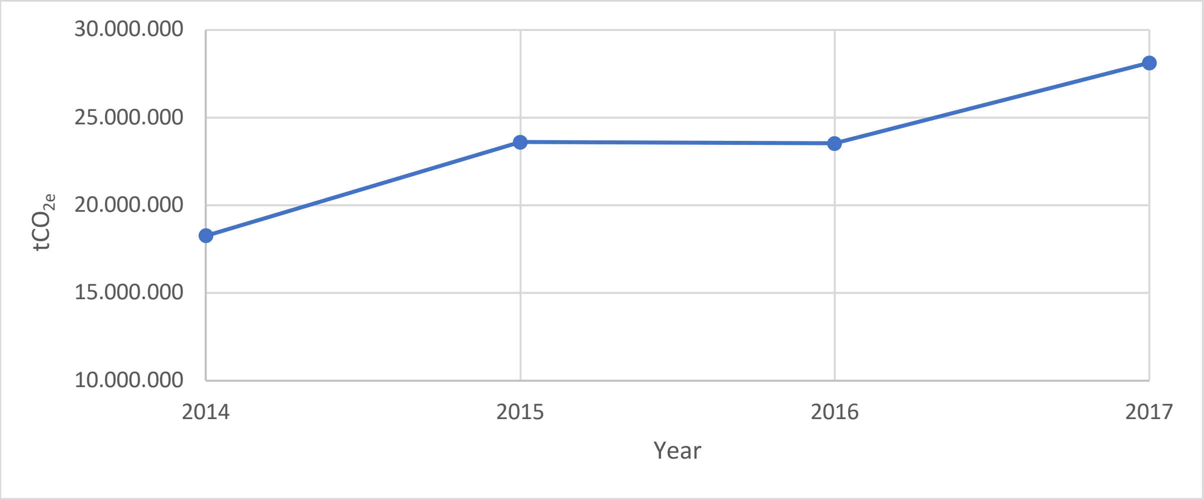


Figure 1.23 – Graph showing the amount of carbon the UK has saved from entering the atmosphere from 2014-2017. Data Source – DCC 2019

Figure 1.22 shows that the county saved 145,974 tCO_{2e} in 2017. The graph does not follow the same trend recorded across the UK (Figure 1.23). However, Figure 1.22 does match Figure 1.20, highlighting that more low carbon energy sources, results in higher carbon savings.

A contributor to recent carbon emission savings is thought to be the fuel efficiency within motor vehicles (DCC 2019). However, Figure 1.18 records an increase of emissions within the transport sector. An increase of 12.95 ktCO_{2e}/yr (1.8%) since 2013, can be seen. Transportation is now placed as the second highest energy demand sector within County Durham (Figure 1.18)

Another possible reason for the increase in transport emissions is the population settlement distribution within County Durham (DCC 2019). Large ex-mining communities lack employment opportunity, resulting in many residents having to commute to other areas to work. If compared with the rest of the UK, County Durham has on average 3% higher transport emissions (DCC 2019). Domestic emissions are also 2% higher within County Durham, if compared to UK averages. This has possibly resulted from the large proportion of old housing stock (DCC 2019). Only the industry/commercial sector recorded 2% lower than the national average (DCC 2019). This could be the result of closures, rather than new energy protocols (DCC 2019).

1.4 Reasons for Undertaking This Project

Although the UK is only responsible for 0.7% of total global emissions, if broken down by per capita, UK emissions are very high (5300 kg per capita in 2017) (DCC 2019).

However, with the resources available, the UK has the opportunity to become a key leader driving towards a carbon neutral future.

County Durham's ambitions mirror those of the UK. The county currently contributes just 0.6% of the UK's total emissions (DCC 2019). Furthermore, events resulting from climate change, are set to cost 20% of the UK's GDP (DCC 2019), equating to £600 million per annum, by 2050 (DCC 2019).

Adaptation to climate change is likely to cost annually, approximately 1-2% GDP, or £80-100 million, making the cost benefit ratio 1:7, in favour of adaptation (DCC 2019). There are other co-benefits regarding adaptation to climate change. A key component is an improved quality of life, as health will improve with less noise, better air quality, and healthier diets. Other elements include enhanced biodiversity, regenerated neighbourhoods (particularly the former coal mining communities), as well as reduced fuel poverty. Finally, switching away from fossil fuels could initiate and stimulate further investment into the county (DCC 2019).

1.5 Aims of the Project

The aim of this thesis was to examine the technical potential of different low carbon sustainable resources in County Durham, to decarbonise the county's energy use, and enable the county to meet their climate emergency 2050 goal, set by Durham County Council.

This study contains a technical evaluation of possibilities. It does not include non-technical factors, such as, funding, governance, legislation, market opportunities, planning permission, and policy. However, the content could be used to influence policy decisions that could support the transition to a carbon neutral future. This thesis aims to aid Durham County Council's understanding of the resource potential that the county possesses, and the potential methods that would support the target of becoming carbon neutral by 2050.

1.6 Methodology

Energy demand and emission data used throughout this study was generated by Durham County Council and was manipulated by the Committee on Climate Change. The Committee on Climate Change published the data to Durham County Council without releasing their method of calculation. Without the opportunity to analyse or critique the method of data collection/calculation meant this was a limitation of this study. Furthermore, due to the data being generated in 2015 meant that this was also a limitation of the study as energy demand and emissions in County Durham are likely to have changed since 2015. Further study is therefore required with current energy demand and emission data as this would impact the relative potential of each low carbon, sustainable resource. The potential of each resource was first examined by understanding how each resource works using published data. Understanding how each resource worked, outlined the details to consider when calculating the overall potential for County Durham.

The resource dependencies were investigated as these were critical for the calculation of the energy potential specific to County Durham. To calculate the energy potential in County Durham for each low carbon sustainable resource, characteristics such as the geology, geography, and land were analysed. To display the energy potential, it was either quantified in absolute energy terms, or as a hypothetical production value. The hypothetical production value was dependant on the specific factors for each resource. For example, a typical onshore wind turbine possesses the potential to generate 'X' GWh of electricity due to conditions local to County Durham however the total energy potential of wind energy in County Durham is dependent on how many turbines are installed. The data and conversion calculations taken from Durham County Council, allowed energy production values to be converted into a carbon emission saving, for the operational phase of the energy system. Embedded carbon associated with manufacture, and transport to site, was not included in the calculation, thus being a limitation of the data. Furthermore, CO_2 emission data throughout was represented as CO_2 equivalent values (CO_{2e}), to account for other greenhouse gas emissions present, in different decarbonisation sectors. However, the algorithms used to convert data submitted were not available for audit. This is a limitation of the study and should be considered with any future work.

Finally, each resource's limitations and economics were examined using published data. This has also been accompanied with case study examples to aid the understanding of how the resource can help achieve County Durham's target of becoming carbon neutral by 2050.

Chapter 2 - Low Carbon, Sustainable Resources

This chapter will review in a technical manner the different low carbon sustainable resources within County Durham. Each section will investigate how the resource works, what the resource depends on, the energy potential in County Durham, the possible limitations to the resource, land use and economics supported with relevant case studies.

2.1 Mine Water Energy

2.1.1 How it works

Mines once used for resource extraction, such as coal mines in County Durham, can now be used as a geothermal heat source due to the water they store (Banks et al 2004). After abandonment, the mines flooded with meteoric water (Gluyas, Personal Communication, 2019). This water is now stored in the void space, left behind from the extracted resource (Gluyas, Personal Communication, 2019). Due to the flow of heat from within the Earth, the water in these mining-induced voids is warm (Gluyas et al 2018). Given the geothermal gradient in NE England of 25 °C km^{-1} (Closer to 35 °C km^{-1} across the Weardale Granite) and the typical depths of the abandoned mines, waters that were tested ranged between 12 °C to above 20 °C (Gluyas et al 2018).

Mines are complex in layout with working faces, tunnels, mine waste and goaf all still present underground (Banks et al 2004). These large surface areas are in direct contact with rock which enables an efficient heat exchange between the two (Banks et al 2004). Furthermore, mines are commonly interconnected in the subsurface and thus convection in the connected water systems provide higher temperatures compared to groundwater at the same depth, leading to a consistently higher extraction rate as available energy is circulated (Watzlaf & Ackman 2006).

An advantage with mine water energy compared with other geothermal sources is the waters known ability to flow to the surface, either pumped or naturally. The water flows through the permeable goaf and rubbish is disposed of down the existing mine shafts (Adams et al 2017). In many other geothermal projects, it is permeability that causes an issue. The resource may be present, however, geologically complex or impermeable strata make extraction difficult relative to mine water. Mine water energy does not have this issue with the abundance of permeable galleries and shafts only several hundred metres below the surface (Adams et al 2017).

Watzlaf and Ackman (2006) demonstrated on the Pittsburgh coal seam that if <30% of the mine water is extracted annually and the mine is continually resupplied, the water will remain at the same temperature due to the Earth's heat flow. However, there is a finite amount of energy and heat transfer rate (Watzlaf & Ackman 2006). In addition, further study is required to understand mine specific resupply rates as local geothermal gradients may differ from the Pittsburgh coal seam. Figure 2.1 shows a cross-sectional view of a typical mine water energy system.

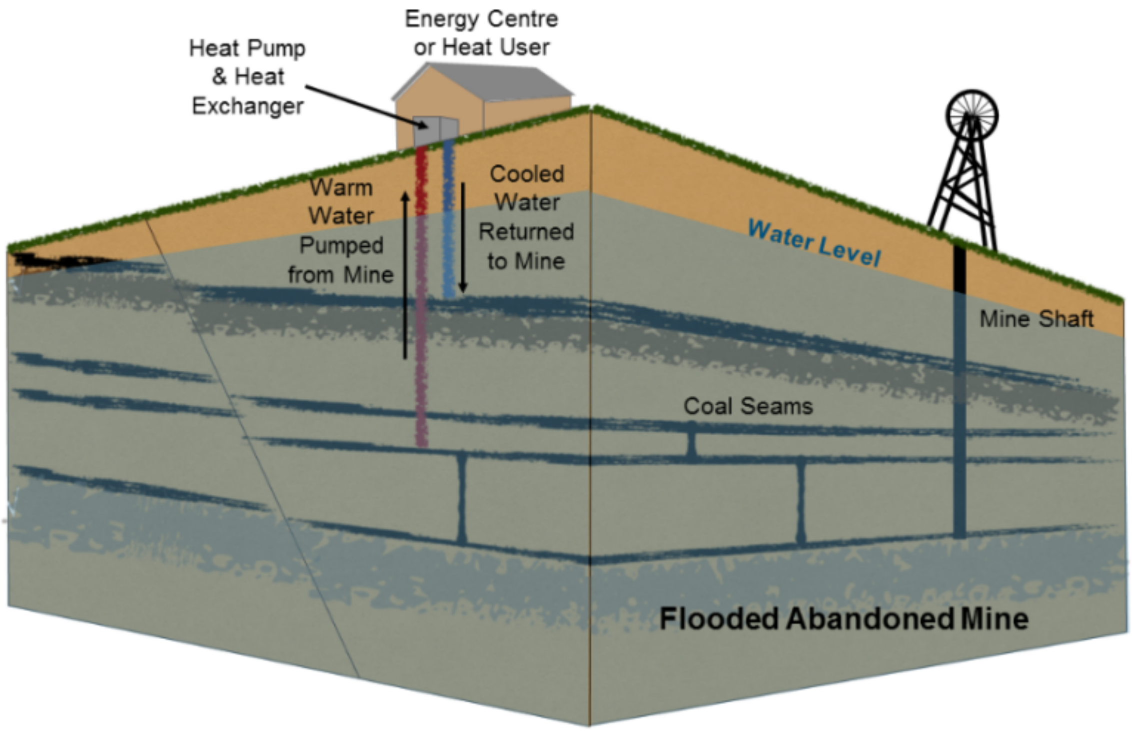


Figure 2.1 – Diagram showing a typical minewater energy system
Source – Adams 2019

2.1.2 What does the resource depend on?

Number of Abandoned Mines

Typically, the larger number of flooded mines present will increase the amount of extracted coal and thus increase the resource potential. In County Durham, there was an early industrial revolution from 1600 to 1800 (Hatcher 2000). Coal was mined along the River Wear and Tyne and by 1700, 800,000,000 kg of coal was being exported from Durham annually (Adams et al 2014). More recently between 1877 and 1956, 30 billion kg of coal was produced from County Durham per year. County Durham's rich coal supply can be seen in Figure 2.2 where areas of heat demand have also been correlated.

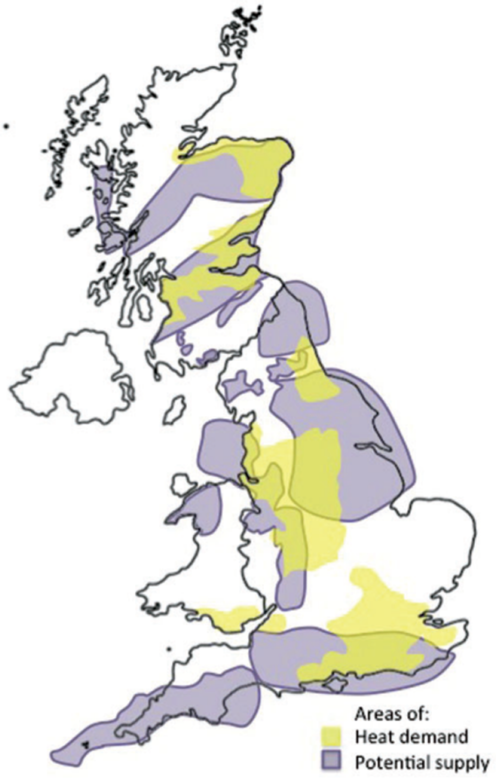


Figure 2.2 – UK map of areas of required heat demand overlain with the potential supply areas of minewater energy. Source – Gluyas 2019

Mining Method

Depending upon the mining method used to extract coal determines how much void space remained within each mine. Throughout the history of coal production, two main mining methods were used after the improvement in safety from bell pit mining (Russell 2012). First was the room and pillar method (Figure 2.3). This is where ‘rooms’ of coal were dug out horizontally whilst pillars of coal were left to support the overburden (Gillespie et al 2013). Some networks that were dug were 800 m deep (UK Coal 2015). The recovery rate of coal from the room and pillar method was low, in some cases <40% (Gillespie et al 2013). Consequently, at the beginning of the 20th century, the coal mining industry switched to using a longwall mining technique (Figure 2.4). In longwall mining, the miners undercut the coal along the width of the seam, collecting the coal as it fell, whilst controlling the collapse of the roof behind the face. This method increased recovery rates to ~80% (Gillespie et al 2013).

The room and pillar method left 50% of void space within the coal seams, whereas longwall mining left only 20% (Adams et al 2019). The mine water resource potential will be impacted by the type of mining method used.

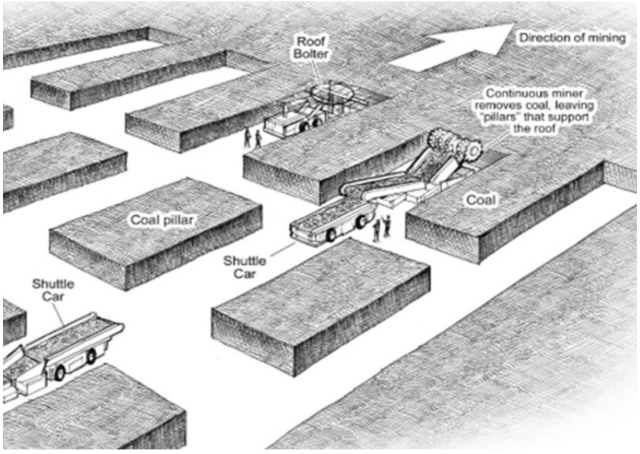


Figure 2.3 – Sketch diagram of how a typical room and pillar mining style was undertaken. Source – Halder & Chakravarty 2018

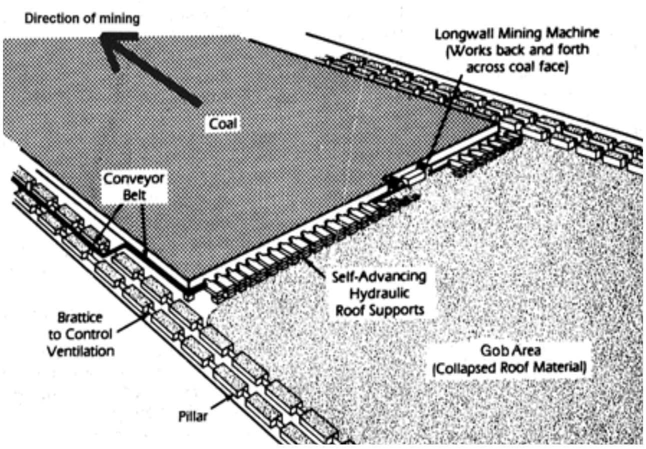


Figure 2.4 – Sketch diagram of Longwall mining process. Source – Messner & Minnucci 2009

2.1.3 Energy Potential in County Durham

The total amount of coal removed from County Durham was approximately 2.5 billion t (DMM 2015). Multiply this value by the density of coal (1.5 t/m^3) calculates the worked volume of coal in County Durham to be ~1.6 billion m^3. However, the proportion of which different mining practices took place to remove that coal is unknown. Consequently, these calculations (Table 2.1) assume that all mining taken place after 1900 was via longwall mining. Individual mine studies would be required to understand the exact resource potential within County Durham as the DMM 2015 study is also an approximate figure from only one source.

Mining Method	**Worked Volume (billion m^3)**	**Volume of water (billion m^3)**	**SHC of Water (J/m^3/k)**	**Thermal energy from 5 °C (J)**
Stoop and Room	0.492	0.246	4200000	5.1x10^{15}
Longwall	1.14	0.229	4200000	4.8x10^{15}
Total thermal energy from Minewater in County Durham (J)				9.9x10^{15}

Table 2.1 – Table of energy data for each mining method used in County Durham. Calculated using the total worked volume from County Durham. Data Source – DMM 2015

County Durham's average household heat consumption is 13,600 kWh (Gluyas et al 2020) Consequently, the county's minewater energy resource has the capacity to heat ~204,000 homes, equating to 91% of the 223,803 homes in the county. This low carbon resource would save 785,618 tCO_{2e}. In comparison, all of County Durham's renewable resources saved 134,000 tCO_{2e} combined in 2016.

In some mines, being flooded with water can pose a threat to groundwater and so they require continual pumping at rates up to approximately 100 l/s. This is to maintain safe groundwater levels, safe drinking water in aquifers and to not have brown, iron rich, water flowing to the surface (Gluyas et al 2020). The amount of heat energy that could be produced from water currently being pumped out in County Durham is shown in Table 2.2.

Minewater already pumped out (million m^3/y)	**Thermal energy from 5 °C (J)**	**Number of homes heated from resource**
35.3	7.4×10^{14}	15,114

Figure 2.2 – Table of Minewater energy data showing how much energy and homes could be heated from the resource of minewater that is already being pumped out to maintain safe water levels. Data Source - DMM 2015

Up to 15,114 (6.7% of the housing in County Durham) homes could be heated by water which already has the infrastructure in place to extract it from the ground. This would have a carbon saving of 58,344 tCO_{2e}.

2.1.4 Limitations of the Resource

Data

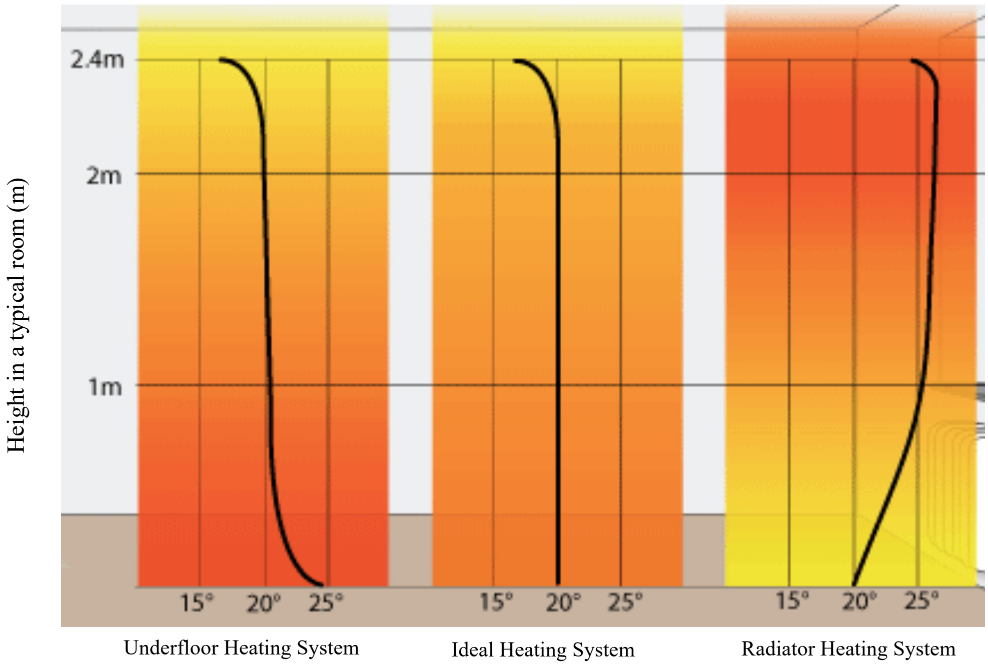
The assumption that only longwall mining was used after the year 1900 is a factor that determines the resource potential, due to the variance in percentage void space left by different mining practices. The year 1900 was used as longwall mining became mechanised after this date, and the vast majority of mines used longwall mining by 1950 (Gillespie et al 2013). However, the process of longwall mining was developed in the late 17th century. Longwall mining therefore could have been used for a longer period than calculated for. Conversely, Rippon (2002) stated that most mines only used longwall methods since 1950. To understand the exact mine water resource potential, detailed surveys of each mine would need to be taken to understand the true volume of water left in the mines.

Proximity to the Mine

For mine water energy to be efficient enough to heat domestic homes, homes must typically be <1 km in distance from the mine where the water is being extracted from, due to heat loss throughout transmission (Adams, Personal Communication, 2019). This is a limitation in County Durham because the county has a large area (2,226 km^2), with a dispersed settlement pattern (DCC 2019). However, Gluyas, (2020) states that out of 2.6 million people in the NE, two million live above previously mined areas. Therefore, it is likely that the 91% housing stock value is unattainable due to not all homes in the County being <1 km distance from a mine. Consequently, a detailed study of County Durham's housing stock and their proximity to the mines should be considered.

The Efficiency of the System

Due to mine waters' low temperature (12-20 °C), it would be used as a domestic heat supply and not to generate electricity as this requires temperatures 50 - 150 °C (Lund 2004). However, domestic heat supply needs to be ~40-50 °C, the temperature must, therefore, be increased. To achieve this a heat pump could be used. Heat pumps use electricity to increase the temperature of the source water. For every kW of energy used by the heat pump, 3-4 kW of heat is produced (Adams et al 2017). When applying the heat within the home, underfloor heating systems have much higher efficiency compared to the typical radiator shown by figure 2.5 (The Green Age 2016). By increasing the efficiency of homes, less energy would be required from the mine water and heat pump system, see section 3.4.1.



Underfloor Heating System

Ideal Heating System

Radiator Heating System

Figure 2.5 – Schematic diagram of the heating efficiencies of different house heating systems. These graphs show that under floor heating systems are more efficient than radiator systems.
Source – Warmup 2017

Maintenance

Figure 2.6 – Iron oxide deposition on temperature gauge used in South Wales mine water energy development site after 4 months of use compared to new temperature gauge. Source – Farr & Tucker 2015

Due to the interaction of oxygenated waters and large quantities of pyrite within the mine, mine water is enriched in iron (Adams et al 2019). When exposed to oxygen, iron oxidises, producing the substance (iron) ochre (Adams et al 2019). Ochre can clog instruments such as pipes & valves etc (Bryant 1988). Clogging can lead to a decreased extraction rate, or breakdown of the system entirely, as the water may not be able to flow through the system (Black, Personal Communication, 2019). An example of ochre clogging instruments is shown in Figure 2.6. To limit this issue mine water can be treated or cleaned. Cleaning options include mechanical descaling using high-pressure jets, 'Pigging' which is the use of a cylindrical abrasion tool down the pipe, phosphate-based dispersing agents or oxygen scavenging reducing agents (Banks et al 2004). Such maintenance practices all continually require financial support, so prevention is more favourable. However, even with continual treatment, clogging can still occur. Treated mine water with just 1 mg/l of total iron present still created clogging issues at the Dawdon mine water project located in County Durham (Bailey et al 2013). To prevent the production of iron ochre, a closed loop system could be used. In a closed-loop system collector fluid does not contact the mine water, although these systems have a limited capacity (Banks et al 2004) Alternatively, an open-loop pressurised system excludes atmospheric oxygen from the system entirely to prevent iron oxidisation. Pressurised systems minimise the degassing of elements such as carbon dioxide which raise the pH of the water and promote precipitation of iron oxyhydrates and carbonate scales (Banks et al 2004) These systems have shown success in two Scottish projects with no clogging issues for 10 years with an iron concentration of 80 mg/l.

2.1.5 Economics

The cost of mine water energy projects can be split into acquiring the mine site, infrastructure and maintenance. Due to a lack of mine water energy projects that disclose their project costs only one example can be used specific to County Durham. Adam Black, a director at Lanchester Wines who were the first business in the UK to make use of mine water energy, stated that £3.5 million was spent on a 4 MW system which can heat 2,323 homes (Black, personal communication, 2019). At this scale, County Durham would need 358 similar size systems to heat all the homes in the County (Gluyas et al 2020). Assuming the costs remained the same, 358 systems would cost £1.27 billion. Although, at this larger scale for domestic use, more costs would have to be accounted e.g. the systems application to homes. Therefore, further study is required for economic data, specific to County Durham's strategy.

2.1.6 Case Study Examples

Lanchester Wines – (Tighe 2019)

Lanchester Wines is a UK wine merchant and importer based in County Durham. They have grown from a family home business in 1980 to now a +£90 million turnover company with 500 staff and recently they have become carbon neutral. Part of their progress towards becoming carbon neutral was their £3.5 million mine water energy project which now keeps millions of bottles of wine chilled and heats the nearby distribution depot (Figure 2.7). The same amount of energy could heat 2,323 homes. The system delivers 4 MW across two systems and 6 kW of heat per kW of power required to run the system. They are the first business in the UK to make use of mine water energy. The director of Lanchester Wines Adam Black states how initial investment and maintenance are the biggest issues to overcome with mine water energy. When exploring the potential of mine water energy, the company spent £250,000 drilling a borehole that yielded no water, due to poor site location. Furthermore, the system still requires approximately £50,000 to finish off the project as well as constant maintenance costs due to clogging and pressure issues. However, the company has recently received its first renewable heat incentive repayment from the government of £117,000. Adam Black predicts the £8 million total spend to make Lanchester Wines carbon neutral will be repaid within 7 years.

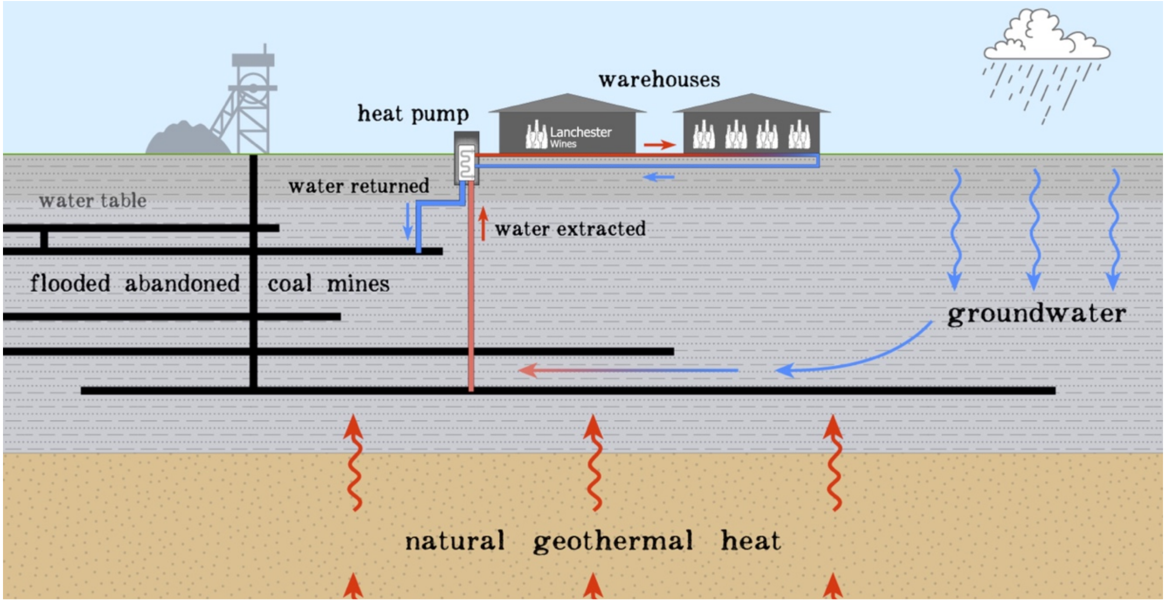


Figure 2.7 – Minewater heat system in place at Lanchester Wines, County Durham. Minewater here is used to cool the warehouse and heat the distribution depot. Source – Lanchester Wines 2020

Heerlen, Netherlands - Renewables Networking Platform (Unknown)

The mine water energy project taken place in Heerlen is a low-temperature district heating system which began in 2008 but has since been improved with two further system enhancements (Figure 2.8). Heerlen had three main mines which closed between 1965-1974. In 2005, with financial backing from the EU and government, five wells were drilled and 8,000 m of underground piping was built to extract the mine water resource. In 2008, the first mine water plant was in operation providing 30,000 m^2 of indoor space heating. The use of mine water energy has reduced carbon emissions by 65% in the region with 500,000 m^2 of indoor space connected to the system. Researchers are now working to improve the system by making it demand-based. This is where patterns of demand over time are recognised so the energy can be distributed more efficiently and effectively over time. The goal is to then have 800,000 m^2 of indoor space connected to the resource, further reducing carbon emissions. A challenge that Heerlen faced was the technologies social acceptance. Like in County Durham, the ex-mining communities went into economic, social and cultural decline after mines were shut down. In Heerlen, old mineworkers were actively involved in the planning phase of the project in an attempt to help rehabilitate the impacted areas. Financing the project was also an issue as most financial institutions are not yet capable of assessing the risks of mine water developments. This problem was overcome with step by step expansion to build up financial trust.

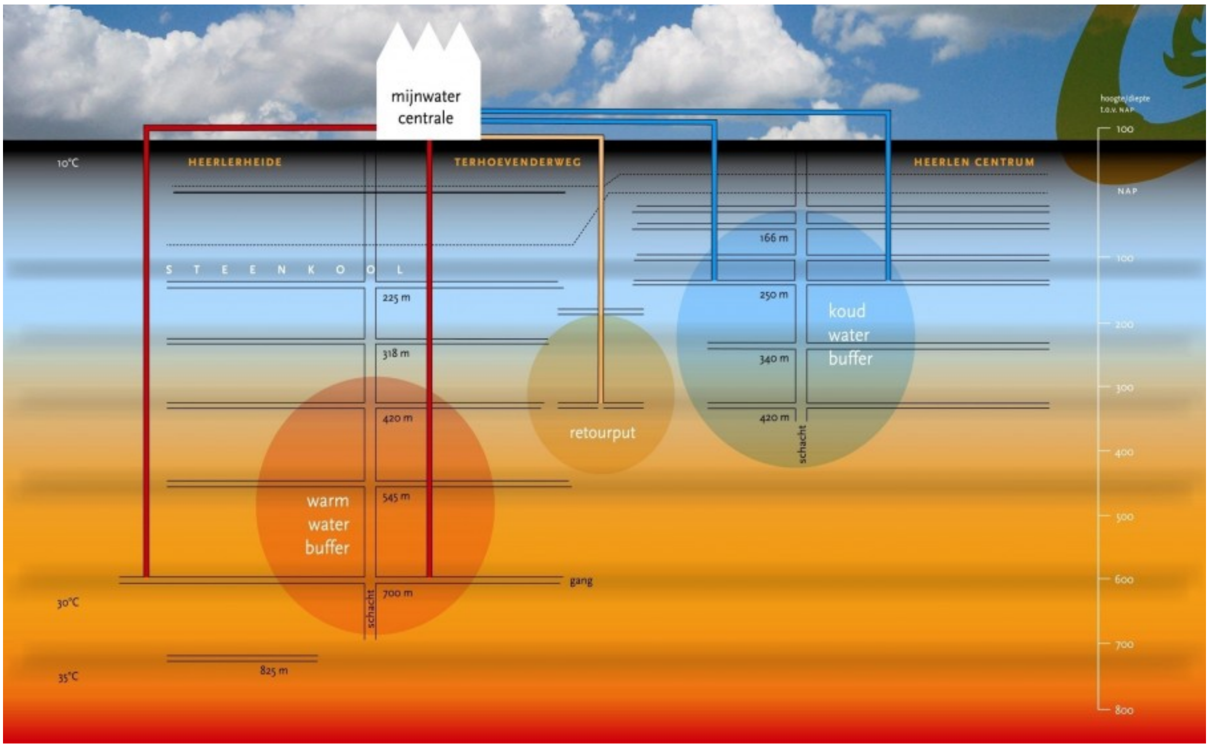


Figure 2.8 – Minewater energy system diagram for Heerlen, Netherlands developed by Mijnwater Centrale.
Source – Cyclifier 2020

Glasgow Geothermal Energy Research Centre – UK Geoenergy Observatories (Unknown)

Using a network of twelve boreholes, the city of Glasgow, Scotland will observe and monitor how water flows through the abandoned mine workings underneath the city. Researchers will study chemical, physical and microbial changes to the environment just below the surface in an attempt to understand and remove the risk of using this heat source as a low carbon, sustainable way to heat homes and cities. This work is being undertaken alongside the British Geological Survey (BGS) and results so far suggest that 40% of the cities heat demand could be filled by mine water energy (Figure 2.9). Furthermore, it is likely, Glasgow will now meet the government's targets to ensure 11% of heat is produced from renewable sources by 2020. The long-term goal is for Glasgow to use mine water energy to become one of Europe's most sustainable cities in the next ten years.

