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How to Achieve a Low Emission Home - A Case Study

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ABSTRACT

This paper contains a holistic approach to carbon reduction within the household, assessing multiple areas of consumption to identify sectors critical to lowering emissions and solutions that are more effective when combined. It finds that emissions from food and transportation overshadow results from heat and electricity and that lowering emissions through lifestyle changes can be as effective as existing engineering solutions.

Keywords: carbon neutrality, household emissions, energy consumption and holistic design

NONMENCLATURE

Abbreviations	
GHG	Greenhouse Gas
DER	Deep Energy Retrofit
HER	Hollistic-Decarbonised Electrification Retrofit
IPCC	Intergovernmental Panel on Climate Change
Symbols	
P	Power Generated
m_{CO2}	Mass of CO_2 equivalent emissions

1. INTRODUCTION

Lowering greenhouse gas (GHG) emissions is vital to preventing global warming, something which has highly negative effects on both human and natural systems including greater chance of climate related disasters such as droughts, heatwaves and wildfires.

Since 1990, GHG emissions from households have remained mostly consistent, rather than decreasing as other sectors have [1]. According to the UK government, residential emissions saw a rise of 6.7% between 2019 and 2020 [2]. Residential emissions made up roughly 20.8% of the UK total in 2020 and it is predicted that it will account for 36% of final energy demand in the UK by 2040, overtaking transportation [3]. This is due to heating by natural gas [2] and increased energy demand, which counters the growing proportion of UK energy provided by low carbon sources (9.4% in 2000 to 21.5% in 2020 [4]). If the UK is to meet the requirements set by the Paris Agreement and the Climate Change Act, residential emissions must be decreased significantly.

Agriculture is another large source of CO_2 production, accounting for roughly 10% of UK carbon emission [5]. The IPCC estimate that globally 8.5% of GHG emissions come from agriculture, with an additional 14.5% coming from land use change (primarily deforestation). It can be clearly seen that this is another key area in fighting climate change at both the national and international level, as 45% of UK food consumption is not sourced in the UK [6]. Agriculture is a market, and as such is influenced by the consumers. Thus, part of a household's carbon footprint is the food that they eat.

There are multiple sources of household emissions outside of those generated by gas and electricity. By considering a holistic approach rather than focusing only on direct building emissions, a greater understanding of the problem and its solutions can be realised. Several studies exist exploring the design of systems that use renewable power sources to meet the energy needs of households. However, investigating the effects of changes to food and water consumption, electricity usage, heating, travel and power production to remove emissions across the household is something that has not been done. Some similar examples are the studies done by Wang et al. [7] and Miao et al. [8], but these do not account for the lifestyle factors that this study aims to.

By assessing the problem holistically, a more complete view can be formed on where individual effort is best spent to reduce personal emissions, and where changes must be made by government agencies to see noticeable improvement.

2. THEORY AND METHODOLOGY

2.1 Theory

For this project household emissions were separate into five sectors: electricity usage, fuel usage for heating (primarily natural gas), food consumption, water usage and transportation. Current research into the value of these emissions was assessed to find the initial equivalent CO2 production (CO2e) values for the case study. This data and research into methods of lowering emissions were used to devise several carbon reduction strategies that could be assessed and compared.

In the study of Wang et al. on building retrofits [8], two methods of reducing building emissions are explored, Deep Energy Retrofit (DER) and Holistic-decarbonised Electrification Retrofit (HER). Several components were repeated in both options: lowering energy consumption directly (through energy efficient appliances, low heating temperature and generally reducing electricity usage); adding insulation to reduce heat loss; electrifying natural gas reliant appliances such as boilers and cookers and implementing renewable power generation to decarbonise any essential energy use. The effects of lower energy usage can be found by multiplying the energy used by the carbon intensity factor provided by the UK government for either grid power or natural gas. Grid power carbon intensity varies between UK regions and is also dependant on time of day and weather conditions. For this project the average grid carbon intensity is used, and when the effects of multiple years are considered the UK government projections are utilised [9].

