From disputed fracking site to renewable energy champion: Balcombe's green transition towards the decarbonisation of residential CO_2 emissions through Community Renewable Energy both now and in the future

Dissertation is submitted in part fulfilment of the BSc in Environmental Geography, University of York

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Date: 10th June 2021

Word Count: 7,999

DECLARATION

I, Katherine Finnerty, declare that the work submitted in this dissertation is the result of my own work and investigation and all the sources I have used have been indicated by means of completed references.

Signed:

Date: 10/06/2021

Acknowledgements

Firstly, I would like to express my gratitude to my supervisor, Lisa Emberson. Her constant support and feedback have been invaluable and has really helped guide me through my dissertation. I am very grateful for her enthusiasm towards this project.

Much of this dissertation would simply not have been possible without the support of Repower Balcombe - in particular Tom Parker and Charles Metcalfe, who gave up their time to provide me with a greater insight into the community project. I appreciate their willingness to distribute my survey to their members, and answer lots of my questions! A massive thank you must go to all the villagers who gave up their time to respond to my questionnaire – I'm very grateful!

I would like to thank my parents who have been endlessly supportive and encouraging, not just during my dissertation and University career, but throughout my entire education.

ABSTRACT

The UK's acknowledgement of the global climate crisis has been manifested through a legally binding target to reach net zero emissions by 2050 across all sectors. Residential emissions, particularly heating and transport, have proven very challenging to decarbonise under the current energy framework in comparison to other sectors. Achieving carbon neutrality for households and transport has been said to require 'community involvement' and decentralisation through community-owned renewable energy projects. This study aims to establish the success of Repower Balcombe, a community-owned solar project, in decarbonising Balcombe's residential emissions, and the viability and effectiveness of such projects in the energy transition. Expansion scenarios are suggested to aid future decarbonisation. The annual household consumption of electricity, gas, oil, wood, and petrol/diesel was collected using an online questionnaire, and the annual electricity generated from the seven solar projects was established to determine the proportion of residential CO_2 emissions that are currently decarbonised by the project. Results from the questionnaire were upscaled to represent Balcombe village using dwelling type. The annual CO_2 emissions from Balcombe were 5,720,107 kg CO_2 ± 1,351,559. The results show that the current projects generate approximately 146,859 kWh yr^1 of electricity, decarbonising 4.1% of electricity emissions. Decarbonising the other fuels would require Repower Balcombe to expand by x156, assuming the government's electrification transition goes as planned. Energy produced by ground-mounted solar was found to exceed demand, and when combined with wind turbines, produced sufficient electricity to power a larger EV fleet and heat pumps. Despite the results showing potential to successfully decarbonise residential emissions, decentralised community energy is currently not viable in the UK due to unfavourable energy policy, making capital investment too high risk. However, community energy in Germany and Denmark has also shown that this method of decarbonising the residential sector can be extremely effective in practice.

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1. INTRODUCTION

The declaration of a climate emergency has rapidly spread across the world through local councils, national governments and international organisations since it was first announced in 2016 (Davidson et al., 2020). This was in response to climbing global atmospheric temperature caused by the increasing concentration of greenhouse gases (GHG) emitted from anthropogenic activities (Allen *et al*., 2018). Carbon dioxide (CO_2) is the most important of these GHGs given its high prevalence and significant anthropogenic contribution (Allen *et al.*, 2018); concentrations increased by 22% between 1980-2021 (NOAA, 2021). The worldwide combustion of fossil fuels to provide energy for a multitude of activities is the dominant driver of rising GHG concentrations, contributing 78% between 1970-2011 (Edenhofer *et al*., 2014). Rising global temperatures have pernicious implications for sea level, weather systems and ecosystems (Allen et al., 2018). Its severity is reflected in the establishment of global treaties, conventions and agreements - all of which share a common goal: to limit and reduce the rate of GHG emissions (Maizland, 2020), through acceptance and enforcement of rapid transitions across all sectors (Allen et al., 2018).

UK ENERGY MIX and POLICY

Industrialised countries such as the UK plays a considerable role in driving exponential GHG emissions. UK emissions are the fourth highest worldwide on a cumulative scale (Evans, 2020). Coal was the primary fuel source in the early 19th century, both commercially and residentially, following severe national charcoal and wood shortages in the 17th century (Nef, 1977). Coal continued to be popular in the 20th century, comprising 95% of energy consumption, given the well-established and resource rich UK coal mines. This meant coal was a cheap, accessible and secure fuel source (Warde, 2007; Fouguet and Pearson, 1998). The remaining 5% came from imported oil and gas (Warde, 2007). Security and affordability of energy supply persistently shapes UK energy policy and will continue to do so in the future, especially with the recurrent rise in energy consumption (BEIS, 2019). The 20th century saw consumption increase by 50% alongside a rise in the percentage of imported oil and gas. This was to meet the demands of growing personal vehicle ownership, the road haulage industry, and the use of natural gas to produce energy (DECC, 2009). Petroleum consumption became more widespread throughout the 20th century, and the discovery of large deposits of natural gas and petroleum in the North Sea resulted in the energy mix in 1980 becoming significantly more diverse than 100 years prior, shown in Figure 1. While fossil fuels enabled governments to meet an exponentially growing demand, concerns arose regarding atmospheric pollution, and so rising GHG emissions began to influence UK energy policy.

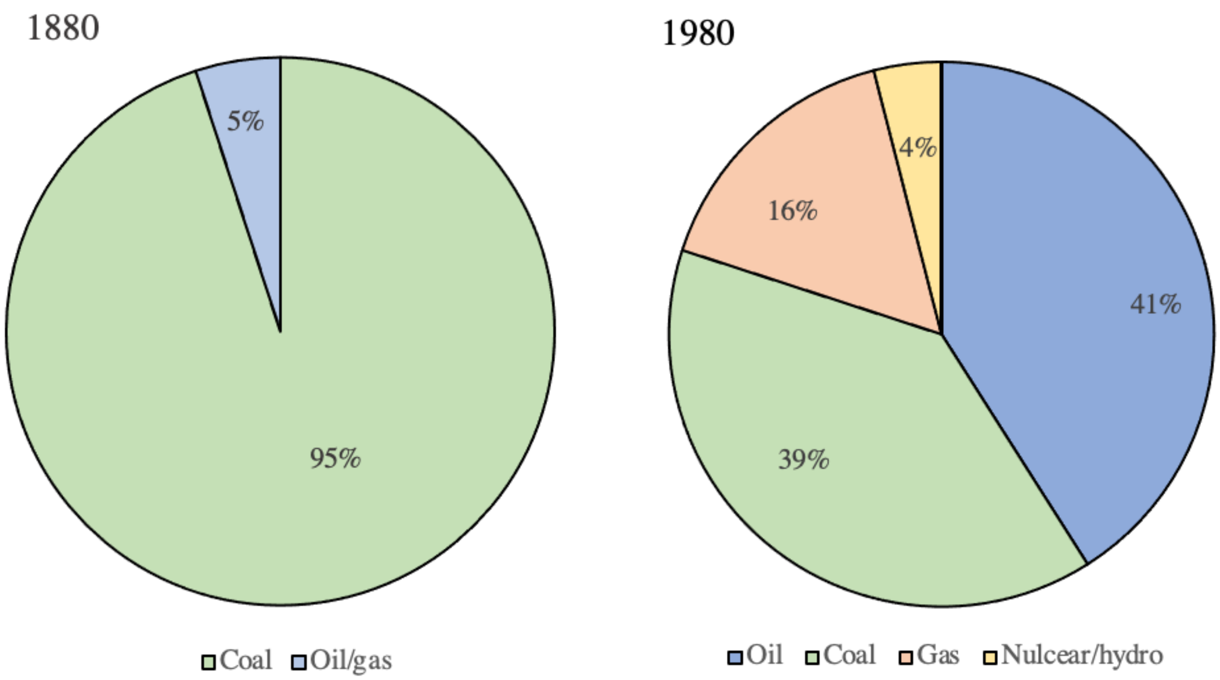

Figure 1: *Pie charts showing the percentage of fuel used in the energy mix in 1880 and 1980 (DECC, 2009)*

The detrimental environmental consequences of fossil fuel combustion were first proposed at the 1992 Rio Earth Summit, bringing the issue to international attention (Pirani, 2019), but concern over GHGs has not been the only driver in the search for alternative fuels. Deployment of renewables first emerged following the 1973 oil crisis in the Middle East which had caused price volatility oil price inflation (Mukora et al., 2008). Wave power was proposed as the solution to secure energy supply across the UK and reduce reliance on other countries (Ruiz-Minguela et al., 2020). Climate concerns now play a pivotal role in determining policy and have helped accelerate the implementation of renewables to meet legally binding carbon reduction commitments (DECC, 2011). The 1997 Kyoto Protocol called for all developed countries to limit their GHG emissions and sparked the UK to consider the penetration of renewable energies (Defra, 2006a). Exceeding the target to reduce GHG emissions by 12.5% before 2012 was driven by improvements to energy efficiencies and intensities (Defra, 2006b). Renewables such as wind, hydropower and biogas reached 6.9% in 2010, falling short of the 10% target (BEIS, 2020b). The Climate Change Act 2008 legally bound the UK to commit to 80% emission reduction by 2050 (Evans, 2016). The target increased and the UK government became the first major economy to commit to zero emissions by 2050 (CCC, 2020). Renewable implementation has rapidly increased since the declaration of these targets; in 2019, renewable energy generated 37.1% of total electricity production in the UK (BEIS, 2020b). Electrification of transport, the UK's largest GHG emission sector, is critical in achieving zero emissions, highlighting the importance of renewable electricity generation in the UK (EDF, 2019).

EMISSIONS

Energy supply (electricity generation), transport (road/railways) and residential sectors (heating/cooking) were the greatest contributors to the UK's total CO_2 emissions in 2019 (BEIS, 2020). The rising penetration of renewables and the phasing out of coal reduced UK CO_2 emissions by 39% between 1990-2018. The majority of this reduction was due to the decarbonisation of the power sector, responsible for 54% of the decline, while transport and heating sectors lagged behind at 14% and 3% respectively (BEIS, 2020). CCC (2016) states that residential emissions accounted for 40% of UK emissions in 2016, incorporating electricity, heating, transport, aviation and waste. Residential emissions have decreased by 37% between 1990-2014, but the majority is attributed to the decarbonisation of waste and electricity (CCC, 2016). Mature renewable technologies have facilitated electricity emission reduction, subsequently reducing residential lighting and appliance use emissions, whereas the decarbonisation of heating, cooking and transport continues to prove notoriously challenging (Broad *et al*., 2020). Low-carbon heating solutions do exist, but the scale of the challenge is great, and one top-down approach is not suitable for the entirety of the UK (Milne *et al*, 2019). Similarly, the transition from oil to electric vehicles (EV) is gradual given the vast number of vehicles in the current fleet (Milne *et al*, 2019). The IPCC have stated that slashing residential CO_2 emissions are essential to suppress global warming trends (Allen et al., 2018). The UK Government has accepted that drastic improvements must be made in the transport and residential sectors, but emphasis has been placed on centralised solutions - whereby a top-down approach is adopted (BEIS, 2020a). An energy transition that "involves the public" has frequently been hailed as the most effective solution (UK Parliament, 2020), and Dubois *et al*, (2019) suggest that the public should be considered key actors to reach net-zero. One method that combines clean energy generation with engagement of the public that could help to tackle tough residential emissions, is "Community Energy" (Devine-Wright and Wiersma, 2012).

COMMUNITY ENERGY

The term 'Community Energy' (CE) does not have a widely accepted and standardised definition (Braunholtz-Speight et al., 2018). CE focused papers often define the term in varying degrees of detail, viewing it as a working term due to its differing situational meanings (Brummer, 2018). Walker and Devine-Wright, (2008) acknowledged its broad meaning and identified the common underpinning principles of the term in its process and outcome dimensions. These shared dimensions indicate that CE should enable everyone in an area to openly participate, and the project should bring local and collective energy benefits. Energy projects can include the generation of electricity and heat, energy efficiency and demand reduction, and energy supply (Braunholtz-Speight *et al.*, 2018). CE is a step towards decentralisation of the energy system through a bottom-up approach (Ghornbani *et al*., 2020).