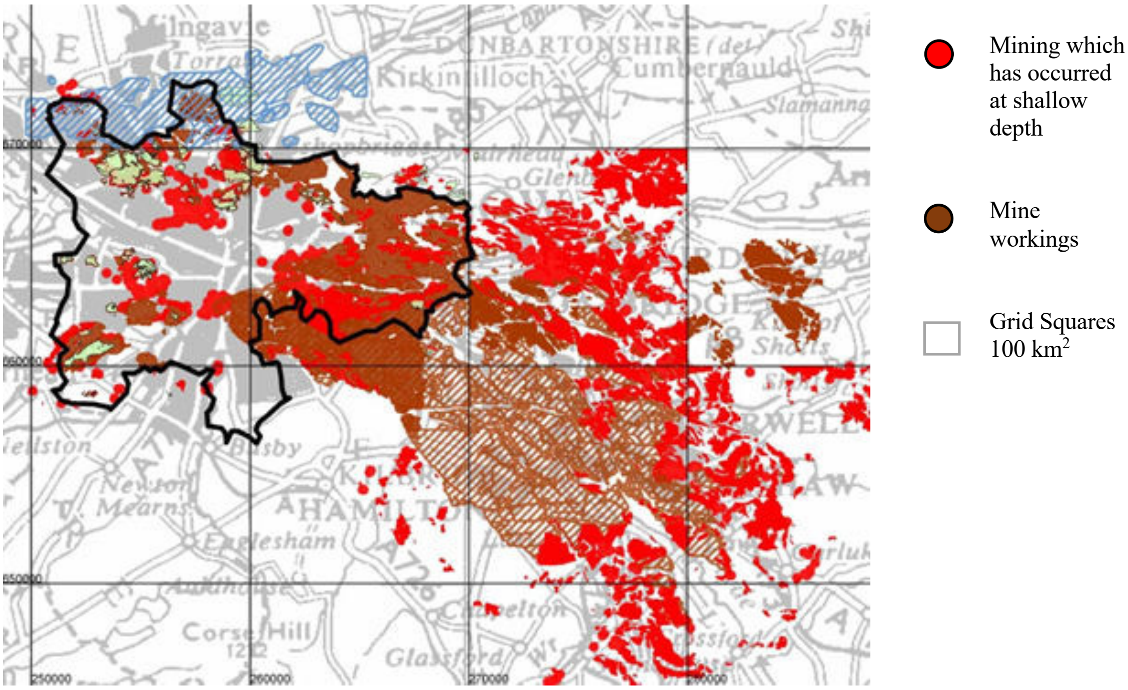


Figure 2.9 – Map of Glasgow, Scotland where brown colour represents known mine workings and red areas are mining that has occurred at shallow depths.
Source – BGS 2020

The Seren Project, South Wales - Farr & Tucker (2015)

The Seren project in South Wales researches mine water that is currently being pumped out of the mines to maintain safe water levels (Figure 2.10). Currently, mine water is pumped at 3,000 l/s with an average temperature of 13.4 °C. From their calculations they predict this water could heat 20,000 homes. From this research, Bridgend council has been granted £6.5 million to drill to 230 m depth to reach waters of ~20.6 °C from the Caerau Colliery (Figure 2.11) to heat 150 homes with the hope to increase to 1,000. This development will on average save homeowners £100/yr from heating bills.

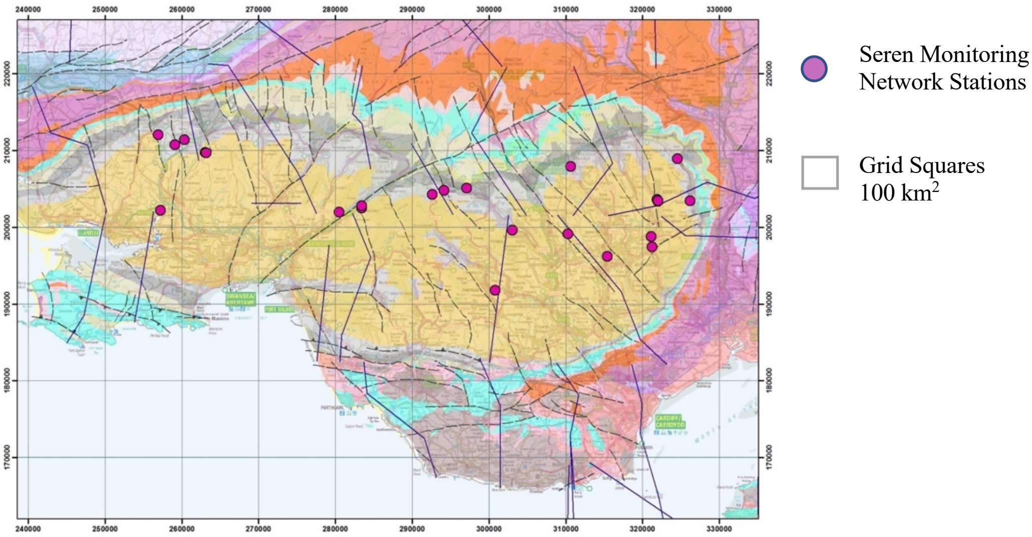


Figure 2.10 – Geological map of the area of study for the Seren Project, South Wales.. Source – Farr & Tucker 2015

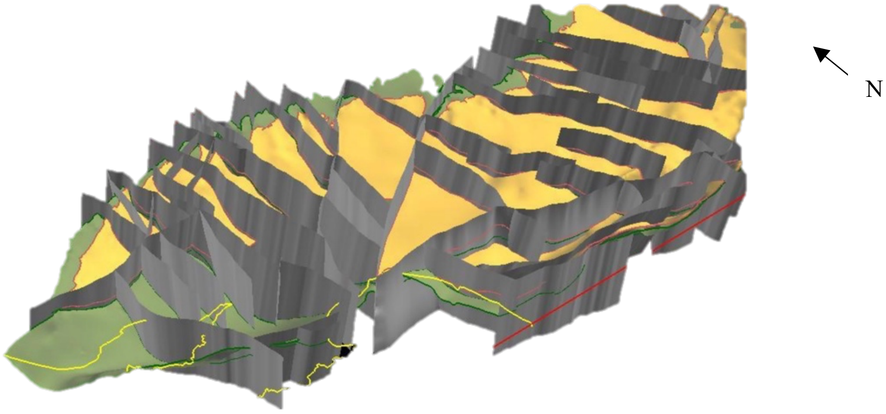


Figure 2.11 – BGS 3D Geological map of base of Seren project coal measures and a 2 m seam. Source – Farr & Tucker 2015

2.1.7 Conclusions

Mine water energy uses water which now infills the void space left behind by extracted coal, post abandonment of the mines in County Durham. The water temperature ranges between 12 - 20 °C due to the Earth's heat flow and geothermal gradient in the NE of England. Mine water energy being a geothermal resource means it has a low surface land use. Furthermore, if < 30% of the water is extracted annually and is constantly resupplied, the resource is sustainable (Watzlaf & Ackerman 2006). The energy potential of mine water depends on the volume of water present in the mines. This is determined by firstly, the volume of coal that was extracted. In County Durham, it is estimated that ~2.5 million t of coal were mined leaving a considerable volume of void space. However, the different mining methods, room and pillar versus longwall mining leaves behind 50% and 20% of void space respectively. Consequently, to calculate the resource potential in County Durham, all mining post 1900 had to be assumed to be mined via longwall methods. From this, mine water could heat up to the equivalent of 91% of all the homes in County Durham. Although there are some key limitations to this resource. Due to heat dissipation throughout transport, end users are required to be <1km from the mine which the water originates from. Secondly, the water temperature is too low to be directly used in the home, therefore a system such as a heat pump, powered by electricity, would be required to increase the temperature. Finally, mine water is prone to producing the substance (iron) ochre which can clog the system leading to failure. There are many maintenance practices which can be used to remove the ochre however an open-loop pressurised system is the best solution for prevention. Economic data for mine water energy can be generated from Lanchester Wines' development in County Durham which cost £3.5 million. To decarbonise domestic heating, County Durham would need 358 similar size systems, therefore costing ~£1.27 billion. County Durham consequently has a large potential for minewater heating however further research into housing proximity is needed to quantify exactly how much of the resource could be realised.

2.2 Deep Geothermal Energy

2.2.1 How it works

Deep geothermal energy is a tested low carbon sustainable technology (Gluyas et al 2018). It makes use of the Earth's heat flow to extract heat energy from petrathermal and hydrothermal geological systems which can be over 5000 m in depth (REA 2020; Figure 2.12). The heat energy gained from these systems can be used for direct heating and/or electricity generation, dependent upon the temperature of the returning geothermal fluids (Gluyas et al 2018). Deep geothermal energy has many advantages which include minimal greenhouse gas emissions and being continuous, this cannot be said for other intermittent renewable resources e.g. Solar (Gluyas et al 2018).

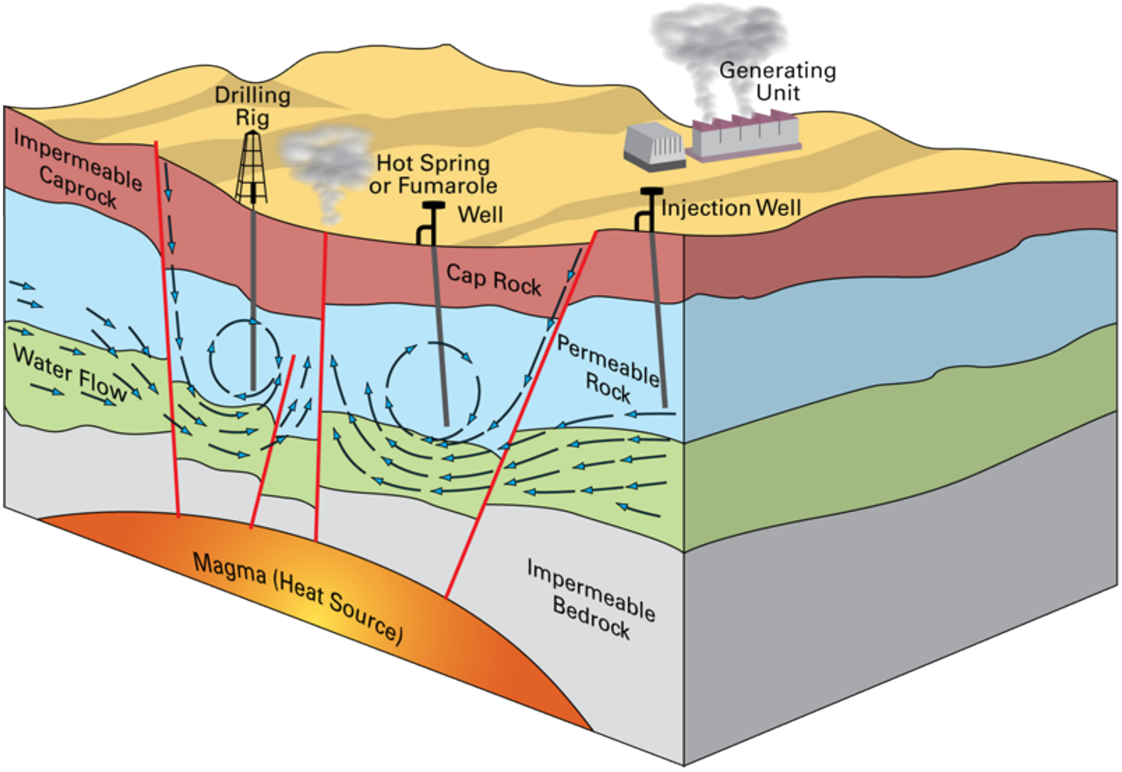


Figure 2.12 – Diagram of a typical Geothermal energy power plant. Source – BGS 2020

There is substantial potential for geothermal energy across the planet, as 99.9% of the Earth's mass is above 100 °C (BGS, 2020). The Earth gained this heat firstly from its accretionary history (Jeanloz et al 2020). The Earth's formation began with smaller masses called planetesimals within the solar system colliding and accreting together producing accretionary heating (Jeanloz et al 2020). Metal that was sinking to form the Earth's core, released gravitational energy, which in turn produced heat allowing the Earth's interior to have a high enough temperature to convect (Jeanloz et al 2020). This heat dissipated through time, although still represents ~10% of the Earth's heat (Nanyang 2018). The remaining 90% comes from the radioactive decay of elements such as uranium, potassium and thorium, which produce daughter isotopes as well as heat (Nanyang 2018). Although everywhere on Earth gets hotter with depth, geothermal potential can vary due to local geology, allowing some locations to have a higher geothermal potential than others as shown in figure 2.13.

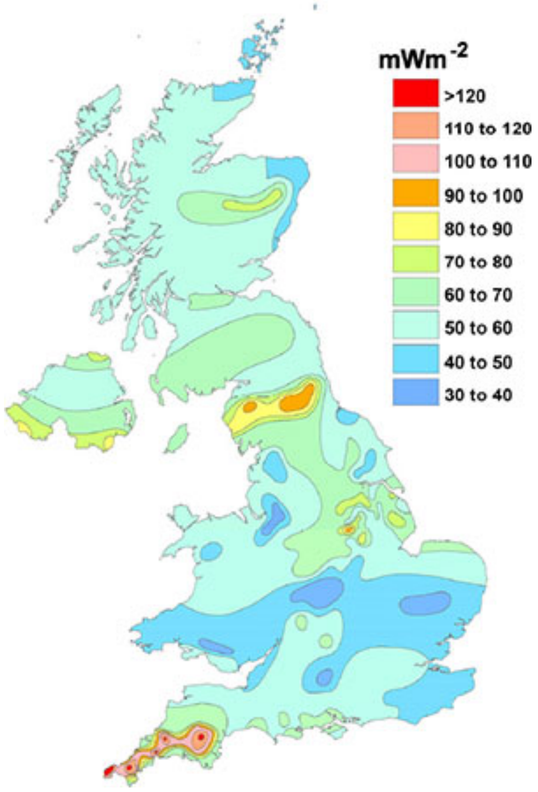


Figure 2.13 – Map of the UK's deep geothermal potential.
Source – BGS (NERC) 2019

The UK's geological history includes repeated rifting and collision events, which have formed two main deep geothermal systems to be explored. Sedimentary basins/aquifers and plutonic granites (Gluyas et al 2018).

Sedimentary basins/aquifers are conduction-dominated hydrothermal plays, which use deep heated groundwater as a source for heat (Hidayat 2017). Plutonic geothermal systems are petrathermal and require artificial stimulation to extract the resource (SKM 2012). County Durham has a plutonic granite geothermal resource named the Weardale Granite (Bott 1972).

Whether a geothermal prospect can be used for direct heating or electricity generation, depends upon the temperature of the returning geothermal fluids. Geothermal fluids ranging from 50 °C -150 °C, are typically used for direct heating systems, whereas efficient electricity generation requires temperatures around 150 °C (Lund 2004). Whereas, SKM (2012) states that fluids greater than 60 °C can be used for direct heating, and above 100 °C for electricity generation however this is not efficient. Due to the variance between studies it is likely to be dependent on multiple factors e.g. Local heating systems.

Electricity from geothermal energy is produced using either a binary, steam or flash power plant (Energy efficiency and Renewable energy 2018). Steam-based power plants use high temperature fluids to produce steam, turning a turbine to produce electricity (Figure 2.14).

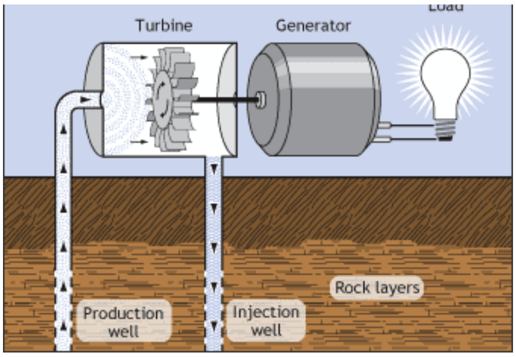


Figure 2.14 – Diagram of how a steam power plant works. Source – US EIA 2019

Binary power plants can use lower temperature fluids that pass through a heat exchange alongside a secondary fluid, which has a lower boiling point than water (Energy efficiency and Renewable energy 2018; Figure 2.15). The secondary fluid vaporises immediately and consequently drives the turbine to produce electricity (Energy efficiency and Renewable energy 2018). Binary plants are closed-loop systems so only water vapour is emitted as a by-product. The lower temperature waters used in a binary system are the most common type of geothermal resource (Energy efficiency and Renewable energy 2018).

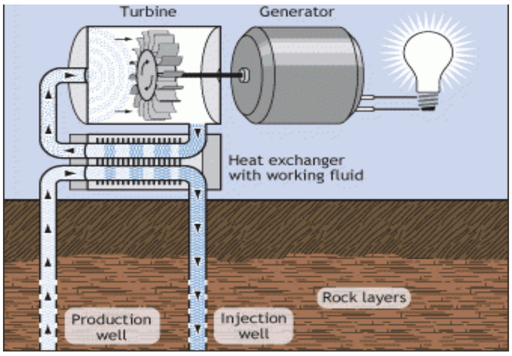


Figure 2.15 – Diagram of how a binary cycle geothermal power plant works. Source – US EIA 2019

Flash steam power plants use fluid temperatures above 182 °C (Energy Efficiency and Renewable energy 2018; Figure 2.16). These fluids are pumped at high pressure into a tank held at a much lower pressure. This pressure difference causes some fluid to vaporise immediately which then drives a turbine, generating electricity. (Energy Efficiency and Renewable energy 2018).

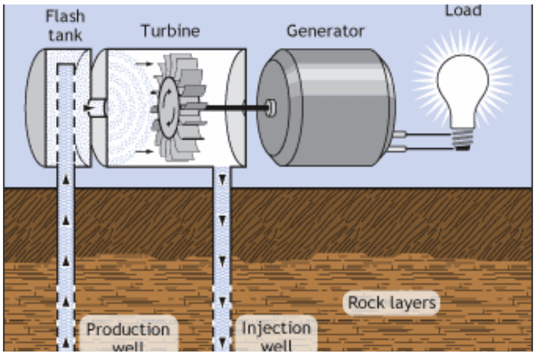


Figure 2.16 – Diagram of how a flash steam power plant works. Source – US EIA 2019

2.2.2 What does the resource depend upon?

The geothermal energy potential from a hydrothermal or petrathermal system will be determined by its temperature, volume and permeability (White 1966). Higher temperatures allow for more heat energy to be removed from the returning hydrothermal fluids. As previously mentioned, the temperature of the hydrothermal fluids determines if electricity can be generated from the system. The temperature (°C) drop of the hydrothermal fluid is multiplied by the mass of the water extracted from the resource, to calculate the extracted energy (Saville, Personal communication, 2019). Used as heat, virtually all of the energy is useful, but power generation is inefficient and only a modest proportion of the extracted energy will produce electrical energy. With a larger volume of fluid available, the mass will also be larger and therefore generate more power.

To allow hydrothermal fluids to flow to the surface, the geology of the geothermal resource must be permeable. This can be an issue in plutonic granites, as they typically have <1% pore space, and usually are dependent on fractures to have associated fluid flow (Gluyas et al 2018). This is the position in County Durham where the Weardale Granite was shown to have non-pervasive fractures throughout and permeability was only associated with the bounding fault (Slitt Vein) (Gluyas et al 2018, Manning et al 2007).

These factors will also impact the extraction and resupply rate of fluids to the geothermal resource (BGS 2020). Geothermal fluids must be continually recirculated through the system via a second borehole (BGS 2020). The rate at which this can occur is dependent upon the permeability of the resource.

2.2.3 Energy potential in County Durham

County Durham’s deep geothermal resource is the Weardale Granite. Formally known as the North Pennine Batholith, the Weardale Granite is the central pluton to a series of five contiguous plutons (Figure 1.3) that covers 1500 km^2 and has an average thermal gradient of 38 °C km^{-1} (Gluyas et al 2020; Figure 2.17). This geothermal gradient is due to the granite’s composition including thorium, uranium and potassium that produce heat energy when decaying (Gluyas et al 2020). The distribution of these elements is heterogeneous, which causes aerial changes in heat production measurements (Elliot et al in prep). The granite also contains albitic feldspar and two types of mica (Gluyas et al 2020). The granite has a non-porphyritic texture, with flat-lying foliation shown by mica and quartz eyes (Gluyas et al 2020). Ur-Pb dating shows the pluton to be 398.3 (±1.6) Ma, and so early Devonian in age (Selby et al 2013). It is likely that the Weardale Granite had an alkali magmatic nature during post-Whinn Sill emplacement (Bott & Smith 2018). Also, the granite’s steep-sided morphology indicates that heat moved through the granite via convection and not conduction. (Bott & Smith 2018)

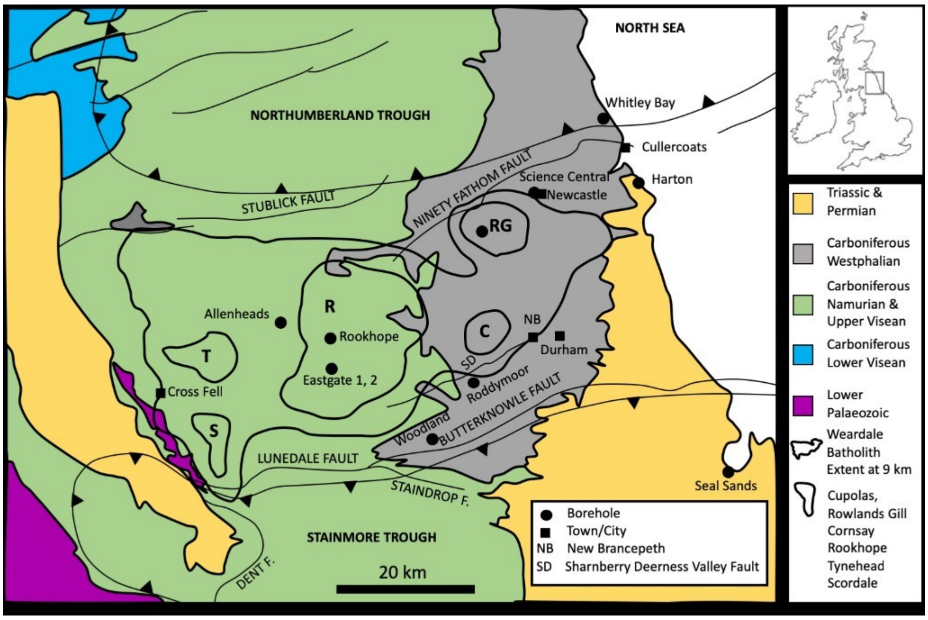


Figure 2.17 – Geological location map of County Durham. Showing the extent of the Weardale Granite with associated bounding faults, Ninety Fathom, Stublick and Butterknowle fault. Source – Gluyas 2020

Exploration of the Weardale Granite has occurred since the first well was drilled in 1961 at Rookhope, which found the granite to be eroded and hot at a depth of 385 m (Bott 1972). Following wells being drilled in Woodlands and Roddymoor, the Eastgate well was drilled in 2004 to a depth of 998m and found the naturally fractured Weardale Granite (Gluyas et al 2018). At 411 m the well flowed saline water at 27 °C, at a rate of 39 l s^{-1} which also gave a heat flow value of 111 mW/m^2 (Manning et al 2007). Further testing may be required as this study may not be representative of the Weardale, as testing came from only one borehole.

From this data, the thermal energy potential of the Weardale Granite using the following equations was calculated. In method 1: m represents the total mass of water (39 kg), c is the specific heat capacity of water (4180 J) and ΔT is the temperature measured in °C that can be removed from the water, 7 °C has been used because of the low initial temperature. Method 2 shows an alternative calculation using measured flow rates.

Method 1:

$$P = m \bullet c \bullet \Delta T$$

$$P = 39 \text{ x } 4180 \text{ x } 7$$

$$P(w) = 1141140$$

$$P(kW) = 1141140 / 1000$$

$$P\ (MW) = 1.141$$

Method 2:

Flow Rate = 1229904000 l/y

1229904000 x 0.001 = 1229904 m^3 of water

SHC of water = 4200000 $J/m^3/k$

Temperature removal = 7 °C

1229904 x 4200000 x 7 = $3.6\text{x}10^{13}$ J

KWh = 10044216

GWh = 10044

GWh = 10

If a constant rate of power is assumed from method 1 then 9.9 GWh could be produced from deep geothermal per year in County Durham. This would save ~2,829 tCO_{2e}/yr and heat ~730 homes, however, the number of homes which could make use of this resource is limited due to the proximity to the source.

In comparison, SKM's analysis of the Weardale's geothermal potential produced similar results of heating 607 homes. The Southampton geothermal site that was tested to be 1.7 MW_{TH} with 12 l s^{-1} flow rate, but 75 °C temperature now heats 2,500 homes via a combined heat and power scheme with ~50 °C waste temperature.

The well drilled at Eastgate 2 (2010) had no fluid flow, and so the permeability associated is now known to be due to the bounding fault of the Slit Vein (Hirst 2012). A well that was drilled at Newcastle Science Central which targeted the Fell Sandstone Group along the Ninety Fathom fault had no associated fluid flow, for reasons which are still unknown (Younger et al 2016). Consequently, in order to realise the technical heat abstraction potential of the Weardale Granite, further research is required to understand the permeability of the geology present.

2.2.4 Limitations of the Resource

Energy density

1 kg of petroleum will deliver ~50 million J of energy when combusted and 1 kg of coal will deliver ~24 million J of energy (Gluyas et al 2018). These fossil fuels are much denser in energy compared with geothermal energy, which would deliver ~126,000 J from cooling 1 kg of water by 30 °C. (Gluyas et al 2018)

Heat flow measurement

Heat flow measurements are useful to determine the potential of a geothermal resource. They are taken via borehole drilling or the cheaper alternative of surface measurements (Gluyas et al 2018). Surface measurements of heat flow can be misleading due to the last ice age producing surface cooling (Westaway & Younger 2013). Consequently, heat flow measurements taken at the surface may be less than expected for a geothermal resource and possibly stop exploration (Gluyas et al 2018).

Greenhouse Gas Emission

Although greenhouse gas emissions from deep geothermal projects is minimal it is still present. Compared with fossil fuels, the emissions are fractional (Kristmannsdottir 2003). In addition, Tester et al (2016) states that deep geothermal projects emit few to zero greenhouse gases. Individual site research should be investigated to understand the potential emission of greenhouse gases specific to heat extraction from the Weardale Granite.

Subsidence

Deep geothermal prospects require large fluid volume extraction (Sekitawan 2016). When these large volumes are removed the pore pressure inside the reservoir decreases, which can distort the pressure stability and subsequently cause pores to compress and the ground to subside (Sekitawan 2016). A geothermal site in New Zealand incurred subsidence of up to 15 m in depth, whereas a site located in Iceland with proper mitigation, the maximum recorded value of subsidence is less than 0.28 m (Sekitawan 2016; Figure 2.18).

Using a field example from Wairakei, re-injection of fluids into the ground has been shown to be the best mitigation practice of subsidence (Chris 2005).

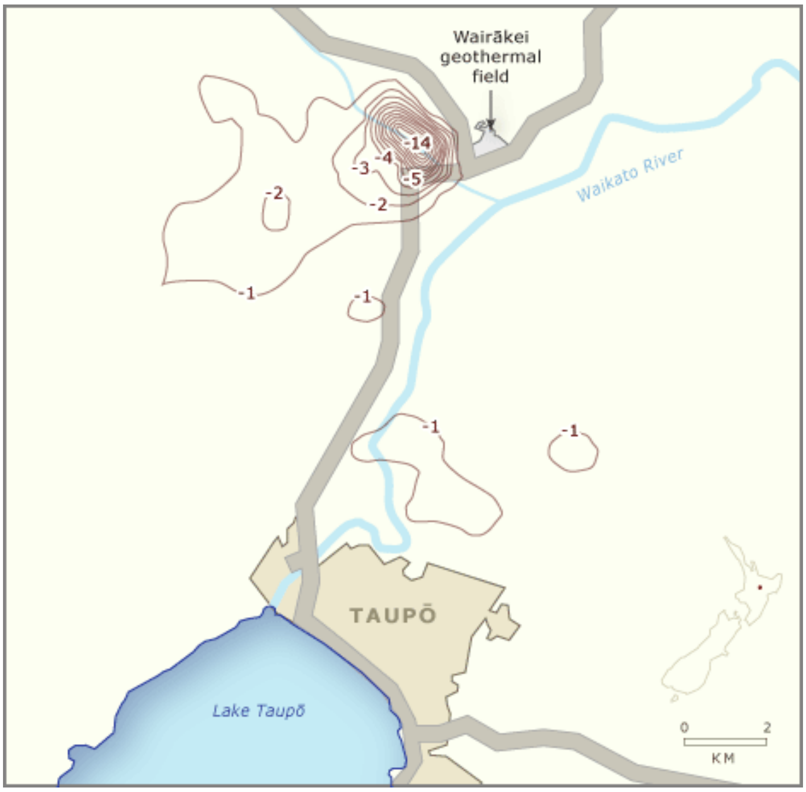


Figure 2.18 – Subsidence map associated with Geothermal energy exploration in Taupo, New Zealand. Source – Te Ara New Zealand Encyclopaedia 2006

2.2.5 Economics

Geothermal Communities (2015; Table 2.3) Produced a cost breakdown of a typical deep geothermal project assuming a project size of approximately 20 MW.

Project Aspect	**Cost (Million £)**
Establishment of Geothermal Site	3.2
Exploring, confirming and assessing the geothermal resource	1.6
Deep drilling of production and injection wells	24.1
Production and injection system	8.8
Acquiring and installing the power plant	30.5
Connection of power plant to transmission grid	8
Admin and management of project	4

Table 2.3 – Cost breakdown of a 20 MW geothermal project. Data Source – Geothermal Communities (2015)

The 20 MW example has a total cost of £80 million. County Durham's likely project size has been shown to be 1.1 MW in size. If costs remain the same when scaled down then County Durham's known deep geothermal prospect of the Weardale Granite would cost approximately £4.4 million, however it is not appropriate to assume this as some costs may differ due to the size of the project and location (Gluyas, Personal communication, 2020). Furthermore, costs may have changed since this 2015 study was published which should be accounted for and is an area for further research. IRENA (2018) states that £0.054/kWh is the average price of geothermal power, consequently if 9.9 GWh_{TH} was achieved the investment cost would be ~£534,600. However, this study was based upon high temperature geothermal resources which the Weardale Granite is not.

In comparison, Southampton's deep geothermal prospect that delivers 1.7 MW of heat, cost a total of £12.6 million during the 1980's from UK taxpayers money.

2.2.6 Case Study Examples

Southampton District Geothermal Scheme – Engie (Date Unknown)

Southampton City Council & more recently Engie, designed and implemented a deep geothermal energy system that currently delivers over 40 GWh of heat, 26 GWh of electricity and 7 GWh of chilled water per year. The borehole has been delivering water from 1700 m depth at 76 °C producing 1.7 MW_{TH} (Figure 2.19). This renewable energy system saves approximately 10,000 tCO_2/yr. The scheme began in 1986, delivering heat from just one borehole. Over time, the network has been expanded by combined heat and power engines, back up boilers and absorption chillers. The city now has five energy centres, heating 2,500 residential homes, several large offices, one hospital, one university, one large shopping centre, a supermarket, several hotels, the BBC studios, a swimming complex and a police station. Furthermore, this system is £250,000 cheaper than fossil fuel sourced energy in Southampton (Manning & Younger, PowerPoint Presentation, Newcastle University).

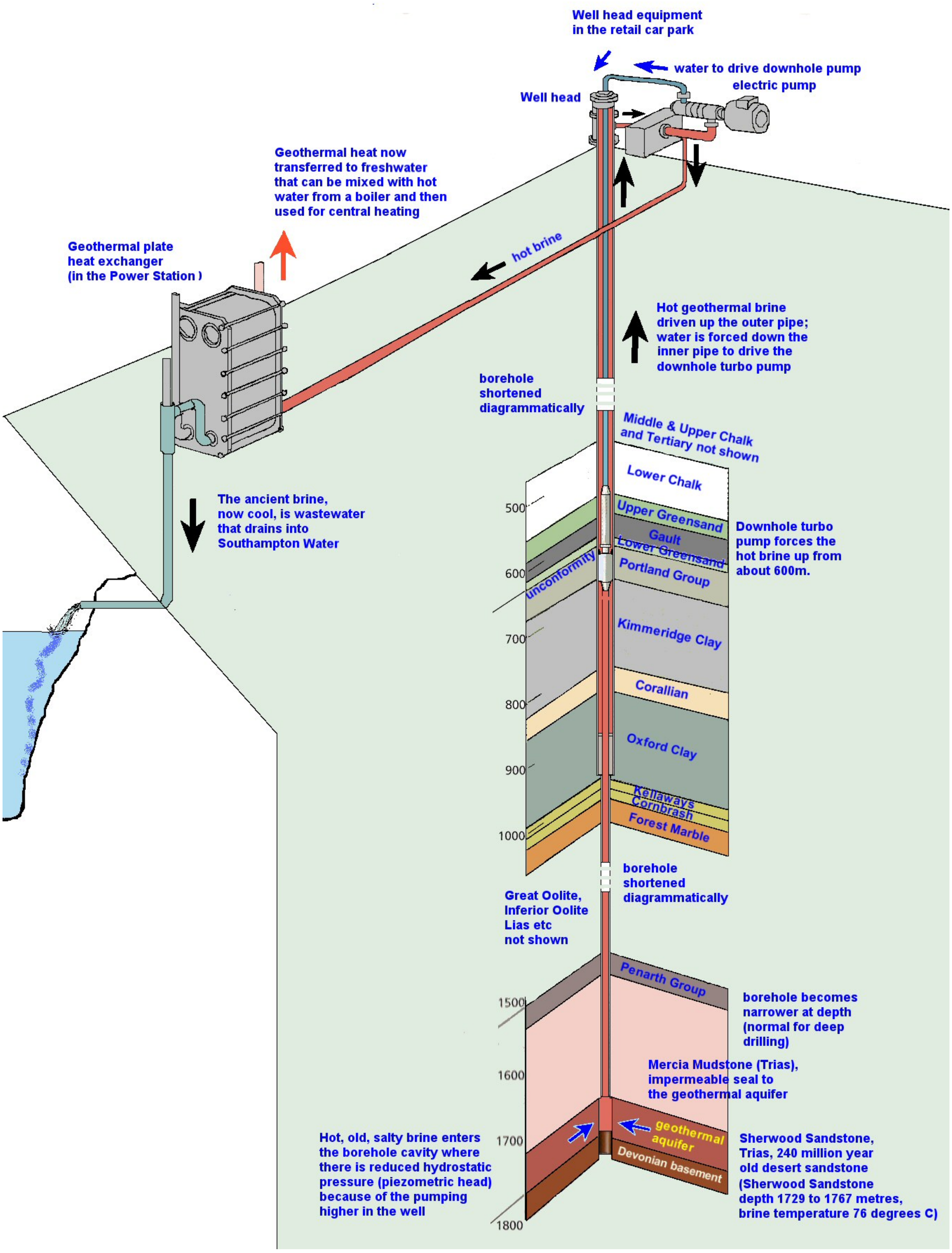


Figure 2.19 – Geothermal energy exploration diagram for Southampton. Shows Geological units encountered throughout borehole and surface infrastructure needed to extract and make use of the resource. Source – Global geothermal news 2018

Hot Dry Rocks Project – Cornwall Council (2019)

During the 1970's the 'hot dry rocks project' was started in Cornwall. It was spearheaded by the world-famous Camborne School of Mines who confirmed high temperatures associated with Cornwall's granite suite. A large area of Cornwall has >120 mWm^2 heat flow that recent studies have suggested could meet Cornwall's entire electricity demand. From 1978 the department of energy began drilling several wells which all failed. This failure led to the discovery that pumping was occurring at too higher pressure causing the rocks to crack and form large cavities (Penhaligon 1986). Drilling in Redruth has reached a maximum of 4800 m depth, hitting temperatures of up to 195 °C (Vaughan 2018; Figure 2.20). The Geothermal power station has a 3 MW capacity and will generate electricity for up to 7,000 homes.

