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CASE REPORT

Carbon neutral Biggar: calculating the community carbon footprint and renewable energy options for footprint reduction

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Abstract The objective of this research was to develop a community carbon footprint model that could be used to assess the size and major components of a community's carbon dioxide (CO_2) emissions. The town of Biggar aims to become Scotland's first carbon neutral town. As expected for this rural community, car transport accounted for nearly half of the CO_2 emissions, with natural gas and electricity consumption resulting in a further 24% and 12% of total emissions, respectively, and air travel being the last major component at 10% of emissions. An assessment was also made of the wind and solar resources of the town. One large wind turbine would provide the town's electricity, while three to four turbines would be needed to offset all CO_2 emissions. In contrast, offsetting by tree planting would require in the region of 2,000 ha of trees.

Keywords Carbon footprint · Carbon offsetting · Emissions · Modelling · Renewable energy · Wind energy

Introduction

From 1750 to 2005, global atmospheric concentrations of carbon dioxide (CO_2) increased from 280 to 379 ppmv (Alley et al. 2007). As stated by the Intergovernmental Panel on Climate Change 'Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level'. The largest contributor to global warming is CO_2, which is responsible for about 63% of the positive change in radiative forcing from 1750 to 2005 due to long-lived greenhouse gases, and comprises 78.7% of greenhouse gas emissions by CO_2 equivalent (Alley et al. 2007). Fossil fuel consumption is responsible for 56.6% of total CO_2 emissions (Alley et al. 2007). There is action at government level as evidenced by the more than 100 signatories to the Kyoto protocol, who agreed to reduce their overall greenhouse emissions by 5% from 1990 levels by 2012 (Ball 2007). The United Kingdom (UK) Government is committed to reducing the CO_2 emissions of the UK to 60% of 1990 levels by 2050 (Odenberger and Johnsson 2007). In addition to action at international and national levels, there is an increasing movement to reduce emissions of greenhouse gases at local and individual levels, which require commensurate measurement tools. The term 'carbon footprint' has become a phrase used to encompass the CO_2 equivalent emissions resulting from the life cycle of a product or activity (Wiedmann et al. 2006). The carbon footprint of a household or individual is therefore the sum of CO_2 emissions resulting from all products or activities consumed. Any agent attempting to reduce CO_2 emissions must have the necessary tools available to measure this reduction. The community carbon footprint model (CCFM) has been developed for this purpose and is described below.

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Carbon footprint model development

The CCFM was developed to estimate the carbon footprint of a community of households and requires analysis of all forms of direct and indirect CO_2 emission from households in a community. The village of Biggar in South Lanarkshire, Scotland would like to become the first carbon neutral village in Scotland and thus provided an ideal case study for the CCFM model to be applied. The aim of the Carbon Neutral Biggar project is to calculate and reduce total community or individual member CO_2 emissions on a year to year basis.

The methodology considered here is bottom up in nature and conducts process analysis on the items being considered using a life cycle analysis (LCA) approach. Details of CO_2 emissions based on production, consumption and disposal of various items in the community are collected. Only by considering all stages of an item's lifecycle can total emission generation can be derived. Essential to this methodology is the consideration of boundary implications so that the risk of double counting emissions is eliminated (Munier 2004). The LCA boundary conditions also determine the amount of data that will need to be collected, which provided the underlining basis for the CCFM.

Information about the community

Emissions from households are only part of the total CO_2 emissions in the community. The UK Department of Environment, Food and Rural Affairs estimated that industrial and commercial sources account for 51% of CO_2 emissions on average in Scotland, while domestic and road transport sources account for 31% and 27%, respectively (Defra 2006). In addition to the development of the CCFM in this paper, which focusses on household emissions, an initial assessment has also been carried out on the feasibility of using a similar model for estimating commercial contributions to the community carbon footprint.

The model was developed and applied to the Scottish town of Biggar. Biggar is a market town within commuting range of the major Scottish cities of Edinburgh and Glasgow. Using postcode data, the number of households in Biggar was determined to be 1,082. Using census data projections, the household occupancy rate was taken to be 1.99, giving a population of 2,153 (General Register for Scotland 2005). Local businesses stem from the tourism, service and agricultural industries, and include hospitals and schools, restaurants, farms, and some manufacturing and consulting firms. To quantify residential information, a survey was distributed to all households in the town of Biggar and the data collected were used to develop and apply the CCFM model. Consumption rates from households of similar categories were determined to remove the need for using national average data and allow a more accurate mechanism for scaling CO_2 emission rates across the whole community. Absolute accuracy was deemed less important than relative accuracy and obtaining measurement uncertainty was a priority. In general, the CCFM provides a community-specific method for scaling the emissions calculated for a subset of households within a region to estimate the emissions for an entire community. Central to this model is ascertaining the percentage of particular household categories that make up an overall community, as this uniquely distinguishes emission characteristics from simple categorical averages and highlights the relevance of a carbon calculator designed for community-specific modelling.

Community footprint model components

When determining which components to include in the CCFM, a balance was struck between those activities which result in the highest emissions, those which can be measured with a degree of accuracy, and those with which the community being modelled have some control over. Given these criteria, energy use, transport and waste data were collected from the community as described below:

1. *Car travel* Published metrics for the CO_2 emissions from the burning of vehicle fuel were taken from Defra (2007), giving 2.63 kg CO_2 per litre of diesel consumed and 2.315 kg CO_2 per litre of petrol. Using these values and the calculated volume of fuel consumption from miles per gallon (MPG) and miles travelled per week (MPW), the calculation of CO_2 emissions for individual households was made. A cross-check of transport emissions was made using data based on fuel and car engine size, as shown in Table 1.
2. *Public transport* Two forms of public transport were considered in this model: transport by train and by bus. Emissions from travel by taxi have also been included, although this is not classified as public transport. The carbon dioxide emission factors (CO_2 kg km^{-1}) used for these methods of transportation are: bus 0.0891, train 0.0602, taxi 0.424 (Defra 2007). These include a consideration of the load factor for the bus and the train to account for the vehicle not running at full capacity on every journey.

Table 1 Average emissions of CO_2 per mile based on fuel and car engine size (Defra 2007)

Fuel type	Car size	Engine size (l)	CO_2 per mile (kg)	CO_2 per km (kg)
Petrol	Small	<1.4	0.2947	0.1842
	Medium	1.4–2.0	0.3479	0.2174
	Large	>2.0	0.4769	0.2981
Diesel	Small	<1.7	0.2424	0.1515
	Medium	1.7–2.0	0.3027	0.1892
	Large	>2.0	0.4240	0.2650

