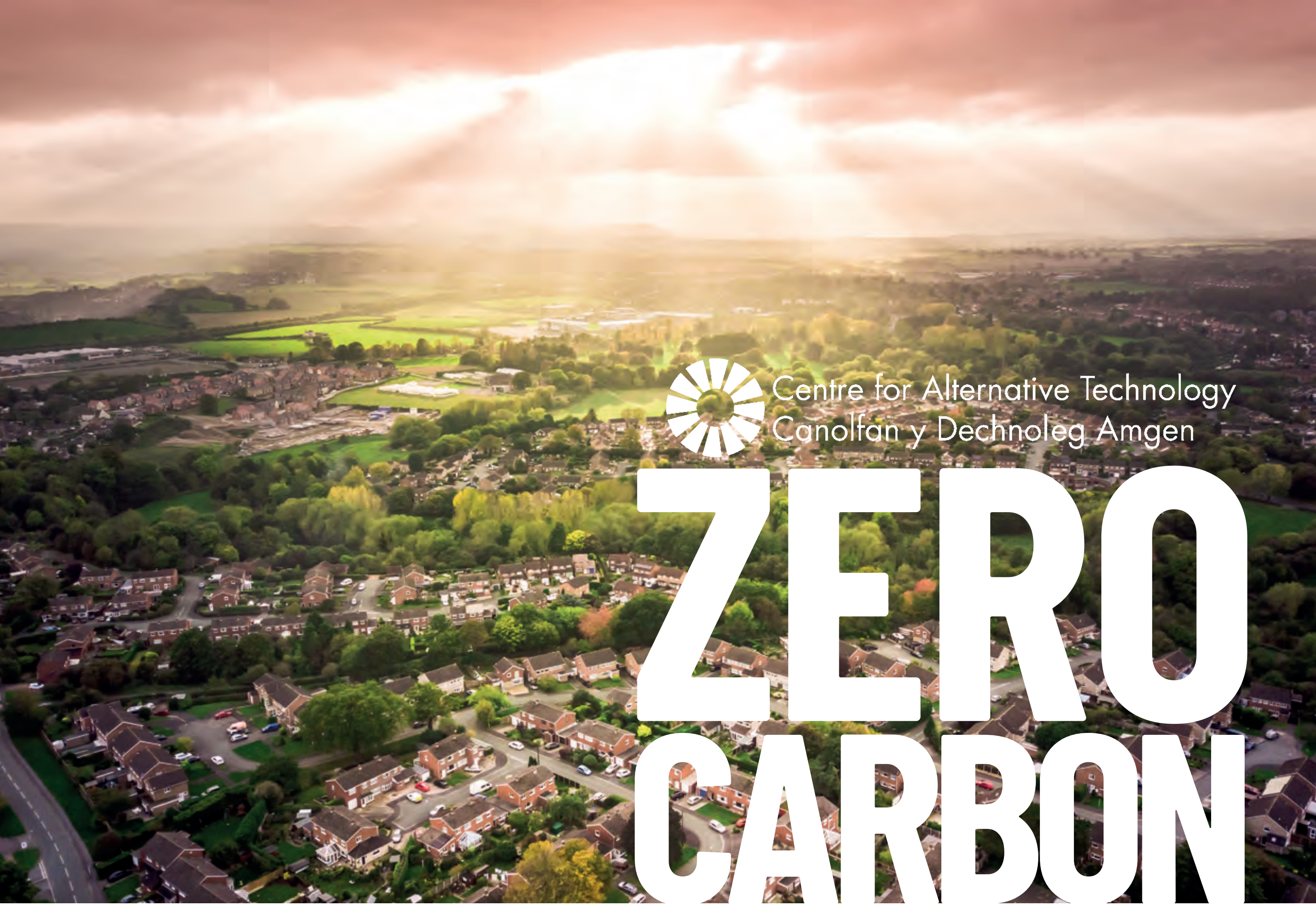

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ZERO CARBON BRITAIN

METHODOLOGY PAPERS

ZERO CARBON BRITAIN

Methodology for power down

Contents

1 Introduction

The following describes how the annual final energy use in the Zero Carbon Britain scenario was derived. Baselines of either 2007, 2010 or 2017 were used. Appropriate reductions in energy use were arrived at using a range of existing studies and some primary research.

2 Population assumptions

	2007	2010	2017	2030
UK	61,319,100	62,759,500	66,040,200	70,499,802
GB	59,557,400	60,954,600	64,169,400	68,408,422

The 2007, 2010 and 2017 from [14]. Projected 2030 figures are taken from [15].

Average number of occupants per household: stable at 2.35.
Number of households:
2007 - 26.0 million
2030 - 29.9 million
The 2007 figure is from [1]; it is an assumption of the ZCB scenario that average occupants per household remains the same to 2030.

3 Space heating

It is necessary to determine a baseline for space heating demand in terms of the heat loss of the UK's buildings (measured in GW/°C). This can then be adjusted for the ZCB scenario based on our assumptions about the extent to which buildings are improved by insulation, airtightness, better glazing and doors etc. It is also necessary to derive a 'base temperature' for ZCB - this is the temperature to which buildings must be heated, after which internal and solar gains are sufficient to bring the building to the required temperature. To calculate this requires the building heat loss but also the average internal temperature and the average internal gains and solar gains. Using the building heat loss and the base temperature we can then determine a predicted space heating energy demand in ZCB by applying hourly or average seasonal temperatures.

3.1 Domestic space heating

DECC 2050 Pathways estimates for 2007 that the average heat loss per domestic building is 247 W/°C, average internal temperatures are 17.5°C, and average internal and solar gains are 1,030 W [1].

In DECC 2050 Pathways level 4, the average heat loss coefficient reduces just over 50% from 247 W/°C to 119 W/°C [1]. This is achieved by the retrofit measures, applied to the stated proportion of dwellings, shown in figure 1 below (they are only applied to 96% of the 2007 potential but this is essentially all dwellings as the 4% are demolished) [5]. All new dwellings are assumed to be Passivhaus standard [5].

Figure 1. Retrofit measures for housing stock in DECC 2050 Pathways level 4 [5].

Measure	Assumed average U-value ($W/m^2.^0C$) before measure	Assumed average U-value ($W/m^2.^0C$) after measure
Solid wall insulation	2.20	0.35
Cavity wall insulation	1.60	0.35
Floor insulation	0.60	0.16
Triple glazing or equivalent	2.20	1.00
Loft insulation	0.29	0.16

Measure	Assumed average air permeability (m^3/m^2. hr@50Pa) before measure	Assumed average air permeability (m^3/m^2. hr@50Pa) after measure
Draught-proofing	15	5

Measure	Number of UK households receiving measures	Year installations complete	Fraction of 2007 potential addressed on completion of roll out
Solid wall insulation (internal or external)	7,659,250	2040	96%
Cavity wall insulation	8,755,936	2030	96%
Floor insulation	11,387,501	2050	96%
Triple glazing or equivalent	22,641,032	2050	96%
Loft insulation	21,439,968	2040	96%
Improved air-tightness	24,050,381	2020	96%

We assume for ZCB that the average heat loss per dwelling is reduced to 119W/°C. It may not be exactly fair to use the DECC 2050 Pathways derived average heat loss per dwelling because in ZCB we assume a lower number of dwellings. However, we can assume that a higher demolition rate occurs, meaning the proportion of retrofitted and ‘Passivhaus standard’ new builds is the same, giving the same average heat loss per dwelling. Multiplying the per dwelling heat loss by the total number of dwellings in the ZCB scenario gives us a total domestic building heat loss of 3.55 GW/°C.

Our assumptions about how average internal and solar gains change is also important. The methodology used by DECC 2050 Pathways [1] is to fix total gains at the same proportion of losses as 2007 - thus gains are reduced by around 60% (50% reduction in heat loss per dwelling plus slightly warmer temperatures reducing losses). In reality what should the reduction in gains be? Solar gains and internal gains from people should be about the same; gains from lighting and appliances should reduce by around 60% in our scenario in line with improved lighting and appliance efficiency; and gains from hot water can be expected to reduce because of better tank insulation but there will also be more hot water storage. The gains from hot water may be crucial to whether the 60% reduction is a good assumption.

The average internal temperature used for ZCB is 16.7°C, as per DECC 2050 Pathways level 3 [1]. This assumes better controls and some behavioural change.

3.2 Services and industry space heating

DECC 2050 Pathways level 4 assumes a 40% reduction in the space heating demand per building for commercial buildings [5].

To derive a heat loss for the service and industrial sectors' building stock for ZCB, we apply a 40% reduction to their space heating demand for 2007, which is estimated by multiplying the 2007 heating energy use from [2] by 0.8 to account for losses. The ratio of the service and industrial heating demand to the domestic heating demand is then used to calculate the service and industrial building stock heat loss from the domestic heat loss. This gives us a heat loss of 2.1 GW/°C.

NB: In ZCB we assume we have the same number of service and industrial buildings as in 2007.

3.3 Total space heating

By combining the heat loss for domestic, service and industrial buildings, we derive a total building heat loss of 5.6 GW/°C.

This is used in the hourly model with a base temperature. This base temperature is calculated as below:

base temperature = average internal temperature (°C) - (Gains (W) / Losses (W/°C))

The average internal temperature, gains and losses are those for the domestic houses from [1]. This base temperature is used for the whole building stock. This calculation gives us a base temperature for the ZCB scenario of 13.1°C.

In the hourly model we can then calculate at each hour:

Space heating energy demand = (base temperature - external temperature) x total building heat loss

4 Hot water

Domestic hot water energy use was 89 TWh in 2007, 82 TWh in 2010 and 81 TWh in 2017 [2]. For ZCB this energy use is converted to hot water energy demand by multiplying by 80% for inefficiency losses. For ZCB, hot water energy demand is assumed to reduce 14% per person from 2007 levels, as per DECC 2050 Pathways level 3 [1], but increase due to population increase to 2030.

Services hot water energy use was 19 TWh in 2007, 20 TWh in 2010 and 14 TWh in 2017 [2]. The hot water energy demand is calculated by multiplying the energy use by 84% for efficiency losses. In ZCB, the hot water energy demand is taken to be the same as for 2017 - this is 12 TWh/year.

5 Cooking, lighting and appliances, and cooling

5.1 Cooking

Domestic cooking used 15 TWh in 2007, 13 TWh in 2010 and 14 TWh in 2017 [2]. Non-domestic cooking used 22 TWh in 2007, 22 TWh in 2010 and 21 TWh in 2017 [2].

For ZCB, the 2007 domestic cooking energy use figure is reduced 40% per household - 32% including the increase in number of households. Non-domestic cooking is reduced 25% from the 2007 level. These reductions are as per DECC 2050 Pathways level 2-4 and 4, respectively [5]. Cooking is assumed to become fully electric.

5.2 Lighting and appliances

Domestic lighting and appliances used 86 TWh in 2007, 77 TWh in 2010 and 76 TWh in 2017 [2]. Non-domestic lighting and appliances used 59 TWh in 2007, 60 TWh in 2010 and 71 TWh in 2017 [2].

For ZCB, the 2007 domestic lighting and appliances energy use figure is reduced 61% per household - 55% in total including population growth. The reduction per household is as per DECC 2050 Pathways Level 3 (Level 4 is not used as it assumes technology breakthroughs) (see the relevant info sheet on [6]).

The 2007 non-domestic lighting and appliances energy use figure is reduced by 30%, as per DECC 2050 Pathways Level 4 [5], although this is slightly less ambitious than DECC because we assume no growth in the number of non-domestic buildings.

5.3 Cooling

Non-domestic cooling energy use was 9 TWh in 2007, and 9 TWh in 2010 and 13 TWh in 2017 [2]. Cooling energy demand (the thermal energy removed) was 27 TWh in 2007 according to DECC 2050 Pathways [1].

In ZCB, despite increased temperatures due to climate change, cooling demand is assumed to be kept stable by better insulation, shading and ventilation of buildings. This is roughly consistent with cooling demand in DECC 2050 Pathways level 3 [1]. The efficiency of air conditioning systems is expected to increase to 600%, as per DECC 2050 Pathways [1].

It is assumed that no significant demand for domestic cooling emerges. This may be a dubious assumption given that climate change is expected to increase mean summer temperatures in the UK by around 1.5°C in the 2020s and 2.5°C by the 2050s (compared to baseline period of 1961–1990) [13]. The mass installation of heat pumps may also make their reverse operation for cooling possible and perhaps likely. That said, the inclusion of a cooling demand in our scenario may not be so important from a system perspective. The energy demand would not be that high - perhaps 10-20 TWh/yr of electricity under DECC 2050 Pathways level 1 scenario [1]. Renewables must already supply much higher heating demands in winter, so cooling may provide a manageable electricity demand in summer, allowing electricity from renewables to be usefully used. That said, storing coolth may be difficult so issues of peak demand would need to be managed.

6 Industry

For industrial energy use, including agriculture but excluding industrial space heating, we get numbers of 331 TWh in 2007, 288 TWh in 2010 and 255 TWh in 2017 [2].

For ZCB, we assume that industrial output returns to 2007 levels per person in the UK, therefore increasing by 16% from 2007 levels, as per population increase. However, industrial energy intensity is expected to decrease by 25% - as per DECC 2050 Pathways lowest or medium energy intensity levels [5, p90-93]. Therefore, industrial energy use is (1.16x0.75) 87% of 2007 levels. This is except for agriculture which stays at 2017 levels as a precaution since there will be less grazing livestock and more energy crops in our scenario.

We do not study the actual make-up of the industrial output but assume it to be quite different from that in 2007. Output of materials and equipment for the energy system will increase, other products will decrease.

The above does not address non-energy fuel use i.e. where fuels such as oil and gas are used to produce materials and chemicals. This was 113 TWh in 2007, 102 TWh in 2010 and 93 TWh in 2017 [2]. To some extent this is only important in ZCB if use of this fuel liberates GHGs. If oil or natural gas were used in a way that didn't release GHGs, for example as a material in plastic or in roads, then it would not be problematic from an emissions perspective. However, where the non energy use of fuel liberates CO2 this process should be changed or must use biogas or biofuel. These non-energy uses of fuels need looking at in more detail.

The 2017 fuel mix for energy in industry was 35% gas; 32% electricity; 17% oil; 9% solid fuel; and 7% heat and bioenergy [2]. In ZCB, the proposed change in industrial fuel mix aims to increase the proportion met by electricity. However, it was identified that some industrial energy uses may be very difficult to meet using electricity. AEA/NERA identifies "50 TWh of industrial process heat not easily served by the combustion of solid biomass. Biogas may be the option facing the least obstacles for these and other hard-to-reach heat demands" [12].

In ZCB we state that biogas meets all the 'high temperature heat' demand except for that currently electrified; 'low temperature process' heat and 'drying and separation' heat is met by two-thirds electricity and one third biomass derived fuels (of this one third is biogas and two thirds is solid biomass); for the non-heat fuel use, 50% of the proportion that was not electricity in 2007 is switched to electricity, the remainder is met by half biofuel and half biogas; for the 'construction & unclassified' fuel use, half is electricity and the remainder is one third biogas, biofuel and solid biomass; for agriculture half is electricity and the remainder is half biogas, half biofuel.

This gives us a fuel mix with more electricity (179 TWh), 63 TWh of biogas, some solid biomass (32 TWh), and a small amount of biofuel (13 TWh). The fuel mix is similar in percentage terms to the DECC 2050 Pathways 'high electrification' scenario fuel mix in 2050 [1, table XI.a], however, there is less liquid hydrocarbon and more methane (see below).

Table 1. Comparison of industrial fuel mix in DECC 2050 Pathways 'high electrification' scenario [1] and ZCB.

Description	DECC 2050 Pathways 'high electrification'	ZCB
Electricity	66%	62%
Solid hydrocarbons	9%	11%
Liquid hydrocarbons	16%	5%
Gaseous hydrocarbons	8%	22%
Heat transport	2%	-

However, the above fuel mix is changed slightly in the hourly model due to a fuel-switching demand response mechanism that, for a proportion of the demand, substitutes biogas for electricity when electricity from renewables is in shortfall and vice-versa when it is in surplus.

7 Transport

UK transport energy use was 724 TWh in 2007, 670 TWh in 2010 and 687 TWh in 2017 [2]. This breaks down for 2017 as:
Rail - 13 TWh
Road - 482 TWh
Water - 41 TWh
Air - 151 TWh

The following analysis was made to determine how the distance travelled by people, goods, vehicles changes in ZCB, as well as how the types of vehicles, fuels used, and vehicle efficiencies change in our scenario.

7.1 Domestic passenger transport

In the analysis for this ZCB scenario, we use distance based baselines for domestic passenger transport (we also include vans in this - only HGVs are included in 'road freight'). Distances travelled are taken from DECC 2050 Pathways [1, table XII.a] for 2007. This has been compared and is similar to the Department for Transport data for 2010 and 2017 [8, tables TSGB0101 and TSGB0103].

To change from the 2007 domestic transport mode mix to the ZCB domestic transport mode mix we firstly apply a 20% reduction in total distance travelled per person. This implies greater use of communication technologies such as video conferencing making journeys unnecessary. It is also expected because of increased urban populations, on average people live closer to where they work and socialise.

Realistic changes to the percentage of the total distance travelled that is done by different modes of transport is established by a mode change analysis. This uses data from the DfT National Travel Survey [9]. We use this data to work out the percentage of journeys of different lengths that are travelled by each mode of transport. The following changes to the mode mix are assumed for ZCB:

1. Transfer 2/3 domestic air travel to rail.
2. Transfer 50% car journeys less than a mile to walking (20%), cycling (15%), e-bike/scooter (15%).
3. Transfer 50% of car journeys of 1 to 2 miles to walking (20%), cycling (15%), e-bike/scooter (10%) and bus (5%).
4. Transfer 40% of car journeys of 2 to 5 miles to cycling (15%), e-bike (15%), bus (5%) and motorcycle/moped (5%).
5. Transfer 30% of car journeys of 5 to 10 miles to e-bike (3%), bus (15%), rail (5%), and motorcycle/moped (7%).
6. Transfer 20% of car journeys of 10 to 25 miles to bus (12%), rail (6%), and motorcycle (2%).

7. Transfer 20% of car journeys over 25 miles to bus (15%) and rail (5%).

This gives us the following change to the domestic transport mode mix:

Table 2. Domestic passenger transport mode mix by distance travelled in 2007 [1] and ZCB.

Mode	2007	ZCB
Walking	2.17%	2.65%
Pedal cycles	0.51%	2.37%
Motorcycles and mopeds	0.70%	2.63%
Cars and Vans	82.51%	61.93%
Buses and Coaches	5.96%	16.37%
Railways	7.01%	11.52%
Domestic air travel	1.14%	0.38%
Electric scooter and bikes	0.00%	2.16%
Total	100.00%	100.00%

Applying the new mode mix to the total distance travelled gives use the distance travelled by each mode.

We then apply percentages for different types of vehicle for each mode e.g. for cars and vans: 90% electric cars and vans, 4% hydrogen and 6% biofuel. DfT (2009) shows that around 90% of distance travelled by car is on journeys under 100 miles and therefore achievable in electric vehicles. The split between hydrogen and biofuel for the remainder is somewhat arbitrary but with the rationale that the lack of a widespread hydrogen distribution infrastructure will mean some biofuel vehicles are required. There is also likely to be some 'vintage' vehicles still running on liquid fuel.

Applying an average occupancy per vehicle and a fuel specific energy use per vehicle kilometre then gives us the transport energy use by fuel type. Average occupancy is taken from [1, table XII.a] for bus and rail using the 2050 values; for cars and vans we assume occupancy increases to an average of 2. Energy use per vehicle kilometre is taken from a variety of sources described here [16].