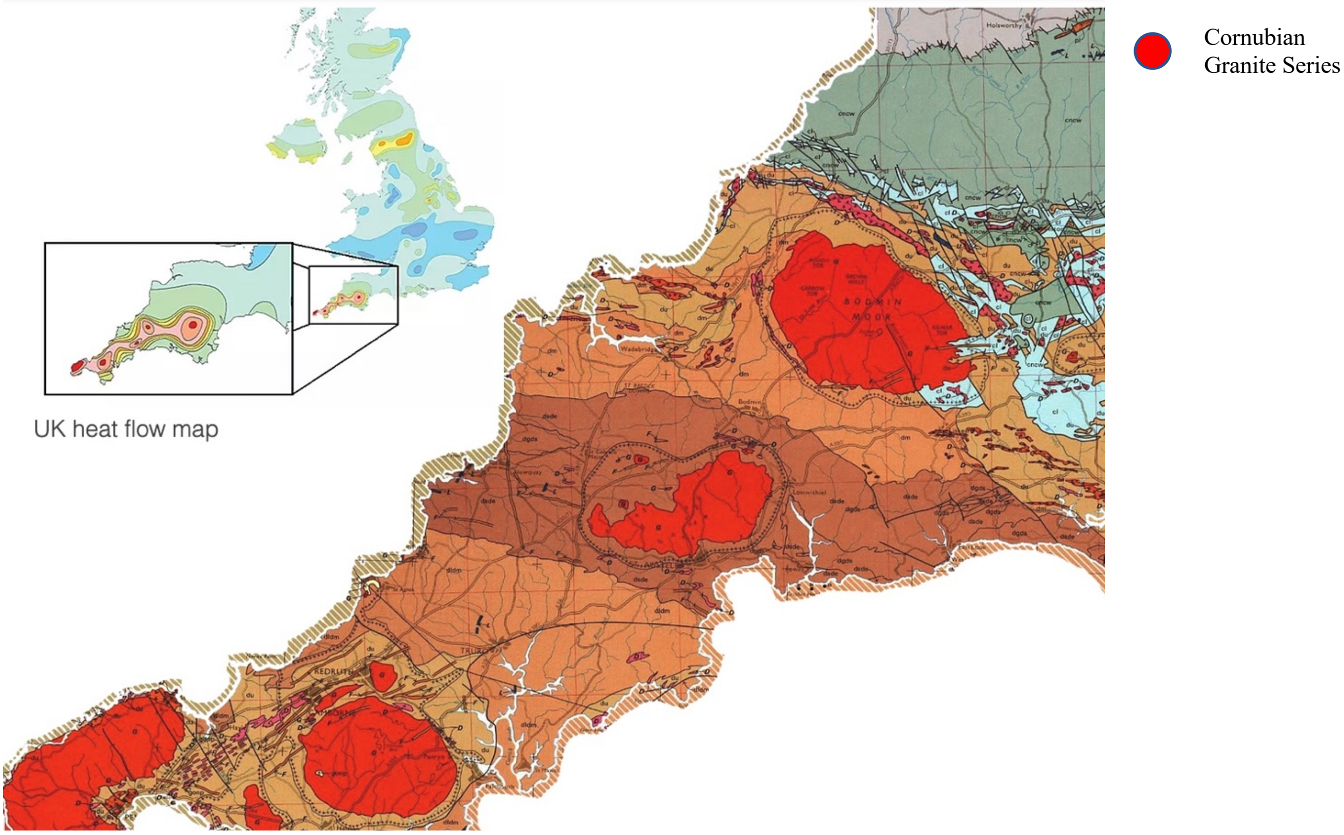


Figure 2.20 – UK heat flow map with enlarged geological map of Cornwall. Geological map shows the outcrop pattern of Cornwall's Cornubian Granite series. Source – BGS 2019

Eden Geothermal Energy Project – Eden Project (Date Unknown)

During the summer of 2020 drilling will begin with the intention of subsequently building a geothermal plant on the site of the Eden project (Figure 2.21). A single well will be drilled to 4,500 m depth that has the calculated potential to heat the project's biomes, offices and nursery greenhouses. If this well is to be a success, a second well will be drilled to generate and export renewable energy, in order to make the Eden Project carbon neutral by 2023.

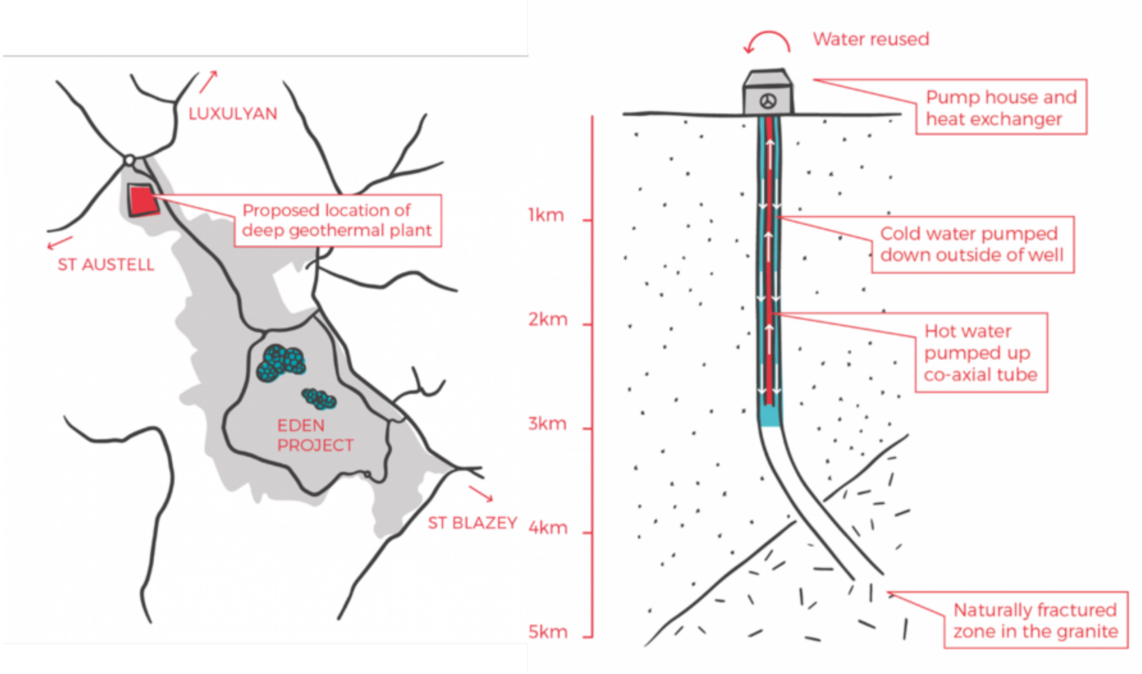


Figure 2.21 – Schematic diagram of the Eden Projects proposed geothermal exploration.
Source – ThinkGeoenergy 2019

2.2.7 Conclusions

99.9% of the Earth's mass is above 100 °C (BGS 2020), deep geothermal energy uses this high heat flow from Earth to extract energy from petrathermal and hydrothermal geological systems which can be more than 5,000 m deep. Although a geothermal gradient is present everywhere on Earth, some locations have greater geothermal potential due to their local geology. County Durham sits on top of a radiothermal granite named the Weardale Granite. The Weardale includes thorium, potassium and uranium in its composition which produces heat whilst decaying. Consequently, the Weardale Granite has been tested to have a thermal gradient of 38 °C km^{-1} covering ~1500 km^2, although due to the heterogeneous distribution of radio thermal elements the heat distribution varies throughout. The Weardale Granite's resource potential depends upon the temperature of returning fluids and if the geology has associated permeability to allow the hydrothermal fluids to flow to the surface and for recirculation of the system. Using data from the Eastgate well which produced saline water at 27 °C at 39 ls^{-1} a potential of ~10 GWh has been attributed to the Weardale Granite. Due to the low return temperature, this energy would be used for heating purposes and not electricity generation. The permeability of the system is thought to be associated with the bounding fault of the Slit Vein, however recent permeability studies along the ninety-fathom fault produced no fluid flow. Therefore, further study is required to understand the permeability of the Weardale Granite. Due to the resource being used for direct heating, proximity to the source is a possible limitation, along with the risk of subsidence and minimal greenhouse gas emission. Economically, we cannot assume costs from example studies would remain the same with a smaller system however an estimate of £4.4 million would be required to make use of Durham's deep geothermal resource. County Durham therefore has a potential for deep geothermal energy however further study is needed surrounding the permeability of the Weardale Granite and housing proximity to make use of the resource.

2.3 Photovoltaics

2.3.1 How it works

The Earth intercepts ~173,000 TW of power from the Sun, which is 10,000 times greater than the current global population power demand (Komp 2016). Photovoltaic cells (PV) are a low carbon sustainable technology designed to capture the suns solar radiation and convert it into electricity (Komp 2016).

Photovoltaic panels are comprised of many solar cells, that are typically made from silicon although other materials are now being used (Komp 2016). Silicon is a semi-conductor and is the second most abundant element on Earth, however it has a high energy cost to produce (Komp 2016). Crystalline silicon is placed between two conductive layers and is connected to neighbouring silicon atoms by four bonds (Komp 2016). Each bond keeps the electrons in place within their individual hole and allow no current to flow. In a solar cell, two different layers of silicon are used (N and P). Type N has extra electrons whereas type P has extra holes (Komp 2016). The point at which these two layers meet (NP Boundary) is the site where the electrons can move, leaving a positive and negative charge on either side of each layer (Komp 2016). When sunlight hits the solar cell, photons strike the silicon atoms, knocking an electron from its bond and leaving behind a hole (Komp 2016). The electron and hole are both now free to move around the solar cell, but due to the electrical field at the NP boundary, the electron is drawn to the N side, and the hole is drawn to the P side (Komp 2016). The mobile electrons are then collected by instruments positioned at the top of the solar cell, allowing the electrons to flow through an external circuit, powering the home (Komp 2016; Figure 2.23).

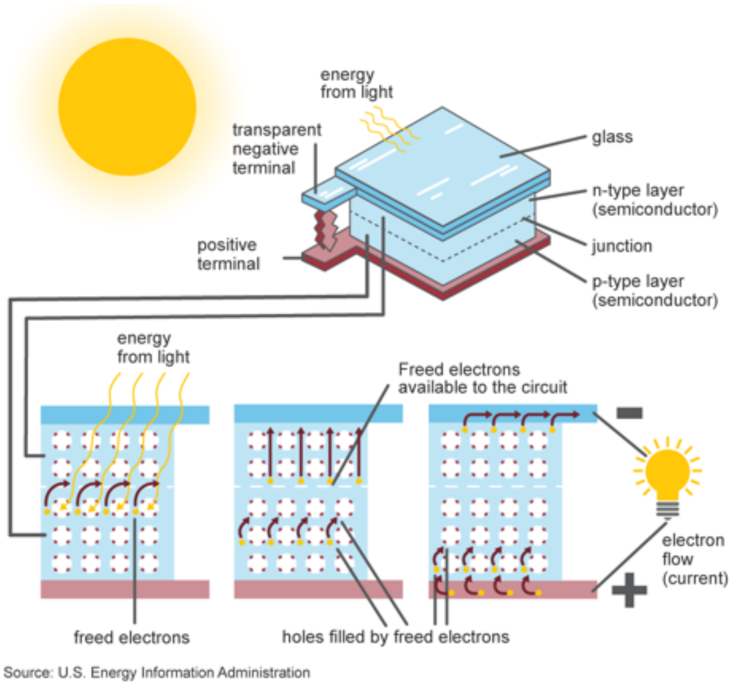


Figure 2.23 – Schematic diagram showing how a typical photovoltaic cell operates.
Source – US EIA 2020

PV can be distributed domestically onto home rooftops or developed on a larger scale in the form of a solar farm.

Domestic photovoltaics produce energy at an efficiency of 20 W/m^2 (MacKay 2013). In comparison, solar farms, due to the spacing between panels, produce electricity at 5 W/m^2 (MacKay 2013). An alternative consideration for solar farms could be to locate them where solar insolation is more intense and cloud cover is minimal, for example in a desert. With these advantageous properties solar farms located in deserts typically produce 20 W/m^2 (MacKay 2013). Another option could be to locate solar farms onto surface water-reservoirs or offshore, called ‘floatovoltaics’. One such ‘floatovoltaics’ solar farm located in Manchester, North West England produces energy at 6.8 W/m^2 (Environmental technologies 2015).

2.3.2 What does the resource depend on?

Solar Insolation

Solar insolation is the amount of electromagnetic energy incident on the Earth's surface (Apricus, unknown). Usually, the higher the intensity of solar insolation, the more electricity photovoltaics are able to produce as more photons can knock electrons from their hole within the solar cell (Komp 2016). Due to the shape of the Earth and its solar cycles, solar insolation is unevenly distributed across the Earth's surface and varies in intensity throughout the year (Bralower & Bice 2020). This uneven distribution can be seen in figure 2.24.

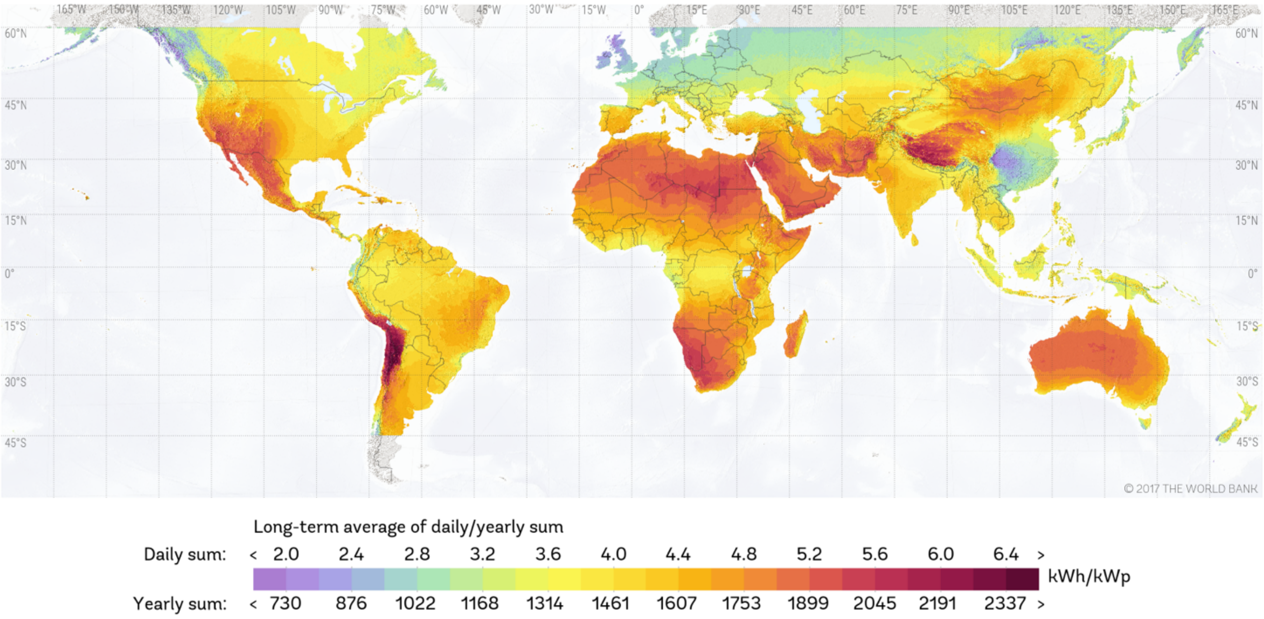


Figure 2.24 – Diagram of how solar energy is distributed unevenly around the globe and therefore creating variations in the electricity production of PV. Source – World Bank Group 2019

Energy generated from solar is classed as an intermittent energy source. Other external factors that can impact solar insolation will include an expanse of cloud cover, as well as relative humidity and heat build-up (Gordo et al 2015).

Number of Panels

Increasing the number of solar panels will naturally increase the surface area which can capture solar insolation, and thus produce more electricity. Typically, on domestic installations, a 4 KW system would require 16 solar panels compared to a 5 KW system that requires 20 solar panels to be installed (Vekony 2020).

Solar Cell Efficiency

Commercially produced solar cells range in efficiencies varying between 15 to 22% (Vourvoulias 2020; Figure 2.25). The most efficient solar cell made to date were 42% efficient. Efficiency is determined by design, placement and orientation. (Vourvoulias 2020).

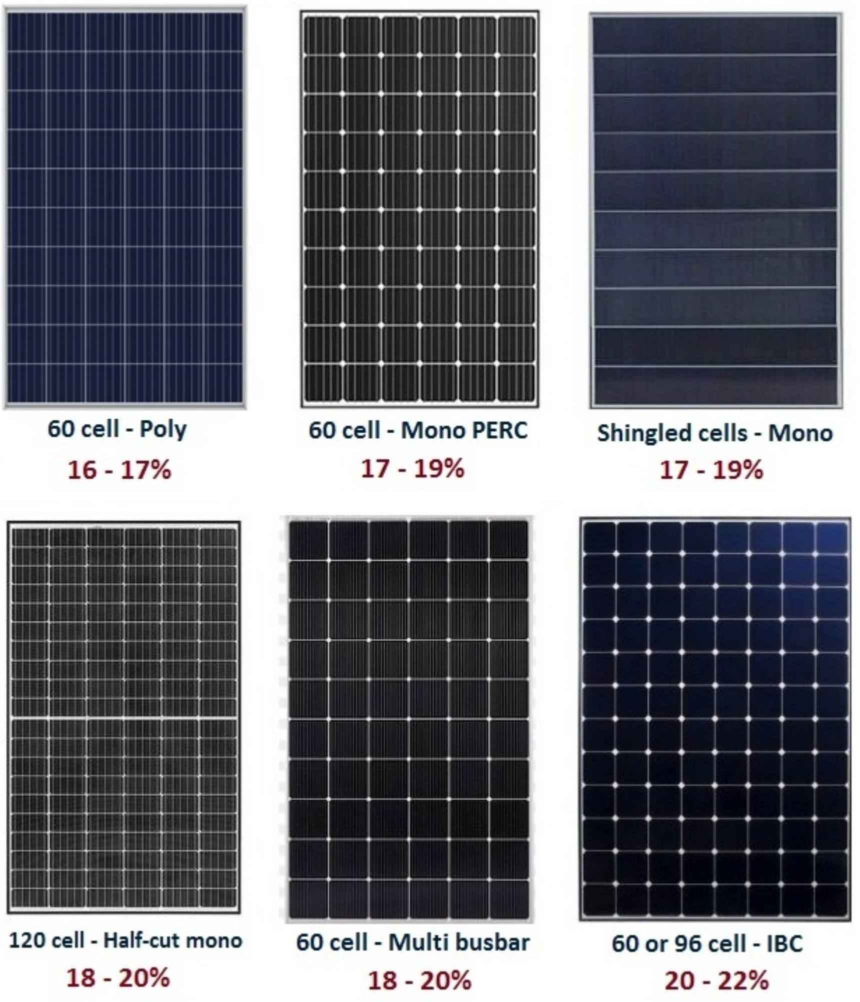


Figure 2.25 – Variations in efficiencies between different types of PV cells
Source – Clean Energy Reviews 2020

Solar cells can be divided into three main types, monocrystalline, polycrystalline and thin film (Green Match 2020). Monocrystalline solar cells are produced from the purest silicon from the three options which lead to the highest efficiencies (Green Match 2020). In addition, monocrystalline cells require less space and are more durable (Green Match 2020). Polycrystalline solar cells are produced by melting raw silicon which is advantageous over monocrystalline cells as the process is faster and less expensive economically (Green Match 2020). However polycrystalline cells have lower efficiencies in terms of power and space as well as having a shorter life span (Green Match 2020). Thin-film solar cells are produced by layering multiple layers of photovoltaic film onto a substrate (Green Match 2020). This production method is easy to produce and allows the solar cell to be flexible which allows for many different applications to be considered. However, due to their large space requirement, they are not usually used domestically. (Green Match 2020).

Solar panels should be arranged to be both south facing and angled from 10-30 ° (Green Match 2020). In doing so it can increase the efficiency of the solar cell as it is being exposed when solar insolation is more intense, as well as extending the duration at which it can capture solar insolation (Green Match 2020). Lower temperatures can make the system operate more efficiently (Green Match 2020). Less energy is lost via heat energy and the semiconductor properties change, resulting in a large decrease in voltage (Energy Efficiency & Renewable Energy 2018). Floatovoltaics on average are 3.5 °C cooler than terrestrial photovoltaics, subsequently producing between 1.58 - 2 % higher system efficiency values (Liu et al 2017).

Decreasing the amount of light reflected from the solar cell can also increase efficiency. Untreated silicon reflects ~30% of solar insolation. Anti-reflection surfaces can reduce the rate of reflection. (Energy Efficiency & Renewable Energy 2018).

2.3.3 Energy potential in County Durham

In terms of total resource, County Durham throughout the year receives on average 3.2 $kWh/m^2/day$ of solar insolation (Weather Spark 2020). This equates to 2,599 TWh/yr for the total area of County Durham.

Domestic PV

In 2017, County Durham produced 44,826 MWh of electricity from 8,291 domestic photovoltaic installations. Each installation producing an average of 5.4 MWh in 2017. The domestic electricity demand in County Durham for 2017 was 788.48 GWh, equating to 3.4 MWh per-home. This demonstrates County Durham's domestic photovoltaic potential because when domestic photovoltaics were installed, they produced 2 MWh above the average household demand. If each house in the County had domestic photovoltaics installed, 1,249 GWh could be generated, saving 353,607 tCO_{2e}.

Terrestrial Solar Farms

On average, solar farms produce electricity at 5 w/m^2 but this is a global average (MacKay 2013). To allow for a more accurate calculation, data collected from County Durham's Tanfield Lea solar farm has been used as an average. Tanfield Lea produces 213 MWh/yr from 15,100 panels and is 0.07 km^2 in size (DCC 2015). By using this as a representative data source for solar farms in County Durham, the average energy production from a County Durham solar farm can be calculated.

Electricity Production per panel (KWh) = Power Produced (KWh) / Number of panels

$$213000 / 15100 = 14 \text{ kWh}$$

Area required per panel (m^2) = Area covered by solar farm (Km^2) / Number of panels

$$(0.07 / 15100) \times 1000 \times 1000 = 4.6 \text{ m}^2$$

Energy production (W) = (213000 / 365 / 24) x1000 = 24000

Energy efficiency (W/m^2) =Energy production (W) / Area covered (m^2)

$$24000 / 7000 = \mathbf{3.4}$$

Energy efficiency of 3.4 W/m^2 measures below the global average for solar farms. From the above calculation County Durham would require approximately 4% (94.6 km^2) of its total land area to support the use of solar farms to meet the total electricity demand of 2,816 GWh. This would demand 1,351 solar farms similar in size to Tanfield Lea to be installed. If energy efficiency from solar farms could be increased to the global average of 5 W/m^2, County Durham would require a land area representing 2.89 % (64 km^2).

Floatovoltaics

If the efficiency of floating photovoltaics was 20 W/m^2, a landmass proportion equal to 0.7% (16 km^2) of County Durham would be required to meet the electricity demand for the county (2,816 GWh). It must be recognised that power data from floatovoltaics is limited. Also, the data could be bias towards locations which favour floatovoltaics installation with higher solar insolation values that would be experienced in County Durham. This risk can be referenced using the example, Montalgre Portugal, which receives a solar insolation value of 5.15 KWh/m^2/day (Weather Spark 2020). The floatovoltaics installed at this location produce electricity at 14.4 W/m^2. For the purpose of this report it is more suitable for calculations to be based upon examples which closely match solar insolation values that County Durham experiences. Manchester, England receives 3.3 KWh/m^2/day (Weather Spark 2020). The floatovoltaics project installed at Godley Reservoir, near Manchester operates at an efficiency of 6.8 W/m^2 (Environmental technologies 2015). County Durham has a total of 12 reservoirs (Google Earth - Table 2.4) that could support floatovoltaics.

Using a more realistic efficiency value of 6.8 W/m^2, 9.72 km^2 would yield 579 GWh/yr. This represents 20.5 % of the county's electricity demand and would result in a saving of 163,897 tCO_{2e}.

Reservoir Name	**Area (km^2)**
Balderhead Reservoir	1.11
Blackton Reservoir	0.26
Burnhope Reservoir	0.38
Cow Green Reservoir	2.7
Derwent Reservoir	2.87
Grassholme Reservoir	0.37
Hishope Reservoir	0.06
Hury Reservoir	0.41
Salset Reservoir	0.95
Smiddy Shaw Reservoir	0.23
Tunstall Reservoir	0.2
Waskerly Reservoir	0.18
Total	**9.72**

Table 2.4 – List of all County Durham reservoirs and associated areas which could be utilised by PV
Data Source – Google Earth 2020

2.3.4 Limitations of the resource

Disproportional Distribution and Intermittence

Due to the shape of the Earth, solar insolation decreases from the equator through to each pole (Bralower & Bice 2020). The distribution of solar insolation not being constant around the Earth's surface therefore impacts the potential of photovoltaics in different locations. Furthermore, at night-time or during cloud cover, as well as throughout low sunlight hour seasons, less solar insolation can be used by photovoltaics to generate electricity.

Inefficient Technology

Efficiency is reduced within photovoltaics when photons are reflected rather than absorbed (Komp 2016). Efficiency is also reduced when dislodged electrons fall back into a hole after mobilisation, without ever moving through the electrical circuit (Komp 2016). In solar farms, gaps or spacing between panels can reduce the systems energy efficiency because each gap is unable to contribute towards the energy being generated (MacKay 2013).

Lack of Suitable Homes

Further study is required to understand what proportion of homes in County Durham would be suitable for domestic photovoltaic installation. As previously mentioned, rooftops should be south facing where possible and angled accordingly. It should be noted that not all homes will be able to support this configuration.

2.3.5 Economics

Domestic Photovoltaics

Domestic photovoltaic systems typically have a 4 KW capacity. An average 4 KW installation will cost £6,000 (Green Match 2020). A total budget spend of £1.3 billion would be required if all 223,040 homes within the county installed domestic photovoltaics. Further study is required to outline how government incentives for homeowners could be improved to make this resource realistic.

Solar Farms

The average cost-spend to install a solar farm is estimated at 1-1.2 £/w (Santhanam 2015). 94.6 km^2 of solar farms with an efficiency of 3.4 w/m^2, would cost ~£385 million to meet the county's electricity demand. If efficiency increases could be found with solar farms within County Durham up to 5 W/m^2, the project cost would total ~£270 million. However, IRENA (2018) demonstrates how solar price has changed as 2018 data states a cost of utility scale solar to be £0.064 /kWh costing ~£180 million to meet the county's electricity demand. It should therefore be noted that this statement is based upon data from 2018 which is likely to have decreased in cost. Although this study was calculated on a global average and not specific to County Durham. Energy Sage (Unknown Date) states that the cost of solar PV modules decreases by ~20% for every doubling in global capacity. Further study is required to find accurate prices for solar farm installations in Durham today.

Floatovoltaics

The Godley Reservoir located in Hyde near Manchester is the only UK example available of floatovoltaics economic data. The site is over 45,500 m^2 incorporating 12,000 panels, costing a total of £3.5 million (Environmental technologies 2015). This equates to £76/m^2. County

Durham possesses 9.72 km^2 reservoir area potential, which at £76/m^2 would cost £738 million. Consideration must be taken that this economic data has come from only one UK study in 2015 and thus accurate and current costs should be investigated further.

2.3.6 Case study examples

Tanfield Lea Solar Farm – Durham County Council 2015

Tanfield Lea is County Durham's first solar farm. The site is located to the south of Tanfield Lea industrial park, laying over agricultural land that covers 7000 m^2. The solar farm consists of 15,100 photovoltaic panels which are approximately 1.6 m each in area. Each panel is arranged at an angle of 27 ° facing due south. The panels have also been raised 1 m above ground level, allowing the agricultural land to continue to be grazed by sheep. The solar farm has been predicted to generate 213,000 kWh/yr. An environmental by-product of the Tanfield Lea solar farm is the regrowth of wildflowers and grasses. Horses which once occupied the land were relocated, allowing plants to regrow and increasing the biodiversity of the area.

Solar Car Park – Northumberland City Council 2019

Northumberland City Council has had plans approved to build a solar farm suspended above their county hall car park (Figure 2.26). The solar farm is forecasted to produce 40% of the county hall's electricity demand which will save approximately 240 tCO_2 per year. The council have coupled this solar farm with 60 new electric charging points for vehicles. The budget supporting this project is £2.3 million. Half of the budget will come from the European regional development fund, with the other half being funded by the council.

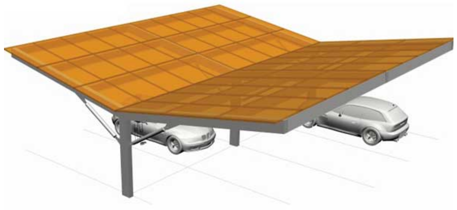


Figure 2.26 – Digitised plans of Northumberland county council photovoltaic car park
Source – Northumberland City Council 2020

Photovoltaics powering waste -Cheshire East Council 2019

From a £220,000 investment, Cheshire East Council has installed its waste transfer headquarters with photovoltaics. The installation has 728 panels within a 229 KW capacity system which will provide annual savings of 100 tCO_2. The photovoltaics will also reduce annual running costs for the building by up to 15%, translating to £33,000/yr. The council forecast for their investment to have been repaid in ~ 6.5 years.

Montalgre, Floatovoltaics – International Hydropower Association 2016

Montalgre located in Northern Portugal is a pilot project to install 840 photovoltaic panels on the water held by the Alto Rabagao dam (Figure 2.27). The system will have an installed capacity of 220 KW, producing an estimated annual electricity output of 300 MWh. This floatovoltaics project covering an area of 2,500 m^2 is predicated to generate energy at an efficiency of 13.6 w/m^2. During the first year of production, the system generated 5% more than forecasted (315 MWh). It was 10% more efficient in comparison to nearby terrestrial solar farms. The system also demonstrated its ability to withstand varying weather. The winters of 2016 and 2017 experienced very low temperatures including heavy snowfalls that the system successfully withstood. Large reservoirs of this type also commonly experience strong winds producing large waves, but the mooring system remains successful. The mooring systems key challenge is its economic feasibility as it accounted for 20% of the total costs.

Figure 2.27 – Floatovoltaics project taking place in Northern Portugal covering $2500m^2$.
Source – International Hydropower Association 2020

2.3.7 Conclusions

Photovoltaics capture the suns solar radiation and convert it into electricity. PV cells can be installed in the form of panels on domestic homes (20 w/m^2) or as a collection of many panels to form a solar farm which can be installed on land (3.2 w/m^2) or on water (floatovoltaics 6.8 w/m^2). Due to the shape of the Earth and solar cycles, different locations have different daily solar insolation values and therefore varying solar energy potential. Furthermore, solar energy is intermittent as energy production does not occur at night and is reduced during times of extensive cloud cover. The type of panel which is used will determine the efficiency and consequently the amount of electricity produced. However, efficiency can be improved by angling panels at 10-30° and facing the panels south. On average, County Durham receives 3.2 kWh/m^2/day of solar insolation. From 2017 data, the average domestic PV installation in County Durham produced 5.4 MWh. Average Durham household electricity demand in 2017 was 3.4 MWh. Consequently, if every house in County Durham has domestic PV installed 1,249 GWh could be produced. Although, not all homes are suitable for installation and do not have south-facing roofs. This would require a total investment of ~£1.3 billion. Terrestrial solar farms in County Durham such as the Tanfield Lea solar farm produce electricity at 3.4 w/m^2 efficiency. To meet County Durham's electricity demand, 94.6 km^2 of solar farms the equivalent of 1,351 same size projects as Tanfield would be required costing approximately £180 million. Alternatively, floatovoltaics could be installed on County Durham's 12 reservoirs. Calculating that floatovoltaics would produce electricity at 6.8 w/m^2 in Durham means 579 GWh would be produced from 9.7 km^2 of reservoir, costing a total of ~£735 million. County Durham therefore has a large potential for photovoltaics in three different settings, all require large scale investment from both the public and government in order to realise their potential.

2.4 Solar Thermal

2.4.1 How it works

Solar thermal energy is a sustainable low carbon technology that uses solar insolation to heat water via an intermediate high boiling point liquid (IRENA 2015). The heated water can then be used for domestic hot water and space heating, or if concentrated, electricity generation (IRENA, 2015).

Domestic Heating

Solar thermal energy used for domestic heating can either be a passive or active system (Vourvoulias 2020). Passive systems use no moving parts, relying on the system design to heat the object in question, such as a greenhouse or a solar oven (Vourvoulias 2020). Active systems typically include a glycol solution that can absorb solar energy (Figure 2.28). The glycol solution is placed within pipes typically found on domestic rooftops. The glycol solution increases in temperature and is then transported to a domestic water storage unit (Vourvoulias 2020). The glycol solution then increases the temperature of the water stored which can then be used domestically. If the stored water is still not at the required temperature, it can be further increased by an electric immersion heater or gas/oil heating boiler (Vourvoulias 2020). Domestic solar thermal systems can provide on average 40-60 % of a home's hot water supply consumption on an annual basis within the UK (Vourvoulias 2020).