3. *Transport by plane* Aviation contributes about 5.5% of UK CO_2 emissions, and passenger numbers at UK airport are increasing at about 6% per year (Woodcock et al. 2007). Due to the forcing effects of other chemicals released by airplanes at high altitudes, the effect that aviation has on climate is estimated to be about 11% of the UK total impact (Sausen et al. 2005). However, due to the uncertainty, an extra radiative forcing factor was not applied in the CCFM. Flight length estimates and corresponding emissions were taken from European flight statistics (European Environment Agency 2006). Because this metric assumes medium haul flight lengths originate in London, an additional factor (for this case study, 600 km) was added to flight lengths not originating in London. Emissions were estimated per flight using the CO_2 conversion factors shown in Table 2.
4. *Household energy consumption* There are numerous different mechanisms available for estimating electricity consumption, or load profiling, e.g. Yao and Steemers (2005). Of the various methods considered, the most accurate method was determined to be profiling a household based on its respective household category. Annual average electricity and natural gas bills for Scotland are £359 and £463, respectively, for the consumption of 3,300 kWh electricity and 18,000 kWh natural gas (DTI 2007). From this and the survey data, the total kWh consumed per household category was determined. With this data, total CO_2 emissions per category were calculated assuming conversion factors of 0.53 kg CO_2/kWh for electricity consumption and 0.208 kg CO_2/kWh for natural gas usage (Defra 2007).
5. *Waste* The majority of the municipal solid waste (MSW) generated in the UK is transported to and disposed of in landfill sites. At landfill sites, the gas generated is estimated to be 50–60% methane (methane has a global warming potential 23 times greater than that of CO_2 (Spokas et al. 2006) and 40–50% CO_2. Waste disposal may also occur by incineration, which, if used for electricity generation may actually be a negative greenhouse gas emission as the electricity generated offsets some of the need for burning fossil fuels (Holmgren and Henning 2004). The CCFM accounts for a proportion of waste collected to go landfill with and without flaring. The site considered is a 1,000,000 tonne site of MSW. The emissions from this landfill site are averaged over the lifetime of the site to give an average emission rate per tonne of landfill MSW of 577 kg CO_2 equivalent per tonne if landfill gas is flared and 1,365 kg CO_2 equivalent per tonne if gas is not flared (Lombardi et al. 2006).

Table 2 Average emissions of CO_2 for different flight types (European Environment Agency 2006)

	CO_2 per passenger km (kg)	Estimated distance of flight (km)	CO_2 per flight (kg)
Short haul	0.172	463	159
Medium haul	0.142	1,708	486
Long haul	0.115	6,482	1,492
Extended	0.115	10,000	2,302

Application of the model

Data about the community

Using data from Royal Mail postcodes, the total number of household addresses in Biggar was calculated to be 1,112. Estimating from the General Register for Scotland that 2.7% of these households were vacant, the total number of occupied properties was taken to be 1,082. The household occupancy rate (number of persons in the dwelling) from the 2001 census was 2.06, which is lower than both the Scottish average (2.27) and the South Lanarkshire average (2.26). Furthermore, since 2001, the occupancy rate for households in South Lanarkshire has decreased by about 2.5%. Applying this information to Biggar, the occupancy rate was calculated as 1.99, resulting in a population of 2,153.

In the week commencing 12 March 2007, a household survey was distributed to all households in Biggar. Households were asked to complete the survey estimating values for the previous 12 months. The survey was also made available online, at community centres and in schools, and an article appeared in the local Lanarkshire Gazette, which helped publicise the survey distribution.

Because survey completion rates were important, design simplicity was stressed. To this end, a range of values was offered for selection wherever possible. Using somewhat arbitrary data ranges compromises the accuracy of the results slightly; however, it was anticipated that this would increase the number of surveys completed, which in turn would increase the representativeness of the data and the ability to model uncompleted surveys. Increasing community involvement is also important because participating in ecological footprinting analysis encourages participating members to take action to reduce their own ecological footprints (Sutcliffe et al. 2008).

Data were collected on each of the model components from 150 households out of approximately 1,000 in the community of Biggar, representing a completion rate of 13%. As a result, a mechanism needed to be implemented

Table 3 Household categories used by the community carbon footprint model in the Biggar application and CO_2 emissions for the major CO_2 emission sources

Household category	Number of surveys returned	Demographic scaling factor	Number of households (%)	Scaled average CO_2 emissions per household (tonnes)				
Total	150		1,089	Air travel	Car travel	Electricity consumption	Gas consumption	Waste
A: Multi-person household—all pensioner	38	3.8	143 (13)	1.20	2.70	1.76	4.89	0.73
B: One-person household pensioner	19	14.3	271 (25)	0.79	0.94	1.82	3.25	0.73
C: One person household	20	6.8	135 (12)	3.75	2.20	1.82	2.05	0.73
D: Couple—no dependent children	34	7.9	269 (25)	1.40	12.07	1.81	4.29	0.73
E: Couple—dependent children	28	6.9	192 (18)	1.69	16.22	2.29	4.21	0.73
F: Lone parent dependent children	7	6.8	47 (4)	1.42	11.03	2.26	3.64	0.73
G: Other	4	6.2	25 (2)	2.13	24.76	2.73	4.72	0.73
Scaled total community CO_2 emissions (tonnes)				1,716 ± 361	8,433 ± 696	2,095 ± 694	4,115 ± 686	792 ± 198

The average CO_2 emissions per household are given for each of the major sources (these are scaled using the demographic scaling factor). Total community emissions are calculated as the scaled average per household per category multiplied by the actual number of households

to scale the input data to account for the emissions of the whole community. The UK national census, which last took place in 2001, provides a useful mechanism for categorising households and aggregating population data. It was assumed that the relative percentage of household types within the community has not changed since 2001. Using these proportions and 2007 survey data, the number of households within each category was calculated as shown in Table 3. Next, a demographic scaling factor was defined for each category, which was used to scale returned survey data of each household category in order to account for all households in the community (Table 3). The total community emissions can be calculated using the scaled average CO_2 emissions per household multiplied by the actual number of households in each category.

Transport by car

It was anticipated that car type details would be easily obtainable from survey respondents, but information concerning MPW and MPG would be less reliable.[1] Still, both types of data were requested, which enabled two types of CO_2 calculation methods and hence a mechanism for verifying the consistency of the completed surveys. The first technique used car ownership figures for the town as given by survey respondents. This number multiplied by a household scaling factor puts the total number of cars in Biggar at 1,282 or 1.18 per household (compared to 1.08 reported in the 2001 census). Using this figure, the CO_2 conversion factor for each car type (as given in Table 1) and the average MPW travelled by that household category, the total car emissions for the community was calculated as 8,433 tonnes (Table 4).

Using fuel consumption figures (MPG) from the survey and the MPW figures, an alternative mechanism for calculating emissions was made using individual household data. The variation in differences between the two methods of calculating household emissions offered a mechanism for gauging the accuracy of the input data. The annual average difference per household was 643 kg CO_2 with a standard deviation of 1,058 kg. The average difference in the two calculation mechanisms was used by the CCFM to estimate the error in the final emissions and so the figures are taken to be accurate to 8%. An annual average of 9,547 miles (15,364 km) travelled per person gives an average CO_2 emissions per household of 7.8 ± 0.6 tonnes and total annual emissions from cars in Biggar of 8,500 ± 700 tonnes CO_2.

Public transport

There is a limited bus service to the nearby town of Lanark and the city of Edinburgh from Biggar. Of the surveys

[1] Although petrol is sold in litres in the UK, distances are typically given in miles and fuel efficiency is still often given as miles per gallon. For conversion purposes 1 mile is equal to approximately 1.6 km and 1 gallon is approximately 4.55 l. Hence 30 miles per gallon is equivalent to about 7.84 l for 100 km.