The effects of insulation and reduced heating were calculated using the heat transfer equation, eq. (1), with the difference between the energy transferred from the new values and the original expenditure representing energy saving and carbon emission reduction. The convective heat transfer coefficient is assumed to be 0.1W/m^{2}K for internal surfaces and exterior surface values are based on the wind speed onsite.

$$Q = \frac{A(T_1 - T_4)}{\frac{1}{h_{12}} + \frac{x_{23}}{k_{23}} + \frac{1}{h_{12}}} \qquad (1)$$

where Q is the heat energy, A is the surface area, T_1 and T_4 are the internal and external temperatures, h_{12} and h_{34} are the internal and external convective heat transfer coefficients, x_{23} is the total surface thickness and k_{23} is the total thermal conductivity.

To calculate the power produced by solar panels, eq. (2) was used. Irradiance was found using the Photovoltaic Geographical Information System (PVGIS), an EU science hub modelling software that contains a large quantity of weather data on specific locations. The roof inclination and azimuth were inserted to find the irradiance under the given conditions per average hour each month. Maxeon 3 panels were used for the calculation of the maximum number of panels on each roof section and the panel efficiency. The power every hour was calculated and extrapolated to the whole month by multiplying the sum of the average day by the number of days in the month.

$$P = G_{tot} A \eta \qquad (2)$$

where G_{tot} is the total irradiance on the inclined plane, A is the panel area and η is the panel efficiency.

For wind turbines, following initial feasibility calculations using eq. (3), an example wind turbine (AirForce 1kw) was used, taking the values from the data sheet for power production at various windspeeds (at a 10 m height). This was found in intervals of 0.1m/s, as more precise intervals gave minimal extra power. The power production graph was used over eq. (3) as it was more accurate due to accounting for variable efficiency of the turbine at different speeds, rather than assuming a set efficiency from the power coefficient.

$$P = \frac{1}{2} \rho A_{swept} V^3 C_p \qquad (3)$$

where ρ is the density of air, A_{swept} is the swept area, V is windspeed and C_p is the turbine power coefficient.

Poore and Nemecek found that meat emissions were significant, and red meat was particularly bad, the emissions value of beef being 50 kgCO2e per 100g protein [10]. As such the savings related to diet are a veganism, vegetarianism and a no beef diet. In each case the replaced animal protein will be assumed to be provided by either mycoprotein or soy alternatives.

Food emissions were calculated differently depending on type, as Poore and Nemecek calculated emission data based on the major classification of the foodstuff. Protein heavy items are calculated based on emissions per 100 g protein, starch heavy items are based on emissions per 1000 kCal and other foodstuffs are based on either emission per kg or L. For foods with multiple components, the calculations were done by using the proportion each item made up of its respective area. For example, if a foodstuff was made of beef, potato and grain, the beef and grain portions would use the protein contents in their relative proportions (i.e., 20% grain and 80% beef) and the potatoes would assume they are 100% of the calories. There is assumed to be no emissions from manufacturing combined foodstuffs, as specific data per product was difficult to obtain.

A 2009 report for the Environment Agency and Saving Energy Trust by Elemental Solutions [11] provided much of the base data for water emissions such as the carbon cost of the UK water supply per L. Water calculations also found the energy used to heat water to the target temperature from the average cold-water temperature for each month [12]. This was done using eq. (4). The "water use" sector included any electricity or fuel used for water-based appliances: baths, showers, dishwashers and washing machines. Where possible manufacturer information on appliance energy usage was used for calculations.

$$E = \eta_{boiler} m C \Delta T \qquad (4)$$

where *m* was the mass of water to be heated, *C* was the specific heat capacity of water, ΔT was the temperature change and η_{boiler} was the boiler efficiency

Vehicle emissions for hydrocarbon vehicles were calculated using eq. (5), and for electric vehicles, eq. (6) (based on the emissions per kWh) was used.

$$m_{CO2} = U_{mCO2}\, d \qquad (5)$$

$$m_{CO2} = \frac{E_{BatTot}}{d_{range}}\, C_{CO2}\, d \qquad (6)$$

where d is the distance travelled, U_{mCO2} is the CO_2 emissions per km, E_{BatTot} was the total battery storage, d_{range} is the average distance the car can travel on 1 charge and C_{CO2} is the grid carbon intensity.