7.2 International aviation

Total UK aviation energy use was 162 TWh in 2007, 143 TWh in 2010 and 151 TWh in 2017 [2].

International aviation used 153 TWh in 2007 [1, table XII.c]. For ZCB we assume there is a two thirds reduction in distance flown from 2007 levels. We do not calculate any energy use for replacements such as rail, coach or ships.

Energy use per passenger km is expected to decrease 1.3% per year to 2030, as per [10, p7] - this gives a 23% reduction in energy use per passenger km. International aviation's energy use is therefore reduced by 73% from the 2007 level.

7.3 Freight

For freight the 2007 baseline is 29 TWh for international shipping and 19 for national navigation in boats and ships [2, 8]; 88 TWh for road freight in HGVs, and 2 TWh for rail [1]. To establish the changes in vehicle kilometres for freight in ZCB an analysis of freight was conducted using statistics for the amount of freight required for different products from [8, tables TSGB0402 and TSGB0502].

For road and rail, it is assumed that the freight of fossil fuels is no longer required. This eliminates 8% of current road and rail freight (as measured in tonne-kilometres). Around 20% of road freight is switched to rail. It is assumed that 140 million tonnes (100 oven dry tonnes at 30% moisture content) of additional road freight of biomass for energy, wastes for energy, biofuel, materials, and harvested wood products for carbon capture is required to be moved 50 km on average, giving an extra 7 billion tonne-km of freight (this is a rough approximation since we do not know the distance these products would need to travel).

These changes mean rail freight is 217% of the 2010 level, whilst road freight is 81% of the 2010 level. The energy use for freight is derived by applying vehicle fuel type percentages and vehicle efficiency figures per tonne-kilometre for 2030 taken from [1,5].

For shipping, a single analysis is done for domestic and international shipping. Since fossil fuel imports are eliminated and food imports are reduced, shipping freight is projected to be reduced by 54%. This is as measured in tonnes of freight and we assume the same reduction for tonne-km. A 33% efficiency improvement is assumed per tonne-kilometre of freight by better engines and logistics. [11, p46] states that 25% efficiency improvements are possible from reduced speeds alone.

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Renewable Energy Supply Methodology

Version 1.1

Contents

1 Introduction

This document provides background information for the sources of renewable energy in our scenario, explaining the assumptions about the installed capacity of the resource. The detailed hourly modelling of the amount of renewable energy produced is discussed in the separate document describing the ***ZCB Energy Model.***

2 Offshore wind power

In our model we assume a total offshore wind capacity of 140 GW. Of this, 60 GW will be “fixed” offshore wind turbines with foundations embedded in the sea bed while 80 GW will come from floating wind turbines.

To assess the resource for fixed offshore wind, we have defined a total of 54 regions, each between 500km^2 and 2,600 km^2 in area, in water depth of less than 60m (green areas in Figure 1). In, these regions cover around 101,000 km^2. Realistically, not all of this area is suitable for offshore wind power development. However, it was beyond the scope of our research to identify which constraints might affect offshore wind farm developments in specific locations. The Carbon Trust (2008) has analysed the constraint on offshore wind power development in the UK and concluded that due to various soft and hard constraints the maximum potential for fixed offshore wind potential in the UK is 36 GW. However, we believe that the Carbon Trust constraint analysis is too pessimistic as many of the ‘hard’ constraints can be overcome. The Carbon Trust report itself states that *“[th]e London Array, currently the largest planned offshore wind development, has demonstrated that even in situations where there appear to be immovable constraints such as busy shipping lanes, creative solutions can be found that offer some benefit to all stakeholders*”. Therefore, rather than trying to identify specific constraints for specific areas we have decided to model all the regions we defined as suitable but to assign a very low power density (installed capacity per area) of 0.59 MW/km^2 (or W/m^2) to each region. This is much lower than the array power density (deployment density) of actual offshore wind farms (for example, the London Array wind farm has an installed capacity of 630 MW in an array covering 100km^2, 6.3MW/km^2). Our assumption is that in each region we have defined only a fraction of the area will actually be covered in offshore wind farms. The total estimate of 60 GW for fixed offshore wind is significantly lower than the estimate for the total practical resource for fixed offshore wind of 116GW provided by the Offshore Valuation Group (2010).

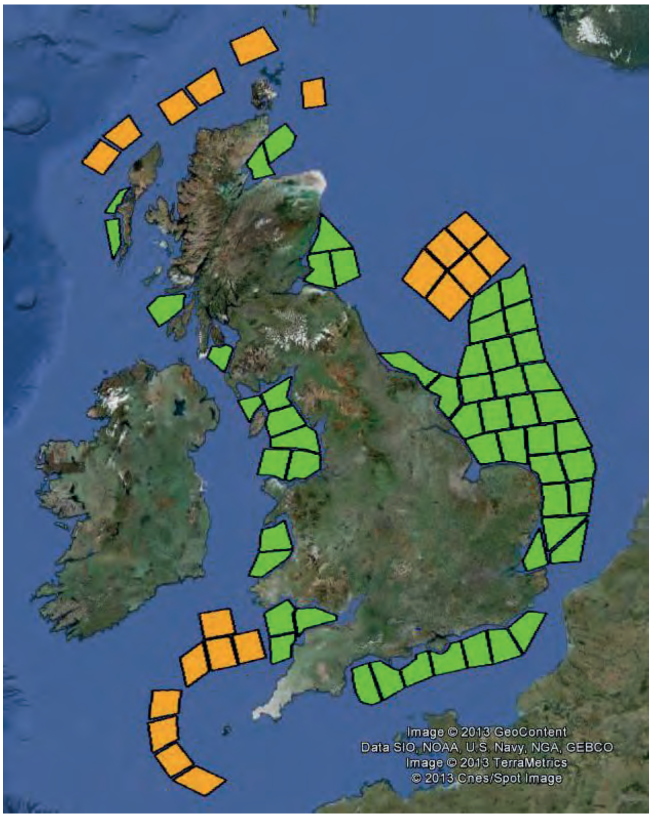

Figure 1: Offshore wind regions

Our report assumes that another 80 GW of offshore wind capacity will come from floating wind turbines in deeper waters. Prototypes of full-scale working prototypes of floating wind turbines have been operational for several years (e.g. Statoil's HyWind turbine off Norway) and it can reasonably be assumed that this technology can be commercially available well before 2030. For our model we have defined 20 regions (orange in Figure 1), with a total area of around 45,000 km^2 for floating wind farms. Our regions are based on the mapping of the practical resource for floating wind farms by the Offshore Valuation Group (2010). We have assigned a capacity of 1.8 MW to each km^2 of floating offshore wind turbine region. This gives us a total floating offshore wind capacity of 80 GW, significantly less than the Offshore Valuation Group's estimate for the practical resource, which is 350 GW.

Using hourly wind speed data, the average annual energy yield from offshore wind turbines is calculated to be 530 TWh. This calculation is described in more detail in the document describing the hourly energy model.

3 Onshore wind power

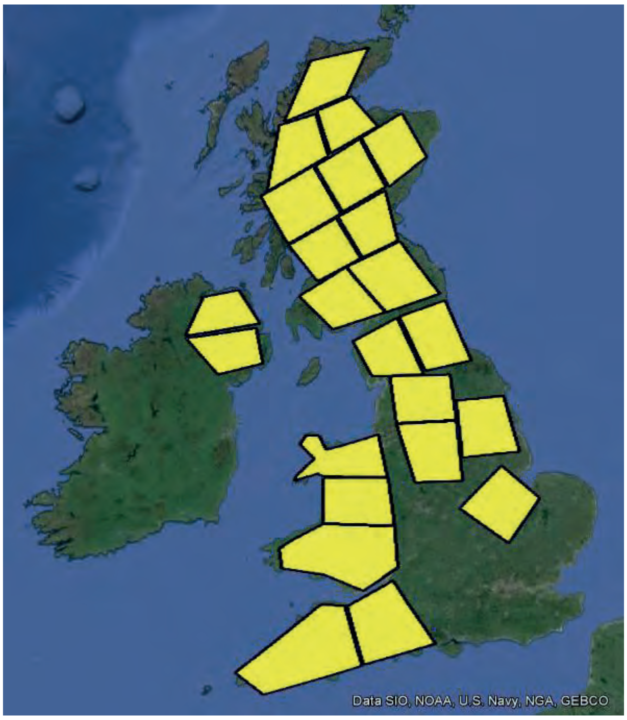

Figure 2: Onshore wind regions

In our model we assume a total installed onshore wind capacity of 30 GW. This equals the 30 GW in the "max" scenario proposed by Pöyry (2010) and is comparable with the "maximum feasible resource potential" of 20 to 30 GW described by Arup (2011).

For our model we have defined a total of 23 regions (Figure 2), covering the regions of the UK with the largest onshore wind potential. We are not suggesting that all these regions should evenly be covered in wind farms – within each region, the largest proportion of the land is probably not suitable for onshore wind power. But determining exactly where onshore wind turbines can be sited is beyond the scope of our research. Instead we simply assign a very low capacity density of 0.20 MW/km^2 – much lower than the actual power density of a wind farm (Whitelee wind farm near Glasgow has 322 MW capacity on 55 km^2 area, or 5.85 MW/km^2).

Using hourly wind speed data, the average annual energy yield from onshore wind turbines is calculated to be 77 TWh. This calculation is described in more detail in the document describing the hourly energy model.

4 Wave power

In our report we assume an installed capacity of 10 GW of wave power. Our current understanding of the technical potential of the UK's wave power resource appears to be still fairly limited, and it is not yet clear what future wave energy converters will look like. The figure chosen for our scenario is in-between the assumptions for the "Very High" (6 GW) and "Max" (14 GW) in Pöyry (2010).

Using hourly data on significant wave height and wave period, we calculated that the average annual wave energy yield is 25 TWh.

5 Tidal power

On our model we assume an installed capacity of 20 GW of tidal power. This includes both tidal range (tidal barrages) and tidal stream generation.

The site with the biggest tidal range potential in the UK is in the Severn estuary, but there is also potential, but there is also potential in other estuaries, including Mersey, Duddon, Wyre, Solway and Conwy. Pöyry (2010) assume, in their "Max" scenario, a total tidal range potential of 9 GW. DECC (2010) use a number of 20 GW for tidal range in their "level 4" *2050 Pathways* scenario.

The key resource areas for tidal stream power generation potential in the UK, according to Arup (2010) are off the north coast of Scotland around the Pentland Firth, between southwest Scotland and Northern Ireland, around the north coast of Northern Ireland, between Scotland and the Isle of Man, off the north, west and south coasts of Wales, and in the English Channel in the region around the Isle of Wight. Pöyry (2010) assume 2 GW and 4 GW of tidal stream potential in their "Very High" and "Max" scenarios, whereas DECC (2010) assume a potential of 21.6 GW in their "level 4" *2050 Pathways* scenario.

Using a mathematical formula to calculate hourly variations in tidal flow patterns, we calculated that the average annual power output from tidal power is 42 TWh.

6 Hydro power

Our model assumes a total of 3 GW of hydropower is installed. This includes the existing 1.5 GW of "large" (>5 MW) hydropower generation plus an additional 1.5 GW of "micro hydro". The total amount of hydropower in Pöyry's (2010) "Max" scenario is 6 GW, the DECC (2010) "level 4" *2050 Pathways* scenario assumes 4 GW.

Assuming an average capacity factor of 30%, our model assumes that 3 GW of hydropower capacity will produce 8 TWh per year.

7 Solar photovoltaic (PV) power

Figure 3 Solar regions

Our model assumes a total installed solar PV capacity of 90 GW of solar PV. We do not explicitly state that all this capacity is roof-mounted, but significant field-based solar farm developments would conflict with other land-use in our scenario. For England, statistical data on roof areas is available from the Generalised Land Use Database (ONS, 2005). According to that source, there are 1,508 km^2 of domestic buildings and 869 km^2 of non-domestic buildings in England, giving a total of 2,377 km^2 of area covered with buildings in England. Assuming that the roof area is roughly proportional to population numbers, it can be assumed that around 2,800 km^2 of the total surface area of the UK are covered with buildings. As we assume that in our scenario around 6 km^2 of roof area are required per 1 GW of PV capacity (17% module efficiency) the area required for 90 GW is 540 km^2. Depending on the average roof slope (as the roof area available is greater than the area covered by buildings) this means that for 90 GW capacity around 15-20% of the total roof area of the UK would need to be covered in PV modules. DECC (2010) in their "level 4" *2050 Pathways* scenario assume that covering all domestic south facing roof space in the UK allows for a PV capacity of 95 GW.

The PV capacity is spread over 11 solar regions, shown in Figure 3, proportionate to the proportion of the UK's population that lives in each region.

Using hourly solar radiation data, we calculate the average annual electricity yield from 90 GW of solar PV to be around 74 TWh.

8 Solar thermal heat

The research on the technical potential for solar thermal heat (solar water heating) in the UK. DECC (2010) state that with 1.6m^2 of solar thermal collectors per person the UK could produce 58 TWh of heat per year (level 3) and with 3.1m^2 of collector area per person this would rise to 116 TWh (level 4).

For our scenario we assume that solar thermal collectors will contribute 25 TWh of heat per year.

9 Geothermal electricity & heat

The research on the technical potential for geothermal heat in the UK is at an early stage. According to a report by Sinclair Knight Merz (2012) there are both medium (160C) and low temperature (below 90C) aquifer (HSA) resources in East Yorkshire and Lincolnshire, Cheshire, Worcester, Wessex and Northern Ireland, though power generation can only be considered a possibility in Cheshire and Wessex. According to the Sinclair Knight Merz (SKM) report, the main areas with "hot dry" (EGS) potential for electricity generation are Cornwall, Weardale and the Lake District. SKM estimate that the total installed generation potential is 9.5GW for electricity and 100GW for heat. However, these figures describe the geological resource and do not consider limiting factors or parasitic energy consumption of power stations (which can be significant). SKM assume that by 2030 realistically 0.68 GW of geothermal electricity and 4 GW of geothermal heat capacity can be installed. DECC (2010) in their "level 4" *2050 Pathways* scenario assume 5 GW of geothermal electricity generating capacity.

For our model we assume that there is a total capacity of 3 GW of geothermal electricity generation capacity, producing 24 TWh of electricity.

Our model also assumes that 15 TWh of heat per year can be produced from geothermal sources.

10 Biomass

Our model assumes that biomass provides a total of 230 TWh of energy per year. Of that,

- 36 TWh is from biomass waste, for anaerobic digestion
- 38 TWh is from grass silage, for anaerobic digestion
- 115 TWh is from Miscanthus and Short Rotation Coppice (SRC), for producing synthetic fuels
- 41 TWh is from Short Rotation Coppice (SRC) and Short Rotation Forestry (SRF), for domestic and industrial heat

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ZERO CARBON BRITAIN

Hourly energy model

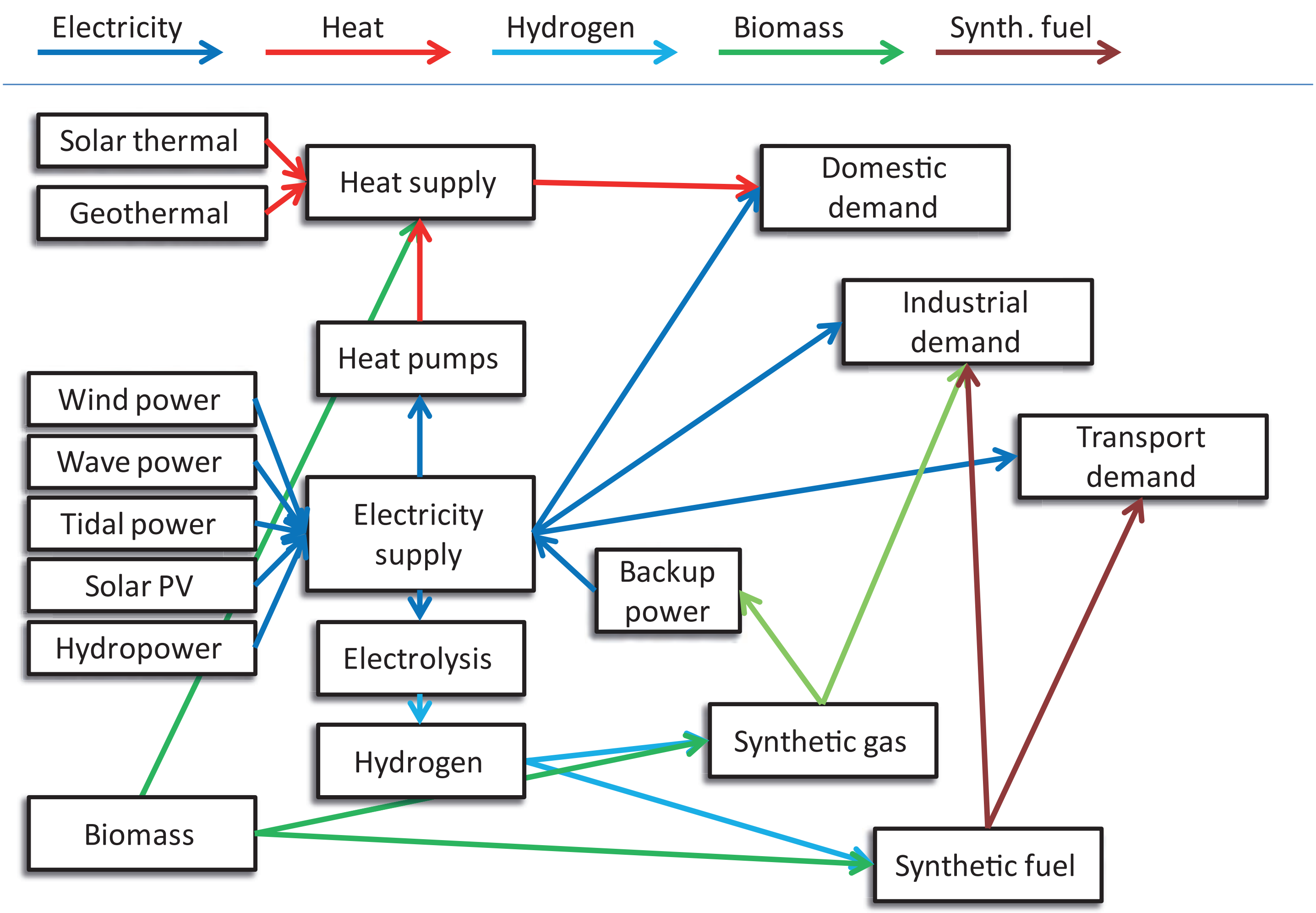
Version 1.1

Contents

1 Introduction

This document describes the hourly energy model, which models hourly flows of energy supply and demands. Our approach is to use historical data on factors which influence supply (wind speeds, wave heights, solar radiation) and demand (electricity demand, temperatures) to simulate energy flows under the assumptions made in our scenario. The ZCB energy model uses hourly historical data for the ten year period from 00:00 on 1 January 2002 to 23:00 on 31 December 2011, this covers a total of 87,648 hours.

The energy model simulates flows of electricity, heat, biomass, hydrogen, synthetic gas and synthetic fuel (see diagram below). Some flows in the model, e.g. the supply of electricity from wind turbines or the heat demand for space heating, are determined by external inputs (e.g. wind speeds, air temperatures) and independent on other flows in the model. Other flows, e.g. electricity supply from backup gas power stations, are reactive and dependent on other flows in the model.



2 Electricity

2.1 Renewable electricity supply

2.1.1 Offshore wind power

For each of the offshore wind regions (Appendix A), hourly wind speed estimates (for 50m height above the surface) are obtained from NASA's MERRA (Modern-Era Retrospective Analysis) database (NASA, 2013), extracted using a tool developed my Marc Stringer of Reading University (Stringer, 2012).