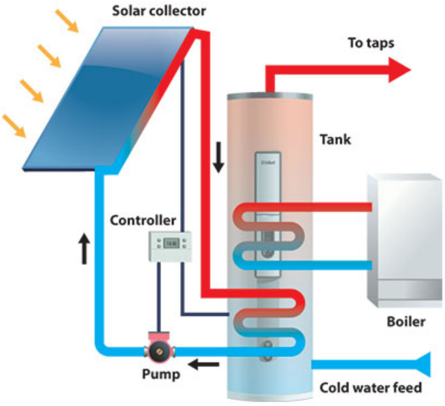


Figure 2.28 – Schematic diagram of how a domestic solar thermal system works. From absorption to usage. Source – Greenfields Heat and Power LTD 2020

Electricity Production from Concentrated Solar Power (CSP)

Concentrated Solar Power (CSP) combines groups of mirrors that concentrate solar energy onto a central collector (IRENA 2012). This concentration of solar energy increases the temperature high enough within the collector to produce steam (IRENA 2012). The steam, in turn drives a turbine to produce electricity (IRENA 2012; Figure 2.29). There are four main types of CSP design; parabolic trough, Fresnel reflectors, dish stirling and solar towers (Green Match 2020).

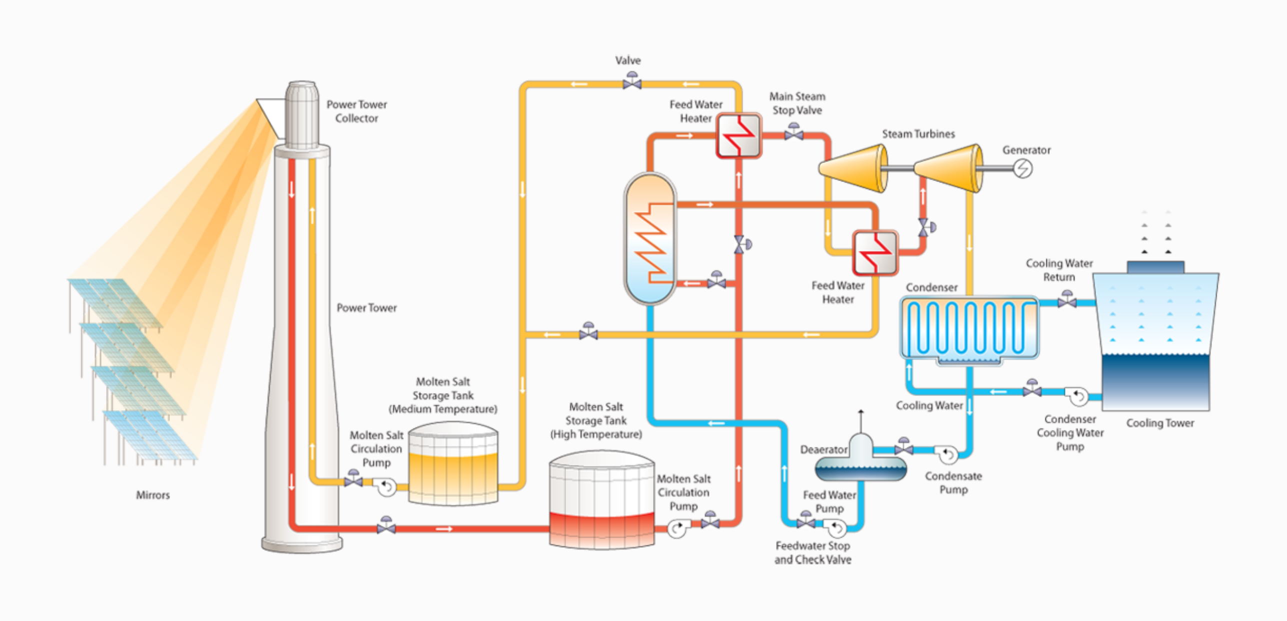


Figure 2.29 – Schematic diagram of a typical system for a CSP plant. Source – Solar Thermal Energy News 2013

2.4.2 What does the resource depend on?

Solar Insolation

Throughout summer months when solar insolation is more intense, UK domestic solar thermal systems can provide 90% of an average home's hot water demand (Vourvoulias 2020). However, due to the intermittency and lower solar insolation throughout winter periods, UK systems annually provide ~40–60 % of the average homes hot water demand (Vourvoulias, 2020). Due to solar insolation being distributed unevenly across the Earth's surface, different locations will have the varying potential for solar thermal energy.

Compatible Equipment

For domestic solar thermal systems to be implemented, households must possess a compatible boiler (Vourvoulias, 2020). Most UK homes have conventional boilers which are compatible with solar heating systems (Vourvoulias 2020). However, the resource will not operate if the home has installed a combination boiler that is not dependant on a hot water tank (Gluyas, Personal Communication, 2020).

Space

CSP demands vast amounts of mirrored panels in order to concentrate enough energy to generate electricity. SEIA (2020) states that per MW of capacity, CSP will require an area between 20,234 – 40,369 m^2. Domestic systems require enough roof-space in order to install the panels needed. Typically, 1 m^2 of solar collector is require per person living in the home (Vourvoulias 2020).

2.4.3 Energy Potential in County Durham

Domestic Solar Thermal

County Durham receives 3.3 KWh/m²/day solar insolation (Weather Spark, 2020). The average County Durham household could reduce its carbon footprint by 400 kg of CO_2/yr if solar thermal systems were in place (Vourvoulias 2020). This saving of 400 kg/yr (0.4 tCO_2/yr) is saved from producing 1.4 mWh of low carbon, sustainable energy. If this is scaled up to the total number of homes within County Durham (231,331), the County could generate 326,887 MWh of energy and thus save 92,532 tCO_2/yr. However, this is unlikely due to not all homes in County Durham having south facing roofs as well as other factors such as lack of roof space.

Concentrated Solar Power (CSP)

Concentrated Solar Power stations produce electricity at ≤ 20 W/m² (MacKay 2013). County Durham would require a CSP station 67 km² in area to meet the county's total energy demand. For CSP to be economically viable it requires a solar insolation value of 5.5 KWh/m²/day (IRENA 2012). Consequently, it is unlikely CSP could be used in any form throughout County Durham. Consideration should be taken when using data from MacKay 2013 as resource efficiency in all low carbon resources is likely to have increased. Further study is required to understand the current W/m² value for all resources.

2.4.4 Limitations of the resource

Intermittent Source

A limitation with domestic solar thermal is the intermittence of the energy source (Gluyas et al 2018). Further study is still required into the storage of solar thermal energy produced in the summer months to be applied throughout the winter period.

Solar Insolation Intensity

The UK has a relatively low solar insolation intensity, County Durham receives 3.3 KWh/m^2/day (Weather Spark 2020). If solar thermal is to be used for domestic purposes, an additional increase in temperature to 60 °C to meet domestic requirement will be needed from either electricity or gas (Vourvoulias, 2020). Consequently, carbon emissions will still be required but significantly less than heating water entirely from current carbon intense systems.

2.4.5 Economics

Domestic

Renewable Energy Hub (2020) states that installation of domestic solar thermal systems will cost between £3,000 and £6,000 per home. It is possible to purchase solar thermal kits for individual homeowners to install priced between £1,500 to £2,500. Such kits are not eligible for any governmental financial support (Renewable Energy Hub 2020). If an average of £4,500 per installation is assumed, the County's 231,331 homes would require an investment totalling £1.04 billion.

Concentrated Solar Power (CSP)

For CSP to be economically viable it requires a solar insolation value of 5.5 KWh/m^2/day (IRENA 2012). County Durham receiving 3.3 KWh/m^2/day therefore makes CSP in County Durham financially unviable. However, as advancements in solar efficiency are made prices change. It is possible that this 2012 study is now not accurate as CSP prices have fallen by 46% since 2010, £0.14/kWh in 2018, although this study is based upon projects in China, Morocco and South Africa which are not representative of County Durham’s solar insolation values (IRENA 2018).

2.4.6 Case Study Examples

Nancy Astor Building – Sustainability Exchange (Unknown)

Andrews Water Heaters have installed two award-winning storage heaters with a SOLARflo heat system into the Nancy Astor Building, at the University of Plymouth. The system is designed to provide abundant and virtually instantaneous hot water to the entire building. This system comprises of 21 m^2 of evacuated tubes which are angled to 20^o to optimise efficiency. The system has a capacity to heat 300 l of water.

Global Garage LTD London Hotel – Solar Energy UK (Undated)

Solar UK LTD has designed and installed a 140-tube solar thermal system located at the Global Garage LTD new 5-star central London hotel. It will provide the entire hotel with 7,200 l of heated water each day used in hotel guests’ showers, wash basins and cleaning services. This system will provide an annual emission saving totalling 19 tCO$_2$/yr (Solar Energy UK Undated).

2.4.7 Conclusions

Solar thermal energy uses the suns solar radiation to heat water. The hot water can be used for space heating or if concentrated, electricity generation (IRENA 2012). Domestic solar thermal systems use pipes containing typically a glycol solution to increase the temperature of a stored water tank (Vourvoulias 2020). On average 40-60% of a UK home's hot water demand can be supplied by a domestic solar thermal system (Vourvoulias 2020). Concentrated solar power uses groups of mirrors to concentrate the suns radiation onto a central collector which increases the temperature, high enough in the collector to produce steam and therefore electricity (IRENA 2012). Solar insolation is unevenly distributed across the Earth's surface so different locations have a varying potential for solar thermal energy. Domestic solar thermal energy potential also depends on houses having compatible boilers and compatible south facing homes with enough roof space (Gluyas, Personal Communication, 2020). CSP requires large amounts of space to have enough mirrors, typically this is 20,234 – 40,369 m^2 (SEIA 2020). The average County Durham domestic solar thermal installation produces 1.4 MWh/yr, therefore if every house had solar thermal installed 327 GWh could be produced. This is likely to require an investment of ~£1 billion if an average of £4,500 is assumed per installation. For CSP to be financially viable it requires a solar insolation value of >5.5 $KWh/m^2/day$ which is not possible in County Durham (3.2 $KWh/m^2/day$) and therefore it is not a potential resource for the County (IRENA 2012). Consequently, County Durham has potential for domestic solar thermal installations however two main limitations exist in that it currently requires unattractive major investment by homeowners and the efficiency of the system throughout the winter is not optimised. Therefore, further study should be based upon incentivising domestic solar thermal projects and the storage of energy collected in the summer to be resupplied throughout winter. Finally, County Durham is unlikely to have high enough solar insolation values to allow CSP to be a viable resource in the county.

2.5 Wind Energy

2.5.1 How it works

Wind energy is a form of kinetic energy which can be harnessed by a wind turbine to produce low-carbon, renewable electricity. The technology can be installed on both onshore and offshore location sites.

A wind turbine has blades that rotate due to kinetic energy from wind energy (EWEA 2020). The blades are connected to a central drive shaft that rotates between 15 – 20 revolutions per minute (RPM) (EWEA 2020, Figure 2.30). The incorporation of a gearbox increases the RPM of the drive shaft to approximately 1600 RPM, enough to efficiently power a generator (EWEA 2020). The generator converts the kinetic energy from the driveshaft into electricity (EWEA 2020).

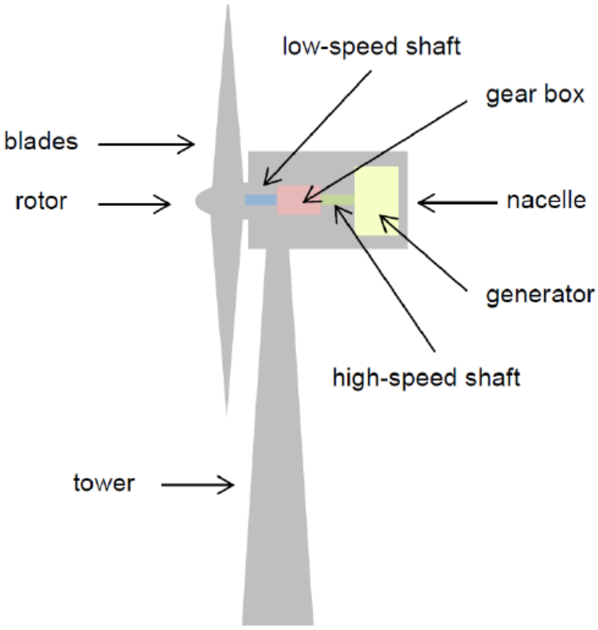


Figure 2.30 – Labelled diagram of a wind turbine. Source – Lexology 2019

The average capacity of an onshore wind turbine in Europe currently is 2.5 – 3 MW and 3.6 MW Offshore (EWEA 2020). Whereas Renewable UK (unknown date) state that wind turbines have a capacity of 1.6 MW and 4.5 MW for onshore and offshore turbines respectively. However, this data is only based upon projects above 100 KW in size and the date of data collection is unknown. Consequently, when calculating wind energy potential EWEA 2020 data will be used. Modern wind turbines have rotor blades that can also swivel upon their axes. This enables the rotor blades to intercept wind energy at the most efficient angle (pitch) (Woodford 2019).

During operation, wind turbines emit no greenhouse gases (EWEA 2020). Greenhouse gas emission that can be associated with the wind energy industry occurs during the manufacture, installation, maintenance and decommissioning of the turbine (EWEA 2020). The total carbon emissions associated with both on and offshore are between 15 and 12 gCO_2/kWh respectively (Thompson & Harrison 2013). Over a 20-25-year lifetime, an average-sized wind turbine produces 80 times more energy than it requires to build and maintain it (EWEA 2020). Figure 2.31 shows how turbine size has increased globally through time.

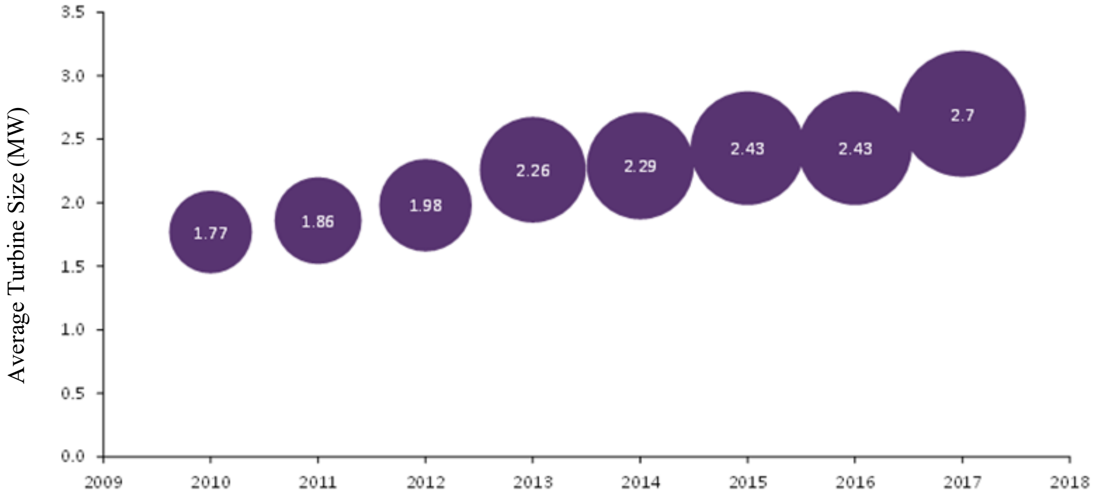


Figure 2.31 – Graph showing the average turbine size change through time. Source – Power Technology 2018

2.5.2 What does the resource depend on?

Wind Speed

Wind speed will partly determine the power output from a wind turbine. Power output from wind turbines increases cubically with increasing wind speed (Campbell 2019). Typically wind speeds of 4 m s^{-1} are required for the blades to rotate (cut in speed) and for electricity to begin to be produced (EWEA 2020). Increased amounts of electricity can be produced until the wind reaches an optimum speed (rated speed) (EWEA 2020). Turbines are typically shut down when wind speeds exceed 25 m s^{-1} because the turbine is deemed unsafe in these conditions (cut out speed) (EWEA 2020; Figure 2.32).

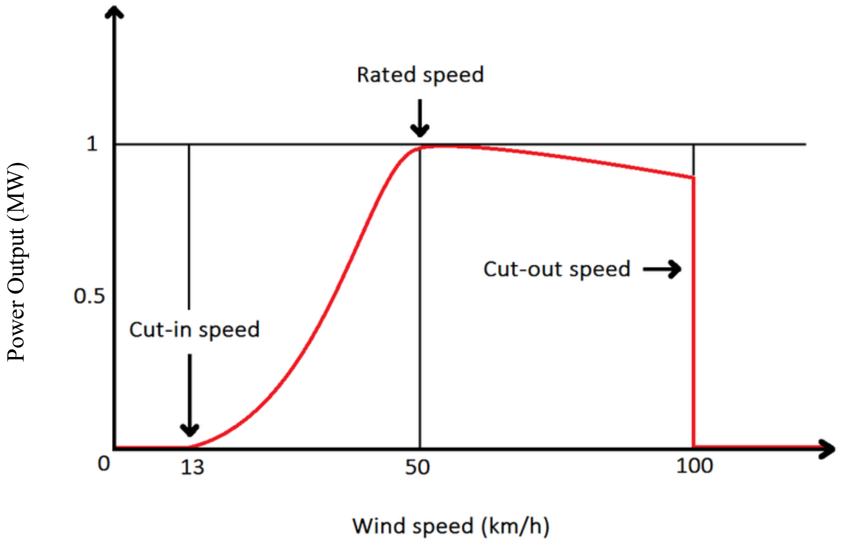


Figure 2.32 – Wind Power curve. Shows that typically 13km/h (4 m/s) is the cut in speed and 100km/h (25 m/s) is the cut out. The point of maximum output is a t 50km/h (14 m/s). Source – Harman, S 2017

County Durham experiences wind speeds on average between 5.4 – 5.8 m s^{-1} throughout the year (Weather Spark 2020). The calmest and windiest days of the year record on average 4.5 m s^{-1} and 7.2 m s^{-1} respectively. The wind speed is recorded from a height of 10 m above ground level (Weather Spark 2020). Wind turbines typically operate ~100 m above ground level depending on their capacity (EWEA 2020). To calculate the wind speeds that turbines in County Durham would experience, the wind gradient must be accounted for. Wind gradient is rate of wind speed with unit increase of height above ground level and is shown in the following equation (Heier 2014).

$$v_w(h) = v_{10} \cdot \left(\frac{h}{h_{10}}\right)^a$$

Where:

$v_w(h)$ = Wind Speed at wind turbine height (m s^{-1})

v_{10} = Wind speed at 10m above ground level (m s^{-1})

h = Height above ground level

h_{10} = Height 10m above ground level

a = Hellman Exponent (0.45)

Time of year	**Wind speed 10 m above ground level (m s^{-1})**	**Wind speed 100 m above ground level (m s^{-1})**
Windiest Period	5.8	16.5
Windiest day of the year	7.2	19.4
Calmer Period	5.4	15.2
Calmest day of the year	4.5	12.5

Table 2.5– Table showing the conversion of average wind speeds 10m above ground to 100m above the ground what wind turbines will experience. This has been calculated for different times of the year in County Durham. Data Source – Weather Spark 2020

Air Density

Air density is dependent upon the local altitude, pressure and temperature (Helmenstine 2020). Denser air exerts an increase in pressure upon the rotor blades and therefore produces a higher power output (Campbell 2019). Standard atmospheric air density at 15 °C and at sea level is 1.225 kg/m^3 (Helmenstine 2020). County Durham in comparison records an air density of 1.234 kg/m^3 (Weather Spark 2020).

Turbine Size

By increasing the rotor blade size, larger turbines can capture higher proportions of the wind's kinetic energy (Business Insider 2017; Figure 2.33). If the cut-in speed of the turbine is met, larger turbines typically will generate more electricity compared with smaller turbines experiencing the same wind speed. Other factors will also determine the power output as larger turbines require more space and higher cut-in speeds.

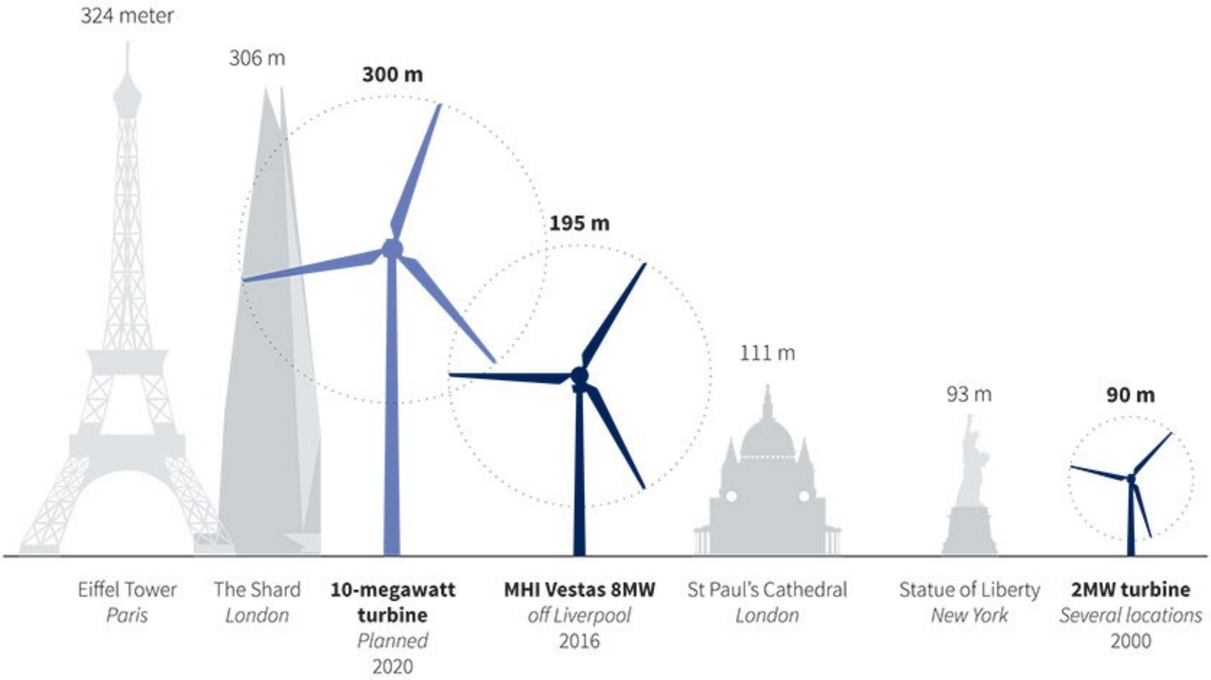


Figure 2.33 – Visualisation of different sized wind turbines and their associated power capacity compared to famous landmarks around the world. Source – Business Insider 2017

Turbine Location

The local topography, buildings and other wind turbines all have the potential to act as a wind barrier called baffles (Woodford 2019). All baffles will decrease the wind's kinetic energy available to the turbine, adversely impacting the electricity output (Woodford 2019). Offshore wind farms typically experience higher wind speeds and incur significantly fewer baffles (Woodford 2019).

2.5.3 Energy Potential in County Durham

Onshore

If the average onshore wind turbine capacity is assumed to be 2.5 MW, the maximum theoretical output of a wind turbine will be 21,900 MWh/yr. Onshore wind turbines generate electricity at 24 % of their theoretical maximum output (EWEA 2020). In one year, this equates to 5,256 MWh.

MacKay (2013) stated that onshore wind turbines typically generate electricity at 2.5 W/m^2 however advancements in technology may have increased this value since 2013, therefore further study is required to understand current efficiency. At this efficiency, 22% of the area of County Durham (490 km^2) would be required to meet the county's total energy demand (10,513 GWh). Alternatively, to meet, the county's electricity demand, 6% (133 km^2) would be required (Figure 2.35).

In 2017, County Durham generated 311,214 MWh from wind energy. It equates to 5,275 MWh from each wind turbine (~60 turbines), which equates to 19 MWh above the national average. The distribution of these turbines can be seen in Figure 2.34.

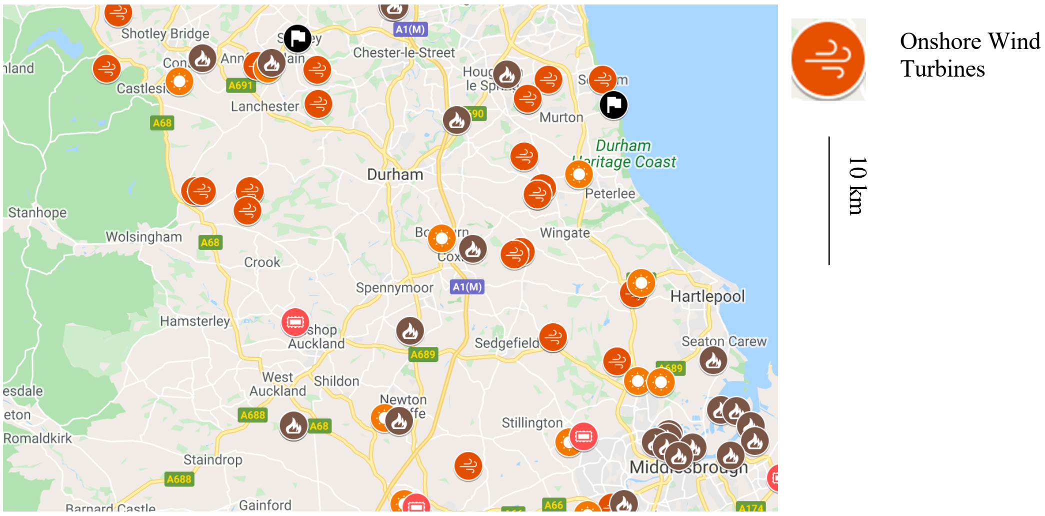


Figure 2.34 – Map of current County Durham renewable energy projects. Onshore wind farms are indicated by wind icon. Source – Mygridgb 2020

The county recording above national average statistics for wind energy demonstrates County Durham's favourable characteristics (wind speed, air density, topography).

Using the average County Durham wind turbine energy production value, the number of onshore turbines required to meet energy demands can be calculated. In addition, using a capacity factor of 24 %, the power capacity required can also be calculated (Table 2.6).

Energy Sector	***Energy demand (GWh)***	***Number of turbines required***	***Power capacity required (MW)***
Domestic Electricity	788.48	150	375
Industrial Electricity	2027.52	384	964
Total	2816	534	1339

Table 2.6 – Table of data showing the number of onshore wind turbines required for different energy sectors in County Durham. Data Source – DCC 2015

Offshore

Offshore wind turbines have an average capacity of 3.6 MW (EWEA 2020). Their maximum theoretical output annually is 31,536 MWh. Furthermore, offshore turbines generate electricity at 41% of their theoretical maximum output (EWEA 2020). The average offshore wind turbine could generate approximately 12,929.76 MWh of electricity (Table 2.7).

Energy Sector	***Energy demand (GWh)***	***Number of turbines required***	***Power capacity required (MW)***
Domestic Electricity	788.48	61	219
Industrial Electricity	2027.52	157	565
Total	2816	218	784

Table 2.7 - Table of data showing the number of offshore wind turbines required for different energy sectors in County Durham. Data Source – DCC 2015

Assuming that spacing requirements between wind turbines were the same onshore as they were offshore this equates to 250,000 m^2 area required per turbine. However, offshore wind turbines are relatively much larger and therefore are likely to require larger distances between turbines.

Consequently, to meet the County's total electricity demand an offshore wind farm 54.5 km^2 in area would be required (Figure 2.36). This calculates offshore wind turbines provide an energy efficiency of ~5.9 W/m^2.

Figure 2.35 – Size of hypothetical onshore wind farm required to meet County Durham's electricity demand (133 km^2). Source – Google Earth.

Figure 2.36 – Size of hypothetical offshore wind farm required to meet County Durham's electricity demand (54.5 km^2). Source – Google Earth

2.5.4 Limitations of the resource

Intermittence

Wind energy is an intermittent energy source. The turbine blades will only rotate when the cut-in speed is met. If the cut-in speed is not met, zero electricity is generated (EWEA 2020). This makes turbine placement integral. The advantage of offshore wind is that higher wind speeds are more consistent, with European seas having enough wind to power the continent seven times over (EWEA 2020).

Location and spacing of turbines

Kinetic energy from the wind is used to rotate the turbine blades in order to produce electricity (EWEA 2020). When wind turbines are positioned too close to each other, they act as a wind barrier to each other reducing overall efficiency (Woodford 2019). Turbines should be spaced typically four times their rotor blade length away from each other (Woodford 2019). Subsequently, wind farms require large areas of space positioned in more remote locations.

Environmental Issues

Wind turbines are known to kill birds and bats through direct collision, feeding/nesting displacement and habitat degradation. Loss (2013), recorded that US wind farms kill a total of 140,000 – 328,000 birds each year. With a reduction in the bird population located around wind farms, there is a noticeable change in species composition within the food chain (Thaker 2018). Thaker (2018) However relates to a study site in India measuring the lizard population with no transferability to UK sites. The Royal Society for the Protection of Birds does however support the growth in onshore and offshore wind energy in the UK provided turbines are located to minimise species loss (Local Government Association, Unknown).

The US National Wildlife Federation stated that failure to address the harm caused to wildlife could result in an economic slowdown in wind power production. Their solution to this issue is choosing the correct sites for wind farms, which comes from working alongside environmental and ecological companies. However again, this does not assume a transferability to the UK wind industry. A technology that has also been considered, called 'Identiflight' (McClure et al 2018) can recognise when birds are heading towards the turbines so they can be shut down in time to allow the bird to pass. The technology is not yet proven and can significantly reduce energy production from wind turbines caused by repetitive shutdown. Offshore wind turbines are not exempt from ecological scrutiny as they also have associated marine ecosystem issues, specifically impacts on species such as porpoises, seals and loons (White & Case 2020). This study was based on American ecosystems and so is not specific to County Durham.

Noise and Visual pollution

Wind farms have been described as visual eyesores (Gibbons 2014). Gibbons (2014) found that the visual pollution caused by wind turbines can reduce house prices up to 12% within a 2,000 m radius. In addition, noise pollution from nearby wind turbines has decreased house prices by 3-7% (Jensen 2014; Figure 2.37). This emphasises the need for a suitable location to be chosen for onshore wind farms.

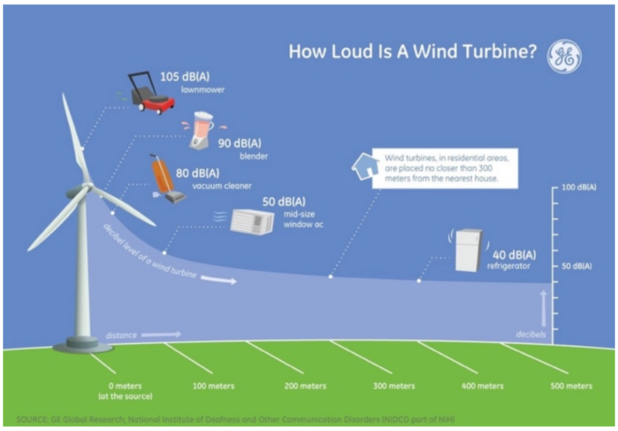


Figure 2.37– Schematic graph showing the volume produced by a wind turbine at increasing distance away from the turbine. This data has been compared to various household appliances for context. Source – GE 2014

2.5.5 Economics

IRENA (2018) stated that the global weighted average for onshore wind projects are 0.042 £/kWh, compared with offshore costs of 0.096 £/kWh. A projection of these cost estimates would show an onshore system to generate 2816 GWh would cost ~£118 million, compared with ~£270 million cost for an offshore system. This offshore economic projection can be compared with (Catapult 2020) 'Guide to an offshore windfarm' where the breakdown of costs per MW can be seen in table 2.8.

Project Aspect	**Cost (£)**
Development & Project management	120,000
Turbine	1,000,000
Balance of power plant	600,000
Installation & Commissioning	650,000
Operation, maintenance & service (per year)	75,000
Decommissioning	330,000
Total	2,775,000

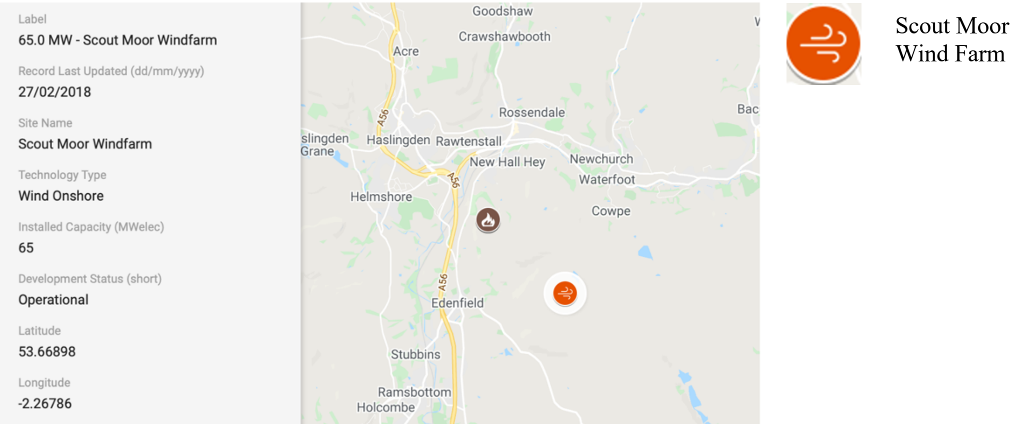
Table 2.8 – Table of costs for various project aspects to an offshore wind farm. Data Source – Catapult 2020

Therefore, for the 784 MW system County Durham would require, the cost would be ~ £2 bn. This broad variance in price between studies shows varying conditions between wind farms. Consequently, consideration must be taken specifically as data taken from IRENA 2018 could have further decreased in price following the general global trend. IRENA (2018) stated that 2018 onshore costs were 13% lower than those in 2017. In addition, offshore costs were 1% lower compared to 2017 data.

2.5.6 Case Study Examples

Scout Moor Wind Farm – Peel Energy

Scout Moor wind farm, near Rossendale, Lancashire (Figure 2.38) is the second largest onshore wind farm in England. The farm has a capacity of 65 MW. It uses 26 wind turbines producing approximately 154,000 MWh/yr, equating to 5,923 MWh per turbine. The electricity generated powers 40,000 homes. The farm covers 5.4 million m^2 and can be seen from 32,000 m away. The project was initially resisted by a protest group but despite this, was granted permission in 2005, and cost £50 million in construction costs.



Label
65.0 MW - Scout Moor Windfarm
Record Last Updated (dd/mm/yyyy)
27/02/2018
Site Name
Scout Moor Windfarm
Technology Type
Wind Onshore
Installed Capacity (MWelec)
65
Development Status (short)
Operational
Latitude
53.66898
Longitude
-2.26786

Figure 2.38 – Location of Scout Moor Wind Farm and associated data.
Source – Mygridgb 2020

Suffolk County Council Offshore Wind – Suffolk County Council (Unknown)

Suffolk County Council currently has two producing offshore wind farms, both are located 22,500 m off the Suffolk coast; called Galloper Wind Farm and Greater Gabbard Wind Farm. Galloper has a capacity of 353 MW. 56 turbines generate enough electricity to power 380,000 homes.