2.2 Case Study

The case study location is in Derbyshire, UK and is a detached house with 4 residents. Energy consumption is above UK average but is only slightly above expected for the household type. Total gas and electric usage were taken from household bills, with average UK data for households used to extrapolate usage throughout the day [13]. Food consumption was found by considering 3 different weeks in the year. Water consumption was found to closely resemble UK average, so this was used. Usage of water consuming appliances was provided by the occupants, as was insulation data and efficiency of appliances. Dimensions were found directly. The case study has electric ovens and hobs, so natural gas was only used for heating, simplifying calculations.

2.3 Methodology

Excel was used for programming, simulating calculating the results due to the large quantity of data that needed to be processed. It also allowed the creation of a user interface that ensured that many options could be combined and compared.

When calculating the savings from insulation or changes to heating temperature, the walls, windows, floor and roof were calculated separately, and the total loss combined to give an estimate of the energy needed to maintain a steady temperature. T_4 was found for the average hours in a day each month (such as the average temperature at 10:00 any day in January) sourced from PVGIS. Average data was used to make the results more applicable long term, as if more specific results (for instance every hour for the whole year) were used then the data would not fit the location long term.

In practice there is a difference between the theoretical value derived and the actual amount used, due to several factors: airflow/convective heat transfer within the building, internal walls, airflow outside (for ventilation/cooling in warmer months), solar heating of the house, periods where the heating is set to different temperatures (or is off), inefficiencies in the heating system (radiator losses, pipe losses etc.) and additional heat input to the building from electronics and cooking. There is also the consideration that the house may simply not always be at the target temperature.

To account for these discrepancies, the theoretical energy loss was calculated before savings were considered (with a target temperature of 20°C being assumed). Then the theoretical and real values were compared, with a percentage error for each month being found. This was then applied to the calculated changes to ensure greater accuracy. This method was deemed acceptable as the study is focused on a general analysis, but if further research was to be done more detailed analysis with specialised software would be advised.

The UK Household Energy Survey was funded by the Department for Environment, Food and Rural Affairs, the Department of Energy and Climate Change and the Energy Saving Trust and provided a breakdown of energy consumption from May 2010 to July 2011 [13]. This data was used to calculate electricity consumption throughout the day, by finding the proportion of the total energy used at any point from the survey and applying that to the case study data for the given month.

Biogas calculations were done using existing data on yields from various feedstocks, and were verified using ECLIPSE, with the assumption that the biogas produced was 60% methane, 40% CO2. There were no considerations made for the temperature that the digester was kept at and its effect on the rate of production. The LHV of this biogas was then used to calculate the energy from combustion, with appropriate losses being applied based on the use such as boiler efficiency, or electrical/thermal efficiency a CHP generator. It was also assumed that biogas is used as needed, as an appropriately sized storage tank would be selected, rather than needing to be used at a constant rate to avoid excess production.

In the calculations for the effect of individual methods upon the house, it was assumed that there was no battery storage, as this would increase cost. This was feasible because when the energy is sent back to the grid it is countering high emission grid energy sources.

Food emission values were found using the weekly shopping list of the case study family and multiplying the relevant information (protein/calorie content or mass) by the emission data from Poore and Nemecek [10]. Poore and Nemecek included 10th percentile results, as their study found that for many foodstuffs the GHG emissions had a large variety across different farms, and that the main source of these emissions tended to vary. These were used for several items that were confirmed to be from lower emission sources.

The average distance travelled each week by members of the case study on both public transport and by car was found by averaging the results of several weeks. For personal transportation, the emission value of the vehicle was found from the manufacturer website. An additional emission factor from manufacturing was found using the manufacturing emissions [14] divided by the predicted vehicle lifespan at the given yearly mileage. For electric vehicle calculations, the typical distance per kWh of energy was used, and electricity used for charging was considered a transport emission. For public transport, values from the government report on company emissions were used [15].

3. RESULTS AND DISCUSION

3.1 Initial Results

The initial yearly emissions from the case study house was 18.23 tonnes CO2e, the exact breakdown found in table 1. Transport and food emissions within the house represent a bigger portion of the case studies of emissions than electricity or gas usage. The food emissions are above UK average, Sandstrom et al finding food emissions in the UK were on average 1150 kg CO2e per person each year [16].

Sector	GHG emissions/(kgCO2e)
Fuel Use	3257
Electricity Use	1222
Food Consumption	6367
Water Use	834
Transportation	6552

Table. 1. Initial emissions from the case study.