For each of the regions, latitude and longitude of the centre point of the region are determined (using the Google Earth polygon and the tool at http://www.earthpoint.us/Shapes.aspx) and hourly wind speeds for that location are obtained using the MERRA extraction tool (Stringer, 2012).

To convert wind speeds to power output, a power curve for an industrial wind turbine (Siemens SWT-3.6) is normalized such that the power output is 0.0 below the cut-in wind speed (3 m/s) and 1.0 at and above the rated wind speed (12 m/s). The normalized power output (between 0.0 and 1.0) at a given wind speed is then multiplied with the assumed installed wind power capacity in that region to give the power output in that region at that point in time.

In this way, power output is calculated for each of the 60 offshore wind regions detailed in Appendix A, for each of the 87,648 hours of the model.

2.1.2 Onshore wind power

The method for calculating hourly onshore wind power output follows the approach described above for offshore wind power. The onshore wind power regions are detailed in Appendix B.

2.1.3 Wave power

Hourly wave power output is calculated based on hourly data on wave height and wave period obtained through the Met Office's Marine Automatic Weather Station (MAWS) network (Met Office, 2013). The data is obtained for five marine automatic weather stations, as listed in Appendix C. The power matrix for the Pelamis P-750 wave energy converter is used to obtain a normalized (between 0.0 and 1.0) power output for a given wave period and significant wave height.

The marine automatic weather stations used for the hourly wave power output calculations (Appendix C) do not necessarily reflect the best regions for placing wave energy converters. Instead, these locations were simply chosen because data was available for these locations.

2.1.4 Tidal power

The hourly energy model for tidal power is based on a mathematical formula describing tidal patterns. We do not distinguish between tidal stream and tidal range technology and we calculate tidal power output as if all generating capacity was installed in one single location. We hope that future research will model the types and locations of tidal energy converters in more detail.

2.1.5 Hydro power

Our hourly model assumes that power output from hydropower is constant at 30% of the installed capacity. This is clearly not an accurate reflection of hydropower output, which depends on rainfall patterns. However, we did not have access to sources of hourly data for river flows that would allow more accurate modelling of hydropower output. However, the contribution of hydropower to the model is very low in overall terms, therefore it is unlikely that improvements to the hydropower model will have a significant impact on the overall model.

2.1.6 Solar photovoltaic (PV) power

To model the hourly output of 90 GW of solar PV capacity, the UK is divided into 11 regions (Appendix D) and the 90 GW capacity is assigned to the 11 regions based on the absolute population figures for each region. For each region, hourly solar radiation (global horizontal irradiance) readings from Met Office stations are obtained through the MIDAS (Met Office Integrated Data Archive System) which was obtained through the British Atmospheric Data centre (BADS, 2013) and averaged to give a single hourly solar radiation reading for each region. As the coverage of the MIDAS data is less than 100% (there are gaps in the data) the number of stations contributing data to each region may differ from one hour to the next.

For our calculations we assume that solar PV output is directly proportional to the global horizontal irradiance level and that PV systems reach their nominal rated capacity at a radiation level of 1000 W/m^2. Our model does not take into account the effects of roof slopes and orientations and does not correct for temperature effects.

2.1.7 Geothermal electricity

For the hourly output of the geothermal electricity plants, we assume that the electricity output is constant at 90% of the installed production capacity.

2.2 Electricity demand

2.2.1 Demand for electric appliances

This is the electricity demand for electric appliances, excluding electricity demand for industrial processes, electric transport and space & water heating.

To model hourly variation of this demand, we have taken hourly electricity demand data obtained from the National Grid (via https://www.elexonportal.co.uk) and scaled it to reflect the changes in electricity demand described in the Power Down section of the report. Electricity demand for electric appliances, including cooking, is 105 TWh per year.

2.2.2 Industrial electricity demand

To obtain hourly figures for the electricity demand of industrial processes, we have calculated the daily electricity demand for industrial processes (assuming demand is evenly spread over all days of a year) and then used a 24h hourly demand profile (24 values summing to 100%) to model the hourly fluctuations of industrial electricity demand. The total industrial electricity demand in our model is 171 TWh per year.

2.2.3 Demand for electric transport

Electric transport in the scenario falls into two categories: Modes of transport which consume electricity at the time when they are used – electric trains and trams – and electric battery vehicles (BEV) which are charged in-between uses. For both forms of transport daily electricity demand is calculated from the annual demand assumptions, and 24h hourly demand profiles are then used to model hourly fluctuations. However, for BEV we assume that there is a certain amount of “smart charging” (see also 3.2.2).

In our scenario, electricity demand for BEV is 57 TWh per year, electric trains and trams consume 13 TWh per year.

2.2.4 Demand for space and water heating

A significant amount of electricity is used to produce space and water heating. This is discussed in more detail in the section describing heat supply and demand. In our model, electricity demand for heating is 65 TWh per year for heat pumps plus 11 TWh per year for electric resistance heating.

2.3 Electricity balancing & storage

2.3.1 Electricity storage & smart demands

We assume a total of 200 GWh of electricity storage and “smart appliances”, in addition to “smart charging” of electric car and a combination of “smart” heating and 200 GWh of heat storage.

The mechanisms used for simulating storage and smart demands are fairly simple: For every hour, the balance of supply and demand during that one hour is compared to the average balance of supply and demand in the 12 hours before and the 12 hours after that hour. Depending on the outcome of that comparison, energy is either stored or withdrawn from storage.

2.2.3 Electrolysis & backup

If, after making use of electricity storage and smart demands, there is still a surplus of electricity generation then up to 25 GW of electricity can be diverted to electrolysis (see section 4.1). Any surplus supply beyond amount this will need to be exported or generation needs to be curtailed.

If, on the other hand, there is a shortfall of supply, then up to 70 GW of backup gas turbine capacity, burning synthetic (renewable and carbon neutral) methane gas, can be activated.

In our model it is assumed that these turbines can be ramped up and down quickly (ramp rates are around 30 GW/h) and can run at an efficiency of around 50%.

Strictly speaking, supply does not always meet demand in our model, as for around 0.1% of the time (>100 hours during the ten year, 87,648 hour model period) there is a shortfall in electricity supply.

3 Heat

This section describes the production of low-temperature heat for space heating and for domestic hot water (baths, showers etc).

High temperature heat demand for industrial processes is modelled separately through industrial demand for electricity and gas.

3.1 Renewable heat supply

3.1.1 Solar thermal

Our hourly model for heat supply from solar thermal we use the same approach as for modelling solar PV electricity production. In other words, solar thermal production is modelled as depending only on the global horizontal irradiance, calculated from hourly Met Office MIDAS station recordings for 11 regions (Appendix D), with solar thermal capacity assigned to the regions proportional to population figures.

This approach is somewhat simplistic as it does not consider the impact of roof orientations and, more crucially, air temperature on heat production from solar thermal panels.

The total amount of heat supplied from solar thermal systems in our model is 25 TWh per year.

3.1.2 Geothermal heat

In our model, hourly heat production from geothermal sources is constant at 1.8 GWh per hour, 16 TWh per year.

3.1.3 Electric resistance heating

Of the heat demand not met by solar and geothermal heat, a fraction of 5% is met by simple direct electric resistance heating, with a 100% efficient conversion of electricity to heat.

3.1.4 Heat pumps

Of the heat demand not met by solar and geothermal heat, 90% is met by heat pumps with an assumed coefficient of performance (CoP) of 3.0, allowing the production of 3.0 GWh of heat for spalce and water heating from 1.0 GWh of electricity.

In reality, the averaged CoP of all heat pumps in the country will not be constant throughout the year as the CoP will be constant as the CoP will depend on the temperature difference between source (air, ground or water) and delivery temperature (temperature of water used for hot water or heating). However, as our model makes no explicit assumptions about heat sources and delivery mechanisms it is not possible to model the hourly variation in CoP accurately.

3.1.4 Biomass

Of the heat demand not met by solar and geothermal heat, 5% is met by biomass boilers with a 90% conversion efficiency.

3.2 Heat demand

3.2.1 Space heating

Heat demand for space heating (both domestic and non-domestic) is primarily dependent on outside air temperature. For our model we use the National Grid's daily weighted average temperature ("Actual Temperature" from http://www.nationalgrid.com/uk/Gas/Data/misc/) to calculate the daily average space heat demand in our model, assuming an increase in heat demand of 5.6 GW for every °C the temperature drops below 13.1°C (specific space heating demand of 5.6 GW/K and base temperature of 13.1°C). Having calculated the daily space heat demand, hourly space heat demands are calculated using a 24h hourly space heat demand profile.

3.2.2 Domestic water heating

In our model we assume that hot water demand is constant on all days of the year, spreading the annual hot water heating demand of 82 TWh equally over all days of the year.

To obtain hourly hot water demand values, a 24h hourly hot water heating demand profile is applied to the daily hot water demand.

3.3 Balancing & storage

Our energy model assumes a single 'heat store' of 200 GWh capacity. In reality, this could either be millions of small domestic water tanks, or larger communal centralised heat stores, or a combination of these. One function of the heat store is to store solar and geothermal heat during hours when the heat supply exceeds the demand. Beyond that, the heat store is also used to allow for "smart" electric heating which increases heat production from electricity at times of low demand to reduce the heat related electricity demand at times when electricity demand exceeds supply.

4 Chemical processes

This part describes the modelling of the various flows of chemical energy fuels in our model. The conversion of electricity, especially electricity produced at times when the supply from renewable electricity sources exceeds the demand, and biomass into chemical fuels (hydrogen, methane and synthetic liquid hydrocarbon fuels) plays an important role in our scenario as it helps us deal with variability and completely replace fossil fuels.

See Wenzel (2010) for a good summary of the role of chemical fuels, and ways to produce them using renewable energy.

4.1 Hydrogen

4.1.1 Hydrogen production

In our model we assume an electrolysis capacity of 25 GW (electricity input) and a conversion efficiency of 80%, which means that at maximum production rate, hydrogen with a heating value of 20 GWh is produced every hour.

Hydrogen is only produced when the supply of electricity from renewable sources exceeds the demand and when there is sufficient capacity for storing hydrogen that is produced.

The electricity consumption for hydrogen production averages to 180 TWh per year, producing 126 TWh of hydrogen per year.

4.1.2 Hydrogen demand

A small amount of hydrogen (10 TWh per year) is used directly as a transportation fuel. In the hourly model, this is modelled as a constant hourly demand of 1.1 GWh of hydrogen for hydrogen vehicles. It is assumed that supply/demand variation of hydrogen transport fuel is handled by a distribution and storage infrastructure that is beyond the scope of our model.

The bulk of the hydrogen is used for the production of synthetic gas (35 TWh per year) and synthetic transport fuels (55 TWh per year), modelled as constant hydrogen flows flows of 4.1 GWh/h and 7.4 GWh/h respectively.

In total, there is a constant hourly demand for 12.6 GWh of hydrogen.

4.1.3 Hydrogen storage

To ensure that a constant hydrogen demand of 12.6 GWh/h can be met from a variable supply fluctuating between 0 and 20 GWh/h, our model includes hydrogen storage, e.g. in salt caverns, with a capacity of 20,000 GWh.

4.2 Renewable gas

4.2.1 Renewable gas production

In our model, renewable methane gas is produced through a combination of two processes

- **Anaerobic digestion**
  The anaerobic digestion of biomass waste and grass silage produces "biogas", a mixture of (bio-)methane and carbon dioxide. We assume that the efficiency of the conversion from biomass to (bio-)methane is 57%
- **Sabatier reaction**
  The Sabatier reaction allows the production of methane gas from hydrogen and carbon dioxide (see Sterner, 2009). In our model, the energy efficiency of the conversion between hydrogen and methane is assumed to be 80%.

In our model we assume that the carbon dioxide required for the Sabatier reaction is sourced from waste carbon dioxide from anaerobic digestion. This means that the production of synthetic methane using the Sabatier reaction is limited by the rate at which biogas is produced. In our model, biogas is produced at a constant rate of 5 GWh/h (42 TWh/year) and synthetic methane at a rate of 3 GWh/h (28 TWh/year). In total, renewable methane gas is produced at a constant rate of 8 GWh/h, leading to a production of 70 TWh per year.

The assumption that biogas can be produced at a constant rate all hours of the year may be problematic unless grass silage is stored over months to allow for a constant biogas feedstock supply.

4.2.2 Renewable gas demand

In our model renewable (synthetic/bio-) methane gas is used in industry, for example for high temperature heat processes, and as a fuel for backup power stations.

Flows of methane gas for industrial use are initially modelled as constant gas flows of approx. 5.7 GWh/h (50 TWh per year). There is then a process whereby a proportion of industrial biogas demand is substituted for electricity and vice versa depending on the availability of electricity from renewables such as wind and solar.

Flows of methane gas to backup gas power stations are highly variable, at peak output the gas consumption of the backup gas power stations is 140 GWh/h for a peak electricity output of 70 GW.

4.2.3 Renewable gas storage

The storage of compressed methane gas in underground storage facilities is the main long-term energy storage mechanism in our scenario. The model assumes the capacity to store 60 TWh (60,000 GWh) of methane gas. We have chosen this capacity because it allows a situation where the final storage content after simulating 87,648 hours (ten years), 34 TWh, is very similar to the initial storage content at model start, 30 TWh. The fact that the storage content never drops below 24 TWh suggests that 60 TWh is more storage capacity than required. However, in simulations with less than 60 GW capacity we find that the methane store is full (i.e. no more gas can be stored) for significant amounts of time, and, because a lot of gas demand for backup electricity generation is towards the end of the simulation period (weather data for winter 2010/11), the final gas storage content is lower than the initial content.

4.3 Synthetic liquid fuel

In our model we produce synthetic liquid fuel from biomass and hydrogen using the Fischer-Tropsch process. These synthetic liquid fuels are used in industry, and for forms of transport (heavy commercial vehicles & aviation) which we assume cannot run on electricity or hydrogen.

4.3.1 Synthetic fuel production

In our model synthetic fuels – bio-kerosene and bio-diesel - are produced from hydrogen and biomass using the Fischer-Tropsch process. In our model, we assume that 1.30 GWh of biomass and 0.61 GWh of hydrogen are required to produce 1.0 GWh of liquid synthetic fuel – a total efficiency of 52% (see Agrawal et al., 2007).

In our model, the fuel production process runs at a constant rate, consuming 6.3 GWh of hydrogen and 13.1 GWh of biomass to produce 9.9 GWh of liquid fuel every hour.

In our model the hydrogen storage capacity is large enough to ensure there is always enough hydrogen available for this process.

Our land use model ensures that enough biomass (115 TWh per year) can be produced per year, the hourly energy model assumes that this biomass can be made available for fuel production at a constant rate.

Our model does not distinguish between different synthetic liquid fuels (kerosene, diesel).

4.3.2 Synthetic fuel demand

In our model, every year 13 TWh of synthetic liquid fuel is used by industry and 74 TWh are used in transport. We do not model hourly fluctuations in the demand for these fuels, the model assumes that the fuel distribution infrastructure has enough storage capacity to buffer these fluctuations.

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Appendix A: Offshore wind regions

Table A1.1: Offshore wind regions for fixed offshore wind turbines

Region	Central Point		Area (km²)	Capacity		Avg. yield (TWh/yr) [A]	Cap. Fac. [A]	Avg. Output [A]	
	Lat	Lon		(GW)	(W/m²)			(GW)	(W/m²)
off_heb1	57.74	-7.53	597	0.35	0.59	1.65	53%	0.19	0.32
off_heb2	57.24	-7.69	1,110	0.66	0.59	3.15	55%	0.36	0.32
off_mull	56.08	-6.47	2,011	1.19	0.59	4.98	48%	0.57	0.28
off_clyde	55.26	-5.21	1,090	0.65	0.59	2.12	37%	0.24	0.22
off_is1	54.49	-4.64	862	0.51	0.59	1.84	41%	0.21	0.24
off_is2	54.57	-3.94	1,493	0.89	0.59	3.05	39%	0.35	0.23
off_is3	54.20	-3.89	1,991	1.18	0.59	4.34	42%	0.49	0.25
off_is4	53.90	-3.63	2,098	1.24	0.59	4.46	41%	0.51	0.24
off_is5	53.63	-4.27	1,895	1.12	0.59	4.24	43%	0.48	0.26
off_is6	53.54	-3.60	1,971	1.17	0.59	4.04	39%	0.46	0.23
off_card1	52.56	-4.54	1,791	1.06	0.59	3.79	41%	0.43	0.24
off_card2	52.25	-4.79	1,637	0.97	0.59	3.47	41%	0.40	0.24
off_bris1	51.42	-4.72	2,017	1.20	0.59	4.41	42%	0.50	0.25
off_bris2	51.36	-4.01	1,660	0.98	0.59	3.00	35%	0.34	0.21
off_bris3	51.01	-4.81	1,440	0.85	0.59	3.15	42%	0.36	0.25
off_ec1	50.29	-3.07	2,008	1.19	0.59	4.23	40%	0.48	0.24
off_ec2	50.32	-2.58	2,011	1.19	0.59	4.29	41%	0.49	0.24
off_ec3	50.37	-1.86	1,764	1.05	0.59	3.73	41%	0.43	0.24
off_ec4	50.42	-1.14	2,008	1.19	0.59	4.24	41%	0.48	0.24
off_ec5	50.47	-0.48	2,007	1.19	0.59	4.30	41%	0.49	0.24
off_ec6	50.46	0.10	2,010	1.19	0.59	4.29	41%	0.49	0.24
off_ec7	50.62	0.70	2,009	1.19	0.59	4.02	38%	0.46	0.23
off_thames1	51.63	1.31	1,442	0.85	0.59	2.75	37%	0.31	0.22
off_thames2	51.60	2.11	2,032	1.20	0.59	4.39	42%	0.50	0.25
off_thames3	51.90	1.97	2,007	1.19	0.59	4.35	42%	0.50	0.25
off_norf1	52.30	2.03	1,999	1.18	0.59	4.30	41%	0.49	0.25
off_norf2	52.26	2.62	1,770	1.05	0.59	4.01	44%	0.46	0.26
off_norf3	52.76	2.05	2,008	1.19	0.59	4.43	42%	0.51	0.25
off_norf4	52.70	2.77	2,132	1.26	0.59	4.93	44%	0.56	0.26
off_norf5	53.11	2.77	2,062	1.22	0.59	4.89	46%	0.56	0.27
off_norf6	53.18	2.08	2,017	1.20	0.59	4.68	45%	0.53	0.26
off_norf7	53.19	1.40	2,061	1.22	0.59	4.43	41%	0.51	0.25
off_norf8	53.25	0.74	2,017	1.20	0.59	4.10	39%	0.47	0.23
off_horn1	53.69	0.49	1,984	1.18	0.59	4.25	41%	0.49	0.24
off_horn2	53.68	1.15	2,079	1.23	0.59	4.84	45%	0.55	0.27
off_horn3	53.64	1.82	2,015	1.19	0.59	4.84	46%	0.55	0.27
off_horn4	53.59	2.56	2,565	1.52	0.59	6.24	47%	0.71	0.28
off_horn5	54.04	2.43	2,016	1.20	0.59	5.01	48%	0.57	0.28
off_horn6	54.08	1.68	2,017	1.20	0.59	4.97	47%	0.57	0.28

off_horn7	54.11	0.87	2,018	1.20	0.59	4.81	46%	0.55	0.27
off_horn8	54.12	0.13	2,036	1.21	0.59	4.39	42%	0.50	0.25
off_horn9	54.62	-0.59	2,008	1.19	0.59	4.01	38%	0.46	0.23
off_dogger1	54.49	0.96	1,901	1.13	0.59	4.68	47%	0.53	0.28
off_dogger2	54.51	1.63	2,038	1.21	0.59	5.12	48%	0.58	0.29
off_dogger3	54.50	2.33	2,026	1.20	0.59	5.12	49%	0.58	0.29
off_dogger4	54.94	2.33	2,010	1.19	0.59	5.15	49%	0.59	0.29
off_dogger5	54.91	1.49	2,045	1.21	0.59	5.20	49%	0.59	0.29
off_dogger6	55.26	1.60	2,001	1.19	0.59	5.13	49%	0.59	0.29
off_dogger7	55.36	2.39	2,070	1.23	0.59	5.35	50%	0.61	0.29
off_firth1	56.23	-2.33	2,010	1.19	0.59	4.02	38%	0.46	0.23
off_firth2	56.23	-1.71	2,014	1.19	0.59	4.62	44%	0.53	0.26
off_firth3	56.67	-1.98	2,011	1.19	0.59	4.46	43%	0.51	0.25
off_moray1	57.95	-3.47	1,420	0.84	0.59	2.97	40%	0.34	0.24
off_moray2	58.21	-2.85	1,898	1.13	0.59	4.62	47%	0.53	0.28
Total			**101,211**	**60.00**	**0.59**	**227.85**	**43%**	**26**	**0.26**

