



THE UNIVERSITY *of* EDINBURGH

Edinburgh Research Explorer

## Climate change impacts on renewable electricity generation

**Citation for published version:**

Cradden, L, Burnett, D, Agarwal, A & Harrison, G 2015, 'Climate change impacts on renewable electricity generation', *Infrastructure Asset Management*, vol. 2, no. 3, pp. 131-142.  
<https://doi.org/10.1680/iasma.14.00034>

**Digital Object Identifier (DOI):**

[10.1680/iasma.14.00034](https://doi.org/10.1680/iasma.14.00034)

**Link:**

[Link to publication record in Edinburgh Research Explorer](#)

**Document Version:**

Peer reviewed version

**Published In:**

Infrastructure Asset Management

**General rights**

Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

**Take down policy**

The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact [openaccess@ed.ac.uk](mailto:openaccess@ed.ac.uk) providing details, and we will remove access to the work immediately and investigate your claim.



1 **Climate change impacts on renewable electricity generation**

2

3 • Dr. Lucy Cradden, BE PhD

4 • Institute for Energy Systems, School of Engineering, University of Edinburgh, United  
5 Kingdom

6 • Dr. Dougal Burnett, BEng MSc PhD

7 • Institute for Energy Systems, School of Engineering, University of Edinburgh, United  
8 Kingdom (now with Nova Innovation)

9 • Mr. Atul Agarwal, BE MSc

10 • Institute for Energy Systems, School of Engineering, University of Edinburgh, United  
11 Kingdom

12 • Prof. Gareth Harrison, BEng PhD CEng MIET SMIEEE

13 • Institute for Energy Systems, School of Engineering, University of Edinburgh, United  
14 Kingdom

15

16

17

18 **Full contact details of corresponding author.**

19 [Lucy.Cradden@ed.ac.uk](mailto:Lucy.Cradden@ed.ac.uk)

20 School of Engineering,

21 Mayfield Road,

22 Edinburgh EH9 3JL

23 +44 131 6505612

24

1 **Abstract**

2 Generation of renewable energy is strongly related to climate, and could be vulnerable as the  
3 climate changes in the coming decades. The assessment of the potential risks is a new and  
4 evolving area of science. In light of the rapid pace of development and more prominent  
5 contribution of renewables to UK electricity generation, this work presents a summary of the  
6 current state of knowledge in the field, and highlights some of the critical parameters and areas  
7 of uncertainty. An assessment of potential changes in the levelised cost of energy is presented,  
8 with the caveat that this is entirely based on existing data, which in some cases is highly  
9 uncertain. The areas of critical research for both understanding climate, and engineering for  
10 adaptation are discussed.

11

12 **Keywords chosen from ICE Publishing list**

13 Energy, infrastructure, weather

14

15

16 **List of notation**

DECC	Department of Energy and Climate Change
GHG	Greenhouse gas
HadRM3	Hadley Centre Regional Climate Model 3
LCOE	Levelised cost of energy
NAO	North Atlantic Oscillation
PV	Photo-voltaic
UK	United Kingdom
UKCIP02	United Kingdom Climate Impacts Programme 2002
UKCP09	United Kingdom Climate Impacts Programme 2009
WEC	Wave energy converter

17

1 **1. Introduction**

2 An increasing amount of renewable generation is being connected to the UK electricity network  
3 in order to address both emission reduction targets in an attempt to mitigate climate change,  
4 and energy security needs as traditional fossil fuel reserves become depleted. Many sources of  
5 renewable electricity are sensitive to increases and decreases in the mean and variability of a  
6 range of climatic parameters, and are thus vulnerable to climate change. Wind power is,  
7 obviously, sensitive to changes in wind speed. Other major sources of renewable electricity  
8 include hydropower, which depends on a balance of rainfall and evapo-transpiration (a function  
9 of temperature and humidity, among other things), and solar power, which relies on incoming  
10 radiation.

11  
12 Many of these climatic factors are projected by the current generation of climate models to  
13 change under future greenhouse gas (GHG) emission scenarios, giving rise to additional  
14 uncertainty in the future potential energy production from renewable sources. Any change in  
15 production will have consequences for the cost of energy and thus the risk must be carefully  
16 considered. Alongside the resources, changes to other parameters that may affect infrastructure  
17 in general such as extreme wind speeds or flooding, could have a major impact on renewable  
18 electricity generation. This, again, would have operational, financial and wider economic  
19 impacts for the energy system.

20  
21 **2. Potential impacts of climate change**

22 ***2.1 Renewable electricity generation mix in the UK***

23 Figure 1 shows the contribution of each type of generation to the total electricity produced from  
24 renewable sources in 2014 (DECC 2015) . Hydropower, which contributed 9% of the total, is  
25 considered to be a mature technology, having been deployed on a large scale in the post-war  
26 era, mainly in Scotland. More recent developments tend to be smaller, 'run of river' schemes,  
27 but are still concentrated in mountainous regions of Scotland.