Table 4 Suggested methods to reduce community emissions without lifestyle changes and the potential CO_2 savings

	Estimated CO_2 emissions (tonnes)	Method	Anticipated CO_2 emission saving (tonnes)
Car travel	8,433 ± 696	Driving practice/biofuels	421–2,958
Gas	4,115 ± 686	Insulation/temperature reduction	312–727
Electricity	2,095 ± 694	Energy efficient lightbulbs	48–209
Air travel	1,716 ± 361	Reduce short haul flights	193–386
Waste	792 ± 192	Reduce/recycle	79–158
Total	17,150		1,053–4,438

returned, 44% indicated use of either the bus or train on a weekly basis. A total number of miles for each household category was calculated and again scaled up for the whole town using the demographic scaling factor for each household type. Despite the poor service availability, the annual average distance travelled by public transport per person in Biggar is 909 miles (1,454 km). The main source of error with the calculation of CO_2 emissions from public transport results from the large range of mileage options offered for selection in the survey. The total emissions that were used for public transport were taken as the mean of the minimum and maximum emissions values calculated. The corresponding uncertainty encompassed the potential range of emissions. The total public transport CO_2 emissions per household were 0.2 ± 0.07 tonnes and the community total was 252 ± 80 tonnes.

Transport by plane

Nearly two-thirds of all households in Biggar, or 63%, took at least one return flight in the last year. Households were asked to select the number of short haul, medium haul, long haul or extended return flights trips taken last year. This range was used in the model in order to calculate the minimum and maximum potential range of flights in each category and resulting aviation-based emissions for the town. The total number of return flights taken was calculated to be 2,964 ± 527, which equates to 2.7 flights per household or 1.4 flights per person. Nearly half, or 48%, of these flights were short haul. The total CO_2 emissions as a result of flights taken by householders in the community were calculated as 1,714 ± 361 tonnes.

Household energy consumption

It was anticipated that householders would find it easier to list the monetary value of their electricity consumption over the last year, rather than the total kWh used. Hence a range of monetary values was offered for households to choose from. Taking the average of all 150 households who returned a survey gave a monetary value that is approximately equal to 3,706 kWh electricity consumed per household. After demographic scaling, the CCFM calculated an average consumption of 3,702 kWh per household over 1,082 households. This amount is slightly higher than the UK average of 3,300 kWh as cited in DTI (2007).

Due to the liberalised nature of the energy market in the UK and the number of different suppliers used in Biggar, there is likely to be a price variation from household to household. Using an online tool (http://www.uswithc.com) that compares electricity prices, it was found that the range of electricity prices per kWh in Biggar varied by up to 27%. This spread, therefore, was taken to be the uncertainty of emissions. The value used for the CO_2 emissions from electricity consumption was computed as the mean of the minimum and maximum values possible from the survey data ranges. An additional uncertainty of 6% was used to account for the range of emissions (minimum to maximum) within each household category.

A top-down approach was also taken to assess total electricity consumption in Biggar. A main substation is located near the town, from which two 11 kV distribution lines supply Biggar and three lines feed the surrounding suburbs. The distribution network operator of the region, Scottish Power, provided analogue data of the current drawn along each of these lines. The hourly current readings provided were used to calculate household and commercial energy demand and 0.2 GWh of street lighting. A total demand of 10.28 GWh was calculated for the whole town of Biggar from June 2006 to May 2007, resulting in 5,376 tonnes CO_2. The area within which Biggar lies showed a split of 66% household consumption and 34% commercial/industrial consumption. This puts the household consumption at 3.39 GWh for approximately 573 households, giving a total household consumption of 6.78 GWh, considerably higher than the 4.04 GWh estimated using the CCFM. The discrepancy is larger than the uncertainty of the CCFM (±33%) and likely derives from the use of discrete values in the survey and the conversion from a monetary value to electricity consumption. Also, demographic scaling from the survey respondents to the whole community and discrepancies in the overlap between the population of Biggar who returned the survey and that of the entire community may add to the discrepancy. Finally, the assumption that commercial activities only use 33% of the distribution line electricity may be slightly understated.

Natural gas is assumed to be used mainly for heating and cooking and is consumed by 76.7% of households surveyed. Scotia Gas (the private natural gas distribution company for Scotland) provided consumption figures for 964 natural gas meters within the Biggar postcode region, including 3% commercial meters and 97% residential (DTI 2005). The average scaled value of natural gas consumed per household is 15,627 kWh, which creates a total of 4,115 tonnes of CO_2 emissions from the community. The issue with variations in pricing discussed above applies equally to natural gas consumption. Consumption, and therefore CO_2 emissions, was adjusted for social tariffs, in the categories for one person households (categories B and C in Table 3), which had considerably lower bills than the area average. Total uncertainty is estimated at ±20%, with some ambiguity arising from the survey (5%) and the rest coming from uncertainty in the £/kWh conversion value (15%).

Waste

Carbon dioxide equivalent resulting from landfill waste is a significant contributor to community carbon emissions. Waste measurements were therefore included in the CCFM to underscore the importance of waste reduction/diversion from landfill as a useful means of emissions reduction. Community level data are available for the tonnage of waste deposited in landfill from a variety of sources. To determine the amount of emissions caused by waste at an individual household level, a mechanism was required to translate a volume of waste (determined by the size of the bin in use) to a tonnage. Survey respondents provided estimates of how full household bins were when collected, which allowed an aggregate volume calculation. This was translated into a mass using a waste density figure. Data collected from household and commercial surveys suggests the average household bin contains 160 l waste and commercial bins were full when collected (Note: waste figures do not include recycled material and survey results show that 83% of Biggar households participate in recycling). This gave an estimate of 169,265,000 l of collected waste, which correlates to 41,500 tonnes for the 39,081 households and 77 commercial properties in the Clydedale area in which Biggar is located. There are models available for estimating the amount of MSW generation (Dyson and Chang 2005) but a simpler method was more appropriate in the community footprint model. For the waste category, the demographic scaling did not work (the standard deviation of values in each category was extremely high indicating there was no similarity in waste generated between households within the same demographic group). As a result, for the waste category, the model uses an average that was calculated as the same for every household in the community. For the Biggar community, a total of 1,112 tonnes of waste was sent to landfill in 2006/2007 or 1,028 kg per household resulting in a total of 792 tonnes of CO_2 equivalent emissions. Still, as in the other forms of CO_2 estimation, some uncertainty is unavoidable. Error due to household estimation of how full the bins are when collected is up to 25%. Also because Biggar waste goes to two landfills, respective waste treatment at each landfill must be considered. Emissions are almost 2.5 times lower at sites where methane flaring occurs in comparison to sites where it does not. Approximately two-thirds of the waste collected from Biggar is taken to a landfill site where there is no flaring and the remaining one-third goes to a landfill where flaring occurs. Given these variables and their respective uncertainties, estimated annual CO_2 emissions from waste in Biggar are 0.7 ± 0.2 tonnes per household or 792 ± 198 tonnes for the community.

Community carbon footprint: residential data

Using data collected from householders in Biggar and the assumptions described above, the CCFM was used to calculate a household carbon footprint for the town. The estimated emissions are shown in Table 3 and Fig. 1 along with the uncertainty in each component of the model. The largest contributions are the emissions from transport, in particular car travel (49%). Household energy consumption (electricity and natural gas) is the next largest contributor (35%). In addition to providing aggregate emission results, individual household footprints were also calculated using the same household survey data used to develop the CCFM. These individualistic results provide a mechanism for community members to compare their respective emissions with each other and the community average, in addition to being able to monitor their results over time. The carbon footprint obtained by simply averaging all individual results was 13.6 tonnes per household, compared with 16.1 tonnes from the CCFM.