The idea of Community Renewable Energy (CRE) may be a grassroot-led innovation, but government support is essential for successful expansion, and to move away from a centralised system (Seyfang et al., 2013). The UK government has been inconsistent with their level of support for CRE over the past 20 years. In 2014 the government published a report promoting the adoption of CRE as essential to tackle climate change by reducing energy bills and promoting wider social and economic community benefits (DECC, 2014). Such support has been communicated through various publications (BEIS, 2020; DECC, 2011). The Renewable Obligation of 2002 was established to support large-scale renewable projects, and the development of the 2009 Feed-in-Tariff helped promote CRE (IEEE, 2018). In response, networks and national programmes evolved to provide guidance and fiscal support for CE (Berka, 2017). In 2019, CRE projects had a total capacity of almost 200 MW, with solar PV contributing 80% of this capacity (CCE, 2020). Research has shown that local communities reap economic and social benefits from CRE. The scheme also works by engaging the public with their household energy consumption and raises awareness about electricity generation (van der Horst, 2008). Such projects generated £4.6 million in local benefit in 2019, through cost saving, and provision of employment (CCE, 2020). The pressing issue of climate change emphasises the importance of CRE projects in meeting emission targets. CCE (2020) found that community-owned electricity in England, Wales and Northern Ireland prevented the release of 60,000 tonnes of CO_2 into the atmosphere. While this is a significant saving, the economic benefits associated with CRE are more localised and tangible, in some cases providing full-time jobs (Kumar, 2019). Indirect benefits of CRE include increasing residents' awareness of the climate issues which may change consumption behaviour (Brummer, 2018). The reduction of CO_2 emissions through CRE is difficult to quantify in the community context. CRE has economic and social benefits which are clearly visible within the community but grasping the capabilities of CRE to decarbonise residential emissions is essential to its success and sustainability.

REPOWER BALCOMBE

Repower Balcombe is a solar photovoltaics (PV) community renewable project which was established following fracking explorations at a site close to the village in 2013. The explorations sparked serious opposition and concern from 82% of local residents (Balcombe Parish Council, 2013), dividing the community. The CRE project was proposed as a means of rebuilding community spirit and repairing divisions within the village. The project's aim is, 'to generate the equivalent to

100% of Balcombe's electricity demand through community-owned and locally-generated renewable energy.' The project puts solar panels on local buildings such as farms and schools, to generate carbon-free energy input to the national grid. As seen across many CE projects, Repower Balcombe have also expanded their impact, and have begun to implement LED light bulbs in schools as an energy efficiency measure (Repower Balcombe, 2020). Furthermore, Repower Balcombe were responsible for the planning permissions of a solar farm at Chiddingly Farm, but government policy changed making investment very high risk. The solar farm was ultimately built, but by a commercial developer. Although a notable achievement, this solar farm will not be included in this study which focuses on those energy projects fully facilitated by government-funded energy policy.

KNOWLEDGE GAP

This literature review has appreciated and acknowledged previous research conducted on household emissions and the benefits of CRE. Whilst this research is key, there is a knowledge gap surrounding the effectiveness of CRE in decarbonising household emissions to help address the challenge of residential and transport emissions in the UK. Therefore, this paper seeks to bridge the gap between the two fields through an investigation into the *internal fuel consumption (IFC)* and *domestic vehicle consumption (DVC)* of Balcombe, and the decarbonisation potential of Repower Balcombe. The study also aims to consider the potential of CRE outside the confines of energy policy. This will be achieved through the following research objectives (RO):

1. To determine the CO_2 emissions associated with 1) internal fuel consumption (IFC) and 2) domestic vehicle consumption (DVC) use in Balcombe.
2. To explore the effectiveness of the Repower Balcombe solar project to generate sufficient electricity to decarbonise residential CO_2 emissions in Balcombe.
3. To calculate the degree of expansion required to fully decarbonise residential CO_2 emissions and explore potential scenarios to achieve this through the implementation of additional renewable technologies.

2. METHODS

This study aims to establish the annual *'residential CO_2 emissions'* in Balcombe (RO1), and the proportion of these emissions that are indirectly decarbonised through the generation of carbon neutral electricity by Repower Balcombe (RO2). In this study the term 'emissions' refers to CO_2 emissions. Residential emissions were determined through two parameters: 1) the *internal fuel consumption (IFC)* of electricity, gas, oil and wood used for lighting, space and water heating, cooking and appliances within the household, and 2) *domestic vehicle consumption (DVC)* of petrol/diesel for leisure and work commutes. To address RO1, the annual emissions from the consumption of each fuel was determined using Equation 1. These individual fuel emissions were totalled, using Equation 2, to give the Balcombe's annual residential emissions.

$$\underset{(\text{kg } CO_2 \text{ yr}^{-1})}{\text{Annual } CO_2 \text{ emissions}} = \underset{(\text{kWh/miles yr}^{-1})}{\text{Activity data}} \times \underset{(\text{kg } CO_2)}{\text{Fuel-specific emission factor}} \quad (1)$$

$$\underset{(\text{kg } CO_2 \text{ yr}^{-1})}{\text{Balcombe annual } CO_2 \text{ emissions}} = \underset{(\text{kg } CO_2 \text{ yr}^{-1})}{\Sigma \text{ annual } CO_2 \text{ emissions from fuels}} \quad (2)$$

To calculate the CO_2 savings from Repower Balcombe's solar projects (RO2), equation 3 was used.

$$\begin{array}{c}CO_2 \text{ savings from} \\ \text{Repower Balcombe} \\ (\text{kg } CO_2 \text{ yr}^{-1})\end{array} = \begin{array}{c}\text{Annual electricity generation} \\ \text{from solar projects (kWh)}\end{array} \times \begin{array}{c}\text{Electricity emission} \\ \text{factor (kg } CO_2)\end{array} \quad (3)$$

The annual electricity generation was secondary data, sourced from Repower Balcombe (2016), but calculating the annual emissions from the residential sector required primary data collection.

2.1. Rationale

An online questionnaire was used to collect this data, to address RO1. The questionnaire asked individual households to provide their annual IFC (electricity, gas, oil) and their DVC data, as well as general household information. Respondents were asked if wood was consumed, but exact figures were not required. An online questionnaire was used rather than focus groups or interviews as it is the most effective method of quantitative data collection whereas focus groups and interviews tend to be tailored to qualitative research (Macloed Clark et al., 1996). Additionally, this study needed a high response rate, making time-consuming interviews and focus groups unsuitable (Adams *et al*., 2008). Online questionnaires uphold respondent's anonymity - encouraging the disclosure of honest answers (Marshal, 2005), and removes the pressure to participate (Lefever *et al*., 2006). An online survey efficiently compiles the data for analysis (Wright, 2005). A pilot study of 5 known participants was conducted to check for technical errors in the questionnaire and highlighted any questions that lacked clarity (van Teijlingen and Hundley, 2002).

2.2. **Questionnaire design**

An introduction page explained the purpose of the study, informed participants of their rights regarding their involvement, and outlined how their data would be handled followed by confirmation of their consent (Subar et al., 2001). The Qualtrics questionnaire was divided into three sections: household information; fuel usage; and vehicle information. As questionnaires often yield a poor response rate, the underlying causes were identified and avoided. Multiple choice questions were used where possible, with textboxes only used where necessary as participants often skip them (Malhotra, 2006). The questionnaire was as short and concise as possible, aided through data analysis of the pilot study which identified redundant questions, and descriptions were provided to avoid confusion (Bell and Waters, 1987). The household information section was placed at the beginning of the questionnaire to ease participants in as the questions were general and straightforward to answer (Lietz., 2010). The questionnaire can be found in Appendix 1.

2.3. **Questionnaire distribution**

Given the localised scale of the study, a defined sampling strategy was not adopted. The study area is the Balcombe Parish, and its boundary is outlined in Figure 2. The Qualtrics questionnaire was distributed via the Balcombe Facebook page with 2000+ members and promoted by Repower Balcombe through an anonymous link. It was emphasised that only households with a Balcombe postcode or those that sit within the Balcombe Parish boundary should participate, and that only one member per household should respond to avoid replicated data. An overview of the respondent sample is shown in Table 1. Aerny-Perreten *et al,* (2015) found that reminders increased response rate. Therefore, two reminders were posted on the Facebook page 1 and 3 weeks after the initial post, and Repower Balcombe sent a reminder email 3 weeks after the initial email. No subsequent reminders were sent due to Lefever *et al,* (2006) finding that respondents felt aggravated after a third reminder.

Table 1: *Sample overview of households involved in the study*

House type	%	Number of bedrooms	%	Number of inhabitants	%
Detached	44	1	11	1	20
Semi-detached	38	2	11	2	33
Flat	4	3	26	3	21
Bungalow	4	4	36	4	22
Terraced	10	5	12	5	4
		6	4	6	0
Total	**100%**	**Total**	**100%**	**Total**	**100%**

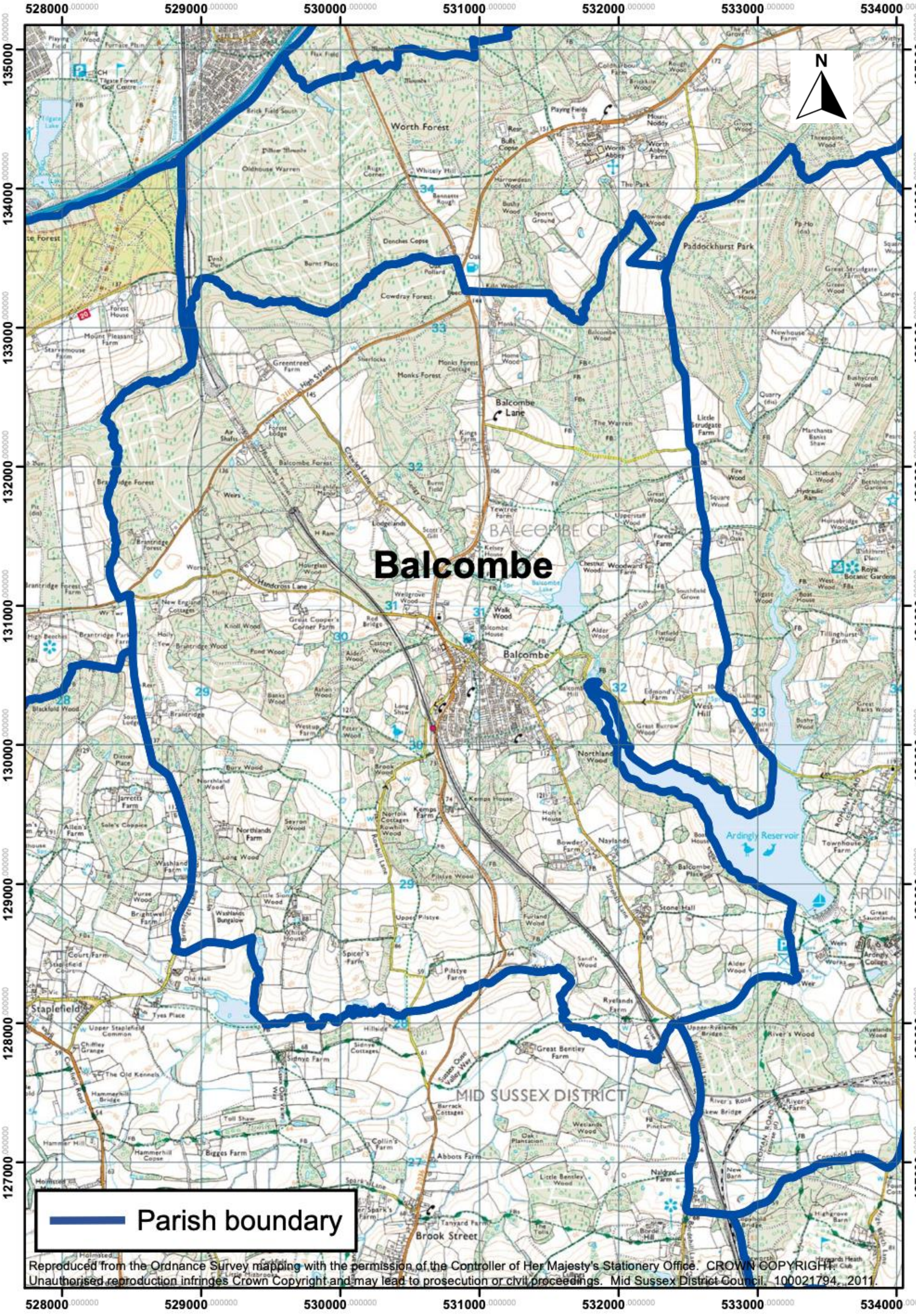

Figure 2: *Map showing the Balcombe Parish Boundary (Balcombe Parish, 2016)*

2.4. **Data analysis**

The questionnaire generated responses from 45 households, with 19 providing IFC and 31 providing DVC consumption. This study aims to investigate the whole village, so the consumption data had to be upscaled to make it representative of Balcombe.