A: Yields and capacity factors are derived using the hourly wind speed model, for details see the description of the hourly energy model

Table A1.2: Offshore wind regions for floating offshore wind turbines

Region	Central Point		Area (km²)	Capacity		Avg. yield (TWh/yr) A	Cap. Fac. A	Avg. Output A	
	Lat	Lon		(GW)	(W/m²)			(GW)	(W/m²)
flo_heb1	58.43	-7.90	2,050	3.69	1.80	18.73	58%	2.14	1.04
flo_heb2	58.74	-7.19	1,990	3.58	1.80	17.79	57%	2.03	1.02
flo_heb3	59.01	-5.57	2,113	3.80	1.80	18.65	56%	2.13	1.01
flo_heb4	59.23	-4.67	2,192	3.95	1.80	19.03	55%	2.17	0.99
flo_ork1	59.73	-3.15	3,023	5.44	1.80	26.21	55%	2.99	0.99
flo_ork2	58.83	-1.66	1,668	3.00	1.80	14.02	53%	1.60	0.96
flo_corn1	49.23	-7.12	2,231	4.02	1.80	17.10	49%	1.95	0.87
flo_corn2	49.57	-7.63	2,011	3.62	1.80	15.74	50%	1.80	0.89
flo_corn3	49.98	-7.79	2,051	3.69	1.80	16.30	50%	1.86	0.91
flo_corn4	50.41	-7.67	2,011	3.62	1.80	16.09	51%	1.84	0.91
flo_bris1	51.09	-5.55	2,083	3.75	1.80	15.65	48%	1.79	0.86
flo_bris2	51.47	-6.21	2,150	3.87	1.80	16.73	49%	1.91	0.89
flo_bris3	51.04	-6.22	2,116	3.81	1.80	16.55	50%	1.89	0.89
flo_bris4	50.93	-6.86	2,062	3.71	1.80	16.40	50%	1.87	0.91
flo_dogger1	55.47	0.71	2,892	5.21	1.80	22.62	50%	2.58	0.89
flo_dogger2	55.88	0.24	2,822	5.08	1.80	22.13	50%	2.53	0.89
flo_dogger3	55.71	1.37	2,387	4.30	1.80	18.83	50%	2.15	0.90
flo_dogger4	56.16	0.93	2,221	4.00	1.80	17.66	50%	2.01	0.91
flo_dogger5	55.91	1.99	2,232	4.02	1.80	17.75	50%	2.02	0.91
flo_dogger6	56.34	1.57	2,120	3.82	1.80	16.94	51%	1.93	0.91
			44,425	**80.00**	**1.80**	**360.90**	**51%**	**41.2**	**0.93**

A: Yields and capacity factors are derived using the hourly wind speed model, for details see the description of the hourly energy model

Appendix B: Onshore wind regions

Table B1.1 Onshore wind regions

Region	Central Point		Area (km^2)	Capacity		Avg. yield (TWh/yr) [A]	Cap. Fac. [A]	Avg. Output [A]	
	Lat	Lon		(GW)	(W/m^2)			(GW)	(W/m^2)
ons_corn1	50.54	-4.33	13,721	1.82	0.13	5.59	35%	0.64	0.046
ons_corn2	50.97	-2.66	9,239	1.22	0.13	3.24	30%	0.37	0.040
ons_wales1	51.89	-3.61	12,029	1.59	0.13	4.22	30%	0.48	0.040
ons_wales2	52.58	-3.37	6,707	0.89	0.13	2.32	30%	0.26	0.039
ons_wales3	53.12	-3.69	5,864	0.78	0.13	2.30	34%	0.26	0.045
ons_eng1	52.59	-0.28	6,614	0.88	0.13	2.29	30%	0.26	0.040
ons_eng2	53.27	-1.78	6,746	0.89	0.13	2.33	30%	0.27	0.039
ons_eng3	53.59	-0.63	6,236	0.83	0.13	2.23	31%	0.25	0.041
ons_eng4	53.95	-2.01	5,815	0.77	0.13	2.12	31%	0.24	0.042
ons_eng5	54.75	-1.77	6,199	0.82	0.13	2.46	34%	0.28	0.045
ons_eng6	54.54	-2.82	5,217	0.69	0.13	1.85	30%	0.21	0.040
ons_sco1	55.18	-3.93	5,849	0.78	0.13	2.21	32%	0.25	0.043
ons_sco2	55.50	-2.77	7,325	0.97	0.13	2.82	33%	0.32	0.044
ons_sco3	55.82	-4.37	5,089	0.67	0.13	1.86	32%	0.21	0.042
ons_sco4	56.18	-3.35	4,802	0.64	0.13	1.79	32%	0.20	0.043
ons_sco5	56.39	-5.03	7,163	0.95	0.13	2.56	31%	0.29	0.041
ons_sco6	56.81	-3.88	5,843	0.77	0.13	2.19	32%	0.25	0.043
ons_sco7	57.19	-2.87	5,377	0.71	0.13	2.15	34%	0.25	0.046
ons_sco8	57.12	-5.23	5,696	0.75	0.13	2.18	33%	0.25	0.044
ons_sco9	57.50	-4.12	4,086	0.54	0.13	1.71	36%	0.20	0.048
ons_sco10	58.04	-4.63	6,142	0.81	0.13	2.59	36%	0.30	0.048
ons_ni1	54.90	-6.64	4,301	0.57	0.13	1.76	35%	0.20	0.047
ons_ni2	54.43	-6.40	4,850	0.64	0.13	1.92	34%	0.22	0.045
Total			**150,909**	**20.00**	**0.13**	**56.71**	**32%**	**6.47**	**0.043**

A: Yields and capacity factors are derived using the hourly wind speed model, for details see the description of the hourly energy model

Appendix C: Wave power

Table C1.1 Wave power data sources

MAWS Station		Location		Capacity (GW)
Name	ID	Lat	Lon	
K4	62105	55.400	12.200	3
K5	64045	59.100	11.401	3
Tubot Bank	62303	51.603	5.100	1.5
Seven Stones	62107	50.103	6.100	1.5
Aberporth	62301	52.300	4.500	1

Appendix D: Solar power

Table D1.1 Wave power data sources

Region	population	capacity (%)	Capacity (GW)	MIDAS stations in region (average)
East Eng & Lon	14,021,000	12%	9	8.6
East Midlands	4,533,000	7%	5	3.5
North East Eng	2,597,000	4%	3	2.0
North West Eng	7,052,000	11%	8	3.3
South East Eng	8,635,000	19%	14	7.8
South West Eng	5,289,000	13%	10	7.5
West Midlands	5,602,000	9%	7	6.9
Yorks & Humber	5,284,000	8%	6	4.7
Scotland	5,254,800	8%	6	22.7
Wales	3,064,000	5%	4	6.4
N. Ireland	1,810,900	3%	2	3.4
Total	**63,142,700**	**100%**	**75**	**76.7**

BRITAIN

Land use model

Contents

1 Introduction

Land in the ZCB scenario has to play 3 roles:

- Providing food for the UK population.
- Providing hydrocarbon fuels and energy storage for parts of our energy demand that cannot be met through renewable electricity generation.
- ‘Balancing’ (or annually ‘offsetting’ in the long-term) residual emissions in the scenario using carbon capture – there are some emissions which we cannot ‘get rid of’ in the scenario – some from industrial processes and waste processing, and some from agriculture (largely livestock and fertiliser).

Everything grown on the land is modelled here, apart from food production. This is done separately via the ‘**Food + Diets**’ model, and priority is given to food production on UK cropland, and on some grassland (livestock is much reduced in the scenario to reduce the greenhouse gases from them). Also modelled separately is the energy system – annual ‘**Power Down**’ and ‘**Power Up**’ models, and an **hourly model** of supply and demand for the UK, based on our renewable energy mix. Out of this, comes a demand for some hydrocarbon fuels (which can be made with biomass from energy crops), and some amount of energy that can be stored (build up the store when there is a plentiful supply of energy, and run it down when energy is in short supply). Our method of energy storage is conversion of biomass to synthetic gas and biogas through anaerobic digestion and by the addition of hydrogen (made through electrolysis with excess energy at times of high supply and low demand).

The aim of the land-use model is to satisfy all three demands above. The requirements of the ‘Food + Diets’ model are absolute: they cannot be changed. There is, however, some flexibility in the energy model which means that what the final land-use in the scenario is depends on a process of iteration.

This document supplies the information behind the land-use model of ZCB. It is these parameters which are used to try and satisfy the energy and carbon capture demands on land. What we can decide, is:

- How much land can be used for what (via assigning kilohectares (kha’s) to various land-uses).
- What products from the land go into different processes, and where they can end up ultimately (via fractional assignment of each product to a number of ‘streams’).

2 Methods

Table 1: ZCB Land-use Types, CS Broad Habitat Types and descriptions (NERC, 2008a).

ZCB Land Use Types	CS Broad Habitats (CS 2007)	Broad Habitat Description
Broadleaf woodland	Broadleaved, Mixed and Yew Woodland	Vegetation dominated by trees >5m high when mature, with tree cover >20%. Scrub (<5 m) requires cover >30% for inclusion in this Broad Habitat. It includes stands of both native and non-native broadleaved trees and yew. Woodlands dominated by coniferous species but with >20% cover by deciduous species are included in this category. Areas of fen woodland dominated by species such as willow (Salix spp.), alder (Alnus glutinosa) or birch (Betula spp.) are also included.
Coniferous woodland	Coniferous Woodland	Vegetation dominated by trees >5m high when mature, which forms a canopy having a cover of >20%. „Coniferous Woodland" includes semi-natural stands and plantations and includes both native and nonnative coniferous trees.
Arable + Horticultural Cropland	Arable and Horticulture	Includes annual crops, perennial crops, woody crops, intensively managed commercial orchards, commercial horticultural land (such as nurseries, commercial vegetable plots and commercial flower growing areas), freshly-ploughed land, annual leys, rotational set-aside and fallow.
	Linear Features	Covers a range of linearly arranged landscape features such as hedgerows, lines of trees, walls, stone and earth banks, grass strips and dry ditches
Improved Grassland	Improved Grassland	Vegetation dominated by a few fastgrowing grasses such as Lolium spp., and also white clover (Trifolium repens), on fertile, neutral soils. Improved Grasslands are typically either managed as pasture or mown regularly for silage production or in non-agricultural contexts for recreation and amenity purposes.
Semi-natural Grassland	Neutral Grassland	Vegetation dominated by grasses and herbs on a range of neutral soils usually with a pH of between 4.5 and 6.5. It includes enclosed dry hay meadows and pastures, together with a range of grasslands which are periodically inundated with water or permanently moist.
	Calcareous Grassland	Vegetation dominated by grasses and herbs on shallow, well-drained soils which are rich in bases (principally calcium carbonate) formed by the weathering of chalk and other types of limestone or baserich rock. Soil pH tends to be high (>6) although it may be as low as 5
	Acid Grassland	Vegetation dominated by grasses and herbs on a range of lime-deficient soils which have been derived from acidic bedrock or from superficial deposits such as sands and gravels. Such soils usually have a low base status, with a pH of <5.5.

	Fen, Marsh, Swamp	Includes fen, flushes, springs, fen meadows, rush pasture and swamp. Fens are peatlands which receive water and nutrients from groundwater and surface run-off, as well as from rainfall. Flushes are associated with lateral water movement, and springs with localised upwelling of water. Marsh is a general term usually used to imply waterlogged soil; it is used more specifically here to refer to fen meadows and rush-pasture communities on mineral soils and shallow peats. Swamps are characterised by tall emergent vegetation. Reedbeds (i.e. swamps dominated by stands of common reed Phragmites australis) are also included in this type.
	Bracken	Areas dominated by a continuous canopy cover of bracken (Pteridium aquilinum) at the height of the growing season. It does not include areas with scattered patches of bracken or areas of bracken which are >0.25 ha
Mountain, Heath + Bog	Dwarf Shrub Heath	Vegetation that has >25% cover of plant species from the heath family (ericoids) or dwarf gorse Ulex minor. It generally occurs on well-drained, nutrient-poor, acid soils. This habitat type does not include dwarf shrub dominated vegetation in which species characteristic of peat-forming vegetation such as cotton-grass Eriophorum spp. and peat-building sphagna are abundant, or that occurs on deep peat (> 0.5 m)
	Bog	Covers wetlands that support vegetation that is usually peatforming and which receive mineral nutrients principally from precipitation rather than ground water. This is referred to as ombrotrophic (rain-fed) mire. The Bog Broad Habitat includes ericaceous, herbaceous and mossy swards in areas with a peat depth >0.5m.
	Montane	Includes a range of vegetation types that occur exclusively in the montane zone such as prostrate dwarf shrub heath, snow-bed communities, sedge and rush heaths, and moss heaths. The distinction between the sub-montane and montane zone is often blurred and the two usually merge through a band of transitional vegetation.
	Inland Rock	Covers both natural and artificial exposed rock surfaces which are >0.25ha, such as inland cliffs, caves, screes and limestone pavements, as well as various forms of excavations and waste tips such as quarries and quarry waste.
Coastal + Fresh Water	Standing Open Waters	Includes natural systems such as lakes, meres and pools, as well as man-made waters such as reservoirs, canals, ponds and gravel pits.
	Rivers and Streams	Covers rivers and streams from bank top to bank top, or where there are no distinctive banks or banks are never overtopped, it includes the extent of the mean annual flood.
Urban Areas	Built-up Areas and Gardens	Covers urban and rural settlements, farm buildings, caravan parks and other man-made built structures such as industrial estates, retail parks, waste and derelict ground, urban parkland and urban transport infrastructure. It also includes domestic gardens and allotments. This type does not include amenity grassland which should be included in the 'Improved Grassland' category

Table 2: Forestry, peatland, agricultural land and priority habitat allocations to CS Broad Habitat (BH) type, and conversion through to land 'available' for use in ZCB scenario (calculated as total area in BH minus 'protected' habitat). 'Productive land' and 'Protected habitat' are taken from different data sources and so totals may not equal those totals in BH types. They are to be used as comparison and further sub-division where necessary for the ZCB scenario. Please see references for definition of each classification.

LCM 2007 Broad Habitat	Area (kha)	Ref	Of which				Of which				**Land Available for ZCB Scenario**	
			Productive Land	Area (kha)	Notes	Ref	**Protected Habitat**	Area (kha)	Notes	Ref	Land Use	Area (kha)
							Upland Mixed Ash Wood	30		[13]		
							Wet Woodland	75		[13]		
							Upland Oakwood	61		[13]		
			FC/FS Broadleaf Woodland	113	[5] [8]	[11]	Lowland Mixed Deciduous	60		[13]		
			Non-FC/FS Broadleaf Woodland	1271	[5] [8] [9]	[11]	Upland Birchwoods	31		[13]		
Broadleaf Woodland	**1385**	**[10]**		**1384**				**257**			**Broadleaf Woodland**	**1128**
			FC/FS Conifer Woodland	670	[5] [8]	[11]						
			Non-FC/FS Conifer Woodland	839	[5] [8] [9]	[11]						
Coniferous Woodland	**1508**	**[10]**		**1509**							**Coniferous Woodland**	**1508**
			Arable crops (c)	4333	[1]	[12]						
			Horticultural crops	171	[1]	[12]						
			Uncropped arable land (d)(e)	608	[1]	[12]						
			Temporary grass (<5 years old)	1193	[1]	[12]					**Temporary grass**	**1193**
Arable and Horticultural Cropland	**6306**	**[10]**		**6305**							**Arable + Horticultural Cropland**	**5113**
Improved grassland	**6256**	**[10]**	**Grass over 5 years old**	**5965**	**[2]**	[12]					**Improved grassland**	**6256**
							Peatlands (Fens)	26	[6]	[14]		
							Lowland Calcareous	45		[13]		

							Grass					
							Upland Calcareous Grass	19		[13]		
			Sole right rough grazing (f)	2737	[3]	[12]	Purple Moor Grass Rush Pasture	59		[13]		
			Common rough grazing	289	[4]	[12]	Reedbed	6		[13]		
Semi-natural grassland	**3289**	**[10]**		**3026**	**[20]**	[12]		**155**			**Semi-natural grassland**	**3134**
							Peatlands (bogs)	2277	[6]	[14]		
							Blanket Bog	1234	[19]	[13]		
			Sole right rough grazing (f)	1582	[3]	[12]	Lowland Dwarf Shrub Heath	93		[13]		
			Common rough grazing	949	[4]	[12]	Upland Dwarf Shrub Heath	1196		[13]		
Mountain, Heath and Bog	**3833**	**[10]**		**2531**				**3566**	**[7]**		**Mountain, Heath and Bog**	**267**
Coastal + Freshwater	**692**	**[10]**									**Coastal + Freshwater**	**0**
Urban Areas	**1459**	**[10]**	**All other non-agricultural land**	**291**		[12]					**Urban Areas**	**0**
TOTAL	24728			21011				3978				**18599**
			Agriculture	17827								

Notes

[1] These are fractionally distributed to cover the entire 'Arable and Horticultural' LCM land class

[2] This doesn't totally cover the LCM land class. For the purpose of this study, the LCM class will be taken to be correct, and all the 'Improved Grassland' is taken to be agricultural land

[3] Sole right rough grazing is distributed (somewhat arbitrarily) between 'Semi-natural grassland' and 'Mountain, Heath and Bog'

[4] Common rough grazing is distributed (somewhat arbitrarily) between 'Semi-natural grassland' and 'Mountain, Heath and Bog'

[5] FC/FS Owned/private owned woodland is distributed fractionally over the woodland (broken down into Conifer and Broadleaf according to the Forestry Commission)

[6] There may be some crossover between 'Peatlands' and other 'Protected Areas' and even land that is grazed (according to 'Productive Land')

[7] 'Peatland (bogs)' and 'Blanket Bogs' are taken to be the same thing and so are not double-counted in the total

[8] Not all of this woodland is currently productive (harvested for timber), roughly 90% of all forested land in the UK is currently 'productive' forestry in one way or another [15]

[9] Non FC/FS woodland (both conifer and broadleaf) also includes 663kha of woodland on agricultural land

[19] NB This number may be low compared to other sources. About 85% of all peatland is blanket bog.