28  
29 Onshore wind turbines are relatively mature, and were responsible for 29% of electricity from  
30 renewables in 2014. . Offshore wind has gained momentum in the last 4-5 years, and  
31 contributed 21% of the renewable generation in 2014. The distribution of installed wind power  
32 capacity around the UK can be seen in Figure 2, created using data from (DECC 2014b). In  
33 total, on- and offshore wind produced around half of all renewable electricity in 2014.

34  
35 Solar power, despite being a fairly mainstream technology in other parts of northern Europe,  
36 particularly Germany, has until recently been relatively uncommon in the UK. The high capital  
37 cost of photo-voltaic (PV) panels, the large areas that they require, and the anecdotal belief that  
38 the UK is 'not sunny enough', perhaps contribute to this. Wave and tidal power produced a tiny  
39 fraction of the renewable electricity generation in 2014 although these technologies are still in  
40 development, with most of the power generated being the result of testing brand-new devices.

1 Bio-energy comes from a number of different sources. In 2014, it contributed 35% of the total  
2 renewable generation, and of this, around a fifth was landfill gas and three fifths plant biomass,  
3 and the remainder made up of smaller contributors.

4  
5 In total, renewables produced 19.2% of the total electricity generated in 2014 (DECC 2015),  
6 increasing from under 3% in 2000 (DECC 2014a). The Climate Change Act 2008 requires that  
7 the GHG emissions in 2050 be '*at least 80% lower than the 1990 baseline*' (Anon n.d.). and  
8 thus to meet this target, the share of renewable energy would be expected to increase further in  
9 the coming decades. National Grid have developed a set of 'pathway' electricity generation  
10 scenarios representing possible generation mixes up to the 2030s in order to model future  
11 demand and network requirements (National Grid 2014). In the 'slow progression' and 'gone  
12 green' scenarios, for example, the proportion of electricity generated by renewables would be  
13 expected to increase from existing levels to 55-60%, with wind contributing 40% of the total  
14 generation output, and the remaining 15-20% assigned to the combined total of bioenergy,  
15 hydro, marine and solar PV, The 'no progression' and 'low carbon life' scenarios have  
16 renewables contributing 30-40% of the total electricity generation, with wind again the main  
17 player in both at between 19 and 26% of the total. In either case, the contribution of wind power,  
18 in particular, to the national electricity supply is expected to increase most significantly. Even  
19 under the lowest scenario assumption, wind power would be expected to double its installed  
20 capacity by 2035, and to more than quadruple under the highest scenario assumption.

## 21 22 **2.2 Climate impacts on renewable resources**

23 Many of the renewable technologies are inherently dependent on climate factors; that is, their  
24 power output is directly related to a specific climate variable. The bio-energy technologies are  
25 slightly different, as they often have some climate dependencies but do not necessarily have  
26 such a direct relationship. Bearing this in mind, each technology will be discussed separately in  
27 this section.

### 28 29 **2.2.1 Wind power**

30 The power density available from the wind ( $P$ , W/m<sup>2</sup>) is a function of the wind speed ( $U$ , m/s),  
31 such that:

$$32 \quad P = \frac{1}{2} \rho U^3$$

33 where  $\rho$  is air density (kg/m<sup>3</sup>) (Manwell et al. 2002). This cubic relationship suggests that small  
34 changes in wind speed could have a proportionately larger impact on wind power availability.

35 The expected power produced by a turbine at a given incoming wind speed can be calculated  
36 using a 'power curve'. A typical power curve for a Vestas V90 3MW wind turbine is shown in  
37 (Vestas Wind Systems A/S. 2004), indicating that, for example, the turbine will start producing

1 power at wind speeds around 3 m/s, reaching full rated power at 15 m/s. The turbine will cut out  
2 at speeds greater than 25 m/s to prevent damage to the turbine.

3  
4 Some typical distributions representing the proportion of time that the wind is blowing at a given  
5 speed are shown with their representative Weibull shape and scale parameters in Figure 3. The  
6 scale parameter is related to the mean wind speed – a higher mean will lead to a larger scale  
7 parameter. The shape parameter is related to the variability of the wind speeds around the  
8 mean, with a distribution having a lower shape parameter showing greater variability. A change  
9 in the characteristic distribution will lead to a different sum total of energy generated over a  
10 given period of time. For example, if the ‘tail’ of the distribution extends to the right, more  
11 extreme wind speeds within the ‘cut-out’ region of the wind turbine might be expected.  
12 Variability at a short time scale is typically the most problematic aspect of wind power, and  
13 increasing variability could be more difficult to manage. Conversely, a reduction in variation  
14 would probably be considered beneficial. The seasonal variations currently follow consumer  
15 demand – i.e. lower output in summer and higher in winter. The consequences of a change in  
16 the seasonal pattern would be judged in the context of any concurrent changes in demand  
17 patterns. For instance, an increase in output in winter would be advantageous if electric heating  
18 were to become more prevalent, whilst a decrease in summer output would be detrimental if air  
19 conditioning were more commonly used.