2.5. **RO1 – Upscaling IFC and DVC, and conversion to CO_2**

2.5.1. **IFC**

Upscaling

Prior to upscaling, normality tests were conducted to ensure that the data collected from the questionnaire was a representative sample. Firstly, skewness and kurtosis values were calculated, and box-and-whisker plots identified any anomalous values which were removed. The modified datasets were statistically analysed to determine their distribution normality using a Shapiro-Wilk test. Additionally, the datasets were compared to two UK-based benchmark datasets - Firth *et al*, (2010) and Wyatt (2013) to ensure the results from this study were comparable to previous work (Table 2). Both studies investigated the IFC emissions from electricity, gas, oil and wood in households. Comparisons were made using consumption (kWh) rather than emissions to eliminate the annual variability of emission factors (EF). Once normality testing was completed, the data was upscaled.

Upscaling the data was approached using fuel and dwelling type. This was possible for electricity and gas because the questionnaire generated sufficient datasets, but oil consumption data was low and was therefore upscaled using an alternative method (see 2.1.1.2). Santin *et al*, (2009) and Wyatt, (2013) suggested that dwelling type, despite being a broad classification, is sufficient to determine a household's IFC without the need for a deeper analysis of parameters. The annual fuel consumption data from the questionnaire was broken down by dwelling type, allowing an average to be determined for each house type. The average consumption for each fuel was combined with Balcombe-specific Census 2011 data on proportions of dwelling types to give the total annual consumption for each dwelling type (kWh).

Table 2: *Benchmark values for each dwelling type for electricity and gas consumption in kWh, and associated CO_2 emissions. Note: emissions factors for electricity vary annual depending on renewable mix*

	Firth *et al*, (2010)				**Wyatt, (2013)**			
	Electricity E.f: 0.43007		**Gas** E.f: 0.19		**Electricity** E.f: 0.44238		**Gas** E.f: 0.18366	
	kWh	**kg CO_2**	**kWh**	**kg CO_2**	**kWh**	**kg CO_2**	**kWh**	**kg CO_2**
Detached	5,084	2,186	24,175	4,594	5,829	2,579	23,435	4,304
Semi detached	4,439	1,909	17,727	3,368	4,366	1,931	17,897	3,287
Terraced	4,488	1,930	17,160	3,261	4,084	1,807	15,618	2,868
Flat (average)	4,590	1,974	12,358	2,348	4,543	2,010	12,129	2,228

Electricity and Gas

The dwelling-approach to upscaling the data required an average energy use to be calculated for electricity and gas datasets for each dwelling type. However, the electricity and gas data were only obtained from detached and semi-detached dwellings, so a method was required to extrapolate for terraced houses and flats. The ideal method for extrapolation was a first principles-based approach.

- First principles approach

To determine average consumption values for terraces and flats, deeper parameter analysis was required. McLoughlin *et al*, (2012) found that the number of occupants had a direct effect on fuel consumption, and Yohanis *et al*, (2008) found similar results for the number of bedrooms. The electricity and gas datasets were tested against the number of bedrooms and number of inhabitants using a one-way ANOVA test to determine whether the data exhibited any relationship. With a significant relationship, this would have been using the bedroom and inhabitant number of the terraces and flats within the dataset to determine average consumption, and therefore emissions. The test determined no relationship, so an alternative approach was used.

- Relative proportion approach

This method used the Balcombe-specific semi-detached and detached data. Average electricity and gas emissions from terraces and flats were calculated as a proportion of semi-detached and detached data. This proportion was determined using the percentage difference between the dwelling types in Firth et al (2010) and Wyatt (2013) benchmark values. The averages were calculated between dwelling types and studies, and then applied to the Balcombe data. An example of the calculation can be found in Appendix 2.

With the average consumption values of electricity and gas per dwelling type, Equation 4 was used to calculate the annual fuel consumption per dwelling type. Equation 5 was used to calculate the total annual Balcombe emissions for gas and electricity consumption (kWh yr^{-1}).

$$\text{Dwelling type total (kWh yr}^{-1}\text{)} = \text{Average annual electricity/gas consumption per dwelling type (kWh yr}^{-1}\text{)} \times \text{Number of households using fuel in village} \tag{4}$$

$$\text{Village total annual consumption of fuel (kWh yr}^{-1}\text{)} = \Sigma \text{ fuel consumption for all dwelling types (kWh yr}^{-1}\text{)} \tag{5}$$

Wood

To limit questionnaire length and complexity, quantity of wood consumption was not required. The data to calculate wood fuel use per hour and energy consumed per household was sourced from The Domestic Wood Use Survey which provides regional-specific wood use data (BEIS, 2016). This data was used inequation 6 and 7. Equation 8 calculated Balcombe's annual wood consumption.

$$\text{Wood fuel use per hour (kWh)} = \frac{\text{Typical heat output (kW)}}{\text{Efficiency (\%)}} \tag{6}$$

$$\text{Energy consumed per household (kWh)} = \text{Wood fuel use per hour (kW)} \times \text{Number of operational hours throughout year (h)} \tag{7}$$

$$\text{Total annual wood consumption in Balcombe (kWh yr}^{-1}\text{)} = \text{Average annual wood consumption (kWh yr}^{-1}\text{)} \times \text{Number of houses consuming wood} \tag{8}$$

Oil

The questionnaire yielded an insufficient oil consumption dataset, meaning an accurate average and dwelling-specific consumption could not be calculated. A benchmark value for annual oil consumption (kWh) for each household was provided by Rix (2020). The proportion of households consuming oil was derived from the questionnaire. Equation 9 was used to calculate the total annual oil consumption in Balcombe.

$$\text{Total annual fuel consumption in Balcombe (kWh yr}^{-1}) = \text{Average annual fuel consumption (kWh yr}^{-1}) \times \text{Number of houses consuming fuel} \quad (9)$$

Calculating CO_2 emissions

Equations 10 and 11 can be used to convert the annual consumption of each fuel in Balcombe into emission using the respective nation-emissions factors, shown in Table 3.

$$CO_2 \text{ emissions from fuel (kg } CO_2) = \text{Total annual village consumption of fuel (kWh yr}^{-1}) \times \text{Emission factor of fuel (kg } CO_2 \text{ kWh}^{-1}) \quad (10)$$

$$\text{Balcombe's total annual ICV } CO_2 \text{ emissions (kg } CO_2 \text{ yr}^{-1}) = \sum \text{Annual } CO_2 \text{ emissions from fuel (kg } CO_2 \text{ yr}^{-1}) \quad (11)$$

Table 3: *Nation-specific emission factors for each fuel in 2020. (UK Government, 2020). N.B. these figures are subject to change as efficiencies improve.*

Fuel	**Emission factor (kg CO_2)**
	per kwh
Electricity	0.23104
Oil	0.24544
Gas	0.18352
Wood	0.01545
Transport	*per mile*
	Vehicle specific - determined using Vehicle Enquiry Service (VES)

2.5.2. DVC

The questionnaire gathered information on 45 vehicles which meant that normality testing was not conducted, as it is only required when N≤30 (larger datasets do require testing due to the central limit theorem) (Ghasemi and Zahediasl, 2012). Allinson *et al*, (2016) also investigated UK household carbon, and was used as the benchmark values for personal transport emissions. Equations 12-16 were used to determine the total annual DVC emissions in Balcombe.

Step 1: converting miles into kilometres

$$\text{Kilometres travelled by vehicle (km)} = \text{Miles travelled by vehicle (m)} \times \text{M to km ratio } 1.60934 \quad (12)$$

Step 2: find emissions (g CO_2)

$$\text{Annual vehicle } CO_2 \text{ emissions (g } CO_2\text{)} = \text{Kilometres travelled by vehicle (km)} \times \text{Vehicle-specific emission factor (g/km)} \quad (13)$$

The emissions are vehicle-specific and were determined individually using the Vehicle Enquiry Service (VES) (DVLA, 2020). The vehicle emissions are directly from the manufacturers at the first point of registration (Morgan, 2020).

Step 3: converting kg to g

$$\text{Vehicle } CO_2 \text{ emissions in kg} = \text{Vehicle } CO_2 \text{ in grams} \;/\; 1000 \quad (14)$$

Step 4: Σ vehicle emissions (kg CO_2)

$$\text{Average vehicle emissions in sample (kg } CO_2\text{)} = \left(\Sigma \text{ All vehicle } CO_2 \text{ in sample} \right) \;/\; \text{Number of vehicles in sample} \quad (15)$$

Step 5: total PCV emissions

$$\text{Upscaled DVC annual village } CO_2 \text{ emissions (kg } CO_2 \text{ yr}^{-1}\text{)} = \text{Average sample } CO_2 \text{ emissions (kg } CO_2\text{)} \times \left(\text{No. of households in Balcombe} \times \text{Average no. of vehicles per household} \right) \quad (16)$$

2.6. **RO2 - Determining CO_2 savings**

Repower Balcombe has solar panels installed at seven sites across West Sussex (Repower Balcombe, 2020) (Figure 2). While there is a carbon footprint of solar PV panels, this study is focused on the net-zero operational solar emissions (Circular Ecology, n.d). Repower Balcombe provides the annual generation for each site every year (kWh). A simple calculation converted the generation statistics to calculate the amount of CO_2 saved (Equation 17).

$$\text{CO}_2 \text{ savings (kg CO}_2\text{)} = \text{Average annual generation (kWh)} \times \text{Emission factor (kgCO}_2\text{)} \tag{17}$$

The EF used was the 2020 value (UK Government, 2020). Sourcing the most recent EF best reflects the emission intensity from the current electricity generation mix (proportion of fossil fuels/renewables). An average annual generation value was taken from 2015-2020 data to account for technical issues affecting generation. Average generation of Chiddinglye Solar Farm was predicted by using Repower Balcombe's generation statistics in equation 18. The average percentage was calculated and applied to Chiddinglye's 5 MW Solar Farm.

$$\text{Capacity to Predicted Yield \%} = \left(\text{Capacity (kW)} / \text{Predicted yield (kWh)}\right) \times 100 \tag{18}$$

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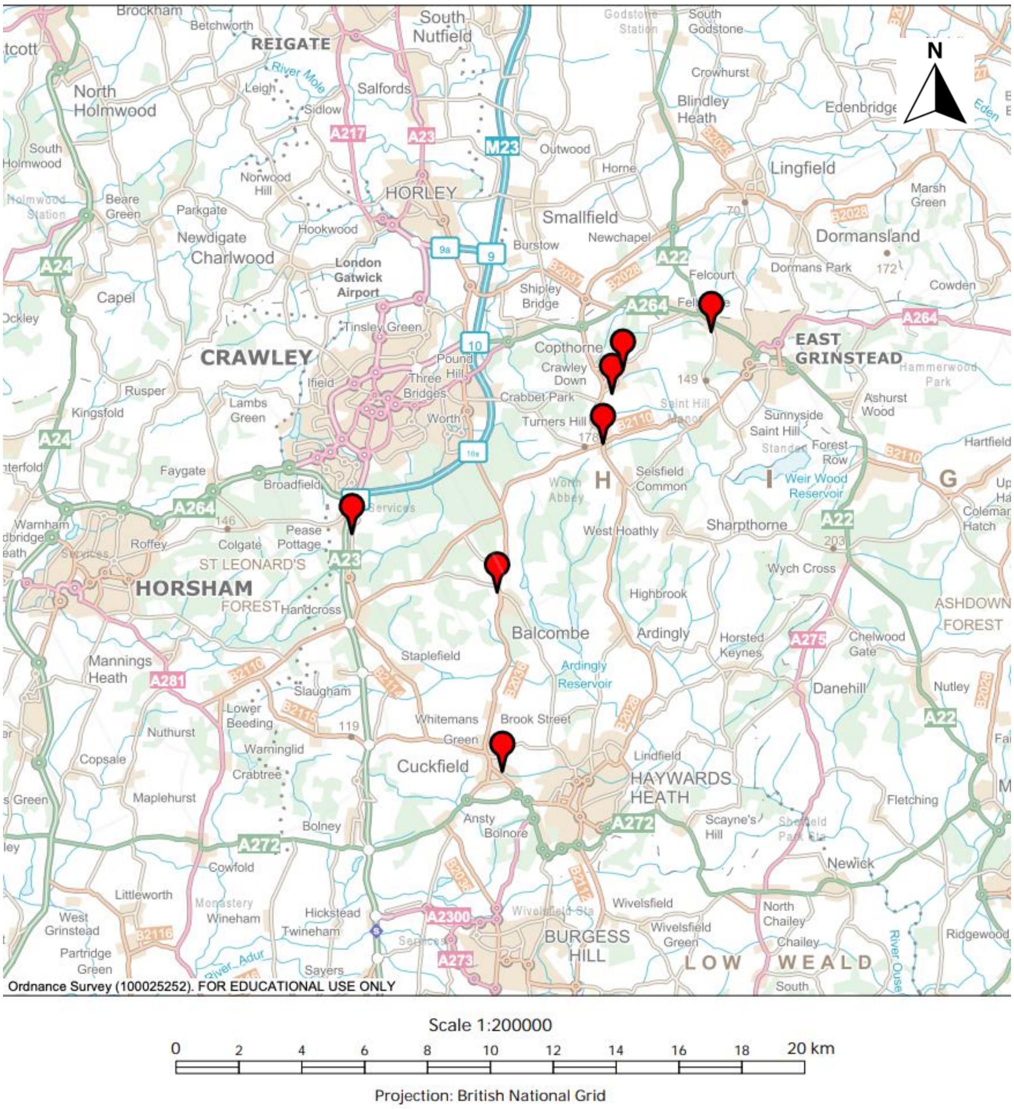

Figure 3: *Map displaying pins that show the location of the seven solar projects across West Sussex*

2.7. **RO3 - Scenarios**

The difference between the annual electricity generation and the demand by Balcombe households was calculated, and the degree of expansion determined. Reducing this difference could be approached in two ways: decreasing demand through education and efficiency improvements or increasing supply with greater renewable capacity (Hoicka and Parker, 2017).