[20] This land includes urban grassland areas - 'amenity grassland'

Refs

[10] NERC (2008a) CS Technical Report No 11/07: Final Report for LCM2007 - the new UK Land Cover Map, D. Morton, C. Rowland, C. Wood, L. Meek, C. Marston, G. Smith, R. Wadsworth, I. C. Simpson, Centre for Ecology & Hydrology, (Natural Environment Research Council), July 2
And
Natural Environment Research Council, November 2008 Countryside Survey: UK Results from 2007 CHAPTER 2 • The National Picture,
Information on use of land-types from correspondance with Lisa Norton (CEH): "Norton, Lisa R." <lrn@ceh.ac.uk>
More information on land-types can be found here: http://www.ceh.ac.uk/documents/LCM2007FinalReport.pdf

[11] Forestry Commission (2007) Forestry Facts & Figures, 2007, A summary of statistics about woodland and forestry, Forestry Commission, 2007, **http://www.forestry.gov.uk/pdf/fcfs207.pdf/$FILE/fcfs207.pdf**

[12] DEFRA (2012) June Surveys/Census of Agriculture/SAF land data Scotland. For more details please see the introduction section of this chapter., '07 June 2012; Table 3.1 Agricultural land use (a) **http://www.defra.gov.uk/statistics/foodfarm/cross-cutting/auk/**
More information: email: farming-statistics@defra.gsi.gov.uk
Enquiries: Jenny Tickner on +44 (0)1904 455332

[13] NERC (2008b) Countryside Survey: UK Results from 2007 CHAPTER 2 • The National Picture, Natural Environment Research Council, November 2008; Table 2.3: Estimated area (‘000s ha) of selected Priority Habitats in Great Britain in 1998 and 2007. Estimates for 1998 could not be calculated for all Priority Habitats.

[14] Bain, C.G., Bonn, A., Stoneman, R., Chapman, S., Coupar, A., Evans, M., Gearey, B., Howat, M., Joosten, H., Keenleyside, C., Labadz, J., Lindsay, R., Littlewood, N., Lunt, P., Miller, C.J., Moxey, A., Orr, H., Reed, M., Smith, P., Swales, V., Thompson, D.B.A., Thompson, P.S., Van de Noort, R., Wilson, J.D. & Worrall, F. (2011) IUCN UK Commission of Inquiry on Peatlands. IUCN UK Peatland Programme, Edinburgh.; Table 1 Summary of organic-rich soils extent and bogs and fen UK BAP type extent; adapted with kind permission from JNCC (2011)

[15] Read, D.J., Freer-Smith, P.H., Morison, J.I.L., Hanley, N., West, C.C. and Snowdon, P. (eds). 2009. Combating climate change – a role for UK forests. An assessment of the potential of the UK’s trees and woodlands to mitigate and adapt to climate change. The Stationery Office, Edinburgh.

2.1 Current day land classification

Countryside Survey (or Land Cover Map – LCM) Broad Habitat Types were used as the basis for the current land-use classification system (NERC, 2008a). These were combined with data on agricultural land-use from the June Agricultural Survey by Defra (DEFRA, 2012), details on forestry from the Forestry Commissions (FC, 2007), on priority habitats from the Countryside Survey (NERC, 2008b); and on peatlands from the IUCN Inquiry on Peatlands (IUCN, 2011).

The final ZCB land-use type crossover with CS 2007 Broad Habitat Types, and their descriptions are as in Table 1.

Once rough allocation of current agricultural land, forestry and protected habitats into CS Broad Habitat Type, then estimations were made of the proportion of land that would be 'available' under the ZCB scenario (i.e. areas not protected, nor peatland, nor currently urban developments). Table 2 summarises the land use allocations, and the calculations showing 'available land' for the ZCB scenario.

2.2 Land Use

A number of potential land-uses in ZCB are described below. The way they are modelled in the scenario is detailed, with justifications for any assumption used.

All values are multiplied by the area of land allocated to them out of the 'land available' to get long-term carbon accumulation in biomass and in Harvested Wood Products (HWP) per year in mega-tonne CO_2-equivalent per year ($MtCO_2e$/yr) (as appropriate – see below) for areas allocated in the model as current natural and productive woodland, new broadleaf and coniferous woodland, and short rotation forestry.

Yield values for short rotation coppice, Miscanthus (perennial grassland), rotational grasses and hemp are assumed to increase with the breeding of more productive varieties. Yields obtainable in the field, however are considerably lower than those obtained in experimental conditions (Searle and Malins, 2014; Alexander *et al.*, 2014). Taking this into account, we estimate that with investment in breeding, on-farm yields will increase to that of 75% of those currently obtained in experimental trials. Yields are multiplied by the areas allocated to them (dependent on the quality of land to get total yields of material per year in million oven-dried tonnes per year (Modt/yr).

Tables 3,4 and 5 summarise the information presented here.

Current 'natural' UK Woodland (~10% of UK woodland according to Read et al. (2009))

- **Biomass accumulation (Trees + Litter):** None (assume all UK woodland is reaching maturity and thus should not take in much more carbon for much longer).
- **Products:** None (this is not productive forest).
- **Product end-of-life:** None.
- **Long-term Soil Organic Carbon (SOC) accumulation:** None. It is assumed that current woodland in the UK has neared equilibrium carbon stocks in soils.
- **Waste:** None.

Current 'productive' UK Woodland (~90% of UK woodland according to Read et al. (2009))

- **Biomass accumulation (Trees + Litter):** None (assume all UK woodland is reaching maturity and thus should not take in much more carbon for much longer).
- **Products:** 90% of both current coniferous and broadleaf forest is assumed to be productive. Each produces timber, and sequesters carbon, at the same rate, over a long time period, as those newly planted forests (below), assuming once a forest is felled, it is replanted. Coniferous and broadleaf forests are treated separately.
- **Product end-of-life:** None.
- **Long-term SOC accumulation:** None. It is assumed that current woodland in the UK has neared equilibrium carbon stocks in soils.
- **Waste:** None.

New Natural Broadleaf Woodland

- **Biomass accumulation (Trees + Litter):** long-term annual accumulation of carbon in trees and leaves is taken from the 'mixed native woodland' example in the Carbon

LookupTables (available here: http://www.forestry.gov.uk/forestry/INFD-8jue9t (Forestry Commission, 2013)). Initial changes in soil carbon due to planting remains as in the example provided, but long-term accumulation is removed. The final figure of 912tCO_2e/ha in the stock at 100 years is divided by the number of years (100) to get an average accumulation every year equal to 9.12MtCO_2e/ha/yr).

- **Products:** None (this is not productive forest).
- **Product end-of-life:** None.
- **Long-term SOC accumulation:** None. It is assumed that the land used for planting any new woodland (mainly land previously grazed) will currently have higher or equal SOC levels and so no long-term accumulation will occur. This may be an underestimate, but would require data that we currently do not have in the land model (soil type and current carbon content) – see 2.9 Carbon sequestration/emissions that are not counted in the scenario. Short-term effects on SOC from land-use change is dealt with elsewhere.
- **Waste:** None.

New Natural Coniferous Woodland

- **Biomass accumulation (Trees + Litter):** long-term annual accumulation of carbon in trees and leaves is taken from table 3.2 in Morison et al. (2012). The figure for Sitka Spruce over 90 years (no harvest, no thinning - SS YC12) is taken as 'representative' of a coniferous forest. It is 8.8tCO_2e/ha/yr.
- **Products:** None (this is not productive forest).
- **Product end-of-life:** None.
- **Long-term SOC accumulation:** None. It is assumed that the land used for planting any new woodland (mainly land previously grazed) will currently have higher or equal SOC levels and so no long-term accumulation will occur. This may be an underestimate (see above). Short-term effects on SOC from land-use change is dealt with elsewhere.
- **Waste:** None.

New Productive Coniferous Woodland

- **Biomass accumulation (Trees + Litter):** long-term annual accumulation of carbon in trees and leaves is taken from table 3.13 in Morison et al. (2012). The figure for Sitka Spruce woodland (YC20, 2m spacing, un-thinned, 51 year rotation) is used as 'representative' of a productive coniferous forest. Values for the long-term stock of carbon accumulated in trees and litter (425tCO_2e/ha) were divided by 100 years to get a long-term annual accumulation of 2.25tCO_2e/ha/yr.
- **Products:** The same 'representative' example from table 3.1.3 was used (SS YC20, 2m spacing, un-thinned, 51 year rotation), and the figure for long-term carbon stock in harvested wood products (HWP) of 147tCO_2e/ha was again divided by 100 (years) to get an average annual accumulation of 1.47tCO_2e/ha/yr.
- **Product end-of-life:** See '2.7 End of life' below.
- **Long-term SOC accumulation:** None. It is assumed that the land used for planting any new woodland (mainly land previously grazed) will currently have higher or equal SOC levels and so no long-term accumulation will occur. This may be an underestimate (see above). Short-term effects on SOC from land-use change is dealt with elsewhere.
- **Waste:** Waste fraction of 0.05 during harvesting is already included in the model of HWP above.

New Productive Broadleaf Woodland

- **Biomass accumulation (Trees + Litter):** long-term annual accumulation of carbon in trees and leaves is taken from table 3.13 in Morison et al. (2012). The figure for Oak woodland (YC4, 1.2m spacing, thinned, 95 year rotation) is used as 'representative' of a productive broadleaf forest. Values for the long-term stock of carbon accumulated in trees and litter (249tCO_2e/ha) were divided by 100 years to get a long-term annual accumulation of 2.49tCO_2e/ha/yr.
- **Products:** The same 'representative' example from table 3.1.3 was used (Oak, YC4, 1.2m spacing, thinned, 95 year rotation), and the figure for long-term carbon stock in harvested wood products (HWP) of 70tCO_2e/ha was again divided by 100 (years) to get an average annual accumulation of 0.7tCO_2e/ha/yr.
- **Product end-of-life:** See '2.7 End of life' below.

- **Long-term SOC accumulation:** None. It is assumed that the land used for planting any new woodland (mainly land previously grazed) will currently have higher or equal SOC levels and so no long-term accumulation will occur. This may be an underestimate (see above). Short-term effects on SOC from land-use change is dealt with elsewhere.
- **Waste:** Waste fraction of 0.05 during harvesting is already included in the model of HWP above.

Short Rotation Forestry

- **Biomass accumulation (Trees + Litter):** long-term annual accumulation of carbon in trees and leaves is taken from table 3.13 in Morison et al. (2012). The figure for Poplar (YC12, 26 year rotation) is used as 'representative' of a short rotation forest. Values for the long-term stock of carbon accumulated in trees and litter (326.33tCO_2e/ha) were divided by 100 years to get a long-term annual accumulation of 3.26tCO_2e/ha/yr.
- **Products:** The same 'representative' example from table 3.1.3 was used (Poplar, YC12, 26 year rotation), and the figure for long-term carbon stock in harvested wood products (HWP) of 132tCO_2e/ha was this time divided by one rotation (26 years) to get an average annual accumulation of 5.08tCO_2e/ha/yr. This is because there is likely to be more than one rotation over a long period. The accumulation in trees + litter on average should not increase much, but the fast-growth and felling on a short rotation should be repeatedly yield the same amount. This is then converted into odt/yr by dividing by the amount of carbon in CO_2 (44/12 = 3.67), and then by 0.5tC/odt (Broadmeadow and Matthews, 2003), so that it may be used as timber in buildings or as biomass for energy or fuel production.
- **Product end-of-life:** None. Since we allocate whether or not this product is used as fuel or as HWP later in the model, we do not include any figure for waste going to landfill from this product stream.
- **Long-term SOC accumulation:** None. It is assumed that the land used for planting any new woodland (mainly land previously grazed) will currently have higher or equal SOC levels and so no long-term accumulation will occur. This may be an underestimate (see above). Short-term effects on SOC from land-use change is dealt with elsewhere.
- **Waste:** Waste fraction of 0.05 during harvesting is already included in the model of HWP above.

Short Rotation Coppice

- **Biomass accumulation (Trees + Litter):** None (due to very short rotation).
- **Products: Table 5 shows the yields obtainable in the near-perfect conditions of crop trials. On-farm yields are generally much lower. However, w**e assume that with large investments in research and seed stock, on-farm yields in 2030 can reach 75% of yields obtained in crop trials today.
- **Long-term SOC accumulation:** None. It is assumed that the land planted on will currently be in equilibrium and therefore no long-term accumulation will occur. Short-term effects on SOC from land-use change are dealt with elsewhere.
- **Waste:** We assume a fraction of 0.05 from that produced is wasted.

Perennial Grass (Miscanthus)

- **Biomass accumulation (Trees + Litter):** None (due to very short rotation).
- **Products: Table 5 shows the yields obtainable in the near-perfect conditions of crop trials. On-farm yields are generally much lower. However, w**e assume that with large investments in research and seed stock, on-farm yields in 2030 can reach 75% of yields obtained in crop trials today.
- **Long-term SOC accumulation:** None. It is assumed that the land planted on will currently be in equilibrium and therefore no long-term accumulation will occur. Short-term effects on SOC from land-use change are dealt with elsewhere..
- **Waste:** We assume a fraction of 0.05 from that produced is wasted, and potentially returned to the land to provide nutrients.

Rotational Grass

- **Biomass accumulation (Trees + Litter):** None (due to very short rotation).
- **Products: Table 5 shows the yields obtainable in the near-perfect conditions of crop trials. On-farm yields are generally much lower. However, w**e assume that with large investments in research and seed stock, on-farm yields in 2030 can reach 75% of yields obtained in crop trials today.

- **Long-term SOC accumulation:** None. It is assumed that the land planted on will currently be in equilibrium and therefore no long-term accumulation will occur. Short-term effects on SOC from land-use change are dealt with elsewhere.
- **Waste:** We assume a fraction of 0.05 from that produced is wasted, and potentially returned to the land to provide nutrients.

Hemp

- **Biomass accumulation (Trees + Litter):** None (due to very short rotation).
- **Products: Table 5 shows the yields obtainable in the near-perfect conditions of crop trials. On-farm yields are generally much lower. However, w**e assume that with large investments in research and seed stock, on-farm yields in 2030 can reach 75% of yields obtained in crop trials today**.**
- **Long-term SOC accumulation:** None. It is assumed that the land planted on will currently be in equilibrium and therefore no long-term accumulation will occur. Short-term effects on SOC from land-use change are dealt with elsewhere.
- **Waste:** We assume a fraction of 0.05 from that produced is wasted.

Table 3: Long-term biomass (Trees + Litter) carbon accumulation (tCO_2e/ha/yr). Original Broad Habitat type is displayed in the first row; potential land-use in the ZCB scenario is in displayed in the first column.

	Broadleaf Woodland	Coniferous Woodland	Temporary grass	Arable + Horticultural Cropland	Improved grassland	Semi-natural grassland	Mountain, Heath and Bog	Urban Areas	**Refs**
Natural Coniferous Woodland	9.11	9.11	9.11	9.11	9.11	9.11	9.11	9.11	Carbon Lookup Tables
Natural Broadleaf Woodland	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	Morison et al. (2012)
Productive Broadleaf Woodland	2.49	2.49	2.49	2.49	2.49	2.49	2.49	2.49	Morison et al. (2012)
Productive Coniferous Woodland	4.25	4.25	4.25	4.25	4.25	4.25	4.25	4.25	Morison et al. (2012)
Short Rotation Forestry	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26	Morison et al. (2012)

Table 4: Long-term HWP carbon accumulation (tCO_2e/ha/yr) [NB See Table 5 for odt/yr equivalents]. Original Broad Habitat type is displayed in the first row; potential land-use in the ZCB scenario is in displayed in the first column.

	Broadleaf Woodland	Coniferous Woodland	Temporary grass	Arable + Horticultural	Improved grassland	Semi-natural	Mountain, Heath	Urban Areas	**Refs**
Natural Coniferous Woodland	0	0	0	0	0	0	0	0	n/a
Natural Broadleaf Woodland	0	0	0	0	0	0	0	0	n/a
Productive Broadleaf Woodland	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	Morison et al. (2012)
Productive Coniferous Woodland	1.47	1.47	1.47	1.47	1.47	1.47	1.47	1.47	Morison et al. (2012)
Short Rotation Forestry	5.08	5.08	5.08	5.08	5.08	5.08	5.08	5.08	Morison et al. (2012)

Table 5 Current yields (odt/ha/yr) of various energy crops.

Crop	Average yields		References
Productive Broadleaf Woodland	0.38 [1.13]		= 0.7 / (44/12) / 0.5 (converting tCO2e/ha/yr into odt/ha/yr (Broadmeadow and Matthews, 2003)) [NB For comparison only] *
Productive Coniferous Woodland	0.8 [1.56]		= 1.47 / (44/12) / 0.5 (converting tCO2e/ha/yr into odt/ha/yr (Broadmeadow and Matthews, 2003)) [NB For comparison only] **
Short Rotation Forestry (SRF)	2.77		= 5.08 / (44/12) / 0.5 (converting tCO2e/ha/yr into odt/ha/yr (Broadmeadow and Matthews, 2003))
	Average yields from crop trials	Yields from crop trials	
Miscanthus	20	7 – 20 (EU)	(Clifton-Brown *et al.*, 2019)
		7 to 15 (temperate)	(Searle and Malins, 2014)
		18	(Ericsson *et al.*, 2009)
		10 to 15	Defra 2019
		Approx. 5.5 to 16 (from graphic)	(Alexander *et al.*, 2014)
Short Rotation Coppice	17 (average of poplar and willow)	Willow 8 – 14 (UK)	(Clifton-Brown *et al.*, 2019)
		5- 20 (Poplar) (EU)	(Clifton-Brown *et al.*, 2019)
		4 – 13 (Willow)	(Searle and Malins, 2014)
		4 – 10 (Poplar)	(Searle and Malins, 2014)
		13 (Willow)	(Ericsson *et al.*, 2009)
		13 (Poplar)	(Ericsson *et al.*, 2009)
		8 – 17.5 (SRC)	Defra 2019
		9 (Willow)	Defra 2019
		10.3 (Poplar)	Defra 2019
		Approx. 4 to 17.5 (from graphic)	(Alexander *et al.*, 2014)
Rotational grasses	14	13 to 17 (Ryegrass)	(Wilkins e Lovatt, 2011)
		13 to 14	(Tilvikiene *et al.*, 2012)
		10 (Tall Fescue)	(Butkute *et al.*, 2014)
		10 (Cocksfoot)	(Butkute *et al.*, 2014)
		12 (Reed Canary Grass	(Butkute *et al.*, 2014)
Hemp	10	10 (western Europe)	(Ericsson *et al.*, 2009)

NB * These figures include decay of wood products too and so cannot strictly be taken as yield figures, but may be helpful for comparison. Using ‘end-of-life’ figures, of 3.6MtCO2e/yr waste wood

Figures in [square parentheses] = paper in landfill from 2603.7kha of productive forest, provides an additional 0.75odt/ha/yr that is produced on average by forestry in the UK.

2.3 Soil Organic Carbon (SOC)

2.3.1 Land Use Change (LUC)

Soil Organic Carbon stocks change as land use is changed. Values are taken from research by J. Bellarby of the University of Aberdeen:

> "Values for LUC have been derived from (Bell et al., 2011), who provide estimates of carbon stocks in % for four land uses (cropland, woodland, temporary and permanent grassland). These are based on several UK databases with a total of 24777 soil samples, which were sampled over the whole UK over a range of soil types and management practices. Therefore the variability of UK soils is reflected, so that it was considered the most relevant data to use. The different soil databases also had to be harmonized into the four land use categories used in (Bell et al., 2011). An additional land use category that may be relevant for the ZCB assessment would be bioenergy. However, this land use can be matched to temporary grassland as the ZCB scenarios use permanent bioenergy crops using e.g. short rotation coppice (SRC).
>
> Median values were applied to a depth of 30 cm with the provided bulk densities to calculate carbon stocks in t C/ha, which was then converted into t CO_2/ha by multiplying with 3.67. Decay rates given in (Bell et al., 2011) were then used to estimate the carbon loss/gain that would occur over 20 years, which was then used to derive carbon sequestration rates in tCO_2/ha/year ... However, there are 3 LUC where a new carbon stock level is already reached after less than 20 years associated with a loss in carbon. SOC sequestration often occurs over a longer time period with the maximum being 177 years. Gains and losses of SOC will be faster in initial years, so that the rates provided … can only be used over the time period stated. If SOC rate would be used over a longer time period it would be an overestimation of SOC sequestered and either different rates for the whole longer time period (e.g. 40 years) would have to be calculated or for the second time period only (e.g. 20 – 40 years). This is obviously not an option for the LUCs where a new carbon stock level is reached in less than 20 years."