Commercial carbon footprint

An initial assessment was made to determine the applicability of a life cycle assessment (LCA) model such as CCFM on commercial properties (including hospitals and schools). As a market town serving the local community, Biggar has a wide range of service (shopping, restaurants, banking, etc.), farming and manufacturing industries, which are difficult to group into narrow categories. Still, a survey was distributed to all businesses, museums and municipal buildings in Biggar. A total of approximately

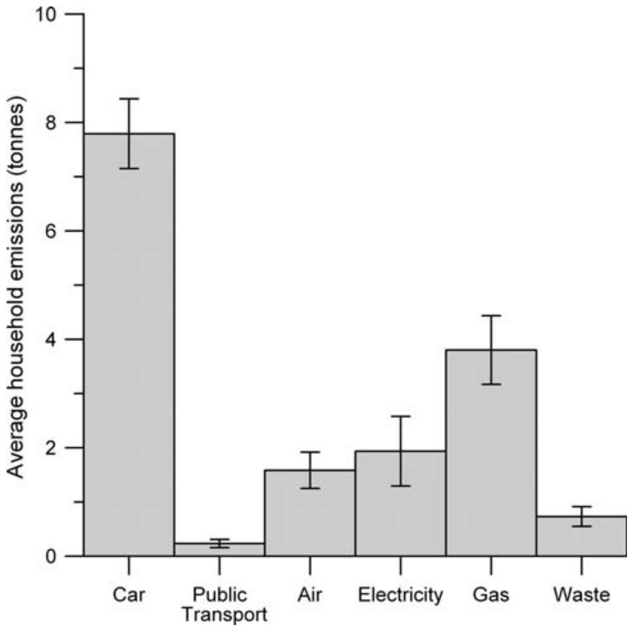

Fig. 1 Biggar's average household CO_2 emissions by category. *Error bars* Estimated uncertainty

100 surveys were distributed, of which 18 were returned—an encouraging return rate, higher than that of the household survey. Of these, approximately half were completed fully but, unlike household consumption patterns, no pattern was found with the data returned in the commercial survey. The community model components all vary greatly from enterprise to enterprise, making modelling using a LCA technique more complex. Calculating the individual component emissions is possible for each enterprise that returned a survey, but because individual results cannot be scaled to reflect the wider business community, a 100% return rate would be required to form an accurate carbon footprint of Biggar's commercial enterprises. Alternatively, a top down approach using aggregate electricity and natural gas consumption data could be used to form a reasonable commercial carbon footprint; however, this approach was not adopted in this study.

Carbon neutral strategies

The aim of the Carbon Neutral Biggar campaign is to reduce the carbon footprint of the community. There are obviously steps that individuals can take to reduce their carbon footprint but, if the community is to become carbon neutral, there will be a need for energy use to be reduced and for other strategies, such as offsetting emissions and using renewable energy sources, to be implemented. Some of the options are considered below. Total community CO_2 emissions are estimated as 17,402 ± 2,715 tonnes, comprising car travel 8,433 ± 696 tonnes, air travel 1,716 ± 361 tonnes, natural gas consumption 4,115 ± 686 tonnes, electricity consumption 2,095 ± 694 tonnes, waste 792 ± 192 tonnes and public transport 252 ± 80 tonnes (Table 3). Thus, the CCFM calculated that the greatest source of CO_2 emissions in Biggar result from transport by car. People in rural areas have few choices regarding transport. In a survey, 89% of motorists agreed with the statement "I would find it very difficult to adjust my life-style to being without a car" (Ryley 2001). Therefore, any attempt to establish a low carbon economy, will have to address this issue. An easy way to reduce emissions resulting from car use is to tackle fuel consumption through use of more efficient vehicles and adjusting driving practices [e.g. compliance with speed limits and other measures can reduce fuel consumption by between 5 and 17% (Dentonkelaar 1994)]. Achieving this would reduce Biggar CO_2 emissions by up to 2,958 tonnes. Car clubs and car pooling are alternatives that have been shown to operate successfully when environmental consciousness is high (Shaheen et al. 1998; Enoch and Taylor 2006). Increased provision of public transport is essential but must meet community needs to ensure bus occupancy rates are high so that CO_2 emissions per passenger-km are lower than cars (Enoch and Taylor 2006). Reductions in CO_2 anticipated from the introduction of 2.5% biofuels into the UK vehicle supply mix on 15 April 2008 have not been considered.

With 48% of flights being internal short haul flights within the UK, there is a great potential for reducing emissions if public transport is promoted more successfully. Travelling on a 463 km short haul flight emits 87% more CO_2 than travelling the same distance on a train (see section on "Community footprint model components" above). Given the estimated CO_2 emissions from short haul flights from Biggar residents was 222 tonnes, a reduction of 193 tonnes is possible by using a different mode of transportation.

The second largest contributor to household CO_2 emissions in Biggar results from energy consumption. Tackling this issue requires renewable energy options, considered below, as well as measures to reduce demand. It is estimated that 40% of energy used in buildings over 10 years old is wasted due to poor quality construction fabric and inefficient building systems (Kelly 2006). Only 6% of Biggar residents who returned a survey lived in homes built in the last 25 years, and at least 38% of those households surveyed had less than the nationally recommended level of 270 mm of roof insulation. Thus, there is a huge potential for energy demand reduction in this community. Improving insulation alone would bring a 20% saving to 38% of households, or approximately 312 tonnes of CO_2. Additional reductions can be made by turning heat down by 1°, which is estimated to save about 10% on heating bills, or 412 tonnes CO_2. In addition to improving efficiency of household appliances (Mansouri et al. 1996), a range of simple behavioural changes can be encouraged to reduce emissions (Wood and Newborough 2007). Lighting currently accounts for 20% of electricity consumption of the average household (Stokes et al. 2004) and 42% of households in Biggar estimated they used some energy saving light bulbs. If the remainder were converted, 800 MWh electricity could be reduced by 20%, equating to an emissions reduction of 48 tonnes CO_2 per year. Significantly larger reductions are possible using cavity wall insulation, double glazing, more efficient boilers and a range of newer technologies such as ground source heat pumps (Everett 2007).

It is assumed here that a 10% reduction in the amount of waste could be achieved by increased reduction and recycling, with up to 20% being possible. Implementation of the minor lifestyle adjustments detailed above would result in cuts of 6–26% of the total CO_2 emissions. There is a great deal of uncertainty in this calculation, but it offers an illustration of some of the easy emissions reductions that can be made.

Even if these changes are implemented, energy demand will remain relatively high. Some CO_2 emissions may be offset but it is likely that additional measures will be needed if the town is to become carbon neutral. In the following section, several solar and wind renewable energy options are discussed, with a focus on individual to community-level scale implementation.