Electricity is currently used for lighting and appliances, and sometimes for heating and cooking. Electrification of heating and transport is one of the government's key priorities to transition to net-zero (BEIS, 2020d), and predictions suggest electricity demand may double by 2050 (HM, 2020). These scenarios suggest renewable technologies to generate sufficient electricity to meet both current demand and increased demand in the future. These scenarios are proposed irrespective of viability determined by energy policy; their purpose is to understand the extent of CRE expansion to decarbonise residential emissions.

- Scenario 1 - roof-mounted solar panels. The average number of panels per solar system was calculated by counting each solar panel using Google Maps, (2021). The sites capacity was divided by the panel number to determine the generation capacity of one panel. This was divided by the current generation to estimate the expansion required to generate the electricity demand.
- Scenario 2 - implement ground-mounted solar (solar farm). Investigating the potential of the Chiddinglye Solar Farm to decarbonise emissions.
- Scenario 3 - implement ground-mounted solar farms and wind turbines to decarbonise all electricity emissions and offer EV charging stations to facilitate the transition to EV's.

District heating was suggested as a means of decarbonising the heating sector for all scenarios.

2.8. **Assumptions**

- The 2011 Census data does not split terraced houses into end and mid-terrace, so the average of the benchmark data, which did make the distinction, was used.
- The Southeast figure given in the Government wood document is representative of Balcombe.
- Participants adhered to the participation requirements and did not input incorrect information.

3. RESULTS

3.1. General questionnaire response

The questionnaire gathered responses from 45 households, which is 6% of all Balcombe Parish households. 42% of respondents filled out the questionnaire entirely, the remainder submitted incomplete responses. The response rate for each question is shown in Figure 4. For reference, an overview of the questions is shown in Table 4.

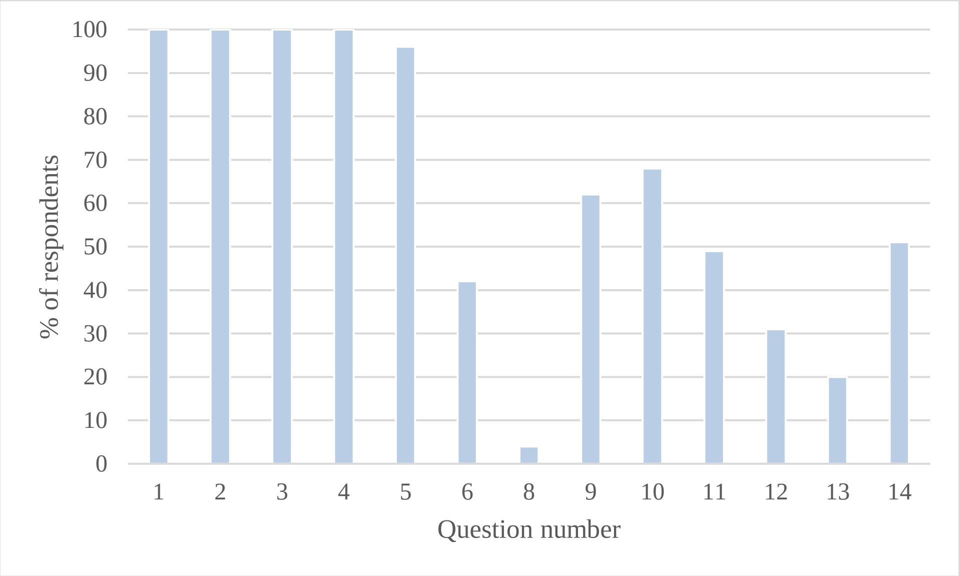

Figure 4: *Bar graph showing the percentage of the total 45 respondents that answered each question. Note - either questions 6 or 7, 12 or 13 and 8 were only displayed depending on the previous response, hence significantly lower responses.*

Table 4: *Overview of the questions*

Question number	Summary of question
1	Dwelling type (e.g., detached, semi-detached)
2	Number of bedrooms in the household
3	Inhabitants in the household
4	Sources of energy used within the home
5	How often gas/electric/oil bills are received
6	kWh of electricity and gas - monthly or annually
7	kWh of electricity and gas - quarterly or annually
8	Number of litres used in the past year (visible to those who selected yes to oil in question 4)
9	Number of vehicles registered to household

10	Number of motorbikes
11	Choice of data provision (registration or emissions information)
12	Vehicle registration
13	Vehicle emission data
14	Mileage of vehicle

3.2. **RO1 - emissions from IFC and DVC**

3.2.1. **IFC**

3.2.1.1. **Sample data**

Electricity was used by all the sample households. Gas was used by the majority at 82.2% of households, whereas oil was only used by 6.7%, shown in Figure 5. While most households used the combination of electricity and gas, one household used all four fuel sources. Two households used only electricity. In two cases, only electricity and wood were used, but for the most part (46.7%), wood provides a complimentary heat source to gas or oil.

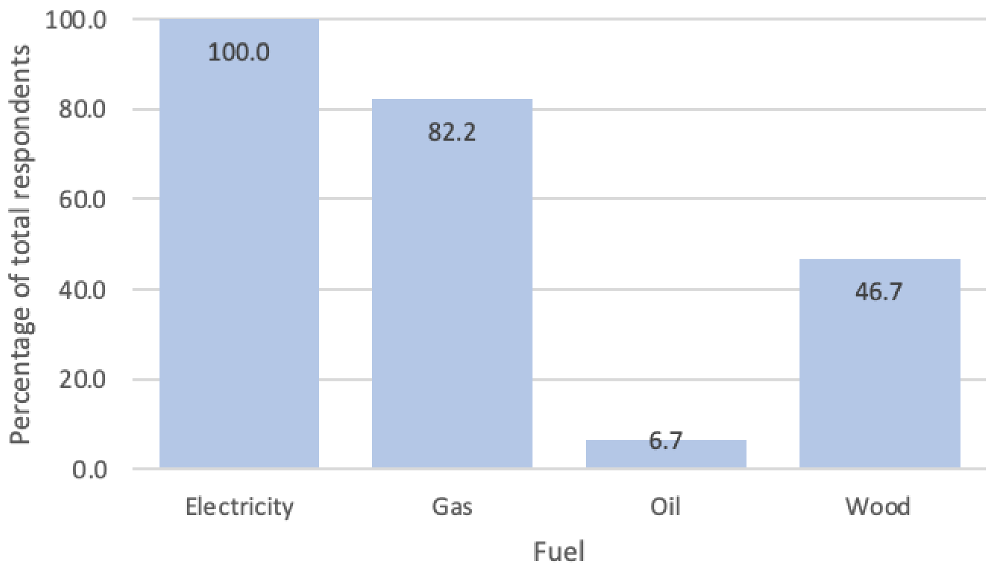

Figure 5: *Bar graph displaying the percentage of respondents using each fuel source from question 4*

Electricity and Gas

The electricity emission dataset had very high kurtosis and skewness values of 17.67 and 4.15, $p<0.05$, respectively, and the box-and-whisker plot revealed two highly anomalous values. Once removed, kurtosis and skewness values lowered to -0.47 and 0.73, $p<0.05$, respectively (Figure 6a). Conversely, the raw gas emissions data had a low kurtosis value at 0.003, $p<0.05$, a skewness of

0.72, $p<0.05$, and the box-and-whisker plot showed no anomalies (Figure 6b). The Shapiro-Wilk normality test showed that the electricity emission data ($W(17) = 0.90$, $p=0.064$) and gas emission data ($W(18) = 0.94$, $p=0.316$) were both normally distributed at the 0.05 significance level.

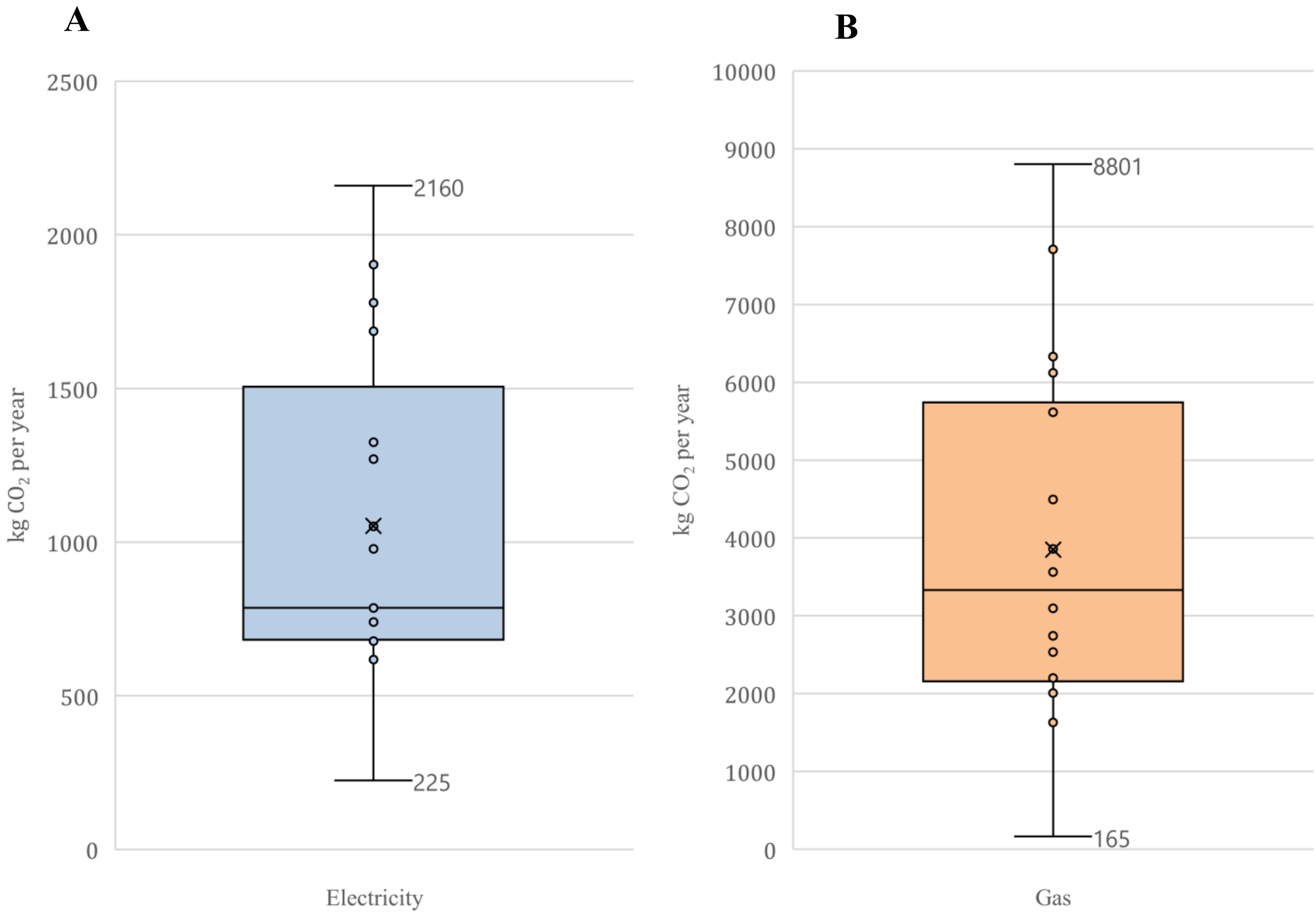

Figure 6 A&B: *Box and whisker plot of normalised annual electricity and gas emissions data (kg CO_2)*

The electricity and gas consumption values (Figure 7) and the uncertainty, determined using the standard deviation, were multiplied by the respective EF to convert them into emissions. The average electricity and gas emissions were greater for detached than semi-detached (Figure 8). Detached houses had average electricity emissions of 1,412 kg CO_2 ±559 and gas emissions of 5,080 kg CO_2 ± 2,232, and semi-detached had electricity emissions of 738 kg CO_2 ± 240 and gas emissions of 2,619 kg CO_2 ± 1,246.