Although some SOC losses occur over shorter periods (some only for 11 years, others for 15), a standard of 20 years is used in the model as a simplification. Given the uncertainty attached to knowledge of SOC loss or gain in LUC, this represents perhaps an *overestimate* of SOC lost during LUC. These values were multiplied by the area of land allocated to each land-use type out of the 'available' land in the model to get total values for SOC lost or gained in the UK over 20 years. We assume SOC stocks remain the same if the land use is unaltered.

Table 6. SOC change in stocks from Land Use Change ($tCO_2e/ha/yr$); W = woodland; P = permanent grassland; T = temporary grassland; C = Cropland. Taken from Bell et al. (2011). Maximum period over which SOC stocks change = 20 years. Original Broad Habitat type ('land converted from')is displayed in the first row; potential land-use in the ZCB scenario ('land converted to') is in displayed in the first column.

Current Land Type (land converted from)	Broadleaf Woodland	Coniferous Woodland	Temporary grassland	Arable + Horticultral Cropland	Improved grassland	Semi-natural grassland	Mountain, Heath and Bog	Urban Areas		
Classified as	W	W	T	C	P	P	P	P		
Land Use in ZCB3 (land converted to)									Refs	
Natural Coniferous Woodland	0	0	1.3	2.6	-0.7	-0.7	-0.7	-0.7	[11]	W
Natural Broadleaf Woodland	0	0	1.3	2.6	-0.7	-0.7	-0.7	-0.7	[11]	W
Productive Broadleaf Woodland	0	0	1.3	2.6	-0.7	-0.7	-0.7	-0.7	[11]	W
Productive Coniferous Woodland	0	0	1.3	2.6	-0.7	-0.7	-0.7	-0.7	[11]	W
Short Rotation Forestry	0	0	1.3	2.6	-0.7	-0.7	-0.7	-0.7	[11]	W
Short Rotation Coppice	-1.6	-1.6	2.8	5.6	0	-11.8	-11.8	0	[11] *	P
Perrennial Grass (Miscanthus)	-1.6	-1.6	2.8	5.6	0	-11.8	-11.8	0	[11] *	P
Rotational Grass (Ryegrass)	-2.8	-2.8	0	2.1	-11.8	-11.8	-11.8	-11.8	[11]	T
Intensive Grazing	-1.6	-1.6	2.8	5.6	0	-11.8	-11.8	0	[11] *	P
Rough Grazing	-1.6	-1.6	2.8	5.6	0	0 / -11.8 **	0 / -11.8 **	0	[11] *	P
Annual Grass (Hemp)	-5.4	-5.4	0	0	-13.4	-13.4	-13.4	-13.4	[11]	C
Food Crops	-5.4	-5.4	-6.6	0	-13.4	-13.4	-13.4	-13.4	[11]	C
Feed Crops for Livestock	-5.4	-5.4	-6.6	0	-13.4	-13.4	-13.4	-13.4	[11]	C

* SOC stocks in 'semi-natural grassland' and in 'mountain, heath and bog' are likely to be much higher than 'improved grassland' and so conversion to more managed areas may result in higher SOC loss than currently heavily managed 'improved grassland', although they are all classed as 'permanent.'

** Since some of this land is already roughly grazed (3026kha 'semi-natural grassland'; and 2531kha 'mountain, heath and bog' then no LUC penalty should apply as long as the land dedicated here is less than this value))

2.3.2 Management Practices

Soil Organic Carbon can be built up or lost from cropland and grassland because of the management practices used. Values were taken as in table 7 from research by J. Bellarby of the University of Aberdeen:

"Cropland: Values for SOC sequestration rates for cropland management practices have been derived from several sources. The most straightforward values were taken from (Smith et al., 2008) for nutrient management and water management/drainage using the mean estimate for a cool moist climate zone. Other values are mainly based on (Smith et al., 2000) using information on land available for respective cropland management practices and accumulation rates in %. Here, rates for manure/slurry/compost and straw incorporation change with potential reduction on livestock numbers. The total amount of arable land that percentages have been related to is 6.2 Mha.

The majority of sewage sludge (62% = 820 000t) is already recycled to agricultural land. Currently 20% only is incinerated and landfilled, which would be available to put additionally on agricultural land for SOC sequestration (WaterUK, 2005). However, this proportion of biosolids has not passed test to be allowed on agricultural land. Therefore, additional measures would have to be taken to make this proportion of biosolids pass as well. It has been assumed that this is the case for 5% of currently incinerated and landfilled sewage sludge, so that about 0.4% of additional agricultural land could be treated with sewage sludge. The accumulation rate of treated agricultural land will be 5.6 t CO_2e/ha. The value provided … has been made applicable to all agricultural land by integrating the agricultural land available for treatment into the sequestration rate (0.4% * 5.6 t CO_2/ha).

A move towards more no till practices is feasible in 36.5 % of land with an accumulation rate of 0.73 % according to (Smith et al., 2000). This accumulation rate has been applied to the carbon stock value for cropland provided by (Bell et al., 2011) resulting in the carbon sequestration rate provided. It has been questioned whether no till is really feasible on that much arable land as e.g. water saturated soils are not suitable and crops can also be more prone to disease. However, this mitigation potential has to be seen in conjunction with water management and drainage.

SOC sequestration from manure is a result of diverting manure application from grassland to cropland as cropland would benefit more from the carbon input of manure. Currently about 60% is spread on grassland rather than on cropland (Defra, 2012). The majority of manure is produced by dairy and cattle (6.35 t/head/year) with some produced by pigs (2.4 t/head.year) summing up to over 83 Mt manure using animal head numbers from EUROSTAT. That means that almost 50 Mt would be available to divert to cropland, so that at an application rate of 20 t/ha almost 2.5 Mha (40% of arable land) of additional cropland could be spread with manure and current livestock numbers. A reduction of livestock numbers by 30 % would reduce the amount that could be additionally amended by manure to only 23 % of arable land. Applying the accumulation rate provided by (Smith et al., 2000) again to carbon stocks provided by (Bell et al., 2011) and considering a livestock number reduction by 30% results in the value provided.

Straw has various uses of which the main one is bedding for livestock. A large proportion of straw not used for anything else is also already chopped and incorporated into soil (Copeland and Turley, 2008). Additional straw would only become available with a reduction in livestock numbers. With a 30% reduction in livestock numbers about 1.6 Mt of straw would become available that could be incorporated into soil additionally. This would mean 2.6% of total arable land could be amended at a rate of 10 t/ha with an accumulation rate of 3.8 t CO_2/ha/year (Smith et al., 2000).

All the various cropland management practices sum up to an SOC sequestration rate of 3.12 tCO_2e/ha/year.

Grassland: In grassland management nutrient and grazing management are the main mitigation options without a big range of sequestration rates associated to it (Bellarby et al., 2013; Dawson and Smith, 2007). Generally, grassland has already the highest carbon stock compared to any other land use (Smith et al., 2000). Therefore, the estimate has been kept very conservative. The total here assumes that half of the grassland may still be improved by either nutrient and grazing management whereas the other half may be improved by plant diversity/improved grass species (using the lower estimate) resulting in an overall total of 0.9 t CO_2e/ha/year. It is acknowledged that much higher sequestration rates could be achieved in particular cases."

One additional change implemented in ZCB is a reduction in the effectiveness of management techniques on cropland. Because the amount of livestock in the scenario is greatly reduced, then the amount of manure available is also reduced. This lowers the effectiveness of the management practices to being 2.18tCO_2e/ha/yr. In the model, all techniques are assumed to be applied (J. Bellarby has already taken into account the fact that not all techniques can be applied to all land), and the values are multiplied by the number of hectares allocated to each land-use in the scenario to get $MtCO_2e$/yr changes in SOC over 20 years. We assume SOC stocks do not change due to management in areas that are not managed grassland or cropland.

Table 7: SOC from Management Techniques (tCO_2e/ha/yr); G = grassland (in the ZCB model, this is improved grassland); C = Cropland. Maximum period over which SOC stocks change = 20 years. Original Broad Habitat type is displayed in the first row; potential land-use in the ZCB scenario is in displayed in the first column.

Current land use	Temporary grassland	Arable + Horticultural Cropland	Improved grassland		
Classified as	C	C	G	**Classified as**	**Reference**
Land Use in ZCB3					
Short Rotation Coppice	0	0	0.9	G	(Bellarby et al., 2013; Dawson and Smith, 2007)
Perrennial Grass (Miscanthus)	0	0	0.9	G	(Bellarby et al., 2013; Dawson and Smith, 2007)
Rotational Grass (Ryegrass)	0.9	0	0.9	G	(Bellarby et al., 2013; Dawson and Smith, 2007)
Intensive Grazing	0	0	0.9	G	(Bellarby et al., 2013; Dawson and Smith, 2007)
Annual Grass (Hemp)	2.18	2.18	0	C	(Smith et al., 2008)
Food Crops	2.18	2.18	0	C	(Smith et al., 2008)
Feed Crops for Livestock	2.18	2.18	0	C	(Smith et al., 2008)

2.4 Land Allocation in the Scenario

The initial step in allocating land use in the ZCB scenario is to take figures from the '**Food + Diets**' model for the land requires for food production (arable land required for growing crops for both for human consumption, and for livestock feed), and the land required for grazing livestock. The area required for food production is allocated to the area of 'arable and horticultural land' available. Land required for livestock grazing is divided so that the majority resides on 'improved grassland' – intensive grazing; but a portion is grazed on 'semi-natural grassland' or 'mountain heath and bog' – rough grazing. It is possible for a proportion to be in urban areas (for example in city farms), though this is not explicitly allocated in the model.

After this, the rest of the land-use is allocated by area.

Because of potential loss of soil organic carbon (SOC) during land-use change (see 'Soil Organic Carbon', above), then an effort was made to reduce, as far as possible, changing land-use during making the scenario. The following 'rules' were adhered to:

- Current forested land remains forested (and woodland is managed as it is now, more or less – natural forests stay so, and productive forests keep producing wood).
- Land that is currently 'arable and horticultural land' is only used for crops for human and animal feed production, with possibly hemp on rotation if there is sufficient space.
- Land that is currently 'temporary grassland' is used for hemp production or other grasses than are currently grown on rotation, or are harvested annually.
- Land that is currently 'improved grassland' is used for grazing livestock, Miscanthus, SRC, SRF and productive (harvested for timber) forestry, or natural woodland.
- Land that is currently 'semi-natural' grass is used for some grazing, SRF, productive and natural and productive forest. SRC and Miscanthus should not be allocated to this land due to high SOC loss.
- Land that is currently 'Mountain, Heath and Bog' can be used for some grazing, SRF and natural and productive forest. SRC and Miscanthus should not be allocated to this land due to high SOC loss.
- No land-use is allocated to Urban areas since urban grassland is counted under 'improved grassland'. Though some urban areas may be used for food production, this is not counted in the model and no data has been found as to how big an area this might be..

The main aim during allocation of land in the ZCB scenario is to balance the needs of the food production model ('**Food + Diets**'), energy model ('**Power Up**', '**Power Down**', and '**Hourly model**') (biomass for biofuels, heating/CHP and biogas/AD), and those of the entire scenario in terms of providing sufficient carbon sequestration that can 'offset' the residual emissions over a long period of time.

2.5 Peatlands

According to Bain et al. (2011), healthy peatland can capture roughly 1.1-2.6 tCO_2e per hectare every year. Since most peatland ('fens' and 'bogs' as defined by NERC (2008b)) is 'protected' land under the ZCB land allocation (i.e. we do not do anything with it in the scenario), then we choose a fraction of it to be restored. It is understood that some peatland is currently used for agricultural purposes – some 161 kha (0.16 Mha – 7% of peatland in the UK) on cropland and temporary grassland (Natural England, 2010). This is not explicitly modelled in the scenario, though if any area is left 'unused' in the 'temporary grassland' and 'arable land' BS categories, then potentially this could be restored. The fraction restored in the scenario should not exceed 0.93 in case no area can be restored on these land-use types. In reality, it may be better to restore arable peatland at the expense of converting some other land-types to arable land. We do not explicitly model this in the scenario.

Since there is an estimated 2.3 Mha of peatland in the UK (ibid.), then we multiply this by the fraction we assume restored, and then by an average of the above figure (1.85tCO_2e/ha/yr) to get the value for the annual accumulation of carbon in peatlands. The remaining peatland is assumed to be emitting GHGs at the same rate as today, therefore, we multiply todays' emissions from wetlands by the fractional area remaining 'unrestored' in the scenario. These two figures are added together to get the 'net carbon accumulation' of peatlands.

N.B. As we do not perform an explicit spatial analysis of the location of onshore wind farms, it is difficult to include their effects on the scenario. We do not restore all peatland in the scenario, as we believe this to be unrealistic. Where wind farms have to be located on peatland (it is assumed that areas that are not peat-forming would be prioritised), then we assume that restoration of the rest of the peatland must happen alongside wind farm development. We do not explicitly count these effects, however.

2.6 Product allocation and energy production from biomass in the scenario

There are various 'products' that come out of the scenario:

- Annual accumulation of carbon stocks in HWP ($MtCO_2e$/yr; over ~100 years)
- Annual tonnage of product from Miscanthus (odt/yr; over 100+ years)
- Annual tonnage of product from short rotation coppice (odt/yr; over 100+ years)
- Annual tonnage of product from short rotation forestry (odt/yr; over 100+ years)
- Annual tonnage of product from rotational grasslands (odt/yr; over 100+ years)
- Annual tonnage of product from hemp (odt/yr; over 100+ years)
- Waste fraction of 0.05 from all products.

These products can be allocated to the 'uses' by fraction as described in table 8. Although some products can have many different uses, those for which they are usually recommended are prioritised here.

Table 8: Potential uses of 'products' from ZCB land-use scenario. 'x' represents where a product may be allocated (as required), and no mark signifies that the product may not be allocated to this use. If required, conversion between $MtCO_2e$/yr and Modt/yr can be used (divide by $MtCO_2e$/MtC (44/12); and then by MtC/Modt (0.5 – Broadmeadow and Matthews, 2003)).

	Use						
	Heating/ CHP (Modt/yr)	Biogas/A D (Modt/yr)	FT Biofuels (Modt/yr)	Buildings and infrastructure ($MtCO_2e$/yr)	Biochar (Modt/yr)	Waste	**Notes**
Productive Broadleaf Woodland ($MtCO_2e$/yr)				x	x	0.05	*
Productive Coniferous Woodland ($MtCO_2e$/yr)				x	x	0.05	*
Short Rotation Forestry (Modt/yr)	x			x	x	0.05	**
Short Rotation Coppice (Modt/yr)	x		x			0.05	
Miscanthus (Modt/yr)		x	x			0.05	
Rotational Grass (Modt/yr)		x				0.05	
Hemp (Modt/yr)		x		x		0.05	

* Waste fraction of 0.05 already applied in long-term annual accumulation of carbon in HWP, so other fractions should add to 1 here (Morison et al., 2012). Also, implicit in the model is a division between long-lived wood produces (e.g. timber) and short-lived products (e.g. paper). Paper is assumed to have a lifetime of roughly 5 years (Morison et al., 2012) and so on a long-term (~100 year) basis passes straight through the HWP stream. It is assumed that almost all of the accumulation of carbon in wood products over this period is therefore in timber and can be allocated as such.
** Waste fraction of 0.05 already applied in long-term annual accumulation of carbon in HWP, so other fractions should add to 1 here (Morison et al., 2012).

Heating/CHP: Products allocated to heating/CHP are converted to TWh energy supplied via a standard conversion of 4.72TWh/Modt (17MJ/kg) (Natural England, 2007).

Biogas/AD: Products allocated to biogas/AD are converted to TWh energy supplied via a standard conversion of 4.72TWh/Modt (17MJ/kg) (Natural England, 2007).

FT Biofuels: Products allocated to FT Biofuels are first converted to TWh energy supplied via a standard conversion of 4.72TWh/Modt (17MJ/kg) (Natural England, 2007; similar values for willow (SRC) and Miscanthus in Biomass Task Force (2005)).

Buildings and infrastructure: Any products that are not already measured in $MtCO_2e$/yr i.e. that from short rotation forestry (HWP from productive coniferous and broadleaf forests are already in $MtCO_2e$/yr), that are allocated to building materials are converted into $MtCO_2e$ by multiplying by the amount of carbon per oven-dried-tonne, 0.5MtC/Modt, (Broadmeadow and Matthews, 2003), and then the amount of CO_2 per tonne carbon (44/12), so that in total there is 1.83$MtCO_2e$/Modt product. According to Sadler and Robson (*undated*), up to 22$MtCO_2e$ (net) could be captured in buildings and infrastructure in the UK every year if natural materials were maximally used – we make sure that this limit is not exceeded in the model.

Biochar: Any products allocated to biochar production are converted to $MtCO_2e$ stored in the biochar by multiplying by 0.72$MtCO_2e$/Modt (derived using percentage content of carbon per odt of feedstock from Shackley and Sohi (2010) and biochar stability factor of 0.68 from Hammond et al. (2011), then converted into $MtCO_2e$). Were biochar applied to land over the course of 100 years to the maximum recommended 'stock' (1800tCO_2e/ha as found naturally occurring (Shakley et al., 2011)), then a rate of application of 18tCO_2e/ha/yr can be used to calculate the potential land are required for application of biochar to soils. This can be compared to the land area used to produce biochar to see if it forms a 'closed-loop' system over 100 years, helping improve nutrient and water retention (Parliamentary Office of Science and Technology, 2010).

Note: The energy produced from the process is added to the Biogas/AD stock (see 3.10 Biomass for hourly energy model). 0.38TWh/Modt is produced according to Shackley and Sohi (2010).

Waste: The 0.05 fraction of waste produces does not tie into any other final processes – it is assumed to be unrecoverable waste produced by harvesting product from the land. In all cases therefore, it is assumed that this proportion of the product remains in, or is returned to the land. It is assumed that in the case of forestry and coppice, it is mostly the leaves and fine roots that are lost. Since these contain the highest proportion of nutrients in the plant matter, then instead of depleting nutrient stocks in the ground, the majority of nutrients are returned, completing the nutrient cycle. Zeng (2008) states that the carbon to nitrogen ratio (for example) in leaves and fine roots is much higher than that of the more 'woody' biomass of trees, and so comparatively little nutrients are 'locked up'. In the case of grasses such as Miscanthus, rotational grass and hemp, the waste fraction is also presumed to be the nutrient- and protein-rich parts of the plant matter that are returned to the soil together with their nutrients.

2.7 End-of-life

Landfill/Silo: The model used to calculate the annual accumulation of carbon in HWP above (in Morison et al., 2012) *includes* the decay of the products after a lifetime in use (equal to the rotation period of the trees) – the products simply completely decay, releasing all their stored carbon back to the atmosphere after this period. An additional factor, therefore, must be used to model any timber or paper that goes into landfill and does not completely biodegrade (there is some additional carbon storage here at the end-of-life).