Solar options

The primary factor in determining the solar resource of a region is its latitude. To optimise the output of any solar conversion device, it is necessary not only to know the amount of solar insolation it will receive, but also to understand the sun's position in the sky at any given time or day of the year (Li and Lam 2007). The optimal tilt angle depends on several factors including the ratio of direct to diffuse radiation. The angle of incidence does not apply to diffuse radiation, but direct beam radiation makes a substantial proportion of global irradiance—approximately 40% in the UK (Smith 1978). Conversely, optimising the angle of incidence may require a tracking device, which is unlikely to be economic on a domestic device. The optimal tilt angle for Biggar is slightly less than its latitude because Scotland is often overcast and because the angle should be biassed for the high summer sun. To ascertain the solar resource of Biggar, Scotland, hourly global irradiance data from the years 1991–1997 were obtained from the nearest UK Meteorological Site, Drumablin. The hourly data were processed to remove erroneous data and formulate daily averages for each month of the year (Fig. 2).

Based on the work of Tang and Wu (2004), for the location of Biggar, a solar collector would lose 27% of potential global irradiance on average over a year if the tilt angle were fixed at a horizontal position instead of being repositioned 12 times to the monthly optimal angles. If the collector is to be mounted permanently in place, positioning it at a tilt angle of 40° will reduce total losses from 27.13 to 6.32% as compared with the horizontal. Obviously repositioning the collector on a regular basis will increase annual energy yields; however, doing so more than twice per year will not increase yields by greater than about 1.2%. Adjusting the pitch twice a year, once at the spring equinox, and again at the autumn equinox, will increase annual irradiance by approximately 5% or 1.7 kWh/m^2 as compared to a stationary pitch of 40°.

Solar thermal

Solar thermal is by far the most prevalent form of microgeneration in the UK today, with 78,470 systems installed as of 2006, representing over 95% of all microrenewable installations in the UK (DTI 2006). Solar thermal devices capture the sun's heat energy and transfer it a secondary medium such as water or air. As such, the objective of thermal devices is to absorb as much shortwave solar radiation and release as little long-wave thermal radiation as possible. Although most radiation incident on solar thermal devices will come from direct solar radiation, unlike photovoltaic technology, solar thermal devices can also receive energy from diffuse radiation sources, which may increase their attractiveness for use in cloudier climates like that of Scotland.

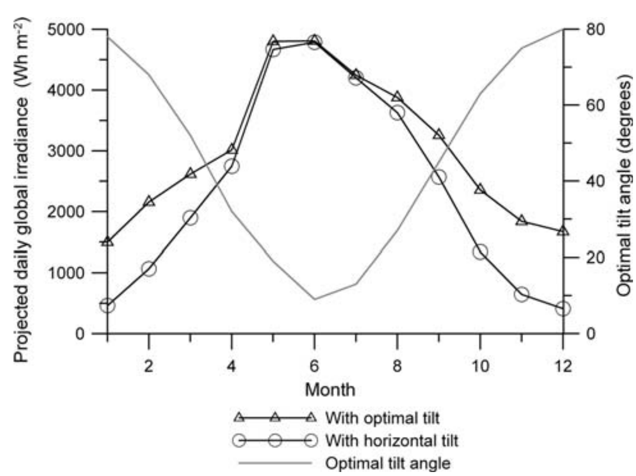

Fig. 2 Daily irradiance (net radiation × sun hours) in Wh/m^2 for a solar collector with a horizontal angle or with optimal tilt. Also shown is the optimal tilt angle for the location of Biggar

There are several variations on solar thermal flat plat devices including unglazed, single and double systems (Smith 1978). Using data from the Meteorological Office site at Drumalbin, which is 13 km west of Biggar, low irradiation levels suggest that at least one layer of glazing should be used in any solar hot water application in Biggar and only a double glazed system would be able to raise water temperature to 50°C during every month of the year. Even with a lowered output temperature of $T_{out} = 30°C$, the annual energy production (AEP) of a double glazed system would be approximately 301 kWh/m^2 in Biggar, which may not be economic in this location. The average UK household uses 2,482 kWh per year to generate hot water (Yao and Steemers 2005). A 3 m^2 double glazed system in Biggar would provide 903 kWh of this load, or about 36%. A more efficient but more expensive technology is evacuated tube, which has zero conduction and convection losses, reflective losses from only a single layer of glass, and near-zero angles of incidence, regardless of the sun's position, due to its curved aperture. All of these factors result in higher collection efficiencies at off-peak hours and months and greater overall AEP. Modelling with the Drumalbin data indicates that the evacuated tube collector will increase AEP by 42, 88, and 231% for $T_{out} = 15$, 30, and 50°C scenarios, respectively, in comparison to the double glazed flat plate system. A 3 m^2 evacuated tube system in Biggar would provide 1,695 kWh of energy per year; enough to meet about 68% of the annual hot water needs of an average UK household.

Photovoltaics

Unlike solar thermal devices, whose energy output is measured in kWh/m^2 and system capacity measured in physical size, photovoltaic (PV) system capacity is measured in watts-peak (Wp) (i.e. the number of watts produced at maximum output). PV efficiencies are determined largely at manufacture, whereas solar thermal efficiencies are determined mainly by usage. The Photovoltaic Geographical Information System (PVGIS) has an online resource for calculating the estimated potential of a photovoltaic system of a given capacity for any latitude and longitude in Europe (Šúri et al. 2007). Using Biggar climate conditions, AEP was determined for a range of PV capacities. The relationship between expected output (in kWh) and PV size is linear, with crystalline PV (efficiency, $\eta = \sim 15\%$) giving power output slightly higher than thin film ($\eta = \sim 6\%$), given the same capacity in Wp and insolation rates. Under these conditions, the thin film system would be much larger in size due to its smaller efficiency. Using an average size of 2 kWp, annual power output is expected to be approximately 1,600 kWh per year for both systems, about 37% of the average household electricity use in Biggar. Balance of system losses are assumed to consist of 9% inverter losses and 5% cable and maximum power point tracking losses.

The prices of PV are expected to reduce substantially in future years. PV manufacturing capacity is growing exponentially and the cost of solar electricity has fallen substantially but is still approximately double the average cost of generation in the United States (Daviss 2007). Compaan (2006) believes that bulk silicon PV is close to its minimum cost per installed watt-peak and de Vries et al. (2007) state that new PV innovation is necessary if prices are to reach 10¢ per kWh by 2050. With current technology, photovoltaics installed in Biggar are not cost effective in comparison to other renewable energies, as is shown below in the section on "Financial and carbon payback periods".

Wind energy

The UK has the best wind energy resource in Europe (Troen and Petersen 1989) and a target of producing 10% of its electricity from renewable sources by 2010 and 20% by 2020 (BWEA 2007). In November 2007, the Scottish Government set a new interim target to generate 31% of Scotland's electricity from renewable sources by 2011 and 50% by 2020. A number of government initiatives towards these goals include community action projects that might be suitable candidates for Biggar (Centre for Sustainable Energy with Garrad Hassan and Partners Ltd 2007). A further possibility is to have individuals or small groups working with domestic or small-scale wind turbines. Hence there are a number of pathways by which Biggar could meet its energy needs using wind energy and these are considered below.

Large-scale wind energy

Unlike solar energy, which is very scalable and traditionally used on an individual basis (Roaf and Gupta 2007), wind power is normally implemented at a relatively large scale level due to the cheaper cost per kWh of electricity generated. In order to achieve this scale in Biggar, community stakeholders could erect their own turbine(s) or approach a wind farm developer and jointly invest in a small wind farm.