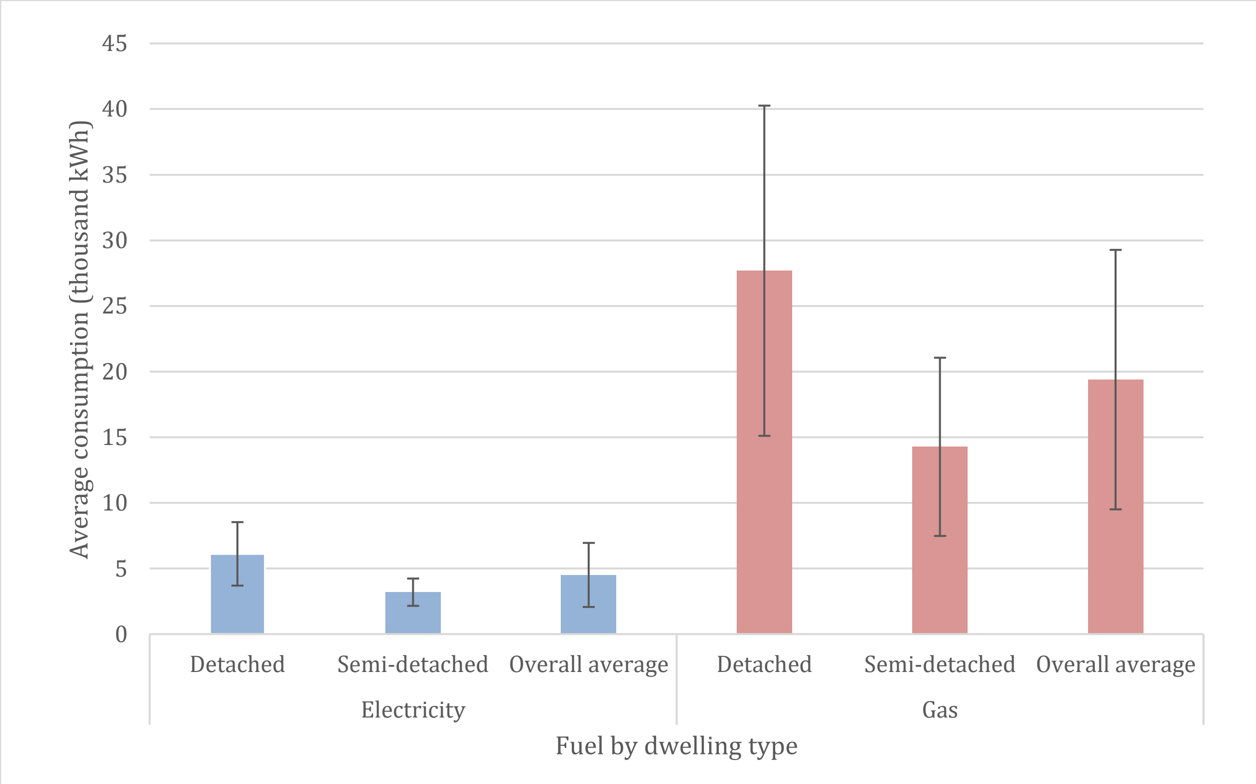

Figure 7: *Bar graph displaying the average annual electricity and gas consumption for detached and semi-detached households, and the overall average (kWh). Error bars represent the standard deviation of the datasets.*

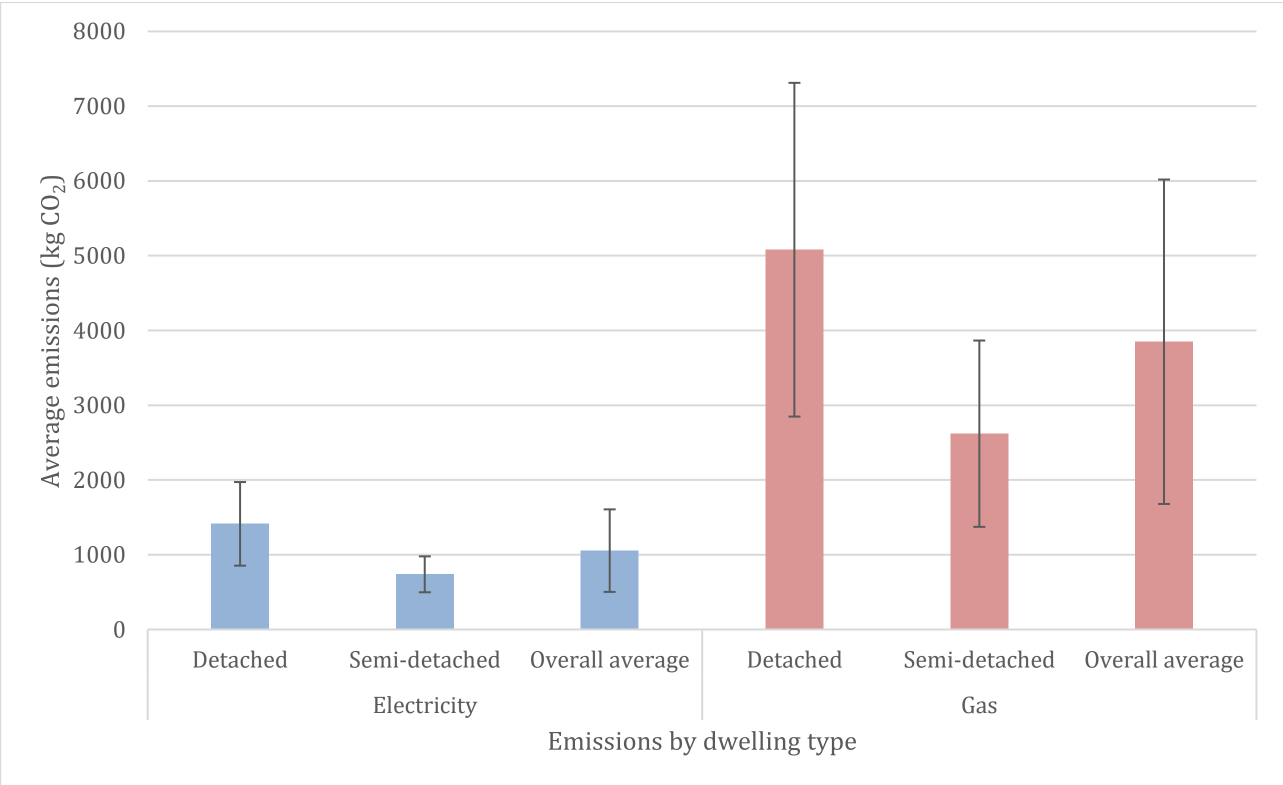

Figure 8: *Bar graph displaying the average annual electricity and gas emissions for detached and semi-detached households, and the overall average (kg CO_2). Error bars represent the standard deviation of the datasets.*

Oil

The questionnaire found that 3/45 households used oil, equating to 6.7% of the sample. This value is similar to the average percentage of oil consuming homes in the UK of 4.4%. Of the 3 households using oil, two were detached, and one was semi-detached. Rix (2020) suggests that the average oil consumption of 3.4-bedroom households in the UK is 25,875 kWh.

Wood

The questionnaire found that 44.4% of households use wood. This was applied to the 755 households in Balcombe. The secondary data suggests that 60% of wood use was in open fires and 40% in closed stoves, therefore 192 households were considered to have open fires, and 144 houses were expected to have closed stoves (Table 5). The total emissions from wood combustion in Balcombe is 50,758 kg CO_2 yr^{-1}. Calculations are shown in appendix 3.

Table 5: *kWh and kg CO_2 from open fires and closed stoves representative of all Balcombe households (755), where open fires and closed stoves are present in 57% and 43% of homes respectively*

	Winter		**Summer**	
	kWh	**kg CO_2**	**kWh**	**kg CO_2**
Open fire	1,622,016	25,060	738,048	11,403
Closed stove	635,904	9,825	289,296	4,470
Total	2,257,920	34,885	1,027,344	15,873

3.2.1.2. **Upscaling IFC**

Upscaling the detached and semi-detached electricity and gas consumption data was attempted using a first principles approach.

First principles approach

A one-way ANOVA test showed no significant relationship between electricity or gas consumption and inhabitant number or bedroom number, at the 0.05 significance level, as shown in Table 6. The relationship between electricity consumption and both inhabitant and bedroom number were ($F=-0.82$, $p<0.94$) and ($F=2.64$, $p<0.094$) respectively, and gas consumption was ($F=-0.13$, $p<0.88$) and ($F=1.01$, $p<0.42$) respectively (Table 6).

Table 6: *Results of the ANOVA one-way test, testing for a relationship between electricity and gas emissions with number of inhabitants and number of bedrooms*

	Electricity emissions		**Gas emissions**	
Variable	**F-value**	**Significance**	**F-value**	**Significance**
Number of inhabitants	0.820	0.940	0.129	0.418
Number of bedrooms	2.641	0.460	0.101	0.880

Relative proportions approach

Comparisons to the benchmark values from Wyatt (2013) and Firth *et al*, (2010) showed inconsistency between values, with detached e-consumption averaging a 10.75% increase from the benchmarks, and semi-detached straying by almost 27% below benchmark values (Table 7). The benchmark detached values showed a high level of uncertainty between the two benchmark studies (16.8% for e-consumption, and 12.7% for g-consumption). However, average semi-detached gas and electric values were 26.9% and 24.8% lower than the benchmark data, while the two benchmark values deviated by only <1.64% (Table 7).

Table 7: *Average electricity (a) and gas consumption (b) in kWh from Firth et al (2010), Wyatt (2013) and this study, and the % difference in past studies compared to this study. Red box indicates greater than study value, green indicates smaller than study value.*

A

	Average electricity consumption (kWh)						
Dwelling type	**Firth *et al*, (2010)**	**Wyatt (2013)**	**Study**	**Firth-Wyatt % difference**	**Study/Firth % difference**	**Study/Wyatt % difference**	**Average difference (%)**
Detached	5084	5829	6114	-14.65	16.80	4.70	10.75
Semi-detached	4439	4366	3470	1.64	-27.9	-25.80	26.9
Terraced	4488	4084		9.00			
Flat	4590	4543		1.02			

B

	Average gas consumption (kWh)						
Dwelling type	**Firth *et al*, (2010)**	**Wyatt (2013)**	**Study**	**Firth-Wyatt % difference**	**Study/Firth % difference**	**Study/Wyatt % difference**	**Average difference (%)**
Detached	24,175	23,435	27,684	3.06	12.7	15.3	14
Semi-detached	17,727	17,897	14,269	-0.96	-24.2	-25.4	24.8
Terraced	17,160	15,618		8.99			
Flat	12,358	12,129		1.85			

The average electricity and gas consumption for all dwelling types using the relative proportions approach is shown in Table 8. The number of houses in each dwelling category using each fuel is shown in Table 9.

Table 8: *Average consumption of fuel per dwelling type with standard deviation (SD (kWh) Terrace and flat averages and SD (in italics) are the values from the relative proportion upscaling approach.*

		Electricity (kWh)		Gas (kWh)		Oil	Wood
		Average	**SD**	**Average**	**SD**		
Dwelling type	**Detached**	6,114	2,418	29,415	10,711		
	Semi-detached	3,193	1,040	14,269	8,091		
	Terraced	*3,975*	*1,464*	*16,094*	*8,053*		
	Flat	*4,228*	*1,557*	*12,037*	*6,022*		
Average						25,875	9,359

Table 9: *Number of houses that use each fuel by dwelling type. This was calculated by applying the proportion of the sample that used easy fuel determined by the questionnaire to the total number of households in each dwelling type (from Census 2011).*

	Electricity	Gas	Oil	Wood
Detached	346	284	51	336
Semi detached	233	191		
Terraced	86	71		
Flat	90	74		

Figures 9 and 10 show the upscaled village-wide electricity and gas emissions. Detached houses generated the highest electricity and gas emissions, contributing 59.0% and 62.7% respectively. Terraced houses generated the lowest electricity emissions at 9.6%, whereas flats generated the lowest gas emissions at 6.1%. The total electricity emissions in Balcombe are 827,379 ± 310,252 kg CO_2, and gas emissions are 2,316,232± 1,041,307 kg CO_2.