Current estimates for how much carbon accumulates in landfill annually are varied. Fawcett et al. (2002) estimate that 24.20$MtCO_2e$/yr was added to landfill in the UK in the form of paper and timber. Corrected for the proportion which comes from UK timber (85% of the carbon sequestered in wood products in the UK is currently in imported timber, according to Broadmeadow and Matthews (2003)), this means roughly 3.6$MtCO_2e$/yr is added to landfill from timber and paper products.

Assuming eventually, even after re-use and recycling, this timber will end up in landfill, and that landfill is designed with carbon storage in mind (i.e. as a 'storage soli'), there is an additional portion attributed to the additional HWPs that come out of new forestry. An estimate of this is made by calculating the fractional increase in 'productive' forest area in the ZCB scenario (currently, about 90% of UK forest area is productive in some way according to Read et al. (2009) = 0.9 x (1385 + 1508) = 2603.7kha of productive woodland in the UK (FC, 2012)), and then multiplying this by the current carbon accumulating in landfill annually. Therefore, this, *in addition* to the original 3.6MtCO_2e/yr is said to be accumulating in landfill.

Concerns about 'breaking the nutrient cycle' by burying natural materials in this way are unfounded according to Zeng (2008), who states that the carbon to nitrogen ratio (for example) in leaves and fine roots is much higher than that of the more 'woody' biomass of trees, and so comparatively little nutrients are 'locked up'.

Biochar: Since we can calculate roughly the amount of material this equates to in Modt (MtCO_2e/yr converted to MtC by dividing by (44/12), and then into Modt by dividing by 0.5MtC/Modt (Broadmeadow and Matthews, 2003)), we can also decide to convert this waste into biochar (see 'Biochar' under 'Product allocation in the scenario') should we want to.

AD Digestate: The digestate from anaerobic digestion (AD), once it has been used to produce energy can be re-used to make biochar, however, in this scenario, it was decided that the digestate should be returned to the soil to act as fertiliser – again, completing the nutrient cycle.

2.8 Carbon sequestration in the scenario

Multiple values for the annual accumulation of carbon in the scenario, that all stem from the ZCB land-use model. These are:

- Changes in SOC from LUC and management techniques (MtCO_2e/yr; over 20 years).
- Annual accumulation of carbon stocks in biomass (trees + litter) (MtCO_2e/yr; over ~100 years) from natural and productive woodlands, and short rotation forestry.
- Annual accumulation of carbon stocks in HWP in buildings and infrastructure (MtCO_2e/yr; over ~100 years) from productive woodlands, short rotation forestry and hemp (if allocated here).
- Annual accumulation of carbon in storage silos (MtCO_2e/yr; over 100+ years) from end-of life of HWP.
- Annual accumulation of carbon in peatlands (MtCO_2e/yr; over 100+ years).
- Annual accumulation of carbon in the form of biochar (MtCO_2e/yr; over 100 years).

Changes in SOC from LUC and land management are summed and checked to be greater than or equal to zero. This represents no net loss of SOC on an annual basis for the first 20 years of the ZCB scenario. We do not count this towards sequestration totals as the processes do not last long enough, and therefore cannot continuously 'offset' any residual emissions in the scenario.

The accumulation of carbon in biomass (trees + litter), HWP in buildings, storage silos, peatlands and biochar is summed to give a final estimate of the amount of MtCO_2e/yr that is sequestered by the system as a whole. This figure represents an average amount sequestered every year (it may differ annually, mainly due to different growth rates of trees as various stages of development, but also due to fluctuations in the amount of HWP that is harvested and used) that is sustainable for a period of 100 years.

2.9 Carbon sequestration/emissions that are not counted in the scenario

Because we calculate emissions reductions on a 'production' accounting basis, we cannot include carbon sequestration from products that are imported. This includes timber and other HWP that are imported, which currently, amounts to 85% of all the HWP used in the UK (Broadmeadow and Matthews, 2003), though in the scenario it is difficult to tell whether:

- This percentage would decrease as more HWP are produced in UK borders, or

- This percentage would increase as the construction industry uses more and more natural materials in buildings.

Were we to conduct emissions accounting on a ‘consumption’ basis, then we could include these imported materials in our model. Similarly, any of these imported materials that ended up in landfill/silos or in biochar production could also be counted as carbon sequestration.

Other potentials for carbon sequestration/emissions that have not been included in the ZCB land-use model include:

- Straw that could be used in buildings (and the potential for other natural building materials), and
- Accumulation of SOC in forest (and other) soils is known to occur on much longer timescales than 20 years. SOC knowledge is very uncertain, and depends heavily on a detailed knowledge of the current carbon levels in the soil (Groenigen et al., 2011). Since we do not have this knowledge (we do not map our land-use changes, but use a measurement of the current ‘available’ area as guidance), then it is impossible to know whether or not there is potential for more sequestration over a longer time period here. Equally, there may be detrimental impacts on SOC in the long-term due to the proposed changes in the model too.
- Although onshore wind plays a significant part in the scenario, again, we have made no estimate of where these wind farms would be. Aside from a rough estimate of what area of peatlands may be affected, we have not explicitly calculated the impact the development of these wind farms might have in various locations.

2.10 Biomass for hourly energy model

The land model is constructed such that the energy requirements of the ‘**hourly energy model**’ are met. Values for biomass/CHP and for FT Biofuels (in TWh) are compared directly to the values from the hourly energy model.

In the case of biogas/AD energy from the Anaerobic Digestion of sewage/waste water treatment, waste from agricultural land – straw from cereal production as described in the ‘**Food and Diets**’ model, and manure is added to the biogas produced before compared to the ‘**hourly energy model**’ via fractions of the ‘stretch case’ in National Grid (2009) (for example, with X% reduction in livestock. only X% of the biogas made from manure in National Grid (2009) is assumed). Additionally, there is a small amount of biogas from landfill that remains, and some from biochar production (see below), which is added to the total. The methane content of biogas from AD of waste is assumed to be around 60% (National Grid, 2008).

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Canolfan y Dechnoleg Amgen

ZERO CARBON BRITAIN

Food and diets model

Contents

Definition of terms

- Food group: Broad nutritional groupings: starchy foods, fruits and vegetables, dairy and meat etc
- Food Category: Group of similar foods represented as one category in the NDNS. The pasta group for example, consists of many different types of pasta and also includes things such as egg noodles. For a full list see Appendix P (DoH, 2011a).
- Food item: individual food such as an apple.
- Dishes: Made up of several food items such as rice and vegetables (dishes are grouped into different food categories based on the main component represented. A vegetable curry for example, would be included in the vegetable food category).

1 Nutrition

We started by designing nutritional parameters in order to be able to create a diet that would satisfy health recommendations. These were:

1. Nutritional profile score for a general score of the 'healthiness' of a food item, category, or diet.
2. Energy and protein intake to assess whether basic nutritional recommendations were met (or unhealthily surpassed).
3. 'Essential' and 'ideal' criteria to assess whether recommended balance between food groups was adhered to.

The latest National Diet and Nutrition Survey (NDNS) results show how much (grams per person per day) of 60 food categories are eaten by an average adult (19-64) in the UK (Henderson, Gregory and Swan, 2002). The most complete dataset relates to 2001 survey data. This dataset and its food categories were used as the basis for the dietary model. Appendix P of the NDNS study gives definitions of all the food items included in each category (DoH, 2011a).

1.1 Nutrient profile scores

The Nutrient Profile Score (NPS) of each food category was calculated using the WXYAP11FVN. nut model (hereafter referred to simply as 'WXY model'), which is designed to 'rate' food items according to how rich in nutrients they are (Rayner et al, 2005). The scoring system works as follows (DoH, 2011b):
Elements associated with poor health if eaten in large quantities (known as 'A' nutrients) were deducted from elements in that are associated with health benefits (known as 'C' nutrients):

$$NPS = A – C.$$

The 'A' score is calculated as follows:
A = Energy + sugars + saturated fat + sodium
Each of the above were given a score out of 10 based on how much of each they contained per 100grams (g) of each food item. Energy was based on how many kilojoules were in 100g (kJ/100g) and the rest how many grams (g/100g). It was the four scores that were added together to make the 'A' score.

The 'C' score is calculated as follows:

C = Fruit, vegetable & nut content + fibre + protein

Each of the values above were given a score out of 5 based on how much of each they contained per 100grams (g) of food.

The score for fruit, vegetable & nut content was based on a further calculation found in Scarborough et al. (2005) which derived the percentage of intake the fruit, vegetable & nut content (percentage intake per 100g). Two additional things were needed for this calculation: a recipe for the food dish and the weights (in grams) of the different ingredients. Both were obtained with a 'Google search'.

Once both the 'A' and 'C' scores were obtained the 'C' score was subtracted from the 'A' score as stated above. This means that the healthier a food is, the lower the score will be. Very often healthy foods have negative scores. See table 1 below for an example of various NPS.

Table 1: An example of nutrient profile scores (NPS) from several different NDNS food categories over a range of different food groups.

NDNS food category	NPS
White bread	1
Wholemeal bread	-3
Cheddar cheese	23
Beef, veal and dishes	3
Bacon and ham	16.5
Oily fish	0.5
Nuts and seeds	1.5
Salad and other raw vegetables	-6.5
Fruit	-3
Biscuits	13
Sugar confectionery	17
Chocolate confectionery	25

A range of food items within each NDNS food category (DoH, 2011a) were used to come up with an average NPS. Any scores for individual food items that had already been calculated were obtained from Rayner et al. (2005). For other foods, McCance & Widdowson's Composition of Foods Integrated Dataset (CoF IDS) data was used to calculate the NPS FSA, 2010). The CoF IDS dataset provides details of total energy (Kilocalories (Kcal)), saturated fat content (g), total sugar content (g), levels of fibre (g), sodium (mg) and protein (g) and so provides all of the components needed for the calculation other than the score for fruit, vegetable & nut content.

1.2 Kilocalories and protein

Eating too much food can lead to obesity and an increased risk of many diet-related diseases, such as heart disease and type II diabetes (Friel et al, 2009). In the UK today, 64% of adults are now overweight or obese (Bates et al, 2011). Monitoring total calorific consumption was therefore included in our analysis. Total protein consumption was also included as this was believed to be a key component to monitor in the Zero Carbon Britain (ZCB) scenario diet. This was due to the perceived reductions in meat that would have to occur in order to reduce GHG emissions as much as feasibly possible. Recommended daily amounts (RDA) for both kcal and protein are 2,250 kcal and 55g respectively (COMA, 1991 and the FSA, 2007).

Values collected for kilocalories (kcal) and protein were also based on how much of each were present in 100g of food. As this data was collected for the NPS above, the same representation of several food items in each NDNS food category was included. There were some categories, however, that did not have these values present from the NPS calculations. In this case, new averages were taken directly from the McCance & Widdowson's Composition of Foods Integrated Dataset (CoF IDS). Each food category was given an average value per 100g.

1.3 Food group balance

Advice from UK government regulations on healthy eating was used to assess the 'balance' between food groups in the diet. The 'Eatwell Plate' (NHS, 2013) was used to construct a healthy diet for ZCB Rethinking the Future (2013). In ZCB "Rising to the Climate Emergency", the new "The Eat-well Guide", (Public Health England 2016) was used to compare the ZCB diet to the current government recommendations. The Eatwell Plate/Guide shows the types of food that should be eaten in which quantities. Foods are divided into 5 broad food groups:

1. Bread, rice, potatoes, pasta and other starchy foods
2. Fruits and vegetables
3. Milk and dairy foods
4. Meat, fish, eggs, beans and other non-dairy sources of protein
5. Food and drinks high in fat and/or sugar (foods high in salt were added to this group)

The different food categories from the NDNS were allocated to the appropriate group and colour coded (see table 2).

Table 2: A table showing the five original food groups and each of the food categories assigned to each group. Groups are also colour coded to match those of the 'Eatwell Plate'.

Group 1 Cereals	**Group 2 Fruit and Vegetables**	**Group 3 Milk and Dairy**	**Group 4 Meat and high protein foods**	**Group 5 High fat, sugar and salt (HFSS)**
Pasta	Greenhouse-grown tomatoes and cucumbers	Milk (Whole, Semi-skimmed and Skimmed)	Eggs	Biscuits
Rice	UK - grown fresh salads	Non-dairy milk	Egg dishes	Buns, cakes, pastries and fruit pies
Other cereals	Seasonal UK vegetables	Cheddar cheese	Beef, veal and dishes	Puddings
White bread	Imported vegetables	Other cheese (e.g. camembert, goats cheese etc)	Lamb and dishes	Dairy Ice cream
Wholemeal bread	Seasonal UK fruit	Yoghurt	Pork and dishes dishes: of which Bacon and ham Sausages	Cream
Soft grain	Imported fruit	Fromage frais and dairy based desserts	Chicken, turkey and dishes	Butter
Other bread	Fruit juice		Coated chicken and turkey	Margarine and other fats and oils
High fibre breakfast cereals			Liver and liver dishes	Savoury snacks (e.g. crisps, Bombay mix etc)
Other breakfast cereals			Burgers and kebabs	Savoury sauces, pickles, gravies and condiments
Oven baked potato products			Meat pies and pastries	Fried or roast potatoes
Other potatoes, potato salads and dishes			Other meat (game, offal, deli meats etc)	Sugars (table sugar, preserves, honey etc)
			White fish coated or fried including fish fingers	Sugar confectionery
			Other white fish, fish dishes and canned tuna	Chocolate confectionery
			Shellfish	Soft drinks (squashes, fizzy drinks etc)
			Oily fish: salmon, herring, mackerel etc	Spirits and liqueurs
			Meat alternatives	Wine
			Beans and legumes	Beer, lager, cider and perry

One notable change was made, however, for this research. The meat group (group 4) was combined with the dairy group (group 3), and re-named the 'high protein' food group. This was considered to be one of the

core nutritional elements of both groups and merging the groups would better allow for the consideration of vegan, and low meat diets in the analysis.
Therefore, four distinct food groups were left (see table 3 for food category allocations):
1. Starchy foods
2. Fruit and vegetables
3. High protein foods
4. High fat, sugar and salt (HFSS) foods

Table 3: A table showing the four adapted food groups and the food categories that are assigned to each. These groups are also colour coded to reflect those of the 'Eatwell Plate'.

Group 1 Starchy Foods	Group 2 Fruit and Vegetables	Group 3 High protein foods	Group 4 High fat, sugar and salt (HFSS)
Pasta	Greenhouse-grown tomatoes and cucumbers Other UK - grown fresh salads	Milk (Whole, Semi-skimmed and Skimmed)	Biscuits
Rice	Seasonal UK vegetables	Non-dairy milk	Buns, cakes, pastries and fruit pies Puddings
Other cereals	Imported vegetables	Cheddar cheese	Dairy Ice cream
White bread	Seasonal UK fruit	Other cheese (e.g. camembert, goats cheese etc)	Cream
Wholemeal bread	Imported fruit	Yoghurt	Butter
Soft grain	Fruit juice	Fromage frais and dairy based puddings	Margarine and other fats and oils
Other bread		Egg dishes	Savoury snacks (e.g. crisps, Bombay mix etc)
High fibre breakfast cereals		Beef, veal and dishes Lamb and dishes	Savoury sauces, pickles, gravies and condiments
Other breakfast cereals		Pork and dishes: of which Bacon and ham sausages	Soups
Oven baked potato products		Chicken, turkey and dishes	Fried or roast potatoes
Other potatoes, potato salads and dishes		Coated chicken and turkey	Sugars (table sugar, preserves, honey etc)
		Liver and liver dishes	Sugar confectionery
		Burgers and kebabs	Chocolate confectionery
		Meat pies and pastries	Soft drinks (squashes, fizzy drinks etc)
		Other meat (game, offal, deli meats etc)	Spirits and liqueurs
		White fish coated or fried including fish fingers	Wine
		Other white fish, fish dishes and canned tuna Shellfish	Beer, lager, cider and perry
		Oily fish: salmon, herring, mackerel etc Meat alternatives	
		Beans and legumes	
		Nuts and seeds	

From the advice surrounding the 'Eatwell Plate' (NHS, 2013) two sets of criteria relating to overall food balance were created. These were designated 'essential' and 'ideal' criteria. The essential criteria relate to things that have been proven to promote health and lower disease risk (see WHO, 2003 and Pan et al, 2012 for two specific examples). The ideal criteria are simply recommended for a healthy diet (FSA, 2007). These criteria are as follows:

Essential criteria:

- A minimum of five portions of fruit and vegetables per day.
- About a third of the diet made up of starchy foods (for example pasta, rice, bread and potatoes (fried potatoes (chips and crisps) are not included in this category. As they are high in saturated fats, they are included in the category below).
- No more than 10% of daily energy intake (kcal) made up of unhealthy foods high in fats, sugar and salt (HFSS).
- No more than 70g of red and processed meats eaten per day.

Ideal criteria:

- Wholegrain cereals (such as brown rice and brown bread) chosen where possible.
- Eat more plant-based protein such as pulses (lentils, chickpeas and baked beans), compared with what is currently consumed in the UK today (average adult consumption is currently 16g per person per day). Plant-based proteins are much lower in saturated fats than animal-based protein.
- More 'good fats' from foods such as oily fish, nuts, seeds and vegetable oils than 'bad fats' from foods such as butter, cheese, crisps, sweets, biscuits, cakes and chocolate.
- Less battered and fried chicken than other forms of chicken.
- Skimmed milk and semi-skimmed milk chosen rather than whole milk.

From this we developed a scoring system. If the diet met one of these recommendations it scored 1 point, if it didn't it scored 0. The healthiest possible diet therefore would score 4/4 from the essential criteria and 5/5 for the ideal criteria.

These scores were assigned as follows:

- A minimum of five portions of fruit and vegetables per day:
    - If the weight (g) of all fruits and vegetables consumed was over 400g per day, then a score of 1 was given. If the weight of all fruits and vegetables was over 320g per day, but an 80g or greater portion of fruit juice was consumed per day then a score of 1 was also given. Otherwise the score was 0. About a third of the diet made up of starchy foods (for example pasta, rice, bread and potatoes (not fried)):
    - If the sum of all starchy foods in the daily diet (kcal) was greater than the total number of daily kilocalories consumed divided by three (one third of the daily diet) then a score of 1 was given. If the score was less than 1/3, it received 0. There was no upper limit placed on cereals. As they are significant contributors to protein and energy intake, however, you cannot create a diet with too many without exceeding these totals or disturbing food balance.
- No more than 10% of daily energy intake (kcal) made up of unhealthy foods high in fats, sugar and salt (HFSS):
    - If the total number of kcal per day from the HFSS group was more than the total number of kcal in the total daily diet multiplied by 0.1 then a score of 0 was given. If it, then it scored 1.
- No more than 70g of red and processed meats eaten per day.
    - If the sum of all red meats in the diet (burgers and kebabs, meat pies and pastries, other meat (game, offal, deli meats etc), beef, veal, lamb, pork, bacon, ham and sausages) was greater than 70g per day then a score of 0 was assigned. If not, then it scored 1.

A similar 1, 0 scoring system was applied to the 'ideal' criteria:

- Wholegrain cereals (such as brown rice and bread) chosen where possible:
    - If the number of grams per day of wholemeal bread and high fibre breakfast cereals outweighed the number of grams per day of white breads and 'other breakfast cereals' then a score of 1 was given. If not, the diet scored 0.
- Eat more plant-based protein such as pulses (lentils, chickpeas and baked beans), compared with what is currently consumed in the UK today:
    - If the diet contained more than 45g of pulses per day then a score of 1 wasgiven. If the diet contained less than 45g per day, it received a score of 0.
- More 'good fats' from foods such as oily fish, nuts, seeds and vegetable oils than 'bad fats' from foods such as butter, cheese, crisps, sweets, biscuits, cakes and chocolate:
    - If the sum of biscuits, buns, cakes, pastries and fruit pies, puddings, dairy ice cream, cream, butter, savoury sauces, pickles, gravies and condiments, sugar confectionery and chocolate confectionery was greater than the sum of white fish coated or fried including fish fingers, other white fish, fish dishes and canned tuna, shellfish, oily fish, meat alternatives, pulses, nuts, seeds and margarine and other fats and oils the score was 0. If there was less of the former than the latter food categories in the diet (measured in grams per day), the score was 1.
- Less battered and fried chicken than other forms of chicken:
    - If the number of grams per day of battered and fried chicken outweighed other forms of chicken then the diet scored 0. If this was not the case or total consumption of both categories was less than 1g/day the diet scored 1. Overconsumption would have resulted in very high protein intake as chicken has the highest protein levels per 100g.