Greater Gabbard is a 500 MW capacity farm, which cost £1.6 bn and its 140 turbines power 530,000 homes annually. Suffolk County Council has now partnered with Scottish Power Renewables, to build the second-largest offshore wind farm within the UK. The East Anglia

Offshore Wind Farm will cover 6000 km^2 with a capacity of 7,200 MW with the ability to power up to 5 million homes.

Walney Wind Farm – Orsted

Walney Wind Farm is made up from a collective group of wind farms, located 14,000 m off the coast of Walney Island within the Irish Sea. Originally this wind farm comprised of two phases, but an extension has now been added to the farm. Phases one and two included the installation of 102 turbines, with a capacity of 734 MW, and were forecast to generate 1,300 GWh/yr. The extension has now added a further 87 turbines with an additional capacity of 659 MW. A potential problem was witnessed at Walney in 2014. A dive vessel used to carry out a routine check, crashed into one of the turbines snapping its anchor cable. It was reported that not much damage occurred to the turbine or the maintenance ship.

2.5.7 Conclusions

Wind energy uses wind turbines to harness kinetic energy from the wind to produce electricity (EWEA 2020). Collections of turbines, called wind farms can either be installed onshore or offshore. County Durham's resource potential depends firstly on the wind speed the county experiences. Power output will begin when wind speeds reach 4 m s^{-1} and will increase cubically with increasing wind speed (Campbell 2019) until an optimum speed of ~14 m s^{-1} is achieved. The turbines will shut down if the wind speed exceeds 25 m s^{-1} for safety reasons. Taking into account the wind gradient, County Durham's wind turbines would experience wind speeds which range from 12.5 to 19.4 m s^{-1}. Denser air, larger turbines and remote locations all can increase the power output from turbines (Campbell 2019 & Reuters 2017). Onshore wind turbines generate electricity at 24% of their theoretical maximum output and ~2.5 w/m^2 (EWEA 2020). Therefore, to supply the total electricity demand of County Durham (2,816 GWh) 534 onshore wind turbines with a total capacity of 1339 MW, covering 133 km^2 would be required, costing ~£118 million. Further study should be taken to understand if and where County Durham has land space to accommodate more onshore wind turbines. Offshore wind turbines generate electricity at 41% of their theoretical maximum output and 5.9 w/m^2 efficiency (EWEA 2020). From this data, County Durham would require 218 offshore wind turbines with a combined capacity of 784 MW, covering 54.5 km^2 of offshore space to supply the total county's electricity demand. This offshore wind farm would cost ~£270 million. Intermittence is also an issue with wind energy. When wind speed drops below the cut in speed, no electricity will be produced. Furthermore, land use, environmental issues, noise and visual pollution are all associated limitations.

2.6 Biomass

Much of the information within this chapter has been acquired from the Open University's Biofuels online course which I undertook to aid this thesis. An acknowledgement must be made to chapter 4 of 'Why people need plants' from the Royal Botanic Gardens (2010).

2.6.1 How it works

Biomass is a carbon-neutral form of energy extracted from recently living material (Royal Botanical Gardens 2010). The materials could be plant or animal in origin. Energy is stored in biomass as chemical bonds within molecules in the organisms' cells and this energy can be exploited by humans (Royal Botanical Gardens 2010). Various techniques are used within the conversion process of biomass into useable energy products that can either be used for heating, generation of electricity or a replacement for liquid fuels for transport (Royal Botanical Gardens 2010). Use of biomass by humans for heating dates back to ~790,000 years ago and located in Gesher Benot Ya'aqov in Israel, where archaeologists found evidence of humans using wood for fire (Royal Botanic Gardens 2010).

Royal Botanic Gardens (2010) stated that biofuels can be produced through the waste material left from plants and animals, as well as being grown specifically as an energy crop. Energy stored in plant biomass is derived from photosynthesis. This is where the plant uses solar radiation and carbon dioxide from the atmosphere, to create sugars held within the carbon-containing structures of the plant. The sugar is usually in the form of glucose but can also vary in type (Royal Botanical Gardens 2010). Photosynthesis occurs inside the chloroplasts found within the plant leaf ((Royal Botanical Gardens 2010; Figure 2.39). The chloroplasts contain chlorophyll, which is a green pigment that captures solar radiation (Royal Botanical Gardens 2010).

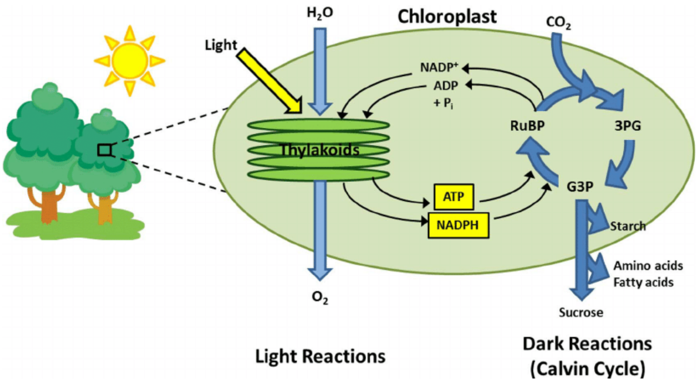


Figure 2.39 – Schematic diagram of the process photosynthesis
Source – Minteer & Rasmussen 2014

Burning of biomass breaks the chemical bonds with the organic material to release the stored energy (Royal Botanical Gardens 2010). Plants containing high amounts of sugar or oil content stored within the structure can be processed to produce transport replacement fuel such as bioethanol and biodiesel (Royal Botanic Gardens 2010).

Burning biofuel is considered to be carbon neutral because the carbon dioxide released on burning was at an earlier time extracted from the atmosphere and metabolised by the plant (Royal Botanical Gardens 2010). Thus, burning the plant or derivative biofuels simply releases the same quantity of carbon dioxide back into the atmosphere. In contrast when fossil fuels are burned, the released carbon dioxide does not come directly from the atmosphere but has been trapped and stored for millions or even billions of years (Royal Botanical Gardens 2010). Due to the varying types of biomass and their differences, it is important to understand each type individually.

Wood

The burning of wood is also considered to be a carbon-neutral process for the same reasons as described above (Royal Botanic Gardens 2010). The key issue is that the carbon dioxide has been released across a very short space of time as the wood burns and that in turn causes a sharp increase in greenhouse gas emissions, but a slow reduction when growing seasonally (Royal Botanical Gardens 2010). However, it must be noted that the climate the wood is being grown determines how long it takes to accumulate the carbon for example tropical forests sequester carbon at a higher rate compared to temperate climates (Arora et al 2011). If used as an energy source, woodland can be grown sustainably, allowing for safe rates of harvesting and replanting typically on a 15-year rotation (depending on the species) to allow for carbon neutral levels of deforestation (Forest Research 2020).

Woodland in County Durham could have other advantages such as creating employment, picturesque landscapes attracting visitors and the temporary storage of rainwater. Temporarily storing rainwater is useful because it delays the full volume of rainwater entering the rivers and therefore reducing the risk of flash flood events.

Harvesting woodland depends on what tree species is being used (Royal Botanical Gardens 2010). Some systems use the whole tree for chipping as opposed to others, which only make use of the tree stem (Royal Botanical Gardens 2010). Typically, when woodland is being harvested for energy use, the process called ‘short rotation forestry’ is implemented (Royal Botanical Gardens 2010). Short rotation forestry is used when the tree species are known to grow quickly (Royal Botanical Gardens 2010). Trees can then be cultivated until they reach an economically optimum size when they are either coppiced or harvested (Forest Research 2020). Harvesting cuts down the entire tree or occasionally including the removal of the tree roots, which are then replaced by the plantation for new tree saplings (Royal Botanical Gardens 2010).

Coppicing processes require the young tree stems to be removed, leaving a coppice stool (Royal Botanical Gardens 2010). The process allows a larger number of new tree stems to grow from the coppice stool. Royal Botanical Gardens (2010) state that coppicing increases carbon sequestration levels, whilst the coppice stool regrows. Willow and poplar stems can be coppiced every three to five years for up to 30 years before the root stocks need to be replenished (BEGIN 2020).

Generating both heat and electricity from the wood involves multiple steps. The first step requires the wood to be dehydrated (Royal Botanical Gardens 2010). Any moisture within the wood will require energy for evaporation during the burning process, thus reducing the efficiency of the system (Royal Botanical Gardens 2010). The wood is then heated in the absence of oxygen (pyrolysis), producing a mixture of gases such as carbon dioxide and carbon monoxide which are in turn purified after partial burning to generate electricity (Royal Botanical Gardens 2010). The ash formed through pyrolysis must be carefully analysed. The ash could contain nutrients that can be used as fertiliser but may contain contaminants from the previous soil (Royal Botanical Gardens 2010). Common types of wood used for energy production include willow and poplar trees due to their fast rate of growth and being able to be densely planted as well as taking up pollutants e.g. nitrate from excess fertiliser (Royal Botanical Gardens 2010).

Grasses

Grasses grow much quicker compared with woodland and produce a large amount of biomass per-unit growing area ~150 g/m^2 (Western et al 2015). Grasses reproduce through underground rhizomes allowing them to spread quickly, easily producing new shoots (Royal Botanical Gardens 2010). However, it can also make species invasive and difficult to control. Certain species of grass are found to be more suitable for energy production e.g. Miscanthus X-Giganteus (Royal Botanic Gardens 2010). Species that contain a high-water efficiency usage, are particularly useful in more arid type climates owing to them requiring less water, whilst still outputting equivalent or higher energy levels than other species e.g. Miscanthus X-Giganteas. The Drax Power Station located in Yorkshire, currently burns through 300 million kg/yr of Miscanthus X-Giganteus (Royal Botanic Gardens 2010).

Within the UK, a disadvantage of using grasses as energy crops is the higher moisture content found at certain times of the year (Royal Botanical Gardens 2010). The result is the biomass fuel acquired from the grass cannot be produced in the same way, reducing potential profit as extra dehydration steps are required (Royal Botanic Gardens 2010). Furthermore, due to associated transport costs, transporting grasses for biofuel usage becomes uneconomic at distances greater than 80 km (Royal Botanic Gardens 2010).

Transport Biofuels

Biomass can also be used to create a suitable replacement for petroleum fuel currently used within the transport industry (Royal Botanical Gardens 2010).

In Brazil, one-third of all cars are fuelled entirely from bioethanol (Royal Botanical Gardens 2010). The remaining two-thirds run from using a mixture of biofuel and petroleum. Brazil obtains 40% of all its transport fuel from fermenting sugar cane. Transportation using biofuels currently offer two main options, biodiesel and bioethanol (Royal Botanical Gardens 2010).

Biodiesel

Biodiesel cannot solely be used as the fuel to power combustion engines. Instead, it must be blended with other petroleum fuels (Royal Botanical Gardens 2010). Biodiesel is produced when oilseed crops are mixed with industrial chemicals, namely methanol, sodium hydroxide and potassium hydroxide (Royal Botanical Gardens 2010). The mixture reaction forms fatty acids and glycerol (Royal Botanical Gardens 2010). The fatty acids continue to react until biodiesel is produced. Rape oilseed is the UK's main oil crop-producing 1,300 l of biodiesel per ha of the crop planted (Royal Botanic Gardens 2010).

Bioethanol

Bioethanol has one distinct advantage over biodiesel in that it can be directly used within traditional combustion engines with minimal engine modification required. Also, there is no dependency for blending with other petroleum fuels (Royal Botanical Gardens 2010).

Biofuel can be produced using three different process methods. The first process uses fermented plant sugars (Royal Botanical Gardens 2010). Another process involves the conversion of the starch-rich material into sugars which is then fermented (Royal Botanical Gardens 2010). An alternative process involves the leaf stem of the plant being extracted from the tough cellulose cell wall, which can then be converted into sugars for fermentation (Royal Botanic Gardens 2010).

Regardless of which process method is used, fermentation must always take place (Royal Botanical Gardens 2010). This is where microbes are introduced that use the plants' sugars as a food source producing ethanol (Royal Botanical Gardens 2010). The ethanol must then be distilled so it can be separated from other components that are produced throughout the fermentation process (Royal Botanical Gardens 2010).

Algae

Algae is a unicellular or multicellular autotrophic aquatic organism (Royal Botanical Gardens 2010). Algae does not require fresh water or agricultural land to grow, because their nutrient requirements can be met with either wastewater or seawater (Royal Botanical Gardens 2010).

Algae produce many different organic molecules, particularly lipids and carbohydrates (Royal Botanical Gardens 2010). At least half of algae's makeup is from sugars that can be used to produce ethanol (Wi et al 2009) or methane via anaerobic digestion (Spolaore et al 2006), as well as the production of biodiesel and biohydrogen (Gavrilescu & Chisti 2005).

Many different forms of algae vary in morphology, longevity and ecophysiology. All the various types of algae can be classified by their pigmentation. Brown (Phaeophyta), red (Rhodophyta) or green (Chlorophyta) (Biology Wise 2020).

One advantage of using algae for energy production is their growth rate. Algae can grow up to 60 m in length (McHugh 2003), incorporating a high biomass yield per unit used (light and area). Non-cultured algae can produce between 3.3 – 11.3 kg/m^2/yr of biomass. Whereas cultured algae can produce up to 13.1 kg/m^2 over a 7-month cultivation period (McHugh 2003)

However, macroalgae biofuel production viability was showed not to be economical using current technology (Pittman et al 2011), despite microalgae being reported to be the most effective raw material used within the production of biofuel (Rajkumar et al 2013). Consideration must be taken though as Pittman et al study took place in 2011 and therefore economic data used could now have changed. Further investigation to the economic viability of algae growth in the UK should be taken.

Biogas

Biogas is a mixture of methane and carbon dioxide, the methane can then be burned to generate heat or electricity (Royal Botanical Gardens 2010). Biogas is formed through the anaerobic digestion of organic matter by micro-organisms. Organic matter can consist of municipal waste, sewage, food waste, animal waste and biomass crops (Royal Botanical Gardens 2010). The residue from a biogas system can be used as an agricultural fertiliser (Royal Botanical Gardens 2010).

It is important to note that biomass can produce materials as well as energy (Bothwell, Personal Communication, 2020). Biorefineries can be used to separate out different components of biomass for efficient usage.

Biorefinery

Biorefineries are facilities that can produce fuels, energy and chemicals from biomass (Figure 2.40). Biomass can be separated into many different components. A biorefinery can make use of this to produce multiple products at the same time (Hingsamer et al 2019). This is important when attempting to remove petroleum fuels from society for energy because biomass can also be used for producing chemical feedstocks, fertilisers, clothes and many more. (Hingsamer et al 2019).

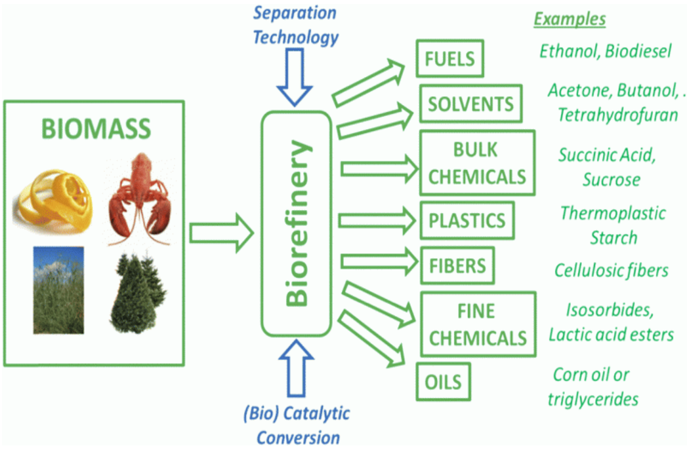


Figure 2.40 – Flow chart of biorefinery process – Source Labio Tech 2016

Currently, it is more economically viable for farmers to produce food crops rather than biomass for energy (Bothwell, personal communication, 2020). Wheat farmers for example use only 10% of the total harvested crop (Bothwell, personal communication, 2020). The remaining 90% of its straw mass is either used for animal feedstock or used to make compost (Bothwell, personal communication, 2020). A biorefinery could make use of the unused straw, fermenting it either into bioethanol, or rotting it down to produce biogas (Bothwell, personal communication, 2020).

Biorefinery's operate at an optimum mix of biological components, made up of 50% carbohydrates and 50% fats to produce biofuels, energy and chemicals (Bothwell, personal communication, 2020). Cooking oil currently used in restaurants, hotels and other industries depend upon all used oil being disposed (Bothwell, personal communication, 2020). Disposal processing is heavily regulated and costly (Bothwell, personal communication, 2020). Disposal processes could now be revised and amended to be used to support the biorefinery process (Bothwell, personal communication, 2020).

2.6.2 What does the resource depend on?

Because biomass is created from recently living materials usually in the form of plants, those same survival factors living plants depend upon remain for biomass. Components include enough sunlight, nutrients, space and water. Biomass energy looks to use the type of species requiring fewer resources, whilst still maintaining a high biomass output to reduce costs.
Algae is advantageous in this respect as it can thrive in very poor growing conditions. Arid type climates usually provide an abundant amount of direct and intense sunlight but can lack sufficient water for crop growth. Farmers within such regions will typically choose crops that can incorporate a high-water use efficiency (Royal Botanical Gardens 2010).

2.6.3 Energy Potential in County Durham

In 2017 County Durham produced 124,508 MWh from plant biomass and anaerobic digestion alone (DCC 2019). Energy crops produce on average 0.5 W/m^2 (MacKay 2013). This production value, therefore, estimates that currently ~28 km^2 of County Durham's landmass is used for energy production from biomass crops. However, this is unlikely to be true, as many biomass power plants import their biomass from different regions of the UK or even internationally e.g. Drax Power Station, Yorkshire. Further study would be required to understand the true amount of land used in County Durham by energy crops.

To meet County Durham's total energy demand of 10,513 GWh/yr, the county would require 2404 km^2 of energy crops equating to 108% of County Durham's total land area. Alternatively, to meet the county's electricity demand, 29% of County Durham's landmass would require energy crop farming. Consequently, the feasibility to grow biomass for energy within the county remains doubtful.

Algae's ability to grow at sea would combat the issue of land availability for biomass in the county. Algae produce on average ~3.9 l/m^2 (All About Algae 2020). Vehicles in the UK consume on average 1,183 l/yr of fuel. Thus, algae could yield from 4046 m^2 the equivalent annual fuel consumption of 13.5 cars. The 292,100 registered vehicles in County Durham would require 87 million m^2 of offshore space for algae growth to replace petroleum transport fuels if an efficiency of ~3.9 l/m^2 was achieved (Durham Insight 2019). However, consideration should be taken as fuel consumption and the number of vehicles may have changed since 2019.

The UK aims to ban all sales of petrol and diesel new cars by 2030. The resource base for energy crops needed to generate enough electricity for transportation usage within County Durham is calculated below.

County Durham 2015 transport energy demand was 3,465 GWh equating to 1,378 W/day/vehicle. County Durham has a car density of 129 cars/km^2 warranting a transport energy demand of 0.1776 w/m^2. When compared with the efficiency of energy crops, 35.5% of County Durham's landmass would be needed by energy crops to meet this demand.

Another biomass resource option for County Durham would be the production of energy using a biorefinery. Bothwell (Personal communication, 2020) stated that a single biorefinery located in the county using opportunistic biomass could provide between 5-10 % of the county's electricity demand and several hundred thousand kg's of industry materials to replace petroleum-based ones. Consideration should be made to this reference as being a personal communication and not currently published by the academic. This data however was made specifically in reference to County Durham taking into account ongoing research. Further research and modelling are needed to understand the true potential of Biorefineries in County Durham.

2.6.4 Limitations of the resource

Impact on food production

It is currently more profitable for UK farmers to grow food crops rather than biomass for energy (Bothwell, personal communication, 2020). Subsidies for the biofuel industry are currently £5.6 – £6.1 billion per annum and is set to increase (USDA 2007). One risk associated with subsiding biofuel production is the potential for food prices to increase (USDA 2007).

Seasonality

Like all crops, energy crops growth is seasonally influenced. Due to energy being required all year round, and if society had an over reliance on energy crops there could be a decreased security of the whole system. However, biofuels can be preserved and so would not have this issue once produced.

Associated greenhouse gas emission

Nitrous oxide is produced in substantial quantities during the biogas production and have a global warming potential that is 265-298 greater than carbon dioxide (EPA 2020). It is also substantially greater in concentration than when released from burning fossil fuels for energy production (EPA 2020). Furthermore, greenhouse gas emissions are a by-product from harvesting and transportation associated with cultivating biomass. Generating electricity from biomass is typically but not always lower in greenhouse gas emissions compared with fossil fuels (Environment Agency 2009). For example, using short rotation coppice chips for energy production produces 35 – 85 % less emissions than a combined cycle gas turbine however straw can produce 35% more emissions (Royal Botanical Gardens 2010). Long transport distances and increased fertiliser input can also reduce emission savings by 15 – 50 % (Environment Agency 2009).

Increased fertiliser and pesticide input to soils

Although crops grown for biomass are chosen specifically to require fewer nutrients, any increase in farming will almost certainly lead to an increase in fertiliser and pesticide use (Royal Botanical Gardens 2010). This could result in secondary environmental hazards such as eutrophication and groundwater contamination (Royal Botanical Gardens 2010).

The Potential loss of biodiversity

The production of energy crops could increase biodiversity due to having an increased number of plant species within an area (Royal Botanical Gardens 2010). However, this could also decrease biodiversity if previously diverse land is removed to grow energy crops (Royal Botanical Gardens 2010). Biomass farming in the tropics has resulted in the loss of tropical forest and wetland (United Nations Environment Programme 2009).

2.6.5 Economics

According to (IRENA 2018) biomass has a cost of £0.047/KWh of energy produced. Consequently, to fill the energy demand of the county (10,513 GWh) using biomass, the cost would be ~£240 million.

The costs of algae for energy usage can be separated into construction and operation costs. Construction costs ~£6.4/m^2 of production (Briggs 2010). To replace petroleum fuels used for the transport sector within County Durham would need 86,032,120 m^2, costing £554 million. Land maintenance carries an estimated cost of £0.93/m^2 ((Briggs 2010). This equates to £85 million operation costs, giving an overall investment of ~£639 million. However, it is unclear if this land cost is the same for the UK and in County Durham, furthermore the costs associated with this 2010 study could have changed throughout time therefore consideration of this should be taken and further study should be taken to find current prices.

The investment cost of a biorefinery is dependent upon both size and operating costs. This will also determine the amount of biomass available to the plant. Detailed cost analysis for these installations is unknown although Loaiza et al (2018) states an average-sized biorefinery would cost £6.6 million. However, this study is only representative of thirteen sustainable biorefineries.

2.6.6 Case Study Examples

Brazil – Royal Botanic Gardens (2010)

Brazil acquires 40% of their transport fuels from the fermentation of sugar cane (Royal Botanical Gardens 2010). Sugar cane fuel production presently uses $4x10^{10}$ m^2. If we compare this to land used for cattle farming, Brazil uses $234x10^{10}$ m^2, averaging just 1.4 cattle per ha, a value considerably lower than the carrying capacity of the land (Royal Botanical Gardens 2010).

The Brazilian government recognised and calculated by slightly intensifying cattle farming; $5.7x10^{11}$ m^2 of land could be freed for sugar cane production (Royal Botanical Gardens 2010). The prospect of this change could provide one-third of the world's transportation fuel needs (Royal Botanical Gardens 2010).

However, Brazil has a different climate to County Durham, one which is advantageous for sugar cane growth. This case study shows how land adjustments could make biomass for energy more available to County Durham.

Drax Power Station, UK – Drax (2020)

Drax Power Station located in North Yorkshire has a 3906 MW capacity and produces 18 TWh/yr from compressed wood pellets which have been 'sustainably sourced' from US forests in Louisiana, Mississippi and Arkansas. Currently Drax produces 12% of the UK's total renewable energy. Four of its six power stations were converted from coal power stations.

County Durham could implement this model of importing sustainably sourced biomass from overseas to combat the issue of land availability and non-advantageous growing conditions.

2.6.7 Conclusions

Biomass is a carbon-neutral energy source released from the chemical bonds within the molecules of organic material cells (Royal Botanical Gardens 2010). Biomass can be used for heating, producing electricity or as a replacement for liquid transport fuels (Royal Botanical Gardens 2010). Although biomass typically releases carbon dioxide into the atmosphere when burned, the process is carbon neutral as the CO_2 extracted from the atmosphere is metabolised by the plant. Thus, burning the plant or derivative biofuels simply releases the same quantity of carbon dioxide back into the atmosphere (Royal Botanical Gardens 2010). There are many different types of biomass including; wood, grasses, sugar cane, oilseed crops, algae and waste material. Growth conditions such as the amount of sunlight, nutrients, space and water are what determines the energy potential for County Durham. Space provides the largest issue to County Durham. Energy crops typically produce energy at 0.5 W/m^2 efficiency, meaning to meet the total energy demand of the County (10,513 GWh), 2404 km^2 of biomass farming would be required (McKay 2013). County Durham's total area is 2226 km^2. Further implications such as the impact on food production, seasonality, increased fertiliser and pesticide use and the loss of biodiversity all lead to biomass for energy purposes being a non-viable option for County Durham (Royal Botanical Gardens 2010). Algae as a replacement of petroleum transport fuels could be a solution to this problem as it can grow in seawater or wastewater. 86 km^2 of offshore space would be required by algae to replace current transport fuels in County Durham. However, this resource is relatively immature and untested at this scale therefore a total investment of ~£639 million would be required for this size project. Furthermore, the UK is set to ban all sales of petrol, diesel cars by 2030 therefore, a switch is required towards electric-powered vehicles. The most viable option for biomass in County Durham is a biorefinery. Biorefineries produce fuels, energy and chemicals from biomass. A single biorefinery investment of ~£6.6 million could produce 5-10% of the County's electricity demand and several hundred t of non-petroleum industry material from 'opportunistic' biomass (Bothwell, Personal communication, 2020).

2.7 Energy from Waste

2.7.1 How it works

The present ‘throwaway culture’ that appears to have evolved in many developed nations is now being challenged by those with a desire to move towards a more circular economy (Hartley 2019). A circular economy focuses on making products last longer, but then recovering materials for other use or benefit if the original product is no longer usable (Hartley 2019). One benefit waste can have on economies is the ability to produce energy either in the form of generating electricity or heat (Hartley 2019). Energy from waste does not just entail obsolete manufactured products we throw away but can also include the waste heat lost from industrial processes, as well as sewage waste.

Energy from Waste Products

Producing energy from waste involves complex and multiple layered processes ranging across combustion, gasification, pyrolysis, anaerobic digestion and landfill gas recovery. (Hartley 2019).

Combustion involves the burning of the waste product that can generate enough heat, which in turn can drive a generator through the production of steam to create electricity (Hartley 2019). Currently, the combustion process is 15-27% in efficiency and provides a net calorific value of 7 million J/kg of waste burned (Hartley 2019).

Gasification is the production of gas generated from waste (Hartley 2019). The waste when mixed with oxygen at very high temperatures produce a synthesised gas, called syngas which has a composition mix of H_2, CH_4, CO and CO_2 (Biofuels 2010).

Syngas can then be used to generate electricity or produce other useful products such as transportation fuels and fertilisers (Biofuels 2010).

The difference with pyrolysis compared to gasification is when decomposition of the waste at high temperatures occurs it is done so without mixing with oxygen (Hartley 2019).

Organic waste such as animal products and food must be processed through anaerobic digestion (Hartley 2019). Microbes are added to the waste in an anaerobic environment, converting the waste to biogas (CH_4) and fertiliser (Hartley 2019). Biogas is also produced from waste at landfill sites (Hartley 2019). Extraction of the waste can then lead to energy production. Energy production generated from plastic waste uses pyrolysis and gasification processes that create gases to be used for transportation fuel or burned for electricity generation (Hartley 2019; Figure 2.41).

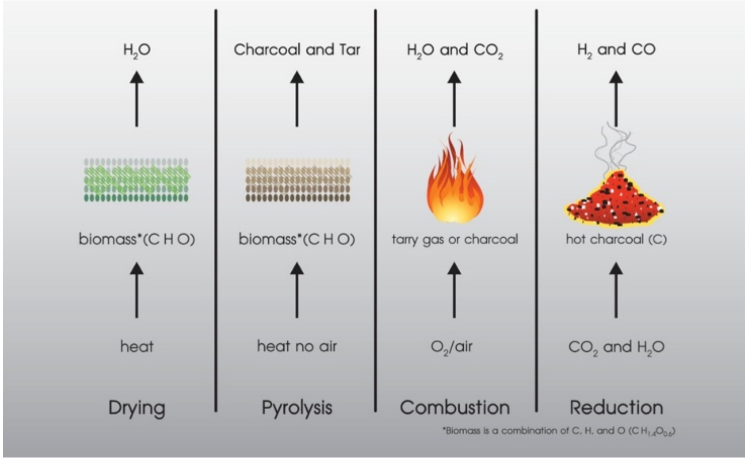


Figure 2.41 – Diagram of the 4 processes of gasification with associated products. Source – Energy Saving Trust 2019

Sewage Gas

(Heidrich et al 2011) stated that wastewater has a calorific value of 7.6 KJ/l. It equates to 9.6×10^{13} J of energy per day for the UK from sewage gas (Heidrich et al 2011). Usable energy is created from sewage through anaerobic digestion (Severn Trent Water 2015). Container tanks housing the waste are kept at a temperature of 35 °C.

This supports the microbes to breakdown the sewage into a mixture of gases, which then can be burned for electricity (Severn Trent Water 2015).

In collaboration with Northumbrian Water Ltd, Newcastle University carried out tests on a new sewage energy processing strategy, called a microbial electrolysis cell (MEC). MECs contain two electrodes. One electrode is covered in electrochemically active bacteria that consume the organic material found in the wastewater (Northumbrian Water Ltd). Consumed electrons and protons are released within the process, resulting in an electrical current (Northumbrian Water Ltd). Hydrogen can also be produced. The process is anaerobic therefore requiring little energy input.

Waste Heat from Industry

Industrial waste heat is the energy that has been rejected from within the industrial process to manufacture products (Papapetrou et al 2018). The waste heat is transmitted in a thermal carrier that can include gaseous, liquid or solid streams. (Papapetrou et al 2018).

(Albert et al 2020) provided the UK with a waste heat-mapping study. The study covered industry sectors including mining, vehicle, food, beverage, iron, steel and data storage. The sectors chosen were based upon their commercial output levels, as well as their high consumption levels of natural gas (Albert et al 2020).

Waste heat calculations use an efficiency value for industry of 30% (Albert et al 2020). Waste heat could be used for both domestic heating systems and industry (Albert et al 2020).

2.7.2 What does the resource depend on?

The resource potential of waste to energy systems depends on the amount of waste available and the infrastructure in place to process it (Hartley 2019). More waste equals more energy, although it is important to consider the waste hierarchy (Hartley 2019: Figure 2.42).

The waste hierarchy table shows that it is preferable to reduce the amount of waste when compared to waste recovery after disposal (Hartley 2019). Social lifestyles could change to fit this, which would result in a decrease in the amount of waste and therefore less energy can be produced. Some waste will still be sent for disposal. It is therefore important to consider what tactic of processing would be most appropriate (Hartley 2019).

Figure 2.42 – Waste hierarchy diagram. Source – Hartley 2019

For waste heat generated from industry, the location of the facility and the grade of the waste heat would determine the quality of the resource (Albert et al 2020). This is because higher temperature fluids have a much higher work potential than lower temperature fluids (Albert et al 2020). The relationship is not linear. Reduced quantities extracted from higher temperature fluids are still more effective than those from lower temperatures with more volume (Albert et al 2020).

2.7.3 Energy Potential in County Durham

Energy from Waste Products

In 2017 County Durham produced 29,245 MWh of energy from the waste collected at six landfill sites (DCC 2019). Each site had an installed capacity of 13.9 MW producing on average 4,874 MWh/yr. The output figures generated from these waste landfill sites represent proportionally just 1% of the county's total electricity need, totalling 2,816 GWh.

A typical waste to energy plant e.g. Powerhouse energy possesses a maximum capacity to produce 81.6 MWh from 40,000 kg of waste plastic per day (Powerhouse Energy, 2020). This would provide a power efficiency value of 2.04 MWh / per 1000 kg of waste plastic. County Durham annually sends 195 million kg's of plastic waste to landfill sites (DCC 2019). This would provide the potential to generate 397 GWh/yr of electricity. Further research is required to understand the average production scale of other plastic to energy plants in the UK and not from a single source i.e. Powerhouse Energy.

Individual waste power plants presently operate to a maximum capacity of 14.6 million waste kg per annum (Powerhouse energy 2020). If the process limits were to remain, it would require the county having to install a total of 13 power plants to meet current demands of the County.

Sewage Gas

In 2017, 995 MWh of energy was generated from three sewage treatment plants, giving a value of 331 MWh per treatment plant used for energy (DCC 2017). Compared to Severn Trent's sewage treatment which produced 208,000 MWh. Pilot studies using MEC technology has shown to produce 0.6-3 l/day of 99% pure hydrogen gas (Heidrich 2013).

However, Cotterill (2016) stated that the technology although having a large potential is not yet ready for rapid rollout.

Waste Heat from Industry

Albert et al (2020) calculated that County Durham wastes approximately 221 GWh of heat from industry. The calculation was derived from data provided by only the mineral and motor industries located within the county, due to a poor response rate of 3% from all industries. An alternative approach for consideration is to use the same 30% heat efficiency value but for the industrial gas demand of the county. Therefore, all industries across the whole of the county require 1227.38 GWh/yr of gas, thus wasting 368.184 GWh/yr of heat. To obtain a more accurate estimate of heat waste from industry, further information must be acquired as waste heat will vary throughout industry.

In total, County Durham has a resource potential of 795.424 GWh generated from waste energy. This represents 7.5% of the total energy needs of the county (10,513 GWh) and would save 225,160 tCO_{2e} in emissions.

2.7.4 Limitations of the resource

Waste to energy

The waste to energy processes of combustion, gasification and pyrolysis are not considered renewable, because they release greenhouse gas emissions from fossil fuel-based products such as plastics (Hartley 2019).

Combustion for example produces 250-600 kgCO_2/1000 kg of waste processed (Hartley 2019). Another limitation relating to the gasification process is that it requires many pre-processing steps (Hartley 2019). The reactors must be closed regularly for cleaning, thus making the process inefficient. Landfill gas is becoming less used due to the declining rates of organic waste being sent to landfill (Hartley 2019). Finally, plastic to energy plants need advanced controls and pre-treatment facilities to become viable (Powerhouse Energy 2020).