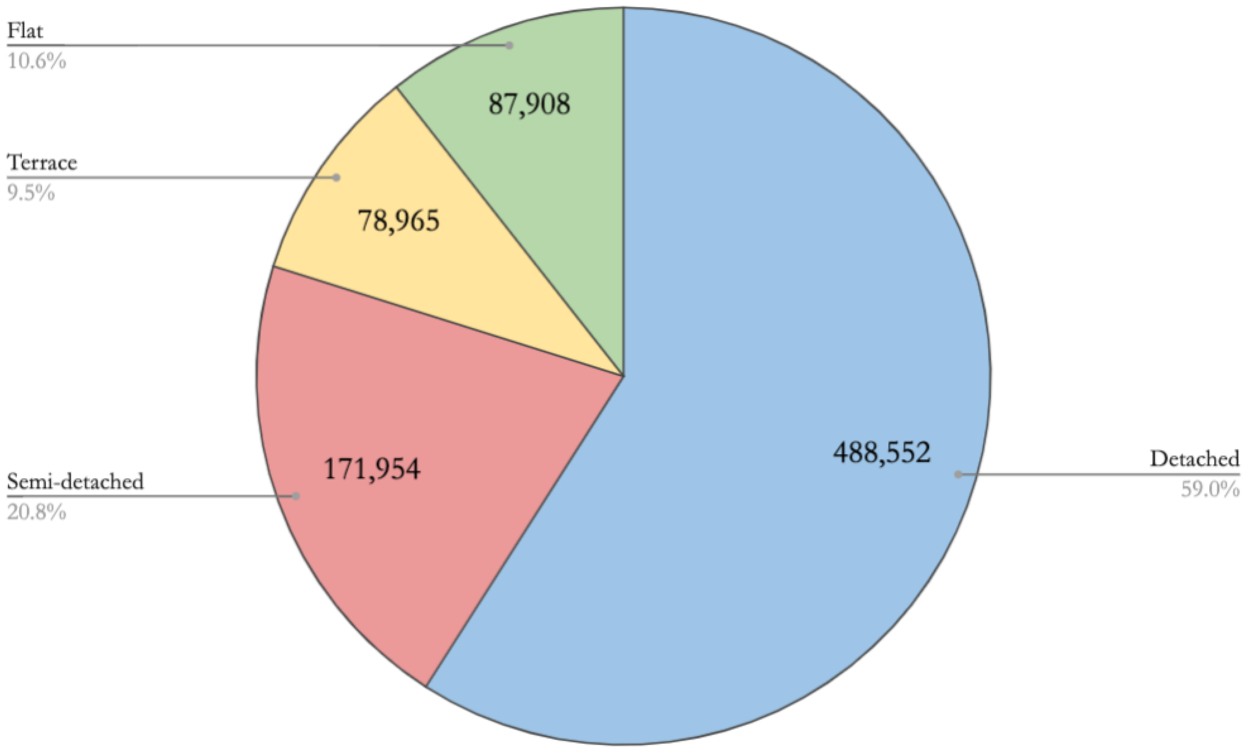

Figure 9: *Pie chart showing the upscaled total electricity emissions in kg CO_2 by dwelling type based on average annual emissions for Balcombe*

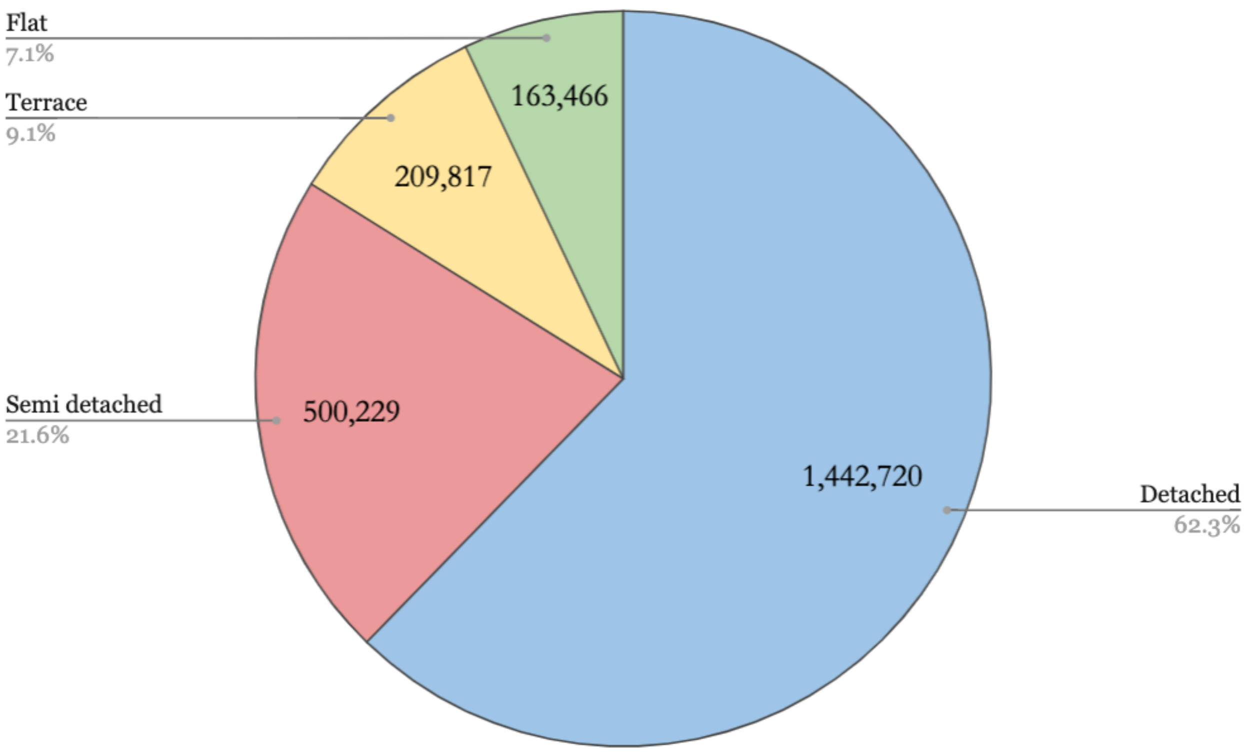

Figure 10: *Pie chart showing the upscaled total gas emissions in kg CO_2 by dwelling type based on average annual emissions for Balcombe*

3.2.2. **Upscaling of DVC and CO_2 conversion**

The questionnaire recorded 58 vehicles from 68% of respondents equating to 31 respondents (Figure 4). The number of vehicles registered to each household varied from 0 to 6, as shown in Table 10. The average number of vehicles per household was 1.87.

Table 10: *Shows the number of households with different number of vehicles registered to the address, and the total number of vehicles*

Number of vehicles	Number of households	Total
0	3	0
1	7	7
2	16	32
3	3	9
4	1	4
5	0	0
6	1	6
Total	**31**	**58**

Of these 31 households, 23 supplied emissions and mileage data, equating to 47 vehicles. The average annual mileage was 6,069 miles (9,767 km), and average per kilometre emissions were 160 g CO_2 (0.160 kg CO_2), resulting in 1,563 kg CO_2 being released per vehicle on average per year. The 46 vehicles in the study produced a combined total of 73,448 kg CO_2 yr^{-1} (Table 12). Therefore, the total emissions are 2,206,326 kg CO_2 yr^{-1}.

3.2.3. **Total emissions**

The total residential emissions from annual IFC and DVC was calculated to be 5,720,107 kg CO_2 but uncertainty from gas and electricity emissions alone suggest that this could vary between ± 1,351,559 kg CO_2 (Table 11). The contribution of each fuel to total emissions is illustrated in Figure 11 (without uncertainty).

Table 11: *The annual consumption of IFC, and CO_2 emissions from IFC and DVC for Balcombe. Uncertainty for electricity and gas emissions has been included and added to the total CO_2 value.*

Source	Upscaled energy consumption (kWh)	Upscaled emissions (kg CO2)	% Of total emissions
Electricity	3,574,748	827,379 ± 310,252	14.5
Gas	14,573,267	2,310,252 ± 1,041,307	40.4
Oil	1,319,621	325,453	5.7
Wood	3,281,359	50,697	0.9
Vehicles	-	2,206,326	38.6
TOTAL	IFC only: 22,748,995	5,720,107 ± 1,351,559	

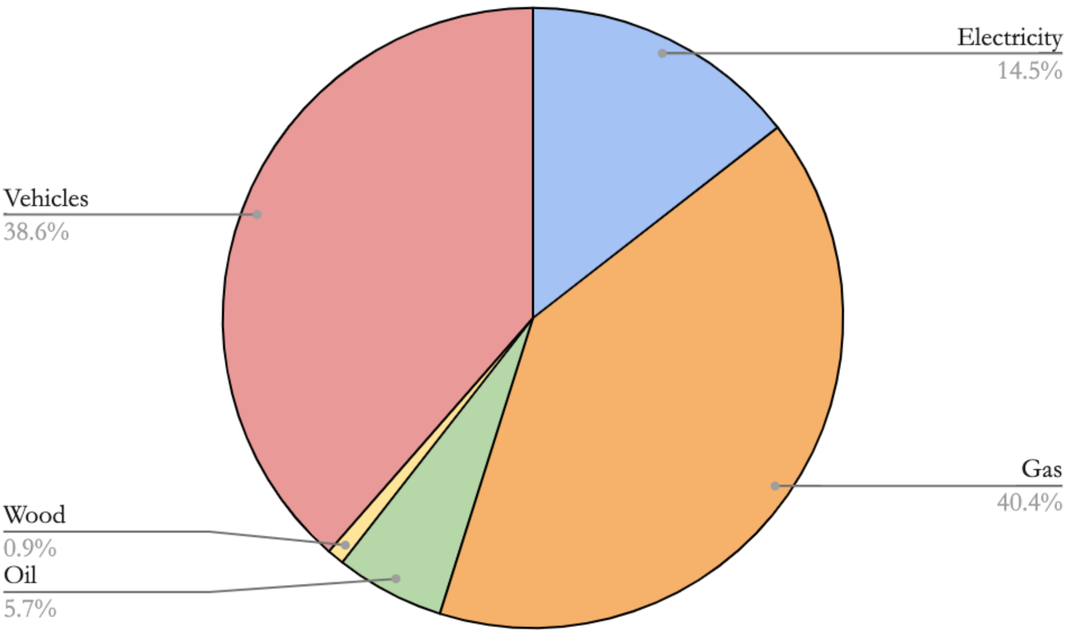

Figure 11: *Pie chart showing Balcombe's total emissions from each sector*

3.3. **RO2 - Determining CO_2 savings**

The annual generation of the seven sites is shown in Table 12. On average 146,859 kWh of electricity is generated annually, equating to 4.1% of Balcombe's electricity demand. The projects prevent the release of 33,930 kg CO_2 into the atmosphere, and therefore decarbonising 0.59% of Balcombe's IFC and DVC emissions. The average ratio of capacity to predicted yield (equation 18) was calculated to be 1.0544, meaning that Chiddinglye 5 MW solar farm generates approximately

5,267,000 kWh yr^{-1} of electricity annually. Had this been under Repower Balcombe's name, almost 1.5x the amount of Balcombe's electricity demand would have been generated.

Table 12: *The amount of electricity generated since 2015 (kWh) across the seven sites, and the total average annual generation*

	Annual generation (kWh)						
Site	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**Average**
Grange Farm	17,298	18,045	16,950	13,784	14,992	14,870	15,990
Turners Hill School		12,188	11,920	10,903	11,741	12,222	11,795
Balcombe School		7,864	7,338	7,514	7,365	8,085	7,633
Crawley Down School			39,296	38,390	38,484	40,752	39,231
Imberhorne School		36,660	42,449	41,945	41,717	43,416	41,237
Holy Trinity School				18,719	18,467	19,419	18,868
Bridges Yard N + S				0	0	12,105	12,105
TOTAL						150,869	146,859

3.4. **RO3 - Scenarios**

The current projects prevent the emission of 33,930 kg CO_2 which equates to 0.548% of Balcombe IFC and DVC emissions. For the purpose of visualising the required future expansion, Table 13 shows that to successfully meet all IFC demands in terms of kWh, generation would need to increase by x154, but to decarbonise all emissions, generation would need to increase by x169. While electricity generation of Repower Balcombe needs to increase to address Balcombe's electricity demand, decarbonising all residential emissions would require diversification of renewable technologies.

Table 13: *Expansion requirement statistics*

	kWh	**kg CO_2**
Total site generation/savings	146,859	33,930
Required generation (for fuel only)	22,748,995	3,513,781
Total required generation	-	5,720,107
Required increase factor	(IFC only) x 154	x 169

The average size of each solar system with Repower Balcombe is 91 panels which equates to an annual generation of 21,096 kWh. Table 14 proposes methods of increasing generation.