It is impractical to measure the wind resource at a predefined, exact location over a long time period unless investment in a wind farm is anticipated. Generally, measurements are taken at the actual site location for 1 year or less, and then corrected to the long-term average using statistical methods or physical models along with long-term data from a nearby site such as a UK Meteorological Station

(Barthelmie 2007). Below we broadly estimate the wind resource at two sites in Biggar in order to estimate their power potential and cost. The chosen locations are not intended to be potential sites, but merely illustrative example sites. The wind turbine selected is the Bonus 1 MW turbine but again this is for illustrative purposes only.

The wind energy potential was calculated using an industry standard model Wind Atlas Analysis and Application Program (WAsP) (Mortensen et al. 2005). Estimates were based on hourly long-term wind speed measurements from two UK Meteorological Stations at 10 m height; from Drumalbin the data period is 1994–2006 and from Salsburgh 1997–2006. Locations are shown in Fig. 3. Both meteorological stations were visited in order to verify that no large obstacles existed near the stations that would interfere with the anemometer measurements. Orographic data for the model were obtained from the Shuttle Radar Topography Mission (SRTM) ftp://e0srp01u.ecs.nasa.gov/srtm/version2/.

The WAsP model assumes that a Weibull distribution is an accurate representation of the observations. The observations are processed to remove local orography, roughness and obstacles, allowing the programme to generate a local 'wind climate' that is not specific to the site but to the local area. Provided that the prediction site remains within the same wind climate (a distance usually close to 50 km) then the wind climate can be predicted at the new site. Thus WAsP generates wind speeds fitted to a Weibull distribution at the new site.

No wind prediction calculations can be made without some degree of error, and ±10% for energy density can be taken as a reasonable standard. However, in this case, because no on-site measurements of the wind speed have been made at hub-height, these errors are likely to be larger. There are small differences in predicted wind characteristics using data from the two meteorological stations; 2.9% in potential AEP predicted by the Drumalbin and Salsburgh data sets for the Small Hill site, and 1.2% AEP between predictions for the Biggar Commons site (Table 5). At 50 m hub heights, the average mean wind speed at the Small Hill turbine site is about 15% greater than at the Biggar Commons site and the AEP is 17% greater. At the site, power conversion via transformers and at the sub-station can be assumed to reduce power by another 4%. With these losses and an assumed 2% turbine downtime for operation and maintenance, the expected annual power output and turbine capacity factors can be calculated for each site. The average capacity factors for the Bonus 1 MW turbine at the Small Hill and Biggar Commons sites are 42.7 and 37.4%, respectively. In relation to a long-term UK average capacity factor of 27% (Sinden 2007), these numbers are high, likely due to the relatively good wind resource in Scotland.

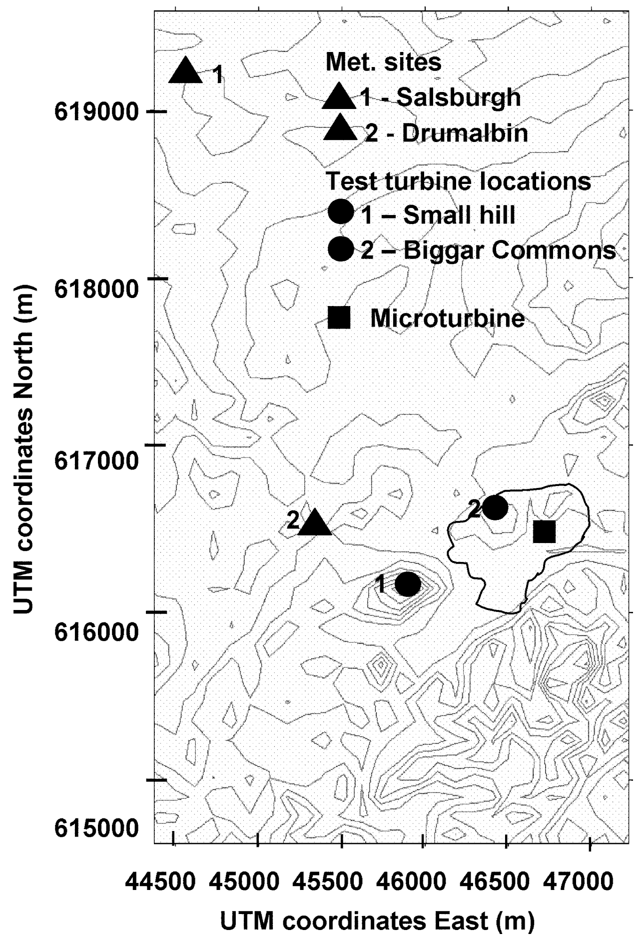

Fig. 3 Map showing the location of the two United Kingdom Meteorological Office sites whose data were used in this study, and the test locations for nominal wind turbines used to investigate possible mitigation/offsetting strategies. *Black line* Approximate outline of town

Community wind power: micro-scale

An alternative to large-scale wind power is to consider domestic-scale wind turbines. Although only 650 micro-wind devices were installed in the UK as of 2006, a study commissioned by the Department of Trade and Industry suggests that, with proper subsides, micro-wind could provide 4.2% of the UK's total electricity needs and reduce 6% of its CO_2 emissions by 2050 (DTI 2006). Micro-wind generation is fundamentally limited because the power output is related to the square of the rotor diameter and the cube of the wind speed, the first of which is inherently small in micro applications and the second degraded in urban regions. It can therefore be difficult to estimate the potential power output of domestic scale turbines, particularly as the economics dictate that very limited measurements, if any, can be made at the site of the proposed installation.

Table 5 Predicted wind speed and power characteristics at two sites near Biggar based on the characteristics of the NEG-MICON 750 kW turbine

	Mean wind speed at 50 m height (m/s)	Mean wind power density at 50 m height (W/m^2)	Net AEP (GWh)	Estimated AEP (GWh)	Capacity factor (%)
Predictor site					
Small hill					
Drumalbin	9.84	1,365	4.07	3.67	42.0
Salsburgh	9.34	902	4.19	3.80	43.4
Biggar commons					
Drumalbin	8.48	804	3.55	3.29	37.6
Salsburgh	8.27	622	3.51	3.25	37.1

AEP annual energy production

In order to determine the AEP of a rooftop micro-turbine, it is necessary to first develop a wind profile that accounts for the presence of the building the turbine is mounted on. Heath et al. (2007) have shown wind speeds follow an exponential function at heights lower than the average urban building height and the traditional logarithmic function at heights higher than the average building height. The mean building height in Biggar is estimated as 7.5 m and, using the methodology in (Heath et al. 2007), the displacement height d is calculated as 2.4 m. With the displacement height known, the surface roughness length, z_0, for the town of Biggar can be calculated as 0.58 m. To further refine the analysis for specific areas in town, a new variable x, representing the distance from turbine location to the town's urban boundary, is introduced. (Mertens 2003) stated that the height of the internal boundary layer, δ_1 in cities is a function of this variable, as depicted by the equation below:

$$\delta_1 = 0.75 z_0 \left(\frac{x}{z_0}\right)^{0.8} \tag{1}$$

Thus for each location studied, the distance to the urban boundary must be known. The mean wind speed U at a particular height, z, for each cardinal direction can be calculated using the following, which was adapted by Heath et al. (2007) from an equation by Taylor and Lee (1984):

$$U(z) = \frac{\ln\frac{(z-d)}{z_0}}{\ln\frac{(\delta_1-d)}{z_0}} \cdot \frac{\ln\frac{\delta_1}{z_{0A}}}{\ln\frac{z_A}{z_{0A}}} U_A(z_A). \tag{2}$$

Equation 2 describes the logarithmic wind profile at heights equal to or greater than the mean building height of the urban area. All variables with the subscript 'A' are analogous to the ones just described, except that they refer to a previously known reference wind speed and roughness. In this case, the reference variables will be averages from the Drumalbin and Salsburgh Meteorological Stations. Measurement height z_A at the meteorological stations is 10 m. Roughness length z_{0A} was taken to be 0.1 m.