3.2 Individual Actions

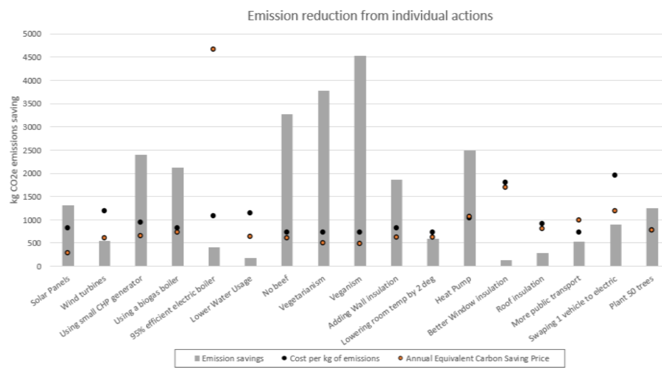

Fig. 1. The carbon reduction and cost per kg of emissions from the individual saving methods

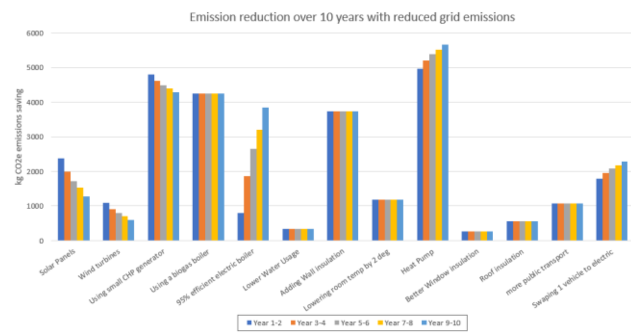

Fig. 2. The effect of lower grid emissions on carbon reduction over 10 years.

Figure 1 shows the effects of individual actions on lowering emissions. The biggest changes come from a modified diet, which matches the family's high emission diet. This is largely due to the case study consuming a larger than average amount of beef, so removing this source lowers emissions by 3273 kg CO2e, a massive proportion and a clear way to reduce GHG production.

The cost per kg of emissions was found using the yearly CO_2 savings and the annual equivalent cost (AEC) of the action (the cost per year over its lifespan). The Annual Equivalent Carbon Saving Price (AECSP) was the AEC of an action minus the savings provided. This represents the financial benefits of paying less for electricity, natural gas and transport fuel, and provides an effective way of measuring the viability of carbon saving methods for households. These results did not consider the changing prices of fuel and electricity.

The cost analysis on the graph shows several options that were significantly more economically viable than others. Options that had a negative "cost" per kg of emissions saved represented actions that saved money in the long term and so were better choices financially.

Figure 1 shows that solar panels are a good choice for reducing emissions. Not only are they an effective method of reducing carbon emissions, but they also proved a financially viable decision as well.

The consideration long-term savings made options involving renewable power production more financially viable due to the high cost of electricity. Options that reduced gas and electricity use are likely to become more viable in the future due to rising gas and electricity prices, which has not been modelled here. Alternatively, options that increased electricity usage such as an electric boiler immediately became significantly worse choices for the same reason. An electric car had some of these concerns, but the money saved on fuel over the vehicle's lifetime countered the added cost of electricity.

Roof and wall insulation were better choices than window insulation for this study. However, this was a biased result, as the case study already possessed well insulated windows but lacked effective roof or wall insulation due to its construction and age.

Changes such as using more public transport (changing 10% of car transport distance to bus/train travel based on the family's usual routes) or modifying diet had zero upfront cost. Changing diets showed savings due to the high cost of meat compared to vegetables. Public transport was less financially viable, representing a net loss due to the saving being fuel cost against the price of bus and train tickets.

Figure 2 shows projected emissions over 10 years, sectioned into 2-year periods. Power generation methods typically reduced in effectiveness at carbon reduction as grid carbon intensity decreases, as with growing renewable power in the electric grid, generating energy at home is less effective at lowering emissions. Heat reduction stayed consistently effective, as the emissions from the burning of natural gas were assumed to remain roughly constant. Heating electrification gradually becomes more effective at reducing emissions over time, so when electrification is considered, the long-term effectiveness must be accounted for. This same effect also applied to swapping to an electric vehicle.