Table 14: *Scenarios to increase electricity generation by 2030. Data based on average of past generation data from Repower Balcombe sites.*

Scenario 1	Roof-top solar	**100% of current residential electricity demand** ● 1 solar panel generates approximately 250 W ● Average of 91 panels per system, ● Average yield per system is 25,001 kWh yr^{-1} ● Annual demand for electricity is = 3,574,748 kWh ● 3,574,748/25,001 = 143 more solar projects needed to cover electricity consumption
Scenario 2	Ground-mounted solar	**100% of current residential electricity demand + extra for EV/heat pumps** ● 5 MW ● 18,500 solar panels ● 5,267,000 kWh estimate ● Covers all Balcombe's electricity demand plus allowance for future electrification
Scenario 3	Ground-mounted solar	**100% of current residential electricity demand + extra for EV/heat pumps** ● 5 MW ● 18,500 solar panels ● 5,267,000 kWh estimate
	Wind turbines	**EV charging** ● 8 x 2.5 kW wind turbines = 4,400 kWh ● 2 x 100 kW = 22,800 kWh ● Total = 27,200 kWh
All scenarios	Heat pumps	**District heating - electric heat pumps** ● Can be ground-source heat pumps, or air-source heat pumps ● An example is Firle Village where district heating is being developed using heat pumps. There are currently two proposed networks serving 2-3 households (BHESCo, 2021) ● In South Norfolk, 30 flats were fitted with ground-source district heating in 2017, which has reduced bills by ⅔ (Finn Geotherm, 2020) ● Potential for heat pumps on individual homes, or community buildings such as Balcombe Primary School, Balcombe's pub - The Half Moon - and Victory Hall ● Heat pumps at village level are not widely implemented in the UK, and so quantifying the potential of heat pumps to decarbonise the heating sector is not yet possible.

4. DISCUSSION

4.1. RO1 - CO2 emissions from IFC and DVC

Analysis of the results show that the CO_2 emissions from IFC and DVC from households across Balcombe equates to approximately 5.72 million kg CO_2 annually. There was a large degree of uncertainty, which is likely due to the small sample size. The average household is a four-bed detached dwelling with an average of 2.58 inhabitants and 1.8 vehicles. The majority of emissions were from the gas and transport sectors, contributing 42.2% and 38.8% of the total respectively, while wood consumption contributed the least at 0.8%. Past literature shows that gas for heating and cooking, and petrol/diesel for transport, is where most domestic emissions originate (CCC, 2016). These high levels of emissions highlight the perpetual challenge associated with the decarbonisation of these sectors and the need for urgent attention (Broad et al., 2020). Allinson *et al*, (2016) found average household emissions from electricity, gas and transport to be 6,911 kg CO_2 yr^{-1}, whereas this study calculated a marginally higher value of 7,078 kg CO_2 yr^{-1}. Exploration of IFC shows that Firth *et al*, (2010) calculated a higher average household emission of 5,827 kg CO_2 yr^{-1} compared to this study at 4,654 kg CO_2 yr^{-1}. While some of this disparity can be explained by changes to emission factors over time, deeper analysis of consumption (kWh) revealed inconsistencies throughout the datasets.

Results from this study concur with the common consensus that detached houses contribute the most emissions compared to other dwelling types – and are responsible for 61% of electricity and gas emissions (Kenny and Gray, 2009; Firth *et al*, 2010, Allinson *et al*, 2016). However, the results show that detached houses had higher electricity and gas consumption compared to the benchmark values. The Covid-19 pandemic could explain this. Respondents were asked to give their most recent annual IFC and DVC values, which would include data derived during the pandemic. In the UK, Covid-19 surfaced during March 2020. From March 2020 until April 2021, UK residents were forced to spend more time at home, with 3 national lockdown periods and a tier system restricting the movement of people. Although industrial and commercial electricity consumption showed a 14.3% annual decrease in 2019, domestic demand increased. (Bahmanyar *et al*, 2020). A survey conducted by Ofgem (2020) found that 55% of consumers were using more energy than usual. However, this does not explain the comparatively low electricity consumption figures for semi-detached dwellings. The large disparity between dwelling type could be due to differences in the age of properties. Many semi-detached dwellings were previously social housing and more modern than the detached dwellings. Age has been found to have a notable effect on the energy efficiency of residential properties, and therefore electricity and gas consumption (DCLM, 2014). Additionally, lower emissions from dwellings in the social sector could result from energy efficiency improvements implemented from the Decent Homes programme (DCLM, 2014).

The average emissions per household from personal vehicles in Balcombe was 1,742 kg CO_2 yr^{-1}, which totalled 2,459,443 kg CO_2 yr^{-1} when upscaled, contributing 38.6% of Balcombe's total emissions. Allinson *et al* (2016) found similar results, recording slightly higher average emissions of 1,870 kgCO_2. There is low uptake of EVs in Balcombe, with only two recorded in the sample. Additionally, the average vehicle mileage in Balcombe was 6,067 miles, but the national average for 2019 was 6,500 miles (Department of Transport, 2020). This can be attributed to Covid-19. Road traffic fell by 73% during the first lockdown compared to recent years owing to the enforcement of government laws to "stay at home" (Carrington, 2020). Annual emissions from vehicles usually average 160 g CO_2 km^{-1}, which is notably higher than the 2020 target of 120 g CO_2 km^{-1} (ICCT, 2016). Older vehicles typically have higher emissions than newer vehicles due to efficiency advances, so it is assumed that the vehicle fleet in Balcombe comprises older vehicles (Kagawa *et al.*, 2013). This study uses the EF provided by the manufacturer at first registration, but numerous investigations question the reliability of these figures in 'real-driving' terms (Hooftman *et al*, 2018). The emissions of vehicles manufactured before 2017 were tested using the outdated New European Driving Cycle which has been criticised for unrealistically low acceleration and restricted ambient temperature brackets (Degraeuwe and Weiss, 2017). Inaccurate real traffic and road profile conditions have led to significantly understated emissions, by 30-40% in some cases (Fontaras *et al*., 2017). Emissions testing has been upgraded to Worldwide Harmonised Light-Vehicle Test Procedure, but the inaccurate values for older cars must be accounted for if the government is to make the UK truly net-zero by 2050.

This study focussed on direct residential consumption emissions, however, it excluded additional household emissions. The combination of direct and indirect emissions provides the full carbon footprint of a household (Fan *et al*., 2012). While this study has accounted for the most prominent direct emission sources, it did not include food and product consumption, waste and public transport emissions (Long *et al*., 2017). Park and Heo, (2007) found that "over 60% of the household energy requirement is indirect" - showing the importance of recognising these 'hidden emissions' when decarbonising the residential sector.

4.2. **RO2 - Determining CO_2 savings**

Repower Balcombe is currently generating enough renewable energy to decarbonise 4% of electricity emissions. Assuming that electricity is used for lighting and appliances, the CRE project is yet to diversify to decarbonise the heating, transport and cooking sectors fuelled by gas and oil/petrol/diesel. One of the reasons for this is a lack of government support, which has prevented the construction of larger CRE solar projects which could successfully contribute towards decarbonisation.

The adoption of CE in various European countries proves that it can be successful (DECC, 2014). In 2010, private citizen investment into energy cooperatives contributed 40% of all renewable electricity generation in Germany, while the major utility companies owned 14% total renewable capacity. The UK government has acknowledged the urgent demand for a decarbonized future energy system and has named CE as playing a “key role” in achieving this (DECC, 2014). Claire Perry stated that “from power stations to solar panels, the future is local” (Bairstow, 2019). The energy revolution towards a decentralised energy system has security and economic benefits, however governmental support is crucial to make CE a viable and sustainable generation method. Feed-in-tariffs are essential for future community renewable energy, and investment is too high risk without tax relief, meaning the high capital costs of developing CE can no longer be covered (CEE, 2019). In 2015, despite outlining the importance of Enterprise Investment Scheme (EIS) tax relief in the Community Energy Strategy a year prior (DECC, 2014), the government cut the tax relief by 30% and feed-in-tariffs by 87% (Nolden *et al*, 2020). These cuts directly impacted Repower Balcombe and its ability to generate the equivalent of Balcombe’s demand for low-carbon electricity, preventing the completion of a solar farm under its name.

Chiddinglye Solar Farm was first proposed by Repower Balcombe in May 2015 and gathered high levels of support from the CE community across the UK (REPOWER Balcombe, 2015). With help from 10:10, a climate charity, the group secured planning permission for a 5MW ground-mounted solar farm just outside Balcombe consisting of 18,500 solar panels (Colthorpe, 2015). The results suggest that the farm would have generated 5,267,000 kWh of community-generated electricity, - supplying 1.3 x the Balcombe’s electricity consumption. Repower Balcombe were forced to abandon the solar farm when the government made CE schemes ineligible for the EIS tax relief (CEE, 2017). The farm was taken over commercially, so the work that Repower Balcombe did to secure the plot did not entirely go to waste, but it is not generating electricity under Repower Balcombe. It is this lack of consistent governmental support that stunts CE projects across the UK (Nolden *et al.*, 2020).

Additionally, a lack of the feed-in-tariff means that the electricity needs to be used locally as it is being generated.

CE can be viewed as a polycentric system, where the involvement and interaction of numerous actors pose an intricate and unique governance challenge (Goldthau, 2014). Multi-scale complexity invariably leads to the emergence of numerous barriers to the CE sector (Brummer, 2018). The current UK energy policy has prevented CRE from flourishing as it has in other European countries (Brummer, 2018). Germany and Denmark are two of the leading CE nations in Europe (Nolden *et al*, 2020), and while their CE structure systems are somewhat distinctive, they receive indifferent support mechanisms from the wider government (Bauwens *et al*., 2016). Both countries now have a combination of fixed feed-in-tariffs, tax exemptions, priority transmission and investment grants (Bauwens *et al*., 2016), which allow for high investment security. A temporary reduction of 25% in feed-in-tariff in Denmark saw a notable slowdown in the emergence of new cooperatives (Bauwens *et al*., 2016). The UK is experiencing similar declines following the continuous reduction in feed-in-tariffs since 2012 and ultimate closure of the tariff in 2019 (Nolden *et al*., 2020). While Nolden *et al*. (2020) argues that the upfront capital costs are perhaps that greatest barrier of all in terms of CE project initiation and the construction of new projects in established cooperatives, feed-in-tariffs need to be secure for investor confidence (Brummer, 2018). The potential capacity of projects such as Repower Balcombe could help to realise the future of CE and its role in decarbonising the sectors associated with residential emissions, if government policy did not enforce barriers to obstruct their development.

4.3. **RO3 - Scenarios**

If Repower Balcombe is to positively contribute towards the decarbonisation of the residential sector, the gap between current generation of 146,859 kWh yr^{-1} and IVC demand of 22,748,995 kWh yr^{-1} must be bridged. To successfully decarbonise all sectors, Repower Balcombe would need to significantly upscale their plans for solar PV and diversify into other renewable technologies to tackle the heating and cooling sectors. The CRE project would need to increase by 26-fold to generate the equivalent of Balcombe's annual electricity demand. While some of the scenarios suggested are not currently viable due to limitations imposed by energy policy, the results suggest CRE could be an effective method to decarbonise residential emissions.

Increasing the generation and penetration of renewable electricity is vitally important, not only to directly decarbonise the electricity sector, but also because of the UK Government's plans for the electrification of the heating and transport sectors (HM Government, 2018; BEIS, 2020c). The success of electrification is dependent on employing renewable sources of electricity ((Knobloch *et al*., 2020). Solar PV constitutes the majority of community capacity in the UK at 80% (CEE, 2020), likely due to a Scolar Programme where £1 million was granted for small solar systems (Nolden *et al*., 2020). Extensification of solar PV use has driven down the price of the equipment by 75% since 2010 (Kumar, 2019). The national target is for electricity to be 100% carbon neutral by 2050 (BEIS, 2019). Under scenario 1, approximately 156 more solar projects, each with 91 panels, would be required to reach the current demand. This would need another 156 very large, south-facing roofs in the area, or a greater number of smaller roofs for smaller systems – making it an unfeasible scenario. Scenario 2 - a 5 MW solar farm, like Chiddinglye - would be a relatively simple solution to meet and exceed current household demand. Repower Balcombe's dedication to the solar farm in 2015 shows that community groups can achieve large-scale projects and highlights the need for energy policy review. Scenario 3, which utilised wind power and a solar farm, could be the most effective option to cover current and future demands. Additionally, diversification of the energy mix brings benefits such as reduced investment risk which may incentive future investors (Sinsel *et al*., 2019). Research finds wind to be a very affordable energy source, although there are many conditions attached to turbine construction (Kumar, 2019). Wind turbines vary in size from 2.5 kW to 2.5 MW, making it a scalable option to install in different locations (CSE, 2016), however very large turbines may not be suitable in Balcombe due to undulating terrain. Eight 2.5 kW turbines at each solar site, along with two larger 100k kW turbines, would generate an additional 27,200 kWh of clean electricity, and prevent the release of 6,284 kg CO_2. However, bridging the gap should also be approached from the other perspective – by reducing demand. Forecasts suggest an 11% rise in household emissions by 2035 highlights the need for urgent demand-side action (LSE, 2018).