The second step in generating the rooftop wind speed profile is to determine the wind profile below the mean building height. This is an exponential function that is described by Eq. 3:

$$U(z) = U_H \exp\left(a\left(\frac{z}{H}\right) - 1\right) \tag{3}$$

where U_H is the wind speed at the intersection of the two functions, which is equivalent to the speed at height H using Eq. 2, and 'a' is a constant equal to $9.6\lambda_F$ where λ_F is the frontal area density of buildings estimated as 15%.

The mean wind speeds at any proposed turbine site can be calculated using Eqs. 2 and 3. The U_H variable needed for Eq. 3 was then taken from this consolidated average at a height of 7.5 m. Rooftop wind speed profiles were calculated for a number of locations in Biggar as shown in Table 6. This wind speed can also be compared with that obtained for central Biggar using the DTI database (DTI 1993), which is 4.0 m/s.

The predicted average wind speed within the urbanised area of Biggar is substantially reduced (between 60 and 70%) from that obtained at the two Meteorological Stations. There is a significant margin of error in these figures because wide-ranging assumptions have been made about building morphology and the general topology of the town. Furthermore, rooftop mounting points of the micro-wind turbine, which would alter mean wind speeds, have not been considered. Using the wind speed data from the above locations, potential power output could be estimated for the six sites using power curves for the small wind turbines the Swift 1.5 kW, Fortis 1.4 kW and Ampair 0.3 kW. For the purpose of comparison the height is assumed to be 10 m. The production and capacity factor depend on the turbine and the latter was found to range from 5.2 to 11.3%.

A La Crosse Weather Station WS3502 equipped with an anemometer and pressure sensor was installed at one of the central locations in Biggar, and recorded wind data from 2 July to 4 August 2007. Although this time scale is far too short to obtain a reliable mean wind speed, it does provide a general idea of the wind regime, which can be compared

Table 6 Predicted potential power output and capacity factors for three different rooftop mounted wind turbines at six random site locations (A–F) in Biggar

Microwind turbine and rated capacity (kW)	Swift 1.5 kW		Fortis 1.4 kW		Ampair 0.3 kW	
	Potential power output (kWh)	Capacity factor (%)	Potential power output (kWh)	Capacity factor (%)	Potential power output (kWh)	Capacity factor (%)
A	1,385	10.5	959	7.8	172	6.5
B	1,255	9.6	850	6.9	152	5.8
C	1,334	10.2	916	7.5	164	6.2
D	1,193	9.1	798	6.5	143	5.4
E	1,522	11.6	1,072	8.7	193	7.3
F	1,152	8.8	764	6.2	137	5.2

Height of installation is assumed to be 10 m

to the urban wind speed calculations performed previously. Before the results could be compared, however, wind data for the remaining months of the year had to be extrapolated using normalised monthly averages from the Drumalbin Meteorological Station. By comparing the short time series with the longer record, the central Biggar wind speed was extrapolated to 3.15 m/s, slightly lower than wind speeds estimated by the DTI or the method above based on Heath et al. (2007).

Financial and carbon payback periods

Here we provide an overview of the expected costs involved in renewable energy investment and compare these with expected energy output for particular technologies implemented in Biggar.

Large-scale wind

The current price for a large wind turbine is approximately €1.2 million per MW-installed, for one- to two-turbine projects. Using August 2007 exchange rates, this rate equates to £816,000/MW-installed in the UK. This cost includes turbine delivery, installation, and commissioning but not electrical connections between turbines and site roads as would be characteristic of a wind farm. The cost modelled for large-scale wind power, without government or tax incentives, will be: £0.816/W-installed. The operation and maintenance cost for large-scale turbines will be taken as 1.75% of the total installed costs.

Microrenewables

The cost of microrenewable purchase and installation (including micro-wind, solar thermal, and PV) is variable depending on a number of factors including Balance of System parts, whether the installation is DIY or professional. Here, data from 14 different case studies were used to identify the per unit average costs of various microrenewable technologies as well as the typical total costs of most systems (see, e.g. http://www.energysavingstrust.org.uk and http://www.tvenergy.org). Figures in Table 7 represent the costs of all expenses associated with the system, including Balance of System parts, value added tax (VAT), and any other miscellaneous expenses involved in installation. The costs do not include operation and maintenance fees; however, these costs may be estimated to range from 0.36% (grid-connected PV) to 2% (micro-wind) of the installed costs, per year.

Comparison of technology costs and energy yields in Biggar

Inspection of the cost data per installed Watt show that micro-wind is over five times more expensive than large-scale wind (Table 7). If the capacity factors of the respective wind systems are also taken into account, large-scale wind is much more cost effective in “£ per kWh produced”. The comparison is harder to judge for solar thermal devices because, although professionally installed flat plate collectors are 2.4 times cheaper than evacuated tube collectors, they also have lower AEP (Table 8). As the AEP ratios are significantly higher than the cost ratio of 2.4 for 50°C hot water, evacuated tube collectors are more cost effective for this temperature than flat plate systems. However, for lower output temperature scenarios, flat plate collectors appear to be more cost effective. This is especially true for DIY flat plate collectors, which are 9.08 times cheaper than evacuated tube systems. It should be borne in mind, however, that, regardless of AEP, evacuated tube collectors will provide more consistent output during winter months and cloudy days than flat plate collectors. It is difficult to judge the value of this in monetary terms, but in terms of carbon reduction, evacuated tube systems are the most effective because natural gas consumption is

Table 7 Approximate cost of microrenewable technologies with and without grants

	Typical costs	Case study per unit average	Case study per unit average after grants
Micro-wind	£2,500–£12,000	£4.09 per W	£3.22 per W
Solar flat plate	£1500–£3000	£559 per m^2	£345 per m^2
Solar evacuated tube	£2500–£4500	£1,362 per m^2	£946 per m^2
Solar DIY flat plate	£450–£650	£150 per m^2	No data
Photovoltaic	£6,000–£14,000	£6.52 per Wp	£3.66 per Wp

Table 8 The ratio of AEP for evacuated tube to flat plate collector for three desired hot water temperatures under Biggar climate conditions

	Temperature		
	15°C	30°C	50°C
Flat plate collector			
Unglazed	1.52	3.98	103.50
Single glazed	1.35	1.96	4.22
Double glazed	1.42	1.88	3.31

Table 9 AEP of micro-wind versus photovoltaic systems in Biggar

	Hub height (wind turbine only)				
	5 m	7.5 m	10 m	12.5 m	15 m
Wind turbine AEP (kWh)	216	770	1,152	1,476	1,757
941 W-p PV system AEP (kWh)	757	757	757	757	757
Ratio of AEP (wind to PV)	0.29	1.02	1.52	1.95	2.32

The systems are approximately balanced in terms of cost of installation

higher in the winter, when flat plate systems have quite poor efficiencies.