Sewage

Wastewater treatment is a high energy-intensive process currently using approximately 3% of the UK's total electricity output (Curtis 2010). Much of the energy produced by the sewage would be used to power the treatment of the water and not redirected back into the national grid (Curtis 2010). Severn Trent Water can illustrate this with only 6 out of 36 water treatment sites producing more energy than is currently needed at each plant. Furthermore, MEC technology has not yet been tested or simulated in realistic conditions and on a large enough scale to be rapidly enrolled (Cotterill 2016).

Waste heat from industry

A limitation with waste heat from industry is the 30% accepted efficiency value that is used to calculate the resource. (Albert et al 2020) calculations were based and used across all industry types throughout the UK. However, different industries will have different efficiencies. Specific efficiency values will need to be acquired from those industries located within County Durham to get a much more accurate value. Low industry response rates also contribute to this issue.

Data protection regulations ensure data confidentiality. Efficiency data statistics will therefore depend upon those companies volunteering information they wish to disclose. Due to the small data pool, any resource potential calculations/projections will have to be completed based upon very limited information and therefore influencing its overall accuracy.

2.7.5 Case Study Examples

Waste to Energy – Sweden

In Sweden, recycling is required by law. Designated collection bins positioned along the roadside are used for collection or drop off purposes and then taken to recycling stations, which on average are located just 300 m away from every residential area (Hinde 2019). The social and environmental benefits from this process reported in 2016 that 31 million kg of waste was put into the ground out of 4.7 billion kg (less than seven-tenths of 1%) (Avfall 2016). Sweden possesses 33 waste to energy plants, providing both heat and electricity to 1.2 million homes, as well as providing standalone electricity to another 800,000. 27% of Gothenburg is heated by waste.

Sewage – Croatia

In 2016, Croatia produced 21,366,000 kg of dry matter and sewage sludge. These figures are likely to pass 100,000,000 kg by 2024 (Durdevic et al 2019). Sewage in Croatia can be converted into 12-16 kWh/person of electricity and 19-24 kWh/person of heat. This is enough for 30-40% of electrical and 80-100% of heat autonomy (Durdevic et al 2019). Durdevic et al (2019) also found that the most cost-effective sewage sludge disposal method is landfilling. Landfilling reports to also have the lowest carbon dioxide emission values.

Waste heat from Industry – ALTEK (2019)

Altek and TWI are EU funded projects focussed on recovering at least 40% of high-grade heat wasted from industry. They have found that both aluminium and ceramic production are two areas of industry with high potential for heat recovery. One issue reported is the hot waste gas recovered is likely to be corrosive, and so the recovery technology will have to support this.

2.7.6 Conclusions

Energy from waste extracts energy from waste products, sewage and heat wasted from industrial processes (Hartley 2019). Energy from waste products requires many processes which can include combustion, gasification, pyrolysis, anaerobic digestion and landfill gas recovery (Hartley 2019). These processes are not considered low carbon as they release greenhouse gases from the petroleum-based plastics (Hartley 2019). Waste to energy power stations can produce ~82 MWh from 40,000 kg of waste plastic per day (Powerhouse energy 2020). County Durham sends 195 million kg of plastic waste to landfill annually which could, therefore, produce 397 GWh/yr of electricity (DCC 2017). However, these power stations currently operate at a maximum efficiency of 14.6 million kg/yr which means 13 stations would be required to meet the current waste demands of the County. Also, the waste requires pre-treatment before it can be converted into energy. This step is typically energy-intensive and high in CO_{2e} emissions. Energy from sewage is produced by microbes anaerobically digesting the sewage to produce a mixture of gases which can be burned to produce electricity. Sewage treatment is energy-intensive and currently accounts for 3% of the UK's total electricity demand (Curtis 2010). Consequently, most of the electricity produced from sewage would be used to power its own treatment works. However, new studies into microbial electrolysis cells have shown to reduce the energy required by sewage treatment and produce hydrogen as a by-product (Northumbrian Water Ltd). This remains a high potential resource however has not been tested at the scale required for rapid rollout. Industrial waste heat captures and reuses the energy which was initially rejected and lost from industrial processes. It is estimated that industry has a 30% heat efficiency meaning County Durham wastes ~368 GWh of heat from its industry (Albert et al 2020). This calculation assumes however that all industry has the same efficiency of 30% however this value was calculated from a 3% response rate. Specific industry calculations are therefore required for County Durham.

2.8 Hydrogen

2.8.1 How the resource works

Hydrogen is the most abundant element in the universe, comprising 75% of the baryonic matter in the entire universe, and makes up 13% of the Earth's crust (Edvinsson 2019). Pure hydrogen occurs only in molecular form (H_2) on Earth, but is found in compounds, such as water (H_2O), petroleum liquids and gases, and typically as hydroxides in rocks and minerals (Adolf et al 2017). Hydrogen is also odourless, colourless, tasteless and flammable. It consists of one proton and one electron (Clennett 2018).

Currently, around 2,000 TWh energy equivalent of hydrogen is produced globally each year, with the UK producing ~26 TWh of that total (ERP 2016). The current hydrogen generation methods used are methane reforming (49%), partial oil oxidation (29%), coal gasification (18%) and electrolysis (4%) (Arup 2015). The uses of hydrogen are currently dominated by petroleum refining, ammonia production, and across the food, methanol, metals, and electronic industries (Adolf et al 2017).

When used as a fuel, hydrogen contains the highest energy per mass of any fuel (120 million J/kg), although due to its low density, hydrogen has a low energy per unit volume (Edwards 2019). Hydrogen has multiple uses in the effort to decarbonise energy. It can be burned for heating, used as an alternative to transport fuels, produced into chemical feedstocks, or used as a store of energy, which may prove vital if the production of energy from renewable resources increases (Edvinsson 2019). The method of hydrogen production will impact the uses and decarbonisation strategy used within County Durham; therefore, it is important to consider each.

Hydrogen Production Methods

Gas Reforming with CCS

Gas reforming requires a stream of natural gas (CH_4) reacting with a stream of water (H_2O) at a high temperature, to produce hydrogen (H_2) (Committee on Climate Change 2018). During this process, carbon dioxide (CO_2) is produced, and therefore must be captured using carbon capture and storage (CCS) for the process to be low carbon (Committee on Climate Change 2018). Methane is currently the most commonly used natural gas for the reforming process (Committee on Climate Change 2018). Hydrogen produced from gas reformation is relatively pure, but some impurities are likely to remain (Committee on Climate Change 2018). If purification technologies are not used, impure hydrogen will be limited in its applications, for example fuel cells can use impure hydrogen (Committee on Climate Change 2018). Currently gas reformation has an efficiency of 65% and is predicted to increase as technological advancements are made to 85% (Committee on Climate Change 2018). Improvements made in efficiency, combined with CCS, would reduce the carbon intensity during current production from 285 gCO_{2e}/kWh to between 11-25 gCO_{2e}/kWh (Committee on Climate Change 2018). The extraction and delivery of natural gas within the process, also produces greenhouse gas emissions, including uncaptured CO_2 from production (Committee on Climate Change 2018). Compared with the current use of natural gas, gas reformation with CCS to produce hydrogen can reduce total greenhouse gas emissions by 60-85% (Committee on Climate Change 2018).

Electrolysis

Electrolysis is a process that uses electricity to separate water into hydrogen and oxygen (Committee on Climate Change 2018). The process uses electrolysers which range in size up to 10 MW (Committee on Climate Change 2018). Electrolysers are suitable to small scale on-site hydrogen production. If larger sites were required, electrolysers would have to be stacked together (Committee on Climate Change 2018). There are currently two main types of electrolyser, alkaline, and solid oxide (Committee on Climate Change 2018).

Electrolysers produce pure hydrogen, making it more applicable to end users requiring fuel cell technology. The current efficiency of an electrolyser is 67%, which could see improvement towards 74-82%, depending upon technological advancements (Sustainable Gas Institute 2017). The process of electrolysis also produces oxygen as a by-product (Committee on Climate Change 2018). Oxygen currently costs £0.015-£0.030/kg to produce (Committee on Climate Change 2018). The process of gas reformation requires oxygen and could run in conjunction with electrolysis (Committee on Climate Change 2018).

Coal, Biomass & Waste Gasification

Gasification uses high temperatures to heat a hydrocarbon intense feedstock to produce syngas (Committee on Climate Change 2018). Syngas is rich in hydrogen, carbon monoxide, carbon dioxide, and methane (Committee on Climate Change 2018). Upgrading the syngas via a water gas shift reaction will separate the hydrogen and convert the carbon monoxide into CO_2 and more hydrogen (Committee on Climate Change 2018). Consequently, CCS is required for this process to be low carbon (Committee on Climate Change 2018). Gasification produces similar purity hydrogen to that of gas reforming, although if waste is used this provides a higher risk of contaminants to the gas (Committee on Climate Change 2018). The current efficiency of gasification to hydrogen is over 60% however the inclusion of CCS is set to reduce efficiency to 52% (E4Tech 2015). This figure is unlikely to improve, given gasification is a mature process. The carbon intensity of coal, biomass, and waster gasification with associated CCS is 27-34 gCO_{2e}/kWh, assuming a 95% CO_{2e} capture rate can be achieved (Committee on Climate Change 2018). This is a 7-56% reduction, compared to unabated natural gas use (Committee on Climate Change 2018).

Applications of Hydrogen

Heating

The Institution of Engineering and Technology (2019) stated, the UK is now able to *'seriously consider'* the opportunity to use hydrogen within the gas grid, to heat both domestic homes and industry. See Figure 2.43 for a comparison of heating fuels for homes.

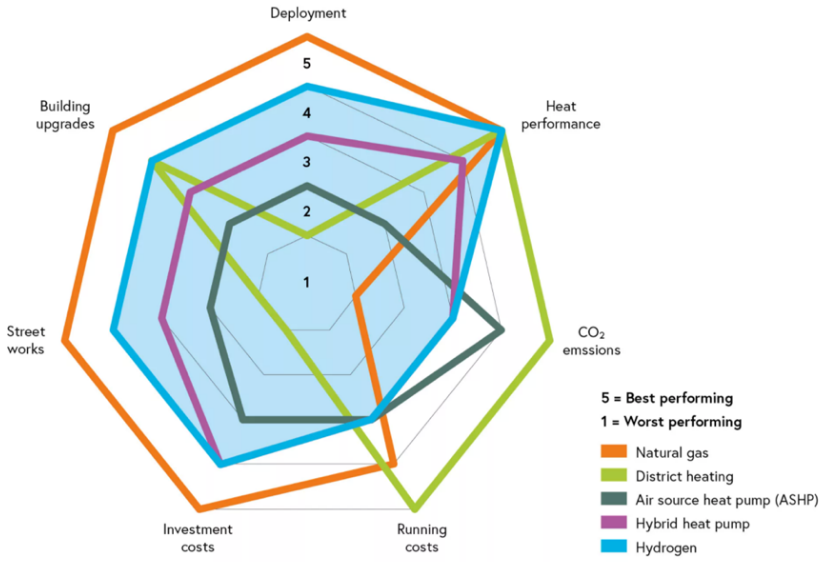


Figure 2.43 – Heat source comparison diagram. Source - Enviro Tech 2019

Combustion of hydrogen produces heat, as well as emitting water vapour. Water vapour is a greenhouse gas that contributes ~60% to the Earth's warming effect (ACS 2020). However, water vapour does not control the temperature of the Earth. The abundance of water vapour contained within the atmosphere, can vary by temperature (Gluyas, personal communication, 2020). If the atmospheric temperature is decreased when containing the maximum amount of water vapour, some vapour will condense into liquid water (ACS 2020).

For combustion in homes to be made possible, the jet inside a conventional gas boiler will need replacing with jets compatible for hydrogen (Fraser-Nash Consultancy 2018). The typical lifespan of modern-day boilers is between 10-15 years, so a migration to hydrogen compatible boilers could be completed using a phased approach, if all the boilers in a specific area require replacement (Committee on Climate Change 2020). Furthermore, all UK gas mains iron pipeline networks, are scheduled to be replaced with polyethene pipes by 2030 (Enviro Tech 2019). A positive by-product to this change is hydrogen's compatibility to polyethene, unlike the previous iron-based pipes (Enviro Tech 2019). Heating via hydrogen could be combined with the use of heat pumps. Heat pumps offer the potential to efficiently provide heat most of the time. Hydrogen could be used during peak demand times during the coldest times of the year (Committee on Climate Change 2018). The committee on climate change (2018) stated that the combination of hydrogen with heat pumps could almost entirely remove the use of fossil fuels in buildings. Furthermore, hydrogen's heating potential could be specifically important in an industry where combustible gases come into contact with the material being produced (Committee on Climate Change 2018).

Transport

Hydrogen can be used to power vehicles using fuel cells (Committee on Climate Change 2018). Hydrogen fuel cells combine hydrogen and oxygen to generate electricity, which in turn is used to power the vehicle (Clennett 2018). Requiring no moving parts, a transport range of ~483 km per tank can be achieved, with the added benefit that only water is emitted from the process (Hydrogen Hub 2020). Vehicles powered by hydrogen fuel cells are more efficient than those using traditional petrol or diesel fuels (Hydrogen Hub 2020). Hydrogen refuelling process takes between 3-5 minutes to complete for domestic type vehicles. This makes hydrogen-powered vehicles much more advantageous when currently compared against the time needed to recharge the equivalent electric-powered vehicles (~1-28 hours) (Pod Point 2020). When a hydrogen vehicle is being driven at low speed, the drivetrain power comes entirely from the vehicle battery (Hydrogen Hub 2020). At a higher speed, the vehicle is powered from the electricity produced within the fuel cell, which at the same time also recharges the battery (Hydrogen Hub 2020). Hydrogen's low weight when compared to other fuels types, can make it particularly beneficial for heavy goods vehicles (HGV's), because it enables the HGV to increase the payload weight of the vehicle, improving its commercial operation efficiency (Clennett 2018). Finally, hydrogen could play a potential role in the decarbonisation of shipping, making use of its low-weight properties (Committee on Climate Change 2018).

Materials

Currently, 65% of the hydrogen produced globally is used to manufacture ammonia and methanol, at 55% and 10% respectively (Hydrogen Europe, Unknown). Twenty-five percent of hydrogen use comes from refinery projects (Zakkour et al 2010).

The production of ammonia (NH_3) uses the Haber-Bosch process that combines hydrogen and nitrogen, at a ratio of 3:1, directly via synthesis (Adolf et al 2017). Synthesis occurs at 500 °C and 200 bars of pressure, with the presence of an iron-based catalyst due to nitrogen (N_2) being very unreactive (Adolf et al 2017). Significant recycling of unreacted gases is required throughout the Haber-Bosch process, because the conversion rate of nitrogen and hydrogen to ammonia, is typically below 20% (Adolf et al 2017).

Methanol production from hydrogen occurs through catalytic hydrogenation of carbon monoxide. This process mixes hydrogen with carbon monoxide over a catalyst, at elevated temperatures and pressures (Adolf et al 2017).

Energy Storage

Hydrogen can be used as a way of storing energy (Adolf et al 2017). It can be stored in large volumes for extended periods compared with current energy storage mechanisms, such as batteries. This is particularly useful when transitioning to low carbon sustainable technologies because electricity is notably difficult to store (Adolf et al 2017). Excess energy from low carbon technologies, could be stored by generating hydrogen and then storing it as an alternative to electricity storage (Adolf et al 2017). As power from renewable energy continues to grow, hydrogen could replace the system backup of natural gas plants (Committee on Climate Change 2018). This could be aided by new natural gas plants being ‘hydrogen ready’.

Hydrogen can be stored using physical or materials-based methods (Adolf et al 2019). Physical storage is the most used and proven method, and can be separated into high pressure, or cooled physical storage (Adolf et al 2019). The storage of hydrogen is particularly difficult when stored in gas form. 5.5 kg of hydrogen gas equates to 66,000 l (Edvinsson 2019). Consequently, the hydrogen gas would require to be compressed 660 times (atmospheres) to reduce down to 100 l, which is a more suitable volume for a vehicle fuel tank (Edvinsson 2019).

If physical storage was required on a much larger industrial scale, storage in either salt caverns or depleted oil/gas fields could be used. Using salt caverns for storage is the preferred option (HyUnder 2014). This is due to operational flexibility and lower levels of potential contamination of hydrogen with other in-situ materials (HyUnder 2014). By liquefying hydrogen (LH_2), the energy density is increased compared with gaseous hydrogen (HyUnder 2014). However, liquefication requires a temperature of ~ -253 °C, or cryogenic hydrogen storage, which are both complex and expensive (Adolf et al 2017).

Material based storage include hydride storage, liquid hydrogen, and surface storage systems (Adolf et al 2017). These methods remain under development, owing to the storage density levels currently being achieved are still not adequate. Also, the cost and time taken for charging and discharging the hydrogen are too high (Adolf et al 2017).

2.8.2 What does the resource depend upon?

Production Method

The method to produce hydrogen will determine the use and the carbon intensity of the process. Gas reforming and gasification both emit significant amounts of greenhouse gases, without the use of carbon capture and storage (CCS) (Committee on Climate Change 2018). CCS being implemented becomes integral, if hydrogen is to play a pivotal role in the decarbonisation of County Durham.

Geological Storage

To use hydrogen as a resource, storage is a key component. As previously highlighted, hydrogen can be stored physically, or materially based and is not dependant on the location at which storage occurs (Adolf et al 2019). Geological storage of hydrogen within either salt dissolution caverns, or disused oil/gas reservoirs, will be determined by the local geology and therefore influencing the choice of location (Heinemann et al 2018). If salt caverns were to be evaluated as an option for storing hydrogen, the depth and deposit thickness, including the nature and amount of insoluble minerals and the structural style of the salt cavern, will all be factors that can determine the feasibility of the project (HyUnder 2017).

Load Factor

Load factor determines the efficiency during hydrogen production via electrolysis (Committee on Climate Change 2018). When an electrolyser is run at low load factors, for example, during intermittent power generation from renewable energy sources such as wind and solar, the efficiencies will be reduced throughout the system (Committee on Climate Change 2018).

2.8.3 County Durham Resource Potential

Heating

Due to hydrogen production not being impacted by location, the resource potential for hydrogen production is equal everywhere in the UK. The committee on climate change (2018) stated three scenarios in which hydrogen should be considered for heating in the UK:

Full Hydrogen

Gas networks would be repurposed to hydrogen, and immediate decisions will be required to allow for the wholesale switch to hydrogen for heating. This would be difficult to deliver, regardless of the hydrogen production method used. The relatively short timeframe for this to be achieved is unlikely for such a large change, including a possible lack of emission reductions.

Hybrid Hydrogen

Gas networks will be repurposed to hydrogen, but an emphasis on the immediate use hybrid heat pumps would lead to drastic emission reductions. This approach would allow more time for a switch away from natural gas to be made, with a greater ability to produce low carbon hydrogen.

Niche Hydrogen

Gas grids would not be switched to hydrogen as the decarbonisation of heating would be supplied through the electrification of the system instead. The deployment of hydrogen would be focussed in areas where the value of hydrogen is greatest such as industry.

County Durham could use hydrogen for heating within a hybrid setting, if it is combined with the use of mine water energy, and hybrid heat pumps. A mixture of these heating strategies would allow for emissions to fall drastically, by the quick implementation of heat pumps, supplemented by mine water being used where possible. This would allow time for low carbon hydrogen production to be made possible and to be used in locations not applicable for minewater energy

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Transport

Electric vehicles are now well placed to deliver decarbonisation to domestic vehicles (Committee on climate change 2018). Hydrogen's major lack of refuelling stations for domestic vehicles renders it unsuitable domestically (Committee on Climate Change 2018). However, hydrogen could play an integral role in the decarbonisation of heavy-duty vehicles such as buses, trains, HGV's and ships (Committee on Climate Change 2018). Hydrogen's low weight would be advantageous for such transport types. The ability of localised hydrogen production may provide an added cost benefit to this (Committee on Climate Change 2018). Currently, the UK shows a repositioning towards the electrification of the transport sector. Unless major rapid advancements are made, hydrogen is unlikely to become a major transport source for domestic transport in County Durham.

Salt Caverns Storage

Storing hydrogen is dependent on location because the salt deposits will depend upon the geological history of the area. Currently, there are 30 salt caverns in use throughout the UK, for natural gas and hydrocarbon storage (ETI 2015). The deepest and largest salt caverns found within the UK are 2,000 m deep and hold 600,000 m^3 respectively (ETI 2015). Previously highlighted in section 1.1.4, the area that is now County Durham and the North East of England experienced Zechstein cycles and evaporite deposition, during the Permian period (Gluyas et al 2016). Consequently, the Billingham Anhydrite Formation and the Boulby Halite Formation were deposited throughout Durham and the Tees Valley area (BGS 2000). The Boulby Halite Formation is ~ 90 m thick on the north-east coast and thins towards the west. (BGS 2000; Appendix 1.0). Further study will be required to explore both the potential and volume of the salt deposits throughout County Durham to store hydrogen. The ETI predict the peak needs for an entire city could be catered for by one single cavern, however this is not specific to County Durham.

2.8.4 Limitations of the resource

Upgrading Equipment

To heat homes entirely using hydrogen, homes require a hydrogen compatible jet to be installed in the conventional gas boiler (Gluyas, personal communication, 2020). Installation costs for homeowners or landlords become a factor, but with average lifecycle timescales for current boilers being around 10-15 years, migration could be phased in, similar to the transition to natural gas throughout the 1960s and 1970s (Clark 2020). Since the turn of the millennium, iron-based gas pipes throughout the UK network are being replaced by polyethene alternatives. It is estimated by 2030, 90% of pipelines will have been replaced (Clark 2020). The old iron-based pipes would have reacted with hydrogen, and it would also have leaked from every joint, but the new polyethene pipes are safe (Clark 2020).

Number of Refuelling Stations

Hydrogen Hub (2020) state there are only 17 hydrogen vehicle refuelling stations currently located throughout the UK. Unless there is a significant expansion of more fuelling stations, it will make purchasing hydrogen-powered vehicles less viable to the general public when compared with other alternative fuel types.

Dominant Supply Pathway

The current dominant supply pathway of hydrogen is through methane reforming (Adolf et al 2017). Gas reforming involves the release of greenhouse gases (CO_{2e}), contributing to the impact of climate change. For the production and supply of hydrogen at a county level scale, consideration would need to be given switching to excess energy from low carbon sustainable resources, or a combination of gas reformation with carbon capture and storage (Committee on Climate Change 2018).

2.8.5 Economics

Committee on Climate Change (2018) estimate that a full decarbonisation of heating via hydrogen and electricity would cost up to 0.7% of the UK's GDP in 2050. Hybrid use of hydrogen would reduce emissions to ~5 $MtCO_{2e}$/yr costing £28 bn/yr (Committee on Climate Change 2018). Additional costs will occur within the production of hydrogen, including the removal of CO_{2e} via CCS, installing heat pumps, and upgrading the gas network. These additional costs equate to £17 bn/yr. The current usage of natural gas for heating costs £30 bn/yr (Committee on Climate Change 2018).

2.8.6 Case Study Examples

Keele University, Staffordshire – HyDeploy (2020)

Hydrogen will be injected into the existing natural gas network to heat the site for Keele University. This network provides heat to 30 university buildings and 100 domestic properties. Hydrogen will make up 20% of the gas mix, which is the highest proportion being tested across Europe. This pilot study will be used to test the practicalities of increasing hydrogen within the gas mix, cost, safety and ease of supply.

2.8.7 Conclusions

Hydrogen can be used to produce heat, chemicals, alternative transport fuels as well as a store of energy (Edvinsson 2019). Gas reforming, electrolysis, and gasification are the main sustainable methods for producing hydrogen. Gas reforming and gasification would require associated carbon capture and storage, to make the process low carbon (Committee on Climate Change 2018). For hydrogen to be used in space heating, conventional gas boiler jets would need replacing by hydrogen-ready jets (Gluyas, personal communication, 2020). This is also the case for the UK iron gas pipe network with the requirement to replace with polyethene alternatives. All pipes should be made hydrogen ready by 2030 (Enviro Tech 2019). Emphasis should first be placed on immediate low carbon heating alternatives, such as mine water, and heat pumps. This would allow for a slower transition, and greater ability to produce low carbon hydrogen. Hydrogen can power vehicles through fuel cell technology (Committee on Climate Change 2018). No moving parts are required, and each vehicle has a ~483 km transport range. Refuelling takes between 3-5-minutes. The only produce using hydrogen to power vehicles in pure water (Committee on Climate Change 2018). However, a drastic increase in the number of refuelling stations is required before hydrogen-fuelled vehicles could be an option to decarbonise the transport sector. Hydrogen's low weight makes it particularly beneficial for HGV's, because the vehicle can increase its transport payload (Committee on Climate Change 2018). Energy can be stored using hydrogen for long periods, when compared to current battery methods. This is particularly useful during decarbonisation as electricity is difficult to store (Adolf et al 2017). Excess energy from low carbon sustainable resources could be stored because hydrogen removes the need for natural gas backup plants to be used in times of high energy demand. Large scale hydrogen storage can take place in salt dissolution caverns (HyUnder 2017). Due to County Durham's geological history, the Billingham Anhydrite and the Boulby Halite formation, could be used as potential hydrogen stores.

2.9 Hydroelectric Energy

2.9.1 How the resource works

Hydroelectric energy or hydroelectricity is the conversion of kinetic energy from flowing water into electricity by rotating a turbine which in turn drives a generator (IRENA 2015). It is considered to be low carbon and renewable as the water cycle is consistently renewed by the sun and the only greenhouse gases emitted occurs during the construction process (Student Energy 2015)

Hydroelectric energy is a mature technology which is used in over 160 countries and which generated 15.8% of the Earth's total energy in 2011 (3,500 TWh) (IRENA 2015). Hydroelectricity exists usually in two configurations, dams with associated reservoirs and run-of-river plants (IRENA 2015).

Dams

Hydroelectric dams are a large barrier along the course of a river. The dam raises the elevation of the water and stores it (Student Energy 2015). Storing water allows for regulated release when there are fluctuations in the demand for water or risk of flooding (IRENA 2015). Raising the elevation of the water increases the hydraulic head. Consequently, when the water is released from the dam, electricity can be generated (Student Energy 2015). This makes hydropower suitable as electricity generation can be regulated and stimulated for peak times (Student Energy 2015).

There are typically four types of dams (British Dam Society 2020). Arch dams are curved in shape which is advantageous for resisting the force of the water behind the dam. Arch dams are usually constructed in narrow, steep-sided valleys (British Dam Society 2020).

Gravity dams rely on gravity to maintain resistance to the water (British Dam Society 2020). In cross-section gravity dams often look triangular. Gravity dams can be installed in wide or narrow valleys however they require stable geology (British Dam Society 2020). There are more than 250 gravity dams in the UK (British Dam Society 2020). Buttress dams were developed from gravity dams but use triangular-shaped walls called buttresses to withstand resistance (British Dam Society 2020). This allows the dam to be constructed from far less material compared to gravity dams (British Dam Society 2020). There are 14 buttress dams in the UK (British Dam Society 2020). Finally, embankment dams are constructed mainly from natural materials (earthfill and rockfill) which are typically quarried nearby (British Dam Society 2020). Most embankment dams have a central impermeable core to stop water passing through the dam (British Dam Society 2020). Embankment dams are usually chosen for wide valleys, and there are over 3,000 of them in the UK (British Dam Society 2020).

Run-of-river systems

Run-of-river systems are smaller in size and use the rivers natural flow to generate electricity. This means that the electricity generated from run-of-river systems is proportional to the flow of the river at any one time (Student Energy 2015). Consequently, these systems are more intermittent than dams and with the lack of any reservoir, no water can be stored (Student Energy 2015). Run-of-river systems, however, are typically significantly better for the river's ecosystem compared to dams (IRENA 2015).

Examples of run-of-river systems come in the form of weirs, barrages and micro hydrokinetic turbines (IRENA 2015). A weir is a low wall made from either stone, concrete or wicker whereas a barrage is similar but much larger in size (>10 m) (IRENA 2015). Micro hydrokinetic turbines use the flow of the river to generate electricity by turning a small set of blades and typically generate 1-10 kW of electricity (IRENA 2015). Micro hydrokinetic turbines being small in size allows them to be deployed in more locations along the river (IRENA 2015). This is a benefit for isolated areas that may be located a long distance away from grid services.

2.9.2 What does the resource depend on?

Head

Head is the difference in water level between the intake site and exit point of a hydroelectric site (Renewables First 2020). The larger the head leads to higher water pressure across the turbine and therefore more power can be generated (Renewables First 2020). Head also influences other factors which the resource will depend upon. A higher head with higher water pressure means a higher flow rate can be transmitted through a smaller turbine which will impact how expensive the project is, the resources used, and greenhouse gases emitted during construction (Renewables First 2020).

Flow

The flow rate will determine how quickly the turbine spins and therefore be associated with how much power is generated. Typically, low head sites have higher flow rates as this usually occurs at the lower end of the rivers catchment area (Renewables First 2020). Conversely, upstream where the rivers' catchment is smaller, the flow will be larger but have a smaller head. (Renewables First 2020).

Efficiency

In micro hydrokinetic turbines, turbine efficiency ranges from 0.25 to 0.592 (Vermaak et al 2014). 0.592 is denoted by the Betz law however, it is only possible for highly efficient machines with low mechanical losses to achieve this efficiency (Vermaak et al 2014).

Small scale river turbines have mechanical losses which consequently reduce efficiency to 0.25. This efficiency value is multiplied by the size of the turbine, water density and the rivers current velocity to calculate power output. (Vermaak et al 2014). However, consideration should be taken as technology efficiencies may have increased since this study. Consequently, further study is required to understand current efficiencies.

Geology

When building hydroelectric dams, the geology is integral to the structural soundness of the construction. Typically, impermeable lithologies are used to stop leakage from dams. The structural geology of lithological units will also need be explored. Structural formations such as folds and dipping beds should be examined to minimise the risk of leakage.

Size of River

Apart from larger rivers having the potential for relatively higher flow and head, the size of the river determines how many hydroelectric projects could be installed along its course. Larger rivers have the potential to generate more energy from installing a larger number of systems along the rivers' length, although this depends upon the distance that is required between projects to not influence power output, which is unknown.

2.9.3 County Durham Resource Potential

County Durham possesses a total of 17 rivers. The two longest rivers being the River Wear and the River Tees (Figure 2.44) with a combined length of ~235 km.

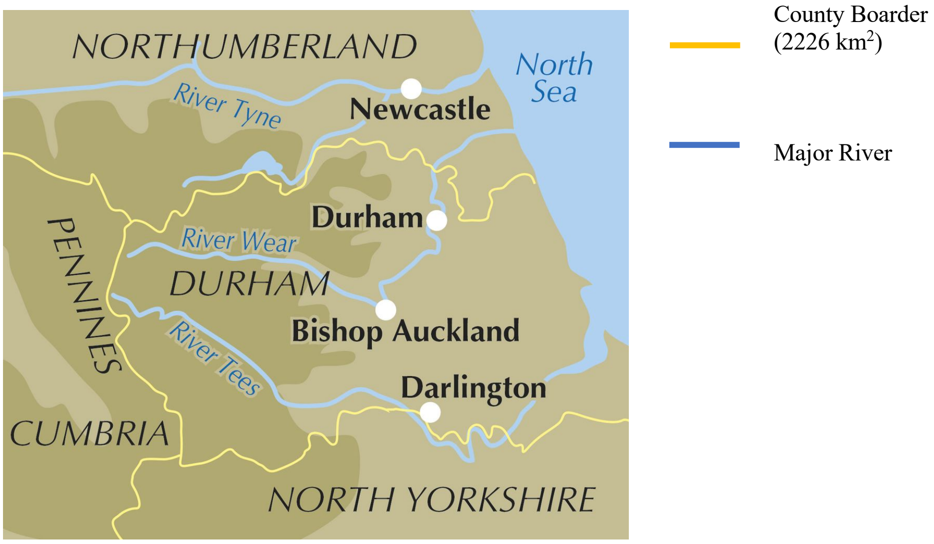


Figure 2.44 – Map of County Durham showing the routes of both the River Wear and River Tees. Source – Cicerone Press 2019

Due to velocity changing with flow and location on the river a velocity cannot be assumed to calculate potential energy from hydropower. Furthermore, due to the downstream impacts of the infrastructure required for hydropower it is difficult to suggest how many turbines could be placed along a section of river. Each site must be carefully considered on an individual basis. However, the British Hydropower Association (BHA) calculated that the North East has 318 potential sites for small scale hydropower creating 27 – 40 MW. County Durham currently has a 100-kW hydropower system at Freemans Reach, Durham City. Individual sites must be considered for hydropower schemes where all depending factors can be calculated.

2.9.4 Limitations of the resource

2.9.4.1 Dams

Environment

Damming water will impact multiple areas of the environment. Firstly, the dam will create a barrier for aquatic animal movement. A consequence of this will be habitat loss and reducing the biodiversity of the river (Bracken et al 2013). Bracken et al (2013) states that culminative impacts from hydropower barriers should be considered by regulatory agencies when planning new hydropower developments. Dams also halt the movement of sediment supply downstream (Hydro Review 2017). By reducing the amount of sediment downstream, this reduces the nutrients available to organisms, and consequently species numbers reduce. Furthermore, rivers downstream of dams can be eroded by 10 m up to a decade after the installation of the dam due to lack of sediment supply which causes damage to riverbank structures or riverside woodland (Hydro Review 2017). The sediment that is blocked by the dam builds upon the reservoir bed, reducing storage capacity and power output. Restricting the movement of water also creates stagnant water in the reservoir (Hydro Review 2017). Stagnant water reduces the oxygen in the water causing underwater organisms to die which subsequently produce methane when decaying, contributing to climate change when released into the atmosphere.

Dam Failure

If the dam fails, this can be catastrophic for nearby communities due to flooding. Weather, structural issues and local geology can all cause the dam to fail. The impacts of failure could lead to loss of homes, infrastructure and even death of communities.

2.9.4.2 Run-of-River

Intermittence

Although run-of-river systems tend to share some issues with hydroelectric dams their main limitation is intermittence. Due to the system depending on the flow of the river, in periods of reduced flow, there will be reduced power generated. If a drought occurs no energy would be generated (Student energy 2015)

2.9.5 Economics

The marine current energy conversion system indicates that hydrokinetic energy prices are ~0.035 £/kWh (IRENA 2018). For 27,330 – 39,810 kW of electricity produced, suggested by the BHA, this would require an investment of £8.3 – £12.2 million respectively. Consideration must be used as economic data could have changed since this 2018 study. Further research should be taken to understand the current cost of projects and those that are specific to County Durham.