20  
21 Considering mainly mean and variability, extensive work to examine the changes in wind  
22 climate projected by climate models has been carried out looking at the Baltic Sea area (Pryor,  
23 Barthelmie, et al. 2005; Pryor, Schoof, et al. 2005). There are some indications of a potential  
24 strengthening in winter wind speeds, but a key message is that the results are considered to be  
25 highly uncertain. In a later review of climate change impacts on wind energy (Pryor &  
26 Barthelmie 2010), the same authors conclude that on the basis of the evidence, the future  
27 changes projected with current models are unlikely to have a discernible effect on wind power  
28 generation.

29  
30 Looking specifically at the UK, two studies (Harrison et al. 2008; Cradden et al. 2012), using  
31 independent models found some evidence of a strengthening seasonal wind speed pattern –  
32 increases in winter, decreases in summer – that could lead to impacts on the expected power  
33 output in these seasons. The authors again had concerns regarding the high degree of  
34 uncertainty in the results.

35  
36 From day-to-day, spatial distributions of wind speeds around the UK depend on the weather  
37 systems affecting the country. The dominant patterns are driven by a storm track bringing in  
38 areas of low pressure from the Atlantic, which follow broadly similar paths across the country.  
39 This leads to higher average wind speeds in northerly and westerly areas. There is some  
40 evidence to suggest that the paths may change under future climate change scenarios – ‘a shift

1 in the storm track' (Jiang & Perrie 2007). In such a scenario, the expected generation from the  
2 existing wind farm configuration could change, possibly leading to a different evolution of  
3 optimal wind turbine sites.

#### 4 2.2.2 Hydropower

5 Hydropower exploits the potential energy of water falling over a vertical height (or head) with the  
6 available power,  $P$  (W), given by:

$$7 \quad P = \rho g H Q$$

8 where  $\rho$  is water density ( $\text{kg/m}^3$ ),  $g$  is gravitational acceleration ( $9.81 \text{ m/s}^2$ ),  $H$  is the head (m)  
9 and  $Q$  is the flow rate ( $\text{m}^3/\text{s}$ ). Power production is determined by river flow rates which vary  
10 substantially within the year and year-to-year. Smaller catchments, particularly in mountainous  
11 areas, may experience variability on much shorter time scales.

12  
13 The design of hydro schemes relies on a form of cumulative probability distribution: the flow  
14 duration curve. The production is limited by maximum (rated) and minimum flows through the  
15 turbines together with specified flow rates that bypass the scheme (compensation flow, typically  
16 the 90<sup>th</sup> or 95<sup>th</sup> percentile). Figure 4 gives an example of a flow duration curve showing a  
17 hypothetical potential change between current and future flow regimes. The shaded areas  
18 indicate the gross energy potential which changes with the flow patterns.

19  
20 The flow in the river at any instant is determined by the catchment area as well as the water  
21 balance: a function of precipitation, evapotranspiration and any water entering or leaving long  
22 term storage. Changes in the volume and timing of precipitation will therefore alter river flows.  
23 The literature highlights a tendency for catchments to 'amplify' changes in precipitation with  
24 substantially greater changes in river flow (Mukheibir 2013). In part this relates to the non-linear  
25 relationship between soil moisture and runoff and the amplification effect is more apparent in  
26 catchments with the lowest proportion of rainfall going to runoff, typically the most arid. The  
27 composition of precipitation (for example, rain or snow) also has a substantial impact, with snow  
28 cover playing a major role in regulating winter and spring flows. Potential evapotranspiration is a  
29 complex function of temperature, radiation, humidity, wind speed and other variables. In a  
30 warmer climate the rate of evaporation will increase along with the ability of the atmosphere to  
31 hold the water. Actual evapotranspiration depends not only on the potential but also the  
32 availability of moisture in soils and water bodies.

33  
34 Hydropower has been extensively assessed for climate vulnerabilities, due to its major global  
35 contribution to energy. Much of the literature is for overseas locations with large hydropower  
36 facilities and relative importance for energy supply, particularly North America (e.g., Weyman &  
37 Bruneau 1991; Minville et al. 2010) and Africa (e.g., Riebsame W E et al. 1995; Harrison &  
38 Whittington 2002). A key finding of many of these studies is that the sensitivity of hydropower  
39 production to changes in climate increases significantly as the amount of reservoir storage

1 declines. In the UK as a whole, hydro now has a more modest role hence few studies exist in  
2 contrast to substantial amounts of climate impact studies focussed purely on hydrology (e.g.  
3 Fowler & Kilsby 2007), water resource systems (Fowler et al. 2007) and reservoir safety (Babtie  
4 Group Ltd. 2002).