To evaluate the cost effectiveness of PV and microwind, we calculate the cost of a 1.5 kW wind system with balance of system parts as £6,135 installed. A PV system with this same cost would be rated at 941 Watts-peak and produce 757 kWh/year at optimal inclination in Biggar (Šúri et al. 2007). Similarly, from Table 9, a Swift 1.5 kW wind turbine will produce between 216 and 1,757 kWh annually at location F (Table 6), depending on hub height. With this information, the cost effectiveness of each system can be compared as shown in Table 9. Given Biggar climate conditions, even at the residential site with the lowest wind speed (Site F; Table 6) microwind is more cost effective than PV for any turbine hub-height above 10 m. Finally, the actual cost of a Fortis 1.5 kW turbine of £3,675 (August 2007) is significantly lower than the standardised cost of £6,135 (Kinsley 2006); however, it is unclear whether this price includes Balance of System costs (such as an inverter) or grid connection expenses, which can significantly raise the overall price (http://www.bwea.com/ref/generating.html). Due to the high cost, photovoltaic technology is the least cost-effective microrenewable option for installations within Biggar. To determine the optimal choice of renewable energies in Biggar, we use software analysis by HOMER as presented below.

Modelling renewable energy options

Modelling household electricity consumption was undertaken in HOMER, a United States National Renewable Energy Laboratory programme for evaluating power options https://analysis.nrel.gov/homer. The first step was to enter the daily electricity demand for all households in Biggar, an average total of 10,974 kWh. These data were then fitted to the average UK diurnal electricity profile. Grid electricity cost information was obtained from the primary supplier of electricity to residents of Biggar: Scottish Power. As of June 2007, the standard package domestic rate for electricity was 10.887 p/kWh plus a daily service charge of 16.60p. A grid carbon intensity of 0.53 kg/kWh was assumed as in the section on "Community footprint model components" above. Finally, renewable energy components were entered into the programme. The results showed that neither micro-wind nor PV were optimal choices in comparison with large-scale wind.

A distinct HOMER simulation was performed for each of four wind turbines, varying in size from 750 to 2,000 kW. Acting conservatively, the AEP for each turbine was taken to be the WAsP output at the Biggar Commons site using Drumalbin data (Table 5). In all simulations, the grid buy-back price for electricity produced in excess of the total household demand was set to 9.10 p/kWh, which corresponded to the current Non-Fossil Purchasing Agency wind power auction price valid through March 2008. Table 10 shows the results of this HOMER simulation, including the costs of production for each turbine, which range from 2 to 3 p/kWh. In comparison, the grid price of electricity, 10.887 p/kWh, is considerably higher. One NEG-Micon 750/44 turbine would decrease electricity expenditures from £436,060 to £256,950 per year and would reduce carbon emissions by over 1,000 tonnes annually. A larger turbine, such as the 2 MW Vestas V80

Table 10 Comparison of wind energy options for offsetting Biggar's CO_2 emissions from electricity from HOMER modelling

Turbine	Rated power (kW)	AEP (GWh)	Annualised turbine cost (1,000 £)	Cost of production (p/KWh)	CO_2 remaining to be offset (tonnes)	Total costs (1,000 £)
None					2,095	436
NEG-Micon 750/44	750	2.2	59	2.7	952	257
Vestas V52	850	3.0	66	2.2	523	176
Nordex N60	1,300	4.1	102	2.5	−36	103
Vestas V80	2,000	7.3	156	2.1	−1,728	−144

or the 1.3 MW Nordex N60, could each provide all of Biggar's household electricity needs while offsetting all CO_2 emissions derived from household electricity.

Mitigation and offsetting strategies

There are many strategies for reducing CO_2 emissions. As discussed above and in Table 4, small non-lifestyle changes could save between 6 and 26% of CO_2 emissions. If these changes are maximised, then up to 4,458 tonnes of the estimated 17,150 tonnes of community CO_2 emissions could be avoided. Further reductions could be made, particularly in the transport and buildings sectors, by straightforward cost-effective approaches including increased insulation and driving efficiency, and by investment in solar hot water and heat pumps. Given the good wind resource in the area, one cost effective strategy for producing electricity and offsetting the community emissions would be to establish a small wind farm. The erection of one utility scale (2 MW) wind turbine would be more than enough to generate the equivalent of the community's electricity needs. To also offset the remaining 13,000 tonnes of CO_2 emissions per year, three to four wind turbines would be needed.

To compare this with offsetting by tree planting, an estimate for annual CO_2 absorption is needed. Estimates have a wide range depending on species, maturity and location of trees. For example, Kirby and Potvin (2007) suggest storage of between 145 and 335 tonnes of carbon (C) per hectare including above and below ground components. Assuming this is land use change from pasture, estimated to store 46 tonnes C ha^{-1} (Kirby and Potvin 2007), we can assume forests to store approximately 100–290 tonnes C ha^{-1} over a lifetime of 20–40 years, giving an estimate of 2.5–14.5 tonnes C ha^{-1} $year^{-1}$. Therefore, offsetting 13,000 tonnes of CO_2 by tree planting would require an offset of 3,391 tonnes C covering an area of 200–1,360 ha each year. Alternatively, Carnell and Milne (1995) give a range of C storage for forests in the UK between 14.1 and 61.9 tonnes C ha^{-1} increasing the area required to 2,000–4,800 ha/year. Clearly these estimates are a vast over-simplification of the complex processes involved but are given here to illustrate the scale of area required if tree planting is employed to offset CO_2 emissions.

Summary

The UK Government has committed to reducing the CO_2 emissions of the UK to 60% of 1990 levels by 2050. Any agent attempting to reduce their CO_2 emissions must have the necessary tool available to them to measure this reduction. Analysis of household consumption data collected from the Biggar community in South Lanarkshire enabled the development of the CCFM based on a LCA approach. The aim of the model was to provide a method for a community to assess its carbon footprint and the uncertainty involved. The results obtained from the case study household survey highlighted that one of the biggest challenges with developing a CCFM was collecting necessary data and scaling them accurately. The CCFM was applied to households within the community of Biggar and a total of 17,402 tonnes of CO_2 was calculated to have been emitted in the 12 months from June 2006 to June 2007. The uncertainty in the calculation was estimated to be 2,715 tonnes. Individual annual household emissions calculated ranged from 2 to 103 tonnes of CO_2. For this rural community, the largest single emissions category (48% of CO_2 emissions) resulted from transport by car, with natural gas and electricity consumption resulting in a further 24 and 12% of total emissions, respectively. Air travel accounted for 10%, waste for 5% and public transport only 1%. Detail is provided of the model components and calculations and an assessment is made of the resulting uncertainties. Relevant strategies are suggested for reducing carbon dioxide emissions. In addition, solar and wind resource assessment was undertaken to evaluate the most cost-effective strategies for renewable energy contributions. A small community wind farm can be shown to be economically viable in this wind climate and could be scaled from one utility scale turbine, which would generate more than the equivalent of the annual electricity demand of the community, to three to four wind turbines, which would generate sufficient electricity to offset all of the community's CO_2 emissions including those from transport.

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