2.9.6 Case Study Examples

Freemans Reach, County Durham – Renewables First (2016)

County Durham currently has a 100 kW Archimedes screw type hydropower scheme located at Freemans Reach on the River Wear (Renewables First 2016). The scheme uses a net river head of 2.83 m and a mean flow of 14 m^3/s (Renewables First 2016). 496 MWh of electricity is estimated to be produced each year which has a CO_{2e} emission saving 248,000 kg/CO_{2e}/yr (Renewables First 2016). Due to the River Wear being a salmonid river the hydro scheme was designed to include an associated fish pass. In addition, a fish counter was also installed which can differentiate between different species of fish. This data is sent directly to the Environment agency (Durham Gate 2015).

2.9.7 Conclusions

Hydroelectric energy is the conversion of kinetic energy from water into electricity (IRENA 2015). It is considered low carbon due to emissions only coming from the construction of the project. Hydropower is also renewable as the water cycle is constantly recycled (Student Energy 2015). Electricity can be produced by either dams or run-of-river systems, both rotating a turbine and associated generator. Hydroelectric dams raise the elevation of water behind the dam and store it, allowing for the regulated release in energy during fluctuations in demand (Student Energy 2015). Run-of-river systems use the rivers natural flow to turn a turbine and produce electricity. That means that the electricity generated by these systems is proportional to the flow of the river causing the resource to my intermittent relative to dams as a rivers flow changes throughout the year. Aside from the flow of the river, hydroelectric energy depends on the rivers size, geology, head and ecosystem (IRENA 2015). Due to hydroelectric energy typically causing a barrier to water this also impacts the downstream ecosystem. Furthermore, dam failure can have catastrophic impacts on nearby communities. Due to a lack of river data and river characteristics varying with location along each river I am unable to assume any values to calculate potential energy output from hydroelectric energy in County Durham. Although, the BHA calculated that the North East has 318 potential sites for small scale hydropower. For an accurate calculation of County Durham's hydropower potential, sites must carefully be considered on an individual basis. However due to the number and size of the river system in County Durham it is likely that as micro-hydrokinetic power increases in maturity that County Durham has a large energy potential.

2.10 Tidal Energy

2.10.1 How the resource works

Tidal Energy is energy produced from the rise and fall of ocean tides (IRENA 2014). Tides occur due to the gravitational forces produced by the moon, the sun and the rotation of the earth. The moon's gravitational energy generates a tidal force. The tidal force causes the ocean to bulge out on the side closest to the moon, creating a high tide. The opposite happens when creating a low tide. Typically, two low and two high tides are experienced each day. This means that tidal energy is characterised by periods of maximum energy generation every 12 hours. Consequently, tidal energy remains a predictable and reliable energy source (IRENA 2014). The kinetic energy from the tides is used to turn a turbine connected to a generator and thus produce electricity (Green Match 2020). Tidal energy is renewable and low carbon with only construction associated greenhouse gas emissions (Green Match 2020). Currently, there are two ways to generate tidal energy: tidal range technology and tidal current technology (IRENA 2014).

Tidal range technology uses the potential energy produced by the difference between low and high tide (IRENA 2014). As the tide rises and falls, water flows into and out of bays and estuaries. The systems used to exploit this resource can either be one way (ebb or flood tide) or two-way energy generation (Figure 2.45). However two-way generation requires reversible turbines (IRENA 2014). Most tidal range projects use bulb turbines which are similar to those used in hydropower dams (IRENA 2014; Figure 2.46).

Tidal reef and tidal lagoon systems are two relatively recent innovations of tidal range technology (IRENA 2014; Figure 2.45). Both require a smaller head difference (2-3 m) compared with a typically tidal barrage (5-10 m) (IRENA 2014).

A smaller head difference has a reduced environmental impact and is easier to construct due to the lower pressure on the structure (IRENA 2014). Furthermore, tidal lagoons would not have to be connected to the shore like tidal barrages which also reduces their environmental impact (IRENA 2014). Tidal lagoons use an artificial barrier to control the inflow and outflow of water through gates (IRENA 2014). Consequently, a time lag can be created between the water elevation inside and outside of the lagoon. The difference in elevation (Hl (t) – Ho (t)) produces the potential energy which can be harvested (Neil et al 2018; Figure 2.45).

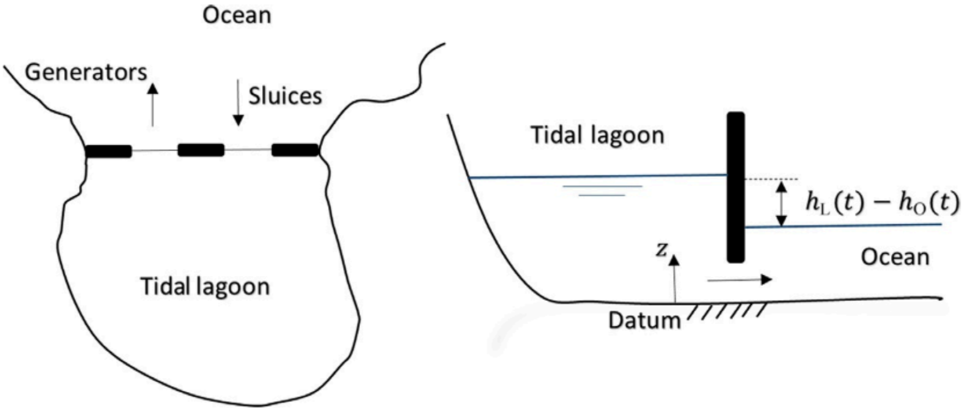


Figure 2.45 – Schematic diagram of a tidal lagoon and ebb tide tidal energy generation systems. Source - Neill et al 2018

Finally, an ultra-low head tidal range technology has been built on the Grevelingen Lake in the Netherlands (IRENA 2014). This technology requires a head difference of just 0.5 m – 1 m (IRENA 2014).

Tidal current technology use turbines and generators to convert the kinetic energy from tidal currents into electricity. There are four main categories of turbines that are used; horizontal axis, vertical axis, reciprocating devices and venturi effect turbines. (IRENA 2014).

In horizontal and vertical type turbines, blades used by the turbines are positioned either parallel (horizontal) or perpendicular (vertical) to the direction of flow of water, which can be seen in figure 2.46 labelled A and C respectively (IRENA 2014) Typically, these turbines are connected to a central rotor shaft which is connected to a generator shaft via a gearbox (IRENA 2014). Open centre turbines however are designed to be mounted on a centred shaft in a static tube which eliminates the need for a gearbox (IRENA 2014). Horizontal and vertical turbines can be enclosed in a duct which concentrates the flow leading to increased power outputs, these are called venturi effect turbines, diagram labelled D in figure 2.46 (IRENA 2014). From all existing tidal projects around the world, 76% are horizontal axis turbines and 12% are vertical axis turbines and the remaining 12% come in the form of reciprocating devices (IRENA 2014). The blades used in reciprocating devices are called hydrofoils, labelled B in figure 2.46 (IRENA 2014). The blade has wings which move up and down as the tidal stream flows past. This up and down movement converts to rotation of the shaft which is connected to pistons supporting a hydraulic system of power generation (IRENA 2014). The advantage with reciprocating devices compared to other tidal current turbines is that the length of the blade needed is not determined by water depth (IRENA 2014).

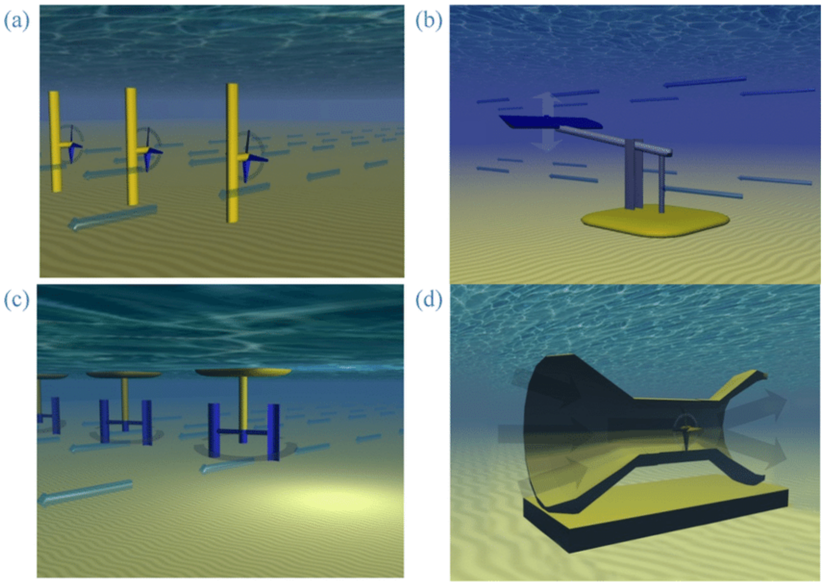


Figure 2.46 – Conceptual diagrams of different tidal current turbines. A (Horizontal Axis), B (Oscillating Hydrofoil), C (Vertical Axis), D (Venturi Effect Device)
Source - Neill et al 2017

Individual tidal current turbines are limited in capacity; therefore, multiple turbines arranged in farms are required to capture the full potential of tidal currents. However, this technology impacts the current flow and so the configuration of these farms is a critical factor to determine their power output (IRENA 2014).

2.10.2 What does the resource depend on?

Tidal Difference

For most tidal energy systems, the height difference between low and high tide must be a minimum of 5 m (Student Energy 2015). Furthermore, the minimum depth must be 15 m to provide space for the turbines and ancillary equipment. In addition, the current velocity must be above 2 m/s to rotate the turbines and generate electricity (Student Energy 2015). Consequently, these conditions typically mean that channels or estuaries are more commonly used for tidal energy (Student Energy 2015).

2.10.3 County Durham Resource Potential

The UK's tidal energy resource is estimated to be more than 10 GW, representing ~50% of the European capacity (Green Match 2020). This would power ~15 million homes and create ~16,000 jobs (Green Match 2020). The Sustainable Development Commission (2007) reported that tidal power could contribute in excess of 20% of the UK's electricity mix.

County Durham currently has no active tidal energy projects. This could be because of a lack of economically/technically viable areas, or a lack of research into the resource. Areas such as Seaham Harbour or locations such as the Tyne, Wear and Tees estuaries may have potential to supply tidal energy but there are currently no specific studies of these bodies of water.

If tidal energy could be implemented in County Durham electricity generation would be intermittent locally. County Durham high and low tides typically last for 6 hours (Weather Spark 2020). However nationally a tidal phase lag around the coastline would provide opportunity for the grid input window to be extended (Burrows et al 2009)

2.10.4 Limitations of the resource

Tidal Cycles

The cycle of low and high tides is constant making tidal energy a predictable energy source (Student Energy 2015). However, they do not always match with the varying energy demands of a population throughout the day. Consequently, to use the full potential of tidal energy, storage systems would be required to store the energy produced when the demand and production balance is not synced (Student Energy 2015). County Durham has a spring tidal range of 5.75 m (Tide Forecast; September 19th 2020) and a neap tidal range of 1.89 m (Tide Forecast; September 26th 2020). The largest tidal range Seaham has experienced was ~6 m. This can be compared to the Servern Estuary with a tidal range of 15 m (Binnie 2016).

Ecological Impacts

Similarly, to hydroelectric power stations, tidal systems which include barriers, can have negative environmental impacts such as habitat destruction and sediment accumulation (IRENA 2014). However, research is ongoing into tidal range technology where impoundments do not have to be closed completely (IRENA 2014).

2.10.5 Economics

Denny (2009) stated that for a tidal energy project to be financially viable capital costs should be less than £478,640 per MW. Tidal energy is associated with high construction costs (£324/KW) and low operation costs. Consideration must be taken, as this financial data from 2009 is likely to have changed. A lack of data surrounding UK projects accounts for using this 2009 study however further study is necessary to understand current tidal energy economic data.

2.10.6 Case Study Examples

La Rance, France – Tethys (Unknown)

Construction of the La Rance tidal energy plant began in 1967 with an initial investment of £85.79 million. The system took three years to build and has a 20 MW capacity. This tidal system has provided electricity to 300,000 homes for 45 years.

Severn Estuary, Britain

The Severn Estuary is the estuary of the River Severn which is the longest river in Great Britain. The estuary has the second highest tidal range (15 m) in the world (Binnie 2016). Much of the estuary however is too shallow to apply horizontal axis tidal turbines. The DECC (2010) showed that an ebb only barrage and a flood lagoon system would be feasible but with appreciable environmental issues. The Servern Estuary has the potential for ~25 TWh/yr constituting 7% of the UK's energy demand however it would need to demonstrate compliance with the EU habitats directive (Binnie 2016).

SeaGen Turbine, Northern Ireland – Power Technology (2020)

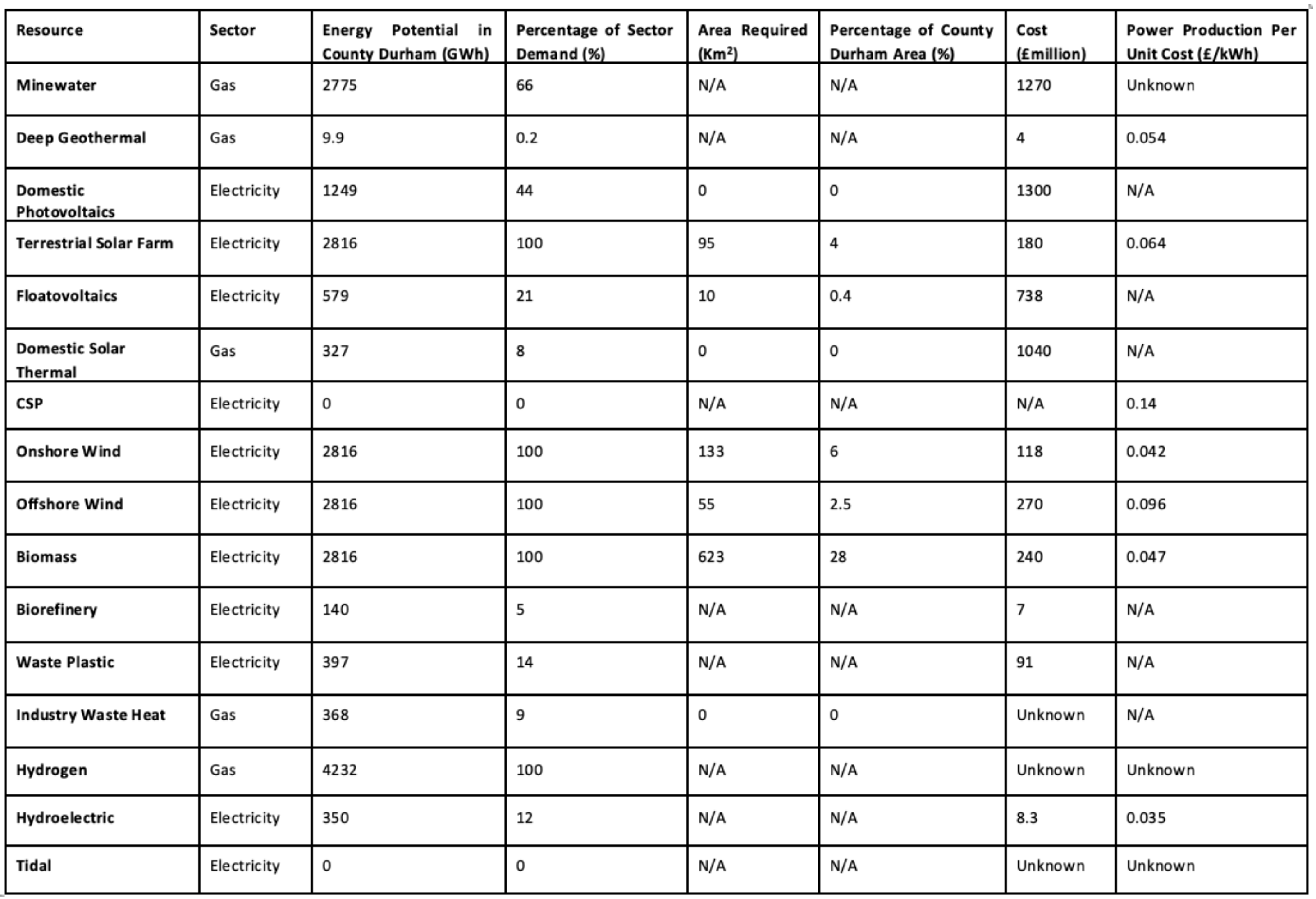
SeaGen was the world's first commercial scale tidal turbine. The system was developed by marine current turbines (MCT) and was commissioned in Strangford Lough, NI in 2008. The £12 million project had 1.2 MW capacity which was predicted to power 1,500 homes annually (Power Technology 2020). Although Strangford Lough is regarded as a tidal 'hotspot' In the UK the system began decommissioning in 2016 after the project completed its lifecycle according to CEO Tim Cornelius 2019.

2.10.7 Conclusions

Tidal energy uses the rise and fall of ocean tides to turn a turbine and create electricity (IRENA 2014). It is low carbon and renewable as greenhouse gas emission is only associated with the construction of the project (Green Match 2020). Furthermore, because tides are cyclical, tidal energy is a very predictable energy source (Student Energy 2015). Although, the varying energy demands of the population do not always match these cycles, therefore a storage mechanism would be required to increase efficiency. Currently, there are two methods to generate tidal electrical energy, tidal range and tidal current (IRENA 2014). Both are dependent on the tidal difference which must be a minimum of 5 m (Student Energy 2015). Consequently, tidal energy is typically restricted to constricted coastal areas and estuaries. County Durham has a low potential for tidal energy due to a lack of suitable locations and small tidal ranges. Further study and advancements in the technology are required so it can be applied to more locations.

Chapter 3 – Discussion

This chapter will compare each low carbon sustainable resource with each other and will consider how effective each resource could be specific to each energy sector of County Durham. Methods of decarbonisation and potential energy scenarios will be discussed using the analysis of each resource outlined in Chapter 2.



Resource	Sector	Energy Potential in County Durham (GWh)	Percentage of Sector Demand (%)	Area Required (Km^2)	Percentage of County Durham Area (%)	Cost (£million)	Power Production Per Unit Cost (£/kWh)
Minewater	Gas	2775	66	N/A	N/A	1270	Unknown
Deep Geothermal	Gas	9.9	0.2	N/A	N/A	4	0.054
Domestic Photovoltaics	Electricity	1249	44	0	0	1300	N/A
Terrestrial Solar Farm	Electricity	2816	100	95	4	180	0.064
Floatovoltaics	Electricity	579	21	10	0.4	738	N/A
Domestic Solar Thermal	Gas	327	8	0	0	1040	N/A
CSP	Electricity	0	0	N/A	N/A	N/A	0.14
Onshore Wind	Electricity	2816	100	133	6	118	0.042
Offshore Wind	Electricity	2816	100	55	2.5	270	0.096
Biomass	Electricity	2816	100	623	28	240	0.047
Biorefinery	Electricity	140	5	N/A	N/A	7	N/A
Waste Plastic	Electricity	397	14	N/A	N/A	91	N/A
Industry Waste Heat	Gas	368	9	0	0	Unknown	N/A
Hydrogen	Gas	4232	100	N/A	N/A	Unknown	Unknown
Hydroelectric	Electricity	350	12	N/A	N/A	8.3	0.035
Tidal	Electricity	0	0	N/A	N/A	Unknown	Unknown

Table 3.1 – Summary table of data for each low carbon, sustainable resource.

Table 3.1 shows a summary of each low carbon sustainable resource energy potential, land use and cost. The sector column refers to which sector (Gas, Electricity or Transport) that the resource could help decarbonise. The maximum energy potential of each resource has been used when there is an absolute amount of energy that can be produced per year. When the energy potential is limited by the amount of the resource that is installed e.g. how many turbines that are installed for wind energy, an energy production value able to decarbonise the entire sector has been used.

To compare each low carbon sustainable resource with each other, and to discuss what range of resources can help County Durham achieve its goal in becoming carbon neutral in respect to energy provision by 2050, comparisons should be centred around the decarbonisation of each sector. As shown in Table 3.1, each resource can be used to decarbonise either heating, electricity or the transport sector. In order for County Durham to achieve their goal, methods that County Durham could use have also been discussed and compared.

To decrease the demand on low carbon sustainable resources, methods that County Durham could reduce the energy demand have been outlined below.

3.1 Reducing Energy Demand

Reducing the energy demand of the county, would also decrease the strain on energy production from low carbon resources.

A reduction in energy demand could emanate from changes in policy for example, initiating incentive schemes for domestic energy resource. Making improvements to public transport could improve overall sustainability and increase service usage. Changing public perception and behaviour through education of energy efficiency, could also be initiated.

Some steps have already been taken in County Durham to improve the efficiency of homes/buildings which could significantly reduce the energy demand of County Durham. A well-insulated home typically uses 25% less energy than an uninsulated one (SWIi, Undated). The SWIi project receives funding from Durham County Council, Durham University, and the European Regional Development Fund, to install advanced solid wall insulation in >200 properties across County Durham. Each property taking part in the scheme, will also receive a ‘next phase’ domestic smart meter, and peer to peer community energy efficiency advice and support. Durham University Energy Institute will be monitoring the households to demonstrate the effectiveness of SWI.

In addition, incentive schemes for residents to install domestic resources, such as solar thermal systems and photovoltaics, should be implemented.

Finally, as predicted by National grid ESO (2020), a network of recharging points throughout the county is required to support the increase in demand for electric vehicles (EV).

3.2 Heat Sector Resource Comparison

Domestic and industrial heat within County Durham is supplied currently by burning fossil fuels (gas, oil, coal) directly within buildings or it is used to generate electricity. This has an energy demand of 4232 GWh annually. The options identified in this study that could be used to displace fossil fuels in this sector are, mine water energy, deep geothermal energy, domestic solar thermal systems, industry waste heat, and hydrogen. The potential of each resource and possible scenarios that could be used for decarbonising County Durham's heat sector by 2050, are discussed below.

3.2.1 Mine Water Energy

County Durham has a large resource of mine water energy due to its coal mining history. Coal mines that have flooded with what is now geothermally warmed water, can now provide the potential energy source to heat the equivalent of 91% of the homes in County Durham (2775 GWh_{TH}; Table 3.1). Production of mine water energy has a small surface land use, relative to other resources, due to its geothermal nature (Table 3.1). Mine water is low in temperature, with fluids tested to be 12 °C to above 20 °C (Gluyas et al 2018). Therefore, the returning fluids will require an additional increase in temperature to directly heat most existing homes. Consequently, domestic heat pumps are likely to be required in conjunction with mine water energy. Heat pumps require electricity, although for every kW of electricity required, heat pumps will produce 3-4 kW of heat (Adams et al 2017). Operation and maintenance challenges exist in a mine water system, with the production of (iron) ochre (Adams et al 2019). An open-loop pressurised system is favourable as this excludes atmospheric oxygen from the system, preventing iron oxidisation from occurring. Finally, a limitation of mine water energy in County Durham is the proximity to the mine that the end user must be. The end user must be located less than 1 km away from the mine (Adams, Personal Communication, 2019).

Consequently, the 91% energy value is unlikely to be achieved because some homes in County Durham are not located within 1 km of a mine. Gluyas et al, (2020) states that out of 2.6 million people in the North East of England, two million live above previously mined areas.

3.2.2 Deep Geothermal Energy

A large source of deep geothermal energy in County Durham is the Weardale Granite (9.9 GWh_{TH}). Previously drilled boreholes used to test the geothermal fluid temperature from the Weardale Granite, returned fluids with a recorded temperature of 27 °C. Due to low geothermal temperatures, this resource is likely to only have the capacity to heat homes within local proximity. Furthermore, there are issues surrounding the permeability of the Weardale Granite. A well that was drilled at Eastgate 2, recorded no fluid flow. The permeability was assumed to only be associated with the bounding fault of the Slit Vein (Hirst 2012). A well drilled at Newcastle Science Central targeted the Ninety-Fathom fault, and incurred no fluid flow for reasons which are still unknown (Younger et al 2016) Further research is needed before this resource can be considered for partial decarbonisation of the heating sector within County Durham.

Decarbonisation of domestic gas is limited to a maximum of 2784.9 GWh using mine water energy and deep geothermal energy. This does not account for how many homes would not be able to make use of these resources. If the Weardale Granite allows for heat extraction due to the permeability issues as well as any non-technical factor, this may stop the resource from being used. Consequently, another low carbon sustainable heat source would be required in conjunction with mine water energy or as an alternative.

3.2.3 Domestic Solar Thermal

Domestic solar thermal systems have the potential to annually heat up to 40-60% of a County Durham homes hot water supply (Vourvoulias 2020). If all the homes in County Durham installed domestic solar thermal systems, 327 GWh of energy would be produced annually (Table 3.1). To install domestic solar thermal systems would require an average investment of £4,500 by the homeowner (Renewable Energy Hub 2020). In addition, an average of 1 m^2 solar collector is required per person living in the home (Vourvoulias 2020). The home must also have either a conventional boiler or a combination boiler, which is not dependent upon a hot water tank, to facilitate the installation of a domestic solar thermal system (Vourvoulias 2020). Not all homes currently have the specific requirements to support the installation of domestic solar thermal systems. To increase the number of installations of domestic solar thermal systems, further investigation is required into the incentive schemes that could be initiated by local and/or national government.

3.2.4 Industry Waste Heat

To decarbonise fossil fuels used throughout industry in County Durham (1227.28 GWh), industry waste heat could be used. Waste heat has a maximum potential to produce 368 GWh across all industry within County Durham. Albert et al (2020) calculated that UK industry had a 30% efficiency value in terms of waste heat. However, this was calculated from a 3% response rate from industry, therefore limiting the specificity to County Durham. For waste heat from industry to be used throughout County Durham, further investigation is required to understand the specific waste heat from individual industries in County Durham to calculate a more accurate figure for energy potential.

3.2.5 Hydrogen

Hydrogen can potentially decarbonise a large proportion of the heating sector in County Durham. Hydrogen could be supplied through the current gas networks once the distribution pipelines have been replaced by polyethene alternatives, which is set to be achieved by 2030 (Enviro Tech 2019). Traditional heating boilers would also have to be modified (Fraser-Nash Consultancy 2018). The current method of production for hydrogen at the scale required has associated carbon emissions, from the gas reformation of fossil fuels. Development of carbon capture and storage would be needed to use this method to decarbonise the heating sector. Alternatively, large-scale production from electrolysis of water, using electricity produced from low carbon sources could be developed. County Durham may have potential for geological storage of hydrogen in salt dissolution caverns associated with the Permian Zechstein evaporite deposits named the Billingham Anhydrite Formation and the Boulby Halite Formation. Further study is required on County Durham's Permian Zechstein evaporite deposits to understand the scale at which hydrogen could be stored.

3.2.6 Heat Sector Decarbonisation Scenarios

Without consideration of the non-technical aspects of these resources, County Durham could take the following approach to decarbonise the gas sector. Firstly, energy demand reduction methods should be implemented such as home efficiency improvements, similar to the SWIi project in County Durham (Section 3.1). This would decrease the strain on low carbon resources which may have an economic and land use impact. Further study could be undertaken to understand what exact proportion of the homes in County Durham could be heated by mine water energy, understanding where mine water could not be used. Depending on the proportion of homes that are suitable, mine water could be implemented where possible in conjunction with the use of domestic heat pumps. During this time incentive schemes supported by local/national government for domestic solar thermal systems could be initiated. Gas networks / domestic heating boilers could be repurposed to a hydrogen system. In addition, the production and storage method of hydrogen could be optimised to be a carbon neutral process by including associated carbon capture and storage methods or developing electrolysis production of hydrogen at scale. Hydrogen could be used to decarbonise the remaining areas of the county where mine water cannot be used. Assuming that mine water and domestic solar thermal resources could be used at their maximum capacity (2775 GWh & 327 GWh), County Durham's heat sector demand could be met by the following approximate proportions (Figure 3.1).

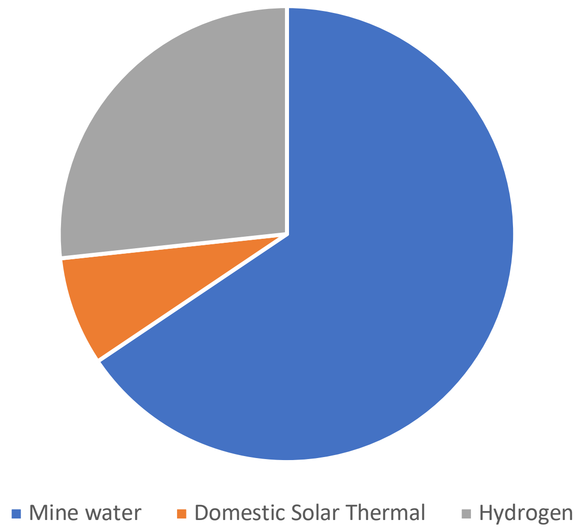


Figure 3.1 – Pie chart demonstrating a potential low carbon sustainable energy mix to decarbonise the heating sector in County Durham. This assumes that the maximum mine water energy and domestic solar thermal systems energy potential could be used.

Another scenario should attempt to demonstrate the potential energy mix, considering the potential number of buildings that could not be heated from mine water energy, due to proximity to the source. Using the equation of 2 million out of 2.6 million (76%) people live above mines in North East England, 76% of mine water's energy potential has been assumed to be available for the purpose of this scenario (Gluyas et al 2020). In addition, because not all homes in County Durham have appropriate roof orientations, roof size, or compatible boilers, a more realistic value for the number of installations of domestic solar thermal systems has been assumed to be 82 GWh based upon 25% of the homes in County Durham having domestic solar thermal systems installed (Figure 3.2)

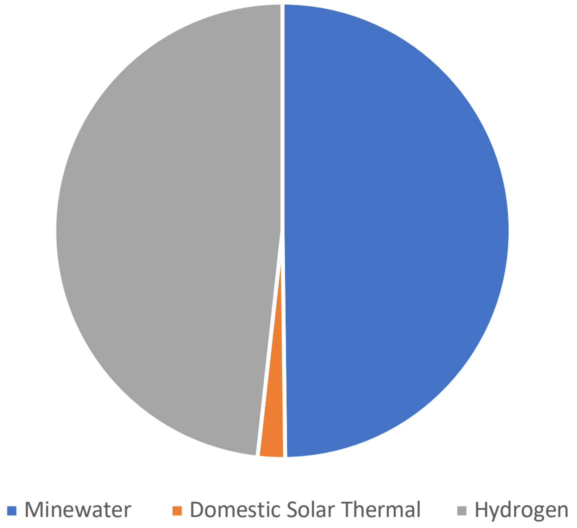


Figure 3.2 – Pie chart demonstrating a potential low carbon sustainable energy mix to decarbonise the heating sector in County Durham. This assumes a 76% resource use of mine water energy and that 25% of the homes in County Durham had domestic solar thermal systems installed.

If mine water energy is not implemented, the gas sector would require either electrification, or repurposing to a full hydrogen system (Figure 3.3) or a combination of both (Figure 3.4). Electrification of the system would place greater demand on other low carbon resources which will become clear in section 3.3; that adding a larger dependency will significantly increase the difficulty of the change.

The Committee on Climate change (2018) stated that for gas networks to be repurposed to hydrogen, decisions will be required now to allow for the wholesale switch to hydrogen for heating. This would be difficult to deliver regardless of the hydrogen production method used. The relatively short timeframe for this to be achieved is unlikely for such a large change due to county wide gas pipework, domestic boiler repurposes, a lack of storage and no low carbon method of production at the scale required. Whereas mine water energy and domestic solar thermal systems, could be implemented immediately.

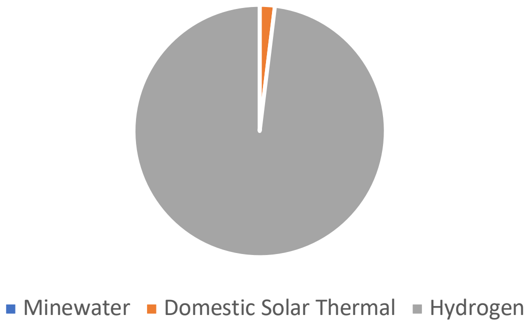


Figure 3.3 – Pie chart demonstrating a potential low carbon sustainable energy mix to decarbonise the heating sector in County Durham. This scenario is based on not using mine water energy and that 25% of the homes in County Durham had domestic solar thermal systems installed. Decarbonisation comes from a full hydrogen system.

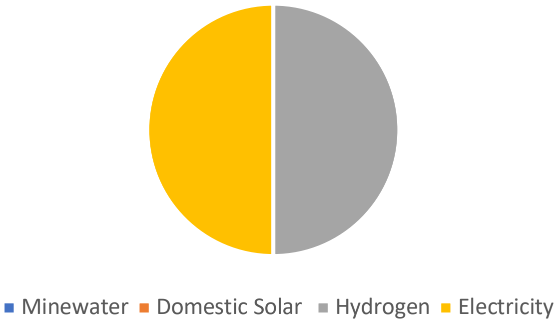


Figure 3.4 – Pie chart demonstrating a potential low carbon sustainable energy mix to decarbonise the heating sector in County Durham. This scenario is based on not using mine water energy and that 25% of the homes in County Durham had domestic solar thermal systems installed. Decarbonisation comes from a 50% hydrogen and 50% electrified system.

Figure 3.5 shows a ternary diagram of the low carbon sustainable resources that could be used to decarbonise the heating sector in County Durham. The lines marked, indicate the maximum proportion of heating energy mix, mine water energy, and domestic solar thermal could technically provide County Durham. The area marked in yellow, indicates the range of energy mixes which can decarbonise the heating sector in County Durham. This diagram also assumes no limit on hydrogen supply.