Heat pumps should be considered for each scenario. They are expected to be crucial technologies to decarbonise the heating sector and phase out the domestic use of oil and gas (Broad *et al*., 2020). Heat pumps can be either air, ground or water source, and are suitable in different situations (Grassi, 2017). They are flexible in size, with small pumps for individual houses, or district heating to supply multiple houses (DECC, 2016). There is a government incentive for the installation of heat pumps provided by the Renewable Heat Incentive (DECC, 2011). Firle Village is a local example of heat pump district heating, supplying up to four properties (Curtis, 2020). The precise contribution of heat pumps is challenging to define, but it is estimated that they will contribute significantly to heating demand by 2050 (Possible, n.d).

5. CONCLUSION

This research project aimed to determine the CO_2 emissions associated with residential fuel consumption from both internal fuel consumption (IFC) and domestic vehicle consumption (DVC) and establish the effectiveness of Repower Balcombe to decarbonise these sectors. Further decarbonisation scenarios were suggested as a means to bridge the disparity between current generation and demand. The questionnaire found residential emissions were substantial at 5,720,107 kg CO_2 ± 1,351,559. Detached households were accountable for the highest emissions - contributing approximately 54% and 63% of electricity and gas emissions respectively, and flats produced the lowest, contributing 11% and 7% respectively. Gas and transport were by far the greatest contributor of emissions, representing 80% of total emissions. It is expected that the results from this study may not be representative of 'normal' annual emissions due to higher household fuel consumption and lower vehicle mileage resulting from Covid-19. At present, the Repower Balcombe focuses primarily on electricity, and generates clean energy equivalent to 4% of the demand in Balcombe. The loss of the Chiddinglye Solar Farm significantly hampered the project: and entire of electricity demand of the village would be covered had the policy facilitated its development under Repower Balcombe.

Conflicting government information together with inconsistencies in their theoretical support for CE and actual policies determining its viability, makes the current environment very challenging for CE. It is likely to remain a barrier until policy supports lower risk investment and higher margins. To directly reduce household related emissions through CE, a shift towards a decentralized system needs to be achieved, where the power of local people can be harnessed. Examples from Germany and Denmark demonstrate the potential of CE. Ground-mounted solar would be the most effective solution to decarbonise the entire electricity sector in Balcombe, but wind turbines could provide additional electricity generation to meet the inevitable increase in demand resulting from further electrification. Wind turbines could help to cover electric vehicle demands and run heat pumps to enable the decarbonisation of the heating sector. Diversification of renewable technologies will be key in addressing emissions from all household sources, particularly as demand for electricity rises.

This study shows that decarbonising residential emissions using renewable technologies is important and feasible. Future studies should investigate the life-time emissions from the construction, operation and disposal of renewable technology equipment. Solutions could be suggested to overcome them - possibly through offsetting techniques. This could help to make IFC and DVC truly sustainable with net zero emissions. Additionally, further research could replicate the methods used here but also consider the emissions associated with waste and air travel.

6. BIBLIOGRAPHY

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7. APPENDICES

7.1. Appendix 1 – Questionnaire

My name is Katie Finnerty, and I am a third year Environmental Geography undergraduate looking for participants to complete this survey surrounding domestic carbon dioxide emissions in Balcombe. I have lived in the village for the past 9 years, and I wanted to explore the Repower Balcombe project, having seen the village transition from fracking for fossil fuels to the generation of renewable energy.

The title of my dissertation is:

From disputed fracking site to renewable energy champion: Balcombe's green transition towards carbon neutrality and the decarbonisation of residential CO_2 emissions both now and in the future.

This study aims to calculate the basic emissions from Balcombe households and personal travel, and this survey will be split into three parts: 1) basic household information, 2) energy and fuel usage within the home, and 3) vehicle information.
The purpose of the study is to calculate what percentage of household emissions are currently being offset by the REPOWER Balcombe project. The project was set up in 2015, and aims to generate 100% of Balcombe's electricity demand through community-owned solar panels installed on local buildings (more about this project can be found at REPOWER Balcombe). The findings will be used to help formulate expansion of the scheme and ultimately establish if renewable energy projects within a community can be adopted nationwide as a means of reducing emissions in the UK. The outcome of this study will be beneficial to participants because a greater understanding of the current performance of the scheme and its future prospects could help Balcombe become a leader in the Community Renewable Energy field.

Your participation in this study is voluntary and you can withdraw at any time during or after the study without having to explain your reasons. This study will be completely anonymous, and the raw data will be reviewed by the primary researcher and dissertation supervisor only. No personal information will be published in the study. Data will be safely stored during the data collection phase, and will be deleted immediately after the research project has been completed.

This survey will take approximately 10 minutes with the relevant information to hand - this includes annual electricity and gas usage (in kWh - on bills), oil usage (litres), and vehicle registrations and milage. The vehicle registration is required because it can be entered into the Vehicle Enquiry Service, which provides specific carbon dioxide (CO2) emissions for each vehicle. However, the survey includes the option for the participant to provide this CO2 data directly using the website if you would prefer to withhold specific vehicle registrations.

I ask that only one resident per household completes this survey, and that participants have a Balcombe postcode.

PLEASE ENSURE YOU HAVE YOUR ANNUAL ELECTRICITY and GAS and ESTIMATED CAR MILEAGE INFORMATION TO HAND PRIOR TO STARTING THE SURVEY, AS THE SOFTWARE DOES NOT SAVE PROGRESS.

If you have any queries or questions regarding this survey and research, please contact Katie Finnerty at kmf515@york.ac.uk.

Do you accept and understand the information above, and are willing to participate in this survey?

- o Yes
- o No

Q1 **GENERAL HOUSEHOLD INFORMATION**
Which of the following best describes your house?

- o Detached
- o Semi-detached
- o Terraced
- o Flat
- o Bungalow
- o Other

Q2 How many bedrooms are in your household?

- o 1
- o 2
- o 3
- o 4
- o 5
- o More than 6 (please state)

____

Q3 How many people live in your household?

- o 1
- o 2
- o 3
- o 4
- o 5
- o More than 5 (please specify)

____

Q4 Which of the following fuels/sources of energy do you use in your home?

	Fuel IS used	Fuel IS NOT used

Electricity	o	o
Gas	o	o
Oil	o	o
Wood or coal (for wood or coal burning stove)	o	o

Q5 For each fuel, please either select how often you receive your bills.

	Monthly	Quarterly
Electricity (2)	o	o
Gas (3)	o	o

Q6 Please provide the amount of kWh of electricity and/or gas for 4 months (preferably a month from each season) **or** your ANNUAL total. This should be clearly stated on your electricity/gas bill.

	Electricity	Gas
Month 1		

Month 2		
Month 3		
Month 4		
OR Annual total		

Q7 Please provide the amount of kWh of electricity and gas for your past 4 quarterly bills **or** your ANNUAL total. This should be clearly stated on your electricity/gas bill.

	Electricity	Gas
Quarter 1		

Quarter 3		
Quarter 3		
Quarter 4		
OR Annual total		

Q8 Please state the approximate number of litres of oil you have used in the past year.

____

Q9 How many vehicles are registered to your house? This includes cars, vans and motorbikes for personal travel only (this includes commuting, but not for business itself).

o 0
o 1
o 2
o 3
o 4
o 5
o 6 or more (please specify how many, if more than 6)

Q10 Are any of these vehicles motorbikes? If yes, please specify how many.

- o Yes ____________________
- o No

Q11 In order to find the carbon dioxide emissions from vehicles, it is necessary to know the grams of carbon dioxide produced per kilometre. The Vehicle Enquiry Service (link to website here) provides this information for each vehicle using the registration number.

You can provide this data in one of two ways. Please tick the box you would prefer.

- o Provide the registration plate, and the primary researcher will gather the emission information
- o Provide the emission data directly using the link to enter the registration number

Q12 Please specify your vehicle(s) registration. If 6+ cars are registered to the house, please use the 6 vehicles which are used most frequently

	Registration number
Vehicle 1	
Vehicle 2	
Vehicle 3	

Vehicle 4	
Vehicle 5	
Vehicle 6	

Q13 Please use this link (Vehicle Enquiry Service) to provide the amount of CO2 produced from your vehicle in GRAMS PER KM (g/km)

- Vehicle 1 ________________________________
- Vehicle 2 ________________________________
- Vehicle 3 ________________________________
- Vehicle 4 ________________________________
- Vehicle 5 ________________________________
- Vehicle 6 ________________________________

Q14 To calculate the emissions produced per year, the mileage of each vehicle is required. The yearly mileage can be found using the past two MOT certificates, but an estimate can also be made.

	Miles travelled in the past year
Vehicle 1	

Vehicle 2	
Vehicle 3	
Vehicle 4	
Vehicle 5	
Vehicle 6	

END OF SURVEY

7.2. **Appendix 2 – Relative proportion calculations**

- Electricity

Balcombe survey data:

- Semi-detached = 738 kg CO_2 ± 240 OR 3,193 kWh ± 1040
- Detached = 1,413 kg CO_2 ± 559 OR 6,114 kWh 2418
-

Calculating terraced houses

- % difference between semi-detached and terraced houses

  Terraced / semi-detached = % difference

  - FIRTH *et al* (2010)
    - Semi-detached = 4,439 kWh
    - Terraced = 4,488 kWh

    $$(4488/4439) \times 100 = 101.1$$

  - WYATT (2013)
    - Semi-detached = 4,366 kWh
    - Terraced = 4,084 kWh

    $$(4084/4366) \times 100 = 93.5$$

  AVERAGE of the two % differences = (101.1 + 93.5)/2 = 97.3%

- % difference between detached and terraced houses
  - FIRTH *et al* (2010)
    - Detached = 5,084 kWh
    - Terraced = 4,488 kWh

    $$(4488/5084) \times 100 = 88.3$$

  - WYATT (2013)
    - Semi-detached = 5,829 kWh
    - Terraced = 4,084 kWh

    $$(4084/5829) \times 100 = 70.1\%$$

  AVERAGE of the two % differences = (88.3 +70.1)/2 = 79.2%

Application to Balcombe semi-detached and detached data:

- Semi-detached:

  $$3193 \pm 1040 \times 0.973 = 3{,}107 \text{ kWh} \pm 1012$$

- Detached

  $$6114 \pm 2418 \times 0.792 = 4{,}842 \text{ kWh} \pm 1915$$

Average = ((3107 ± 1012) + (4842 ± 1915))/2 = 3975 kWh ± 1464.

Relative proportion calculated value for average consumption of fuel for terraced houses in Balcombe = 3975 kWh ± 1464.

7.1. **Appendix 3 – Wood calculation**

Energy (kwh) = wood fuel use per hour x number of operational hours
Survey found 20/25 houses use wood/coal - 44.4%
Wood emission factor = 0.01545
Operational hours: ● Winter: 20 ● Summer: 9.1
Wood fuel use per hour: ● Open fire:17.6 kWh ● Closed stove: 9.2 kWh
Fuel type: 92% logs, assumed 100%
WINTER: ● Open fire ○ 17.6 x (24 x 20) = 8448 kWh per household ■ 24 weeks (6 month x 4) ■ 20 hours ○ Emissions 8448 x 0.01545 = 130.5 kgCO_2 for winter ○ 130.5 x 192 = 25,056 kg CO_2 for winter ■ 192 = number of houses using open fires in Balcombe ● Closed stove ○ 9.2 x (24x20) = 4,416 kWh per households ○ Emissions 4416 x 0.01545 = 68 kg CO_2 for winter ○ 68 x 144 = 9,792 kg CO_2 for winter
Winter total = 34,848 kg CO_2
SUMMER ● Open fire ○ 17.6 x (24x9.1) = 3844 ○ Emissions 3844 x 0.01545 = 59 ○ 59 x 192 = 11,328 kg CO_2 ● Closed fire ○ 9.2 x (24x9.1) = 2,009 ○ Emissions 2009 x 0.01545 = 31 ○ 31 x 144 = 4,464 kg CO_2
Summer total = 15,849 kg CO_2
Overall total = 50,697 kg CO_2