- Skimmed milk and semi-skimmed milk chosen rather than whole milk:
  - If semi skimmed milk (1.8% fat), skimmed milk and non-dairy milk consumption per day is more (in grams) than the sum of whole milk (3.8%. fat) consumption per day then the score is 1. If consumption of whole milk is greater then a score of 0 is given.

1.4 Calculating the nutrition of a diet

When modelling the average diet today, the amount of food reported to be eaten was then corrected for under reporting, this is believed to be approximately 25% (Henderson et al, 2002). When modelling the scenario, the diet is based on actual consumption levels, rather than reported levels, so under-reporting is not considered in this case.

The number of grams reported for each food category was multiplied by the NPS for each category and the amount of protein and kcal per 100g of food. When all the protein and energy values for each food category were added together, this provided average daily amounts for the diet. The NPS and scores relating to food balance were also totalled. This allowed us to rate the diet from a nutritional perspective.

For a diet to be considered 'healthy' it had to have a negative NPS (the more negative, the better), it had to score 4/4 based on the essential criteria and 5/5 for the ideal criteria and it had to provide at least 55g protein and 2,250 kcal per person per day (based on RDA).

The current average diet, based on NDNS data, could only be profiled against these nutritional parameters. For the ZCB scenario diet, however, they were used to help create a new diet. NPS were used within food groups to increase healthier foods over less healthy ones and the food balance criteria was used to limit overconsumption of the different food groups and to ensure minimum nutritional requirements for fruits and vegetables, for example, were met. No official limit to protein and kcal was set for this new diet, but as over consumption is more common in the UK than under consumption, energy and protein content were monitored closely and limited to as close to the above figures as feasibly possible.

2 Greenhouse gas emissions

2.1 Life cycle analysis

Greenhouse gas (GHG) emission scores are usually based on how many kilograms (kg) of carbon-dioxide-equivalent (CO_2e) are released into the atmosphere for every kilogram of food that is produced (stated as kg CO_2e/kg). Carbon-dioxide-equivalents (CO_2e) are used to reflect the importance of other greenhouse gases in the food system. Values therefore take account of nitrous oxide (N_2O) and methane (CH_4) emissions as well as those from carbon dioxide (CO_2).

These CO_2e values are most commonly obtained by doing a life cycle analysis (LCA) on the food item in question. LCA determines the emissions of a product from producing it on the farm (for example soil emissions, emissions from animals and their manure and emissions from the use of fossil fuels in agricultural machinery), processing and retail emissions (such as packaging, refrigeration and transport) and household emissions (such as storage and cooking). Data for the LCA of each product has been collected from three primary sources: the How Low Can We Go? report (hereafter referred to as HLCWG) (Audsley et al., 2009a), the Barilla study (Barilla, 2012) and a journal paper called 'The relative greenhouse gas impacts of realistic dietary choices' (Berners-Lee et al., 2012). The HLCWG report gives separate values for UK produced goods and goods produced abroad (that we import to eat). Most of their LCA values are based on raw commodities (for example wheat instead of flour or bread). Their analysis also only goes as far as the 'regional distribution centre' (RDC) which they state encompass about 56% of total emissions. Values based on this study have therefore been re-calculated to represent 100% of emissions. Barilla (2012) is based on a fuller LCA and so already represents 100% of emissions. Data is taken for UK emissions where possible, but some of these values may represent European averages, or averages from data gathered in other parts of the world. This will not represent the most accurate data for emissions in the UK, but as LCA is still relatively new, many products have simply not been analysed. The Berners-Lee et al. (2012) is based on UK food consumption GHG emissions. This study was particularly helpful in providing values for some of the more processed products (for example puddings, cakes and crisps) that would be difficult to gauge from the HLCWG raw commodity values.

GHG emissions factors for each of the food categories were obtained by compiling averages of the different foods within each NDNS category. For example, the emissions factor for vegetables in the UK

(1.78 kg CO_2e/kg) is an average of 12 values from 12 different vegetables. All of these values are taken from the HLCWG report. The value for cheddar cheese (9.68 kg CO_2e/kg) was taken from an average of five different studies from Barilla (2012), and represents studies conducted outside of the UK.

A number of modifications were made to the GHG emissions factors various food categories to encompass specific issues. They were:

2.1.1 Weighted average adjustment for imports

Some of the GHG emission values used in the report are based on weighted averages. Import data from the FAO was used to assess how much we import from both the rest of Europe and the rest of the world (RoW) (FAO STAT, 2013a). Average GHG emissions for products both produced at home, and imported were then weighted based on the percentage of each that contributes to our end consumption.

2.1.2 Adjustment for different cuts of meat

Using the UK figures from the HLCWG report gives us GHG emission factors for 1kg of carcass weight. This means the weight of an animal without its skin and internal organs but with the bones and individual cuts of meat. In order to separate this value into several components, we worked out what proportions of the pig went to making each component (ham, sausages and pork). Values for liver were proportioned based on the amount of offal produced per animal (Farview Farm, 2013).
For cow meat, the Barilla (2012) value for minced beef was used to represent burger meat. These emissions were subtracted from the over all emissions to provide a value for beef meat.

2.2 Calculating the GHG emissions from a diet

The LCA emissions factors for each 'food category' were then used to calculate the total emissions for each diet being modelled. The amount of each food category (g/day) was multiplied through several modelled factors (see land use section below) in order to ascertain how much would need to be produced (tonnes per year) for the whole of the UK population (estimated to be approximately 63,181,775 people (ONS, 2010)). This value was then multiplied by the emissions factor (KgCO_2e/Kg) and divided by 1,000,000 to get the emissions associated with each food category (Mt CO_2e/ population/year for each food category). All of the emission scores from the food categories were added up to give the total GHG emissions per diet on a UK population basis over one year (MtCO_2e/UK population/year).

The current UK diet was modelled first, using values for the current average diet from the NDNS (Henderson, Gregory and Swan, 2002) and current population, in order to see if predicted figures were inline with known estimates for UK food-related GHG emissions. Our model estimates that the amount of GHG emissions attributable to the UK's food supply is 187 Mt CO_2e/UK population/year. DEFRA statistics estimate emissions of 174 Mt CO_2e/UK population/year (Holding, Karr and Stark, 2011) The HLCWG report estimates these emissions to be somewhere between 152 and 159 Mt CO_2e/UK population/year (Audsley et al, 2009a) and the Berners-Lee paper estimates emissions of 167 Mt CO_2e/UK population/year (Berners-Lee et al., 2012). Our emissions are a little higher than these other estimates therefore, but were considered to be reasonable.

2.2.1 Changes to GHG emissions in the ZCB scenario diet model

To model a diet in our scenario (where emissions from energy-related processes (transport, refrigeration, processing, farm machinery) are dealt with in other sections – namely 'Power Up' and 'Power Down'), each GHG emission value needed to be divided in several components so that we could attribute the proportions of emissions associated with carbon dioxide, nitrous oxide and methane production. As the GHG emissions from transport and other industrial processes have either been removed completely or addressed in calculations elsewhere we needed to remove all emissions associated with these areas.
Williams et al. (2008) breaks down the proportions of emissions into several parts of the life cycle. It breaks down pre-Regional Distribution Centre (RDC) emissions factors into those 'on the farm' and 'post farm gate' emissions up to the RDC for seven different food items. These seven different food items were used to create proxy values for all food categories within the NDNS (see table 3).

Table 3: Proxies used to remove carbon dioxide emissions from totalGHG emission scores per food category

NDNS Food Categories	Proxy commodity	NDNS Food Categories	Proxy commodity
Group 1 - Cereals		**Group - 4 Meat and high protein foods**	
Pasta	Potatoes UK	Eggs	Poultry
Rice	Potatoes UK	Beef, veal and dishes	Beef
Other cereals	Potatoes UK	Lamb and dishes	Lamb
Bread	Potatoes UK	Pork meat Poultry	Poultry
Breakfast cereals	Potatoes UK	Chicken, turkey and dishes	Poultry
Oven baked potato products	Potatoes UK	Burgers, kebabs, meat pies and pastries	Beef
Other potatoes, potato salads and dishes	Potatoes UK	Other meat (game, offal, deli meats etc)	Beef
Group 2 - Fruit and Vegetables		Meat alternatives, Pulses, Nuts and seeds	Apples NZ
Greenhouse-grown tomatoes and cucumbers	Av Tomato Spain	**Group 5 - High fat, sugar and salt**	
Other UK - grown fresh salads	Potatoes UK	Biscuits, cakes and puddings	Potatoes UK
Seasonal UK vegetables	Potatoes UK	Dairy Ice cream, cream and butter	Beef
Imported vegetables	Potatoes Israel	Margarine and other fats and oils	Potatoes Israel
Seasonal UK fruit	Apples UK	Savoury snacks (e.g. crisps, Bombay mix etc)	Potatoes UK
Imported fruit	Apples NZ	Savoury sauces, pickles, gravies and condiments	Potatoes UK
Fruit juice	Strawberries Spain	Soups	Potatoes UK
Group 3 - Milk and Dairy		Fried or roast potatoes	Potatoes UK
Milk (Whole, Semi-skimmed and Skimmed)	Beef	Sugars (e.g. table sugar, preserves, honey etc)	Potatoes UK
Non-dairy milk	Apples NZ	Sugar confectionery	Potatoes UK
Cheese	Beef	Chocolate confectionery	Apples NZ
Yoghurt	Beef	Soft drinks (squashes, fizzy drinks etc)	Potatoes UK
Fromage frais and dairy based desserts	Beef	Spirits and liqueurs	Potatoes UK
		Wine	Strawberries Spain
		Beer, lager, cider and perry	Apples UK

These proportions vary significantly between different food categories. The HLCWG report gives a breakdown of post-RDC emissions. These two sources were used to apportion GHG emissions factors between those due to fossil fuel use (energy and transport), and others that would not be dealt with elsewhere in the report. The effect of this for the food and diets model was that any CO2 emissions were reduced to zero.

Field emissions (representing nitrogen oxide release) were reduced by 19% (based on several studies: Elliot *et al.*, 2014; Misselbrook *et al.*, 2014; Thapa *et al.*, 2016), due to increased nitrogen use efficiency. Use of denitrification inhibitors was not included due to concerns over safety (Dairy Reporter 2013), and uncertainty over possible increases of indirect GHG emissions volatilised ammonium (Elliot *et al.*, 2014, Lam *et al.*, 2017). This gave us our new emission scores for the ZCB report.

After reading several journal articles relating to methane emissions it was decided not to include any methane reduction technologies in the final ZCB emission scores. The results of studies looking into methane reduction techniques are still producing highly variable results (Hongmin et al, 2011; Huws *et al.*, 2018; Grainger and Beauchemin, 2011; Jafari *et al.*, 2019). Successful techniques and implementation methods for these techniques are therefore very unlikely to occur by 2030. As one of the criteria for the ZCB research was to only include already proven technologies, methane reduction techniques were not considered to be far enough along in their development to be included. All of the methane emissions associated with the various food categories therefore remained.

The population figure was also increased in the ZCB scenario diet model. (Approximately 70,580,000 people are expected to be living in the UK in 2030 (ONS, 2010) so this is the figure used for the ZCB diet).

3 Land use

As our model is based around NDNS data – dietary surveys of the population, the amount of food reported represents what is consumed 'on the plate'. This data was in the form of food that was reported to have been eaten in cooked weights, and whole dishes. This does not provide us with a value for how much food is *produced*. We therefore needed to convert what was reportedly eaten 'on the plate' to the associated production of agricultural commodities coming 'out of the farm'. Various steps were necessary for this conversion:

3.1 Cooked to raw conversions

The number of grams reported from survey data is reported as prepared/cooked food weights. Conversion factors were therefore used to adjust for this. Pasta for example, once cooked, is a lot heavier than in its dry form as a lot of water is absorbed. Conversely, raw carrots would weigh more when bought as preparation of the carrot generally involves pealing and 'topping and tailing'. These conversion factors were taken from (Bowman et al, 2011), and applied to individual food categories.

3.2 Raw foods to commodities

Values were also obtained to convert foods as we would buy them (e.g. pasta) to their associated raw commodity (wheat). These values are taken from 'technical conversion factors' complied by the FAO (FAO, 2013), and applied to individual food categories.

3.3 Waste inclusion

Wasted food both at home and throughout the supply chain
Food waste figures were incorporated into the model and based on figures from the food and agricultural organisation (FAO, 2011). These figures are broken down into two separate categories: household waste and all other waste (i.e. on the farm and throughout the supply chain). All values for food waste were based on figures for European countries (who waste approximately 31% of food) with a few notable exceptions:

- Imported fruits and vegetables (based on an average between North Africa, West and Central Asia and South and South-East Asia – with an average wastage of 52%)
- Non-dairy milk and meat alternatives (based on averages from North America and Oceania and Industrialised Asia – with an average wastage of 20%)
- Pulses, nuts and seeds (based on averages from North America and Oceania and Industrialised Asia – with an average wastage of 20%)
- Cocoa beans (based on averages from North America and Oceania and Industrialised Asia – with an average wastage of 20%)
- Wine (an average between Europe, North America and Oceania and Industrialised Asia – with an average wastage of 49%)

The values were chosen to represent a range of other food waste figures of these products from around the world.

3.4 Yields

The amount of each food category required (based on the most common raw commodity per food category (see table 4)) can then be converted into the amount of land required to produce it using 'yield factors'.

Table 4: Raw commodities for each NDNS food category

NDNS Food Categories	Raw Commodities	NDNS Food Categories	Raw Commodities
Group 1 - Cereals		**Group - 4 Meat and high protein foods**	
Pasta	Wheat	Eggs	Layer Hens
Rice	Rice	Beef, veal and dishes	Cows
Other cereals	Barley + Oats + Misc Cereals	Lamb and dishes	Lamb
Bread	Wheat	Pork meat (bacon, ham, sausages)	Pigs
Breakfast cereals	Wheat + Other Cereals Average	Chicken, turkey and dishes	Poultry
Oven baked potato products	Potatoes	Coated chicken and turkey	Poultry
Other potatoes, potato salads and dishes	Potatoes	Liver and liver dishes	Poultry
Group 2 - Fruit and Vegetables		Burgers, kebabs	Cows + Sheep
Greenhouse-grown tomatoes and cucumbers	Protected veg grown in UK	Meat pies and pastries	Cows + Sheep + Soya x2
Other UK - grown fresh salads	UK grown 'salad' veg	Other meat (game, offal, deli meats etc)	Cows + Sheep + Soya x2
Seasonal UK vegetables	UK grown veg	White fish coated or fried including fish fingers	Fish
Imported vegetables	RoW grown veg	Other white fish, fish dishes and canned tuna	Fish
Seasonal UK fruit	UK grown fruit	Shellfish	Fish
Imported fruit	RoW grown fruit	Oily fish: salmon, herring, mackerel etc.	Fish
Fruit juice	UK + RoW grown fruit	Meat alternatives,	Soya
Group 3 - Milk and Dairy		Beans and legumes	Pulses
Milk (Whole, Semi-skimmed and Skimmed)	Milk	Nuts and seeds	Nuts + seeds
Non-dairy milk	Soya	**Group 5 - High fat, sugar and salt**	
Cheese	Cheese	Biscuits, cakes and puddings	Wheat + Sugar + Oil + Eggs
Yoghurt	Milk	Dairy Ice cream, cream and butter	Milk
Fromage frais and dairy based desserts	Milk	Margarine and other fats and oils	Vegetable Oils
		Savoury snacks (e.g. crisps, Bombay mix etc)	Wheat + Potatoes + Oil
		Savoury sauces, pickles, gravies and condiments	Wheat + Sugar + Oil
		Soups	Veg + Condiments + Potatoes
		Fried or roast potatoes	Potatoes
		Sugars (e.g. table sugar, preserves, honey etc)	Sugar
		Sugar confectionery	Sugar
		Chocolate confectionery	Cocoa
		Soft drinks (squashes, fizzy drinks etc)	Sugar + Fruit
		Spirits and liqueurs	Sugar + Fruit + Wheat
		Wine	Grapes
		Beer, lager, cider and perry	Barley + Apples + Pears + Wheat

The yield factor tells us how much of each food category can be grown per hectare of land (tonnes/hectare). The yield factors for crops are taken from DEFRA (2011 and DEFRA 2012) for produce from the UK; and FAO STAT (2013b) for crops that can only be grown overseas. Yield factors for livestock and fish were a little more complicated. For livestock, yield factors were developed by dividing the current number of tonnes of meat produced (data taken from DEFRA, 2011) by the amount of land currently used to rear the animal (data taken from Audsley et al., 2009b). In the case of cows and sheep, the amount of land used was based on grassland only. Crops grown for feed were factored into the model separately (also using data from DEFRA (2011)) on the amount of cereal production is used currently in the UK for animal feed. For pigs and chickens, yield factors were developed by dividing the current number of tonnes of meat (or eggs) produced (data also taken from DEFRA, 2011) by the amount of land currently used to grow their feed (data taken from Audsley et al., 2009b). Land calculations are based on feed crops only as pigs and chickens do not have specific agricultural land assigned to them, as they do not graze on grassland as cows and sheep do. This calculation was also used for farmed fish as they are fed 'fishmeal' which contains some plant sources (most commonly soya) (MMO, 2013).

3.5 Calculating land use estimates for each diet

The land use portion of the model allowed us to convert grams consumed per person per day into tonnes required to feed the whole population per diet per year. Each food category went through each of the stages described above in order to enable this conversion. Cooked foods were converted to their raw equivalents to represent how they would be bought in the supermarket. These foods were then converted to a raw commodity agricultural equivalent. Wasted food both at home and throughout the supply chain was also accounted for. The amount of each food category required was then also multiplied by total population and by the number of days per year (365.4). Finally, grams per day values were converted to tonnes per year (by dividing by 1,000,000). Finally the number of tonnes required per year was divided by a 'yield factor' to work out how many hectares of land were required per food category. These values were then put into one of seven columns: UK arable land, UK arable land for feed, UK Grassland, rest of world (RoW) arable land, RoW arable land for feed, RoW Grassland and UK Greenhouses. These were then totalled to obtain data on all of the land required for each diet for the whole of the UK population.

3.5.1 Changes to land use in the ZCB scenario diet model

In our scenario, we assumed food waste would be cut by 50%. This is in line with UK targets for 2030 (Forum Europe, 2013).

Any food categories that contained food items that could be grown in the UK, but were currently imported (all or in part) were changed to UK production only. Some fruit and vegetables and some pulses were also included in UK glasshouse production.

In the ZCB scenario, the amount of crops grown for feed was reduced proportionally to the reduction of cows and sheep. The amount of food wasted in tonnes, within the ZCB scenario was also used to calculate how much food waste could be used as pig feed to save on cropland. This proportion was then deducted from the arable land in the scenario.

A further calculation was of the agricultural waste; that in the translation from food stuff to commodity – straw from cereal production then feeds into the 'Power Up' model to be used to produce energy through anaerobic digestion (AD).

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