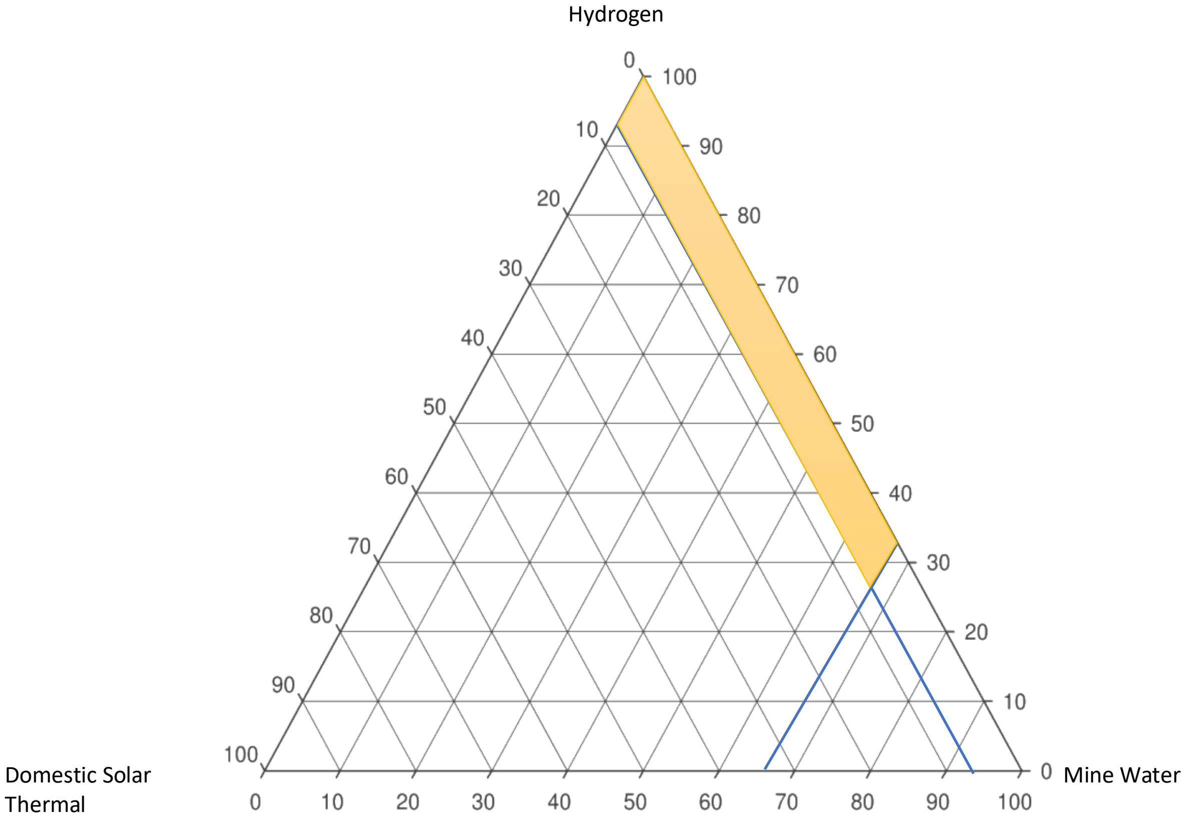


Figure 3.5 – Ternary diagram of low carbon sustainable resources for heat in County Durham. Area marked in yellow shows range of energy mixes that are able to decarbonise the heating sector.

3.3 Transport Sector Resource Comparison

Chapter 2 showed that apart from electric vehicles, only biofuels and hydrogen are potential low carbon alternative transport fuels that are available to decarbonise the transport sector, but both have many limitations.

3.3.1 Biofuels

Using biodiesel in vehicles currently requires blending with other petroleum fuels, which causes greenhouse gas emissions and also requires vehicle engine modifications to be applied (Royal Botanic Gardens 2010). Bioethanol requires only minimal engine modifications and does not require blending with any other petroleum fuels. However growing crops for energy has an efficiency of 0.5 w/m^2 (MacKay 2013). Consequently, growing crops for biofuels is not viable to decarbonise the transport sector in County Durham, due to the land that the resource requires.

3.3.2 Algae

Algae can be grown in seawater allowing production to occur offshore, removing the issue of land use. Rajkumar (2013) stated that algae were the most effective raw material for biofuels. An offshore space of 87 million m^2 would be required by algae to decarbonise the transport sector in County Durham. This size of offshore space for algae is calculated to require an investment of ~£639 million (Briggs 2010). Although it is likely that costs would have changed since this study as technological advancements are made. With a lack of large-scale algae projects worldwide the resource is relatively immature compared with other low carbon technologies. Therefore, it is unlikely that algae could support the large-scale transition to a low carbon transport sector.

3.3.3 Hydrogen

Hydrogen has many advantages for being used as a transport fuel. On average per tank a hydrogen fuelled vehicle has a range of ~483 km (Hydrogen Hub 2020). Hydrogen fuelled vehicles have an average refuelling time of 3-5 minutes, compared with a typical electric vehicle (EV) which has a refuelling time of ~1-28 hours (Pod Point 2020).

Hydrogen's low weight, compared to other fuel types, can make it beneficial for HGV's and ships, as it increases the payload volume which can be carried, consequently increasing commercial efficiency (Committee on Climate Change 2018). Currently, there is a lack of hydrogen refuelling stations across the UK, for all types of vehicle. In addition, the UK is set to move toward the electrification of transport. The National Grid EDO (2020) calculates that 80% of homes will have an electric vehicle charger by 2050. For hydrogen to be used as a future transport fuel, rapid development and installation of refuelling stations is required in addition to the method of production outlined in section 3.2.5.

Due to biofuel and hydrogen's relative impracticality to be used as transport resources, as well as the UK's trend towards electric vehicles, the transport sector in County Durham is likely to require electrification.

3.4 Electricity Sector Resource Comparison

With the transport sector requiring electrification, 6281 GWh of energy per year must be produced from low carbon sustainable resources, to decarbonise both the transport and electricity sector in County Durham. Currently in County Durham, 515.58 GWh of energy is produced annually from low carbon resources (Figure 1.19). Thus 5765.32 GWh, is required from new low carbon sustainable resources.

3.4.1 Domestic Photovoltaics

Each installation of domestic photovoltaics within County Durham, produced an average of 5.4 MWh in 2017 (DCC 2019). The average energy demand per home in 2017 across the county was 3.4 MWh (DCC 2019). Consequently, when photovoltaics was installed, they produced on average 2 MWh more than the homes energy demand. If all the homes in County Durham had photovoltaic panels installed, 1249 GWh would be produced. Currently, installation of photovoltaic panels requires an investment of ~£6,000 by the homeowner (Green Match 2020). Due to a possible lack of enticing incentive schemes, < 4% of the homes in County Durham have photovoltaics installed (DCC 2019). Further study is required, investigating what incentive schemes would be most effective in County Durham for both the public and the government.

3.4.2 Terrestrial Solar Farms

Terrestrial solar farms produce electricity at ~3.4 w/m^2 efficiency using data from County Durham's Tanfield Lea Solar Farm. At this efficiency, to produce 5765.32 GWh of electricity, 193 km^2 of solar farms are required, equating to 2757 same size projects as Tanfield Lea. Using a 0.064 £/KWh power production per unit cost value (Table 3.1), this project would cost ~£368 million (IRENA 2018). Consequently, it is not viable to decarbonise both County Durham's electricity and transport sector from terrestrial solar farms alone.

3.4.3 Floatovoltaics

A UK case study shows floatovoltaics installed on Godley Reservoir in Manchester, produces electricity at an efficiency of 6.8 w/m^2 (Environmental technologies 2015). Due to both Manchester and County Durham sharing similar solar insolation values, an assumption has been made that if floatovoltaics were installed in County Durham, 6.8 w/m^2 efficiency could be achieved. If all the reservoirs in County Durham had floatovoltaics installed, ~579 GWh of electricity could be produced. Due to the relative immaturity of the technology, costs are high. Using the same cost per unit production as the floatovoltaics installed on Godley Reservoir, Manchester, an investment of ~£738 million is required to install floatovoltaics on all the reservoirs in County Durham (Environmental Technologies 2015). Although further study is required, as the lack of economic data is a clear constraint that limits the accuracy of the economic projection for this resource.

3.4.4 Concentrated Solar Power (CSP)

Concentrated Solar Power (CSP) requires high solar insolation values. IRENA (2012) stated that CSP projects were uneconomical when solar insolation is <5.5 KWh/m^2/day. County Durham receives ~3.3 KWh/m^2/day, making this resource not viable economically for the county (Weather Spark 2020). However, further study should be taken to understand current costs, as CSP has decreased by 46% in price, since 2010 (IRENA 2018). Although it should be recognised that this 2018 study was based upon projects in high solar insolation locations, such as, China, Morocco, and South Africa.

3.4.5 Biomass

Growing crops for electricity in County Durham demand high land usage. Biomass produces energy at an efficiency of 0.5 w/m^2 (MacKay 2013). Although, efficiencies may have increased since this 2013 study and so further study is required to understand the exact efficiency specific to County Durham. Due to the energy demand of County Durham being 0.53 w/m^2 , growing crops for energy would not be viable because of the land constraints in County Durham (DCC 2019). An alternative option would be to import biomass from overseas, however this has high levels of embedded carbon from transportation of the biomass.

3.4.6 Biorefinery

Biorefineries could use waste biomass from farmers or industry, known as opportunistic biomass. Bothwell, Personal Communication (2020), stated that a single biorefinery could provide between 5-10 % of the county's electricity demand, and several hundred thousand kg's of industrial materials to replace petroleum-based ones.

3.4.7 Hydroelectric Energy

Due to velocity varying throughout the length of a river, and specific site location data being unknown, this study was unable to calculate the number of hydropower schemes that could be installed in County Durham. Although, County Durham has 17 rivers with the two largest (River Wear & River Tees) having a combined length of ~235 km. County Durham has a 100-kW hydropower scheme located at Freemans Reach, Durham City Centre (Renewables First 2016). The British Hydropower Association (BHA), calculated that the North East of England, possesses the potential siting for 318 small scale hydropower schemes, generating ~27- 40 MW. Further study is required to understand County Durham's specific potential using specific site river studies. Using the power production per unit cost data in Figure 3.1, 27 - 40 MW would require an investment cost of ~£8.3 – 12.2 million.

3.4.8 Tidal Energy

Tidal energy is dependent upon specific geographic characteristics such as, a tidal difference of more than 5 m, minimum depth of 15 m to support the installation of equipment and a current velocity greater than 2 m/s (Student Energy 2015). Areas of constricted land, such as channels and estuaries, are typically more suitable for tidal energy (Student Energy 2015). County Durham has no ongoing tidal energy projects possibly due to a lack of suitable site locations, or a lack of research. Until further field study is carried out to understand if County Durham has any suitable locations for tidal energy, the resource has limited potential in decarbonising the electricity and transport sector. Potential sites which could be explored include Seaham Harbour, and the estuaries of the River Tyne, Wear and Tees.

3.4.9 Waste

Waste in the form of plastic or sewage can be processed to generate electricity. County Durham sends ~195 million kg of plastic waste to landfill annually (DCC 2019). Using plastic to energy power stations, 195 million kg of plastic waste would generate 397 GWh/yr of electricity. Plastic power stations are limited in the amount of plastic they can convert daily. To make use of County Durham's entire waste plastic resource, 13 similar sized power stations to powerhouse energy would be required. The process also has associated greenhouse gas emissions, making it less suitable for County Durham. In addition, the average sewage plant in County Durham produces 331 MWh each year, although this is likely to be less than what is required to run the sewage plant itself (DCC 2019). Microbial electrolysis cell (MEC) technology has shown to produce 0.6 – 3 l/day of 99% pure hydrogen (Cotterill 2016). This technology is untested on a large scale but should be investigated further if a hybrid hydrogen system is to be employed in County Durham (Cotterill 2016).

3.4.10 Wind Energy

The energy potential from wind energy, is determined mainly by the wind speed that is present. For wind turbine blades to rotate, wind speed needs to be greater than 4 m/s (EWEA 2020). The electricity generated by the turbine increases as wind speed increases, until it has reached an optimum wind speed of ~14 m/s (EWEA 2020). For safety reasons, turbines will fail to work in wind speeds greater than 25 m/s (EWEA 2020). Using wind gradient calculations, it was calculated that wind turbines sited in County Durham will experience wind speeds between

~12.5 m/s and 16.5 m/s. Based on wind speed alone, County Durham's geographical location is advantageous for wind energy. This is demonstrated by the average onshore wind turbine in County Durham generating 5275 MWh of electricity during 2017, which is 19 MWh higher than the national average (DCC 2019). Assuming this production value can be replicated with future wind turbines in County Durham, the county would require 1092 new onshore wind turbines to decarbonise both the electricity and transport sector in County Durham. 1092 wind turbines would require ~263 km^2 of land space assuming an efficiency of 2.5 w/m^2 (MacKay 2013). Wind energy efficiencies are likely to have increased since the MacKay 2013 study, and so further study should be undertaken to determine the current efficiency specific to County Durham.

The average offshore wind turbine produces 12,929.76 MWh annually. To produce enough electricity to decarbonise both the transport and electricity sector in County Durham, 445 offshore turbines would be needed, across ~112 km^2 of offshore space.

Although offshore wind turbines are more efficient and require no onshore land space, they are economically more expensive than onshore wind turbines (Table 3.1; IRENA 2018). The number of onshore or offshore wind turbines required to decarbonise both the electricity and the transport sector, would require an investment of ~£242 million or ~£553 million respectively (Table 3.1; IRENA 2018).

3.4.11 Electricity and Transport Sector Decarbonisation Scenarios

To decarbonise both the transport and electricity sector in County Durham, a mix of low carbon sustainable resources are required, as the energy demand is too high to be solely generated by one resource. To implement these resources, decisions must be made on which aspects need to be prioritised for example, land, investment, or efficiency.

County Durham has a low potential for concentrated solar power, biomass and tidal energy. Hydroelectric power cannot be directly quantified and requires site specific research before an energy potential can be calculated. Furthermore, plastic waste to electricity power stations currently have associated greenhouse gas emissions, thereby requiring further development to be carbon neutral.

Photovoltaics, wind energy and a biorefinery, all have the potential to significantly contribute to the decarbonisation of County Durham’s transport and electricity sector.
The energy potential from domestic photovoltaics is dependent upon how many homes have installed the resource. For calculation purposes, assuming all the homes in County Durham had PV installed, the resource has a maximum energy potential of 1249 GWh. To make this possible, further research is required into what incentive schemes could be initiated in County Durham to support this scale of installation. Floatovoltaics are dependent upon how many reservoirs the resource is implemented on, but the resource has a maximum energy potential of ~579 GWh. A biorefinery located in County Durham would have an energy potential of ~140 GWh. It is dependent upon the volume of opportunistic biomass that is available and how many biorefineries would be implemented. If all three of these resources were implemented in County Durham, 1968 GWh of electricity would be produced annually. Consequently, 3797 GWh must be decarbonised via a mixture of terrestrial solar farms, onshore wind energy, and offshore wind energy, which all have individual advantages and limitations.

Offshore wind energy has the highest efficiency and requires no land space, although, it is the most expensive. Terrestrial solar farms are more expensive than onshore wind energy but generate electricity at a high efficiency and subsequently require less land. Although, the onshore wind energy efficiency value was calculated in 2013 and therefore is likely to have increased, making onshore wind energy more effective in County Durham.

If County Durham prioritised land space, 294 offshore wind turbines would be required to produce 3797 GWh, requiring an investment of ~£364 million.

To produce 3797 GWh requiring the smallest investment, would cost ~£159 million and would need ~720 onshore wind turbines equating to ~173 km^2 of land (~8% of the landmass of County Durham).

Figure 3.6 shows a potential energy mix County Durham could use to decarbonise the electricity and transport sector.

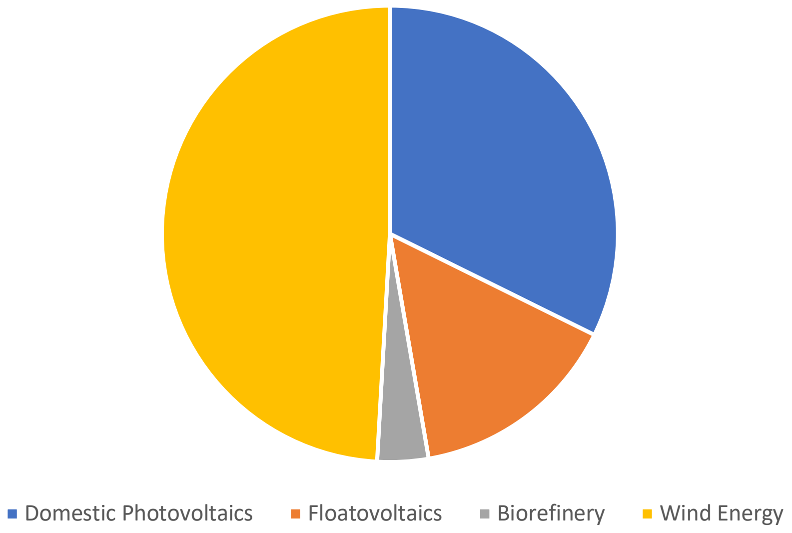


Figure 3.6 – Pie chart demonstrating a potential low carbon sustainable energy mix to decarbonise the electricity and transport sector in County Durham. This scenario is based on domestic photovoltaics, floatovoltaics and a biorefinery to be used to their maximum capacity. The remaining energy demand is produced by wind energy.

A 50% mixture of both onshore and offshore could produce 3797 GWh of electricity, using 359 onshore turbines combined with 147 offshore turbines. This would require 87 km^2 of onshore land space, and 37 km^2 of offshore space, with a total investment of ~£262 million (Figure 3.7).

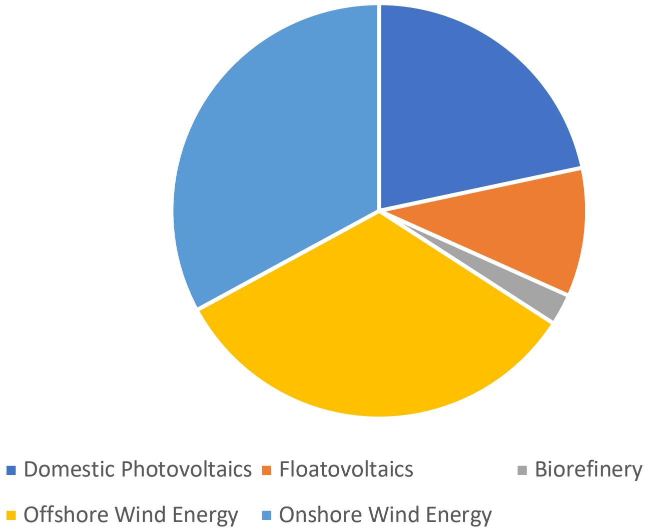


Figure 3.7 – Pie chart demonstrating a potential low carbon sustainable energy mix to decarbonise the electricity and transport sector in County Durham. This scenario is based on domestic photovoltaics, floatovoltaics and a biorefinery to be used to their maximum capacity. The remaining energy demand is produced a mixture of offshore and onshore wind energy.

Another scenario should also be based upon the energy mix required if no more domestic photovoltaics were installed and floatovoltaics were not used. This could occur due to the current lack of incentivisation in domestic photovoltaics and the high cost of floatovoltaics. Figure 3.8 shows that without the installation of domestic photovoltaics and floatovoltaics 5580 GWh per year must be produced through wind energy. To generate this amount of electricity, 528 onshore turbines requiring 127 km^2 of land use combined with 216 offshore turbines that require 53 km^2 of offshore space, would be needed. The cost of investment of this wind energy would be ~£385 million.

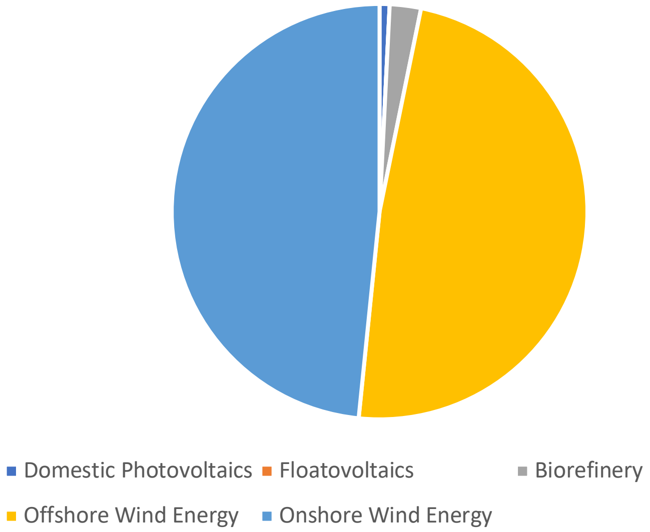


Figure 3.8 – Pie chart demonstrating a potential low carbon sustainable energy mix to decarbonise the electricity and transport sector in County Durham. This scenario is based on no further installation of domestic photovoltaics and no installation of floatovoltaics. The remaining energy demand is produced a mixture of offshore and onshore wind energy.

3.5 Progression of Study

It is important to understand what the major limitations of this study were, to promote further research opportunities to help the county achieve its decarbonisation goals.

A key limitation of this study was due to the emissions and energy demand being based upon data from 2015. Due to the downward trend in emissions of the UK national grid, these figures presented are likely have decreased by the time of publication and will continue to decrease into the future. In addition, algorithms used to convert CO_2 equivalent values were not available to audit purposes. Therefore, an area for further study would be to continually update the energy and emissions data used in this study which then may impact which low carbon sustainable resources are more/less beneficial for County Durham.

Much of the land use data used for resources originated from MacKay 2013. Further study should be taken to understand the current land use efficiencies of resources.

This study provides a technical evaluation of possibilities and options available. Non-technical aspects including funding, governance, legislation, policy, planning and market opportunities, have not been explored. An evaluation of the non-technical aspects would be beneficial.

Some low carbon sustainable resources such as nuclear energy, have not been investigated in this study, as it does not make use of any characteristic specific to County Durham, which was what this study set out to achieve. However, nuclear energy is likely to play a role in the UK's decarbonisation strategy and therefore requires further research into how nuclear energy could be implemented in County Durham.

Due to the privacy of economic data in most private low carbon projects, there is a lack of economic data to base conclusions on specific to County Durham. A separate investigation is required to understand the true economics for each technology within County Durham, working alongside potential industry partners.

Progression of this study could include the land use data provided throughout this study. Modelling where low carbon resources could be installed in County Durham.

Consideration should be given to a human society research project being undertaken, to hypothesise and provide evidence which domestic home efficiency initiatives would gain the most interest throughout the county.

County Durham possesses the potential to become carbon neutral by 2050 using its low carbon, sustainable resource base. This discussion demonstrates the scale of that challenge excluding considering of any non-technical factors that play a vital role in implementing sustainable resources. Consequently, it is evident that reducing energy demand should first be prioritised. this will decrease the strain on low carbon resources. In addition, further study is required with many resources to realise their energy potential outlined throughout this thesis.

Chapter 4 – Conclusions

This chapter concludes the total energy production potential, land use and economics of County Durham's resource base for decarbonising the heating, electricity and transport sector in County Durham. Using the information discussed throughout this study, a potential strategy County Durham could use to become carbon neutral by 2050 using a low carbon sustainable resource base has been concluded.

4.1 Energy Production Potential

Table 3.1 shows that County Durham has a low carbon sustainable resource base which ranges from 9.9 GWh to 2,816 GWh in total for each resource. Hypothetical energy production values have been used to demonstrate the energy potential of low carbon resources where their energy potential is dependent upon the quantity that installed for example, the number of wind turbines. Figure 3.1 shows, that by using a mixture of low carbon sustainable resources it is possible for the county to meet its annual energy demand of 10,513 GWh.

County Durham's low carbon sustainable resource base produces an uneven energy mix, where many resources are able to contribute to the decarbonisation of the heating and electricity sector, but there is a lack of alternative transport fuels to decarbonise the transport sector (Figure 3.1). Sections 2.6 and 2.8 show that hydrogen and algal biofuels are currently in their infancy as major transport resources. This lack of alternative transport fuels produces the need for the transport sector to be electrified, which matches the trend shown nationally (National Grid ESO 2020).

4.2 Land Use

To maintain areas of natural beauty in County Durham and to save land for future development, resources which do not have a high land use, could be prioritised.

Growing biomass for energy, terrestrial solar farms, and onshore wind farms all have a significant surface land use (Table 3.1). Resources which are geothermal in nature, such as mine water, and deep geothermal energy, use underground geologically derived energy sources, therefore resulting in a low surface land use. In addition, resources which can be installed offshore or on bodies of water such as, floatovoltaics, hydroelectric power, algae, and offshore wind farms are advantageous in terms of land use.

Domestic resources such as photovoltaics and solar thermal systems have no land use, although, the number of installations in County Durham are currently low (DCC 2019). A potential explanation for this could be the lack of local/national governmental incentive schemes that help homeowners invest in domestic renewable technologies.

A limitation of analysing resources land use was that data for many resources was based upon data from MacKay 2013. This study may potentially not represent the current land use efficiency of resources as it is likely that efficiencies would have increased since 2013. Further study should be taken to understand the current land use efficiencies of resources, specific to County Durham.

4.3 Economics

Due to the private nature of economic data in many renewable projects, the economic data used throughout this study was limited. Consequently, a total amount of investment that County Durham would require to become carbon neutral could not be calculated. However, some conclusions can be drawn as to which resources may be preferable to County Durham's carbon natural strategy.

Low carbon sustainable resources which require significant investment to be made by homeowners reduces the total investment required from private sources and therefore should be incentivised. These include domestic photovoltaics and solar thermal systems. In County Durham currently < 4% of homes have domestic photovoltaics installed (DCC 2019). This could be due to the high initial investment to install domestic systems with a lack of incentive schemes from local/national government. Further study could be taken hypothesising what initiatives could be initiated and quantifying the proportion of homeowners which would consequently invest in domestic renewable technology.

Low carbon resources that have had time to be tested, installed and optimised such as photovoltaics and wind energy are typically lower in price per unit production (£/kWh) compared to relatively new technologies such as floatovoltaics, algae and mine water. This could impact County Durham's timing of investments. Further study could be taken considering different strategies of investment i.e. Investing first in mature resources at lower cost allowing new technologies to increase in efficiency and decrease in cost.

4.4 Decarbonising County Durham

4.4.1 Reducing Energy Demand

Reducing the energy demand of County Durham, will decrease the strain on new low carbon resources to produce energy. Reducing energy demand could come in the form a variety of sources such as policy change, improvements to public transport and behaviour change. Increasing the efficiency of homes will also reduce energy demand. The SWIi project has already been initiated in County Durham to improve the efficiency of homes/buildings. Incentive schemes for residents to install domestic resources such as solar thermal systems and photovoltaics should be implemented. Finally, as predicted by National grid ESO (2020) a network of recharging points throughout the county is required to increase the demand for electric vehicles.

4.4.2 Decarbonise Heating

County Durham has a large low carbon sustainable resource base available to decarbonise the heating sector. A mixture of mine water, domestic solar thermal systems and hydrogen can decarbonise the heating sector (Figure 3.5). When used with domestic heat pumps, mine water energy can potentially heat up to the equivalent of 91% of the homes in County Durham sustainably. However, end users are required to be within 1 km from the producing mine and so it is unlikely that 91% can be achieved (Adams, Personal communication, 2019). Initially using mine water with heat pumps would allow time for the current gas networks to be repurposed for a hybrid hydrogen network. This would then remove the issue of homes/industry which are not located less than 1 km from a producing mine. The Royal Society (Undated) stated that it is undesirable to build long lived assets which commit to emissions for decades such as gas infrastructure without CCS which ultimately becomes a stranded asset. Consequently, if hydrogen is implemented as part of the decarbonisation of gas for heating then its production method and storage should be carefully considered. However, County Durham may have the potential to store hydrogen in salt dissolution caverns formed during the Permian. Domestic solar thermal systems can provide 40-60% of a home's annual hot water supply in County Durham but currently require large scale private investment from homeowners. Incentivisation schemes should be implemented to increase the number of homes with domestic solar thermal systems installed.

4.4.3 Transport + Electricity

County Durham cannot currently produce a viable alternative transport fuel from low carbon resources at the scale required to decarbonise the transport sector. Biofuels require and land use which is too high for County Durham. Furthermore, growing crops for energy is currently uneconomical for farmers compared with food production. Algal biofuels and hydrogen are both within their infancies of being a major transport resource. However, hydrogen does have benefits if used within HGV's due to its extremely low weight but lacks research and implementation thus far (Committee on Climate Change 2020). If biofuels or hydrogen technology cannot be advanced as transport resources, then the transport sector in County Durham must be electrified which is consistent with the UK's plans as set out in the National Grid ESO 2020.

Currently 515.68 GWh is produced by sustainable low carbon resources in County Durham, thus 5,765 GWh will need to be produced from new resources to decarbonise both the transport and electricity sector in County Durham if energy demand is not reduced. The scale of this demand, assuming domestic PV (1249 GWh) floatovoltaics (579 GWh) and a Biorefinery (140 GWh) could be installed to their maximum capacity, 3,797 GWh is required to decarbonise the transport and electricity sector.

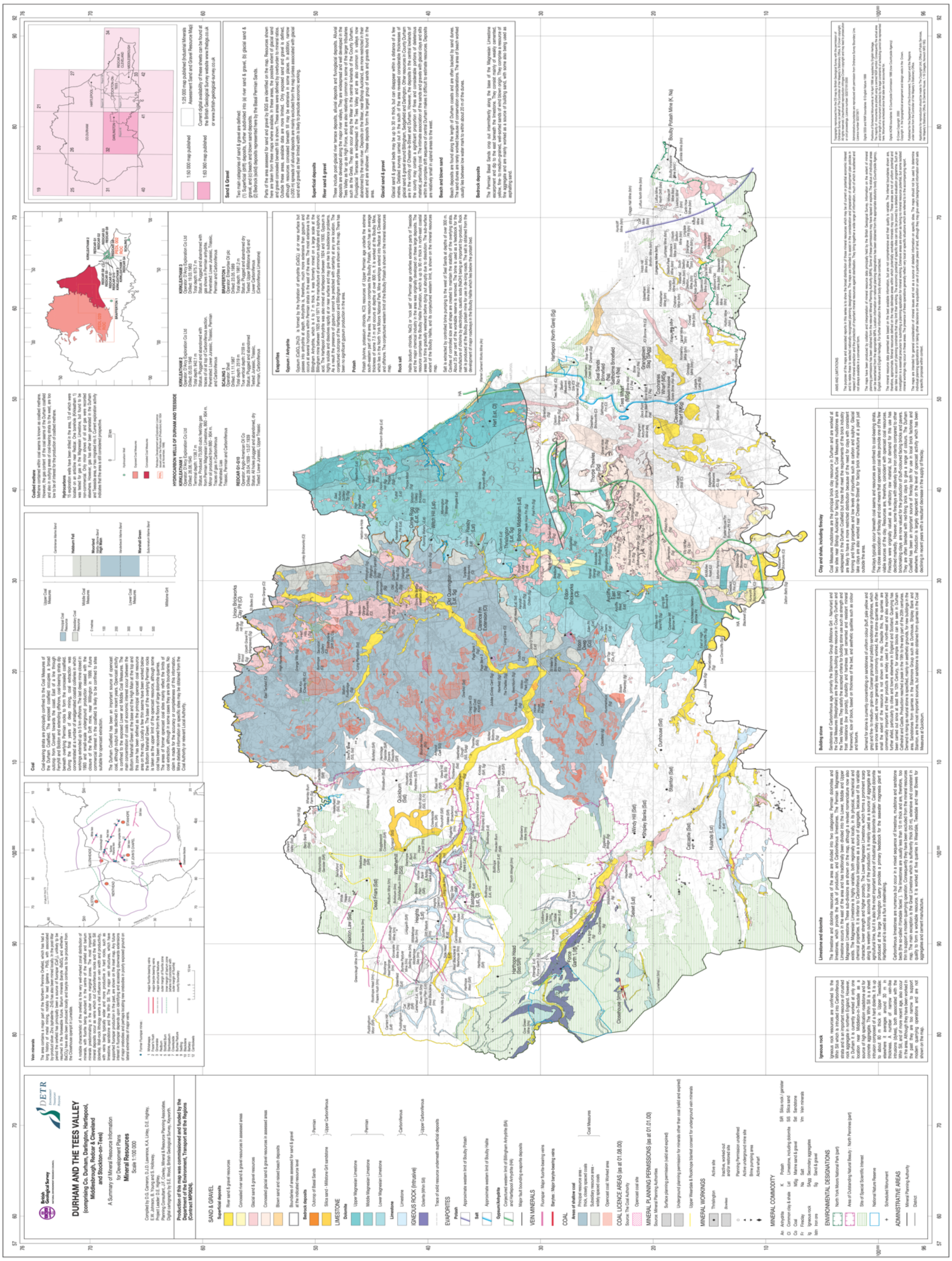
The sustainable low carbon resources which are capable of producing energy in County Durham at this scale, are wind energy and terrestrial solar farms. Terrestrial solar farms have a high price per unit production compared to onshore wind. In addition, it is expected that onshore winds efficiency has increased since MacKay 2013 where efficiencies were calculated from. Due to onshore wind farms having a high land use and many ecological and public issues, offshore wind or a mixture of both could be used. By considering both land use and economics, a mixture of both 50% onshore and 50% offshore could produce 3,797 GWh of electricity from 359 onshore turbines and 147 offshore turbines. This would require 87 km^2 of onshore land space and 37 km^2 of offshore space with a total investment of ~£262 million. By prioritising a mixture of both onshore and offshore wind energy projects, less mature technologies are given time to increase in efficiency and therefore potentially decrease in price. This scale of project would require large scale local and national investment however would not commit the county into long lived carbon emissions. A more realistic scenario, accounts for not all the homes in County Durham being able to install domestic photovoltaics and floatovoltaics not being installed due to their current high investment cost. Therefore, 5,580 GWh per year could be produced from, 528 onshore turbines requiring 127 km^2 of land, combined with 216 offshore turbines that need 53 km^2 of offshore space. The cost of investment of this wind energy would be ~£385 million.

4.6 Conclusions and Recommendations

County Durham does possess a large low carbon sustainable resource base which can support a transition to carbon neutrality by 2050. County Durham's low carbon sustainable energy resource mix favours the production of heat and electricity over alternative transport fuels. To reach carbon neutrality, County Durham should make use of its mine water energy resource with associated heat pumps whilst allowing time for gas networks to be repurposed for hydrogen and schemes to be initiated to incentivise the installation of domestic low carbon resources and home energy efficiency improvements. Due to land use, there is currently no low carbon resource which can decarbonise the transport sector through the production of alternative fuels as long as hydrogen remains within its infancy as a transport resource. Consequently, transport is required to be electrified, which matches the current UK trend. To decarbonise the remaining electricity and transport sector, emphasis should be placed firstly on reducing energy demand. Furthermore, resources which require less, or no land space should be prioritised such as floatovoltaics, and biorefinery's to preserve County Durham's areas of natural beauty and ecology. If domestic photovoltaics, floatovoltaics and a biorefinery, were all installed to their maximum capacity in County Durham, a significant energy demand still exists. This remaining energy demand can be produced by the implementation of a mix of wind energy and terrestrial solar farm projects. Although, it is likely that the current efficiency of wind energy outweighs the potential for terrestrial photovoltaics in County Durham. The mixture that is used to decarbonise the transport and electricity sectors in County Durham is dependent on which aspects are prioritised by County Durham for example land use, investment, or efficiency. In order for County Durham to become carbon neutral by 2050, large scale further research and government action is integral to make use of the county's large low carbon sustainable resource base.

Appendix

1.0 – Geological map of County Durham – Marks the extent of both the Boulby Halite and Billingham Anhydrite – Source – BGS 2000



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