3.3 Combined System

Fig. 3. shows the results of the combined action presented in table 2. Electrification can be seen to be more effective with a heat pump, however its startup cost is double the price so is a harder measure to adopt

System	Components	Startup Cost	Saving per year
Electrification retrofit 1	Solar, heat pump, insulation, electric boiler, reduced water	£28,950	£885
Electrification retrofit 2	Solar, electric boiler, insulation, windows and roof insulation, reduced water	£13,950	£177
Biogas boiler retrofit	Biogas boiler, insulation, reduced water	£9,700	£479
Biogas CHP retrofit	Biogas CHP, insulation, reduced water	£12,000	£945
Passive Systems retrofit	Insulation, reduced electricity, reduced water, lower heating temperature	£7,600	£549
Lifestyle changes	Reduced temperature, reduced electricity, reduced water, veganism, 10% more public transport	£0	£1,700
Electric Vehicles	Both vehicles electric, solar	£79,150	£2,809

Table. 2. Combined actions considered

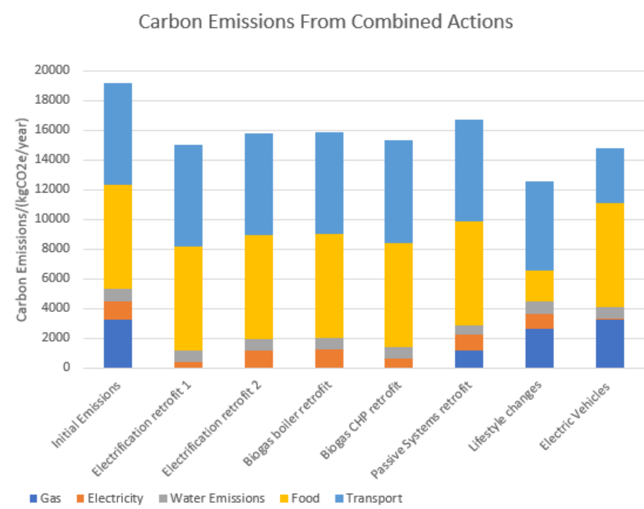

Fig. 3. Carbon reduction from combined actions

on a large scale. Biogas systems proved cheaper, and gave greater savings than an electric boiler, so represent a good option for low-cost options.

Lifestyle changes had no monetary cost, reductions occurring due to decisions such as using less electricity and veganism. This option provided the greatest emission reduction and, having no startup cost, is the cheapest way to lower emissions. The passive system retrofit involved lowered consumption through higher efficiency/low energy appliances and insulation.

Electric vehicles gave high emission reduction and yearly savings, but the initial cost was unfeasible. Due to the nature of the occupant's jobs, replacing private travel with public transport was a limited opportunity.

4. CONCLUSION

Current suggestions assume biomass can be sourced locally. This makes the designs that use it unfeasible for complete carbon reduction long-term. However, if a dedicated feedstock market was established it would be more feasible. This will increase cost and emissions slightly due to transport requirements but allows greater scale adoption of the design. There are problems that this presents such as a greater proportion of farmland being used for biogas, but if carefully managed it holds high potential for carbon reduction. Alternatively, feedstock could be produced at home utilizing the family garden, although this would likely not meet all needs.

From the results of the study, it can be concluded that the best way to reduce emissions is to make lifestyle changes that remove high emissions from food and reduce consumption. The recommended lifestyle changes for this case study are to lower water/electricity use by 10% (bringing them closer to UK average), combined with removing beef from the family diet (an easier change than complete vegetarianism). These changes should reduce emissions by 3.47 tonnes CO2e.

However, this cannot remove all emissions from the home, and so these options are best combined with a biogas CHP generator (with digestor), wall insulation and solar panels (which are a particularly financially viable option). This will increase the reduction to 8.5 tonnes CO2e, save £1650 each year (not including the savings from less beef) and cost £16,000 initially (for roughly 10 years payback period). These options were considered over transportation changes due to transports higher cost per kg of emissions reduction.

Overall, the most effective individual method of lowering household emissions is a reduction in meat consumption, due to minimal cost. Solar panels, better insultation and a reduction in water use were all also very financially viable. Despite transportation emissions representing a larger portion of the "carbon footprint", buying an electric car was not as feasible as reducing household emissions due to high initial cost.

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