Hourly Energy Model

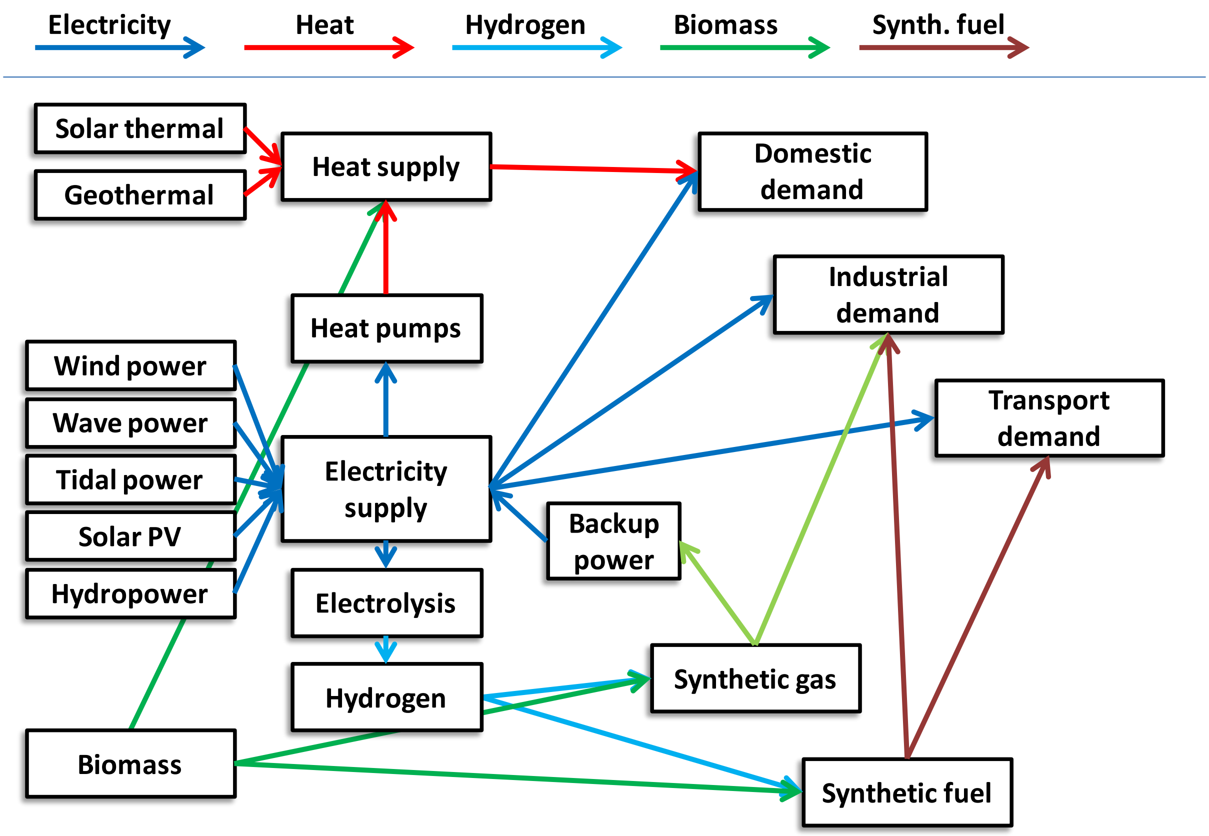
V 1.0

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 75 GW of solar PV capacity, the UK is divided into 11 regions (Appendix D) and the 75 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 31 TWh per year, electric trains and trams consume 11 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 50 TWh per year for heat pumps plus 30 TWh per year for electric resistance heating.

2.3 Electricity balancing & storage

2.3.1 Electricity storage & smart demands
We assume a total of 25 GWh of electricity storage and “smart appliances”, in addition to “smart charging” of electric car and a combination of “smart” heating and 100 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 35 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 45 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 15% 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, 85% 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 4.4 GW for every °C the temperature drops below 12.8°C (specific space heating demand of 4.4 GW/K and base temperature of 12.8°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 96 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 100 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 35 GW (electricity input) and a conversion efficiency of 70%, which means that at maximum production rate, hydrogen with a heating value of 24.5 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 (14 TWh per year) is used directly as a transportation fuel. In the hourly model, this is modelled as a constant hourly demand of 1.6 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 (44 TWh per year) and synthetic transport fuels (68 TWh per year), modelled as constant hydrogen flows flows of 5.0 GWh/h and 7.6 GWh/h respectively.

In total, there is a constant hourly demand for 14.2 GWh of hydrogen.

4.1.3 Hydrogen storage

To ensure that a constant hydrogen demand of 14.2 GWh/h can be met from a variable supply fluctuating between 0 and 24.5 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 6 GWh/h (54 TWh/year) and synthetic methane at a rate of 4 GWh/h (35 TWh/year). In total, renewable methane gas is produced at a constant rate of 10 GWh/h, leading to a production of 88 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 modelled as constant gas flows of approx. 7 GWh/h (61 TWh per year).

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 90 GWh/h for a peak electricity output of 45 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 7.7 GWh of hydrogen and 16.3 GWh of biomass to produce 12.5 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 (143 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 12 TWh of synthetic liquid fuel is used by industry and 98 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 (km^2)	Capacity		Avg. yield (TWh/yr) [A]	Cap. Fac. [A]	Avg. Output [A]	
	Lat	Lon		(GW)	(W/m^2)			(GW)	(W/m^2)
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 (km^2)	Capacity		Avg. yield (TWh/yr) A	Cap. Fac. A	Avg. Output A	
	Lat	Lon		(GW)	(W/m^2)			(GW)	(W/m^2)
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**