5  
6 Harrison (2005) examined the impact on a potential low-head mini-hydro scheme on the River  
7 Teviot in the Scottish Borders, using a software suite simplified from Harrison & Whittington  
8 (2002). The use of the UKCIP02 scenarios for 2020 suggested that use of uniform annual  
9 changes in precipitation and temperature underestimates the extent of change, with  
10 substantially larger drops in summer flows than increases in winter flows. In production terms,  
11 the turbine capacity limit means that virtually no additional power is produced during the winter  
12 relative to current conditions. However, the significant drops in summer flows mean that the  
13 scheme is idle for more of the season and consequently summer production drops by over a  
14 fifth. The larger potential in winter means that annual production is impacted to a lesser degree  
15 although the drop is still appreciable.

16  
17 A more recent study by Duncan (2014) applied the UKCP09 Weather Generator to  
18 sophisticated hydrological models of five representative catchments in Scotland. The range of  
19 flows bounded by the 10% and 90% probabilities for the weather generator-derived baseline  
20 (1961-1990) and the 2050s (2040-2069), are shown in Figure 5 for the River Ewe. Observed  
21 data was found to be in line with modelled baseline flow duration curves, giving confidence that  
22 the weather generator and hydrological model will produce plausible flow duration curves for  
23 future climate. There is an increase in magnitude of flows at the higher percentiles and a  
24 significant decrease in baseflows. This would be consistent with other findings that increased  
25 storm events will drive large storm response while greater evapotranspiration will reduce  
26 summer low flows. Capacity factors for a hypothetical 16MW hydro scheme were shown to drop  
27 with significant falls in the summer. Slightly higher capacity factors are seen in winter albeit  
28 constrained by the turbine rating and design flow.

### 29 *2.2.3 Solar power*

30 Solar power presently contributes a relatively small proportion of generated energy, but  
31 generous Feed-in-Tariffs have helped stimulate recent growth. Further increases are expected  
32 as solar technologies mature and costs reduce. Solar irradiance levels reaching the surface of  
33 the earth, and thus solar power output, are dependent on cloud cover (Crook et al. 2011), (Pan  
34 et al. 2004). Human activity can cause a change in atmospheric particles (aerosols) which  
35 increase (or decrease) the volume of cloud condensation nuclei.

36  
37 The impact of climate change on solar energy has been explored to some degree. (Gueymard &  
38 Wilcox 2011) investigated the long term solar resource in the U.S. and highlighted the seasonal  
39 changes in the solar resource. (Pan et al. 2004) uses a regional climate change model with



1 results suggesting that seasonal irradiance in the US may decrease by up to 20% by the end of  
2 the 2040s.

3  
4 (Burnett, D. et al. 2014) characterises the UK solar resource to provide a detailed assessment  
5 of the baseline climate which is combined with UKCP09 probabilistic output to explore the effect  
6 of climate change. Future UK solar resources at a regional and local scale are estimated. The  
7 results show an overall increase in resource over the UK, especially in southern and south-  
8 westerly locations. However, there will be increased seasonal variability, most notably in  
9 southern regions. It is expected that present regional differences in solar resource will be further  
10 increased in the future with southerly regions benefiting from increased solar energy resource in  
11 summer, while the relatively poor northerly resources will decrease slightly. In winter most  
12 regions will witness increased cloud cover and slightly reduced solar energy resource.

#### 13 *2.2.4 Wave power*

14 Wave energy converters (WECs) rely on waves formed by the interaction of the wind with the  
15 ocean surface. Waves observed at a location have a seemingly random appearance because  
16 they are, in fact, a large number of interacting harmonic waves of different amplitudes, periods,  
17 directions and phases (Holthuijsen 2007). These individual waves may be generated great  
18 distances away from the location of the observer - for example, the wave climate on the western  
19 coast of the UK is greatly influenced by waves generated in the middle and western regions of  
20 the North Atlantic.

21  
22 A time-series of surface elevations (or waves) can be transformed into an energy variance  
23 spectrum from which parameters describing the sea state like significant wave height ( $H_s$ ) and  
24 energy-averaged wave period ( $T_e$ ) may be obtained. The power flux (in kW per metre of wave  
25 front) can be calculated from these as:

$$26 \quad P = 0.49H_s^2T_e$$

27  
28 The wave climate is likely to change as a direct consequence of changes in wind patterns. The  
29 increase in the roughness of waves in the North Atlantic has been discussed for over three  
30 decades (e.g. (Neu 1984; Carter & Draper 1988). Changes such as these would be expected to  
31 have some effect on electricity generation by WECs.

32  
33 A study of the Wave Hub site in Cornwall (Reeve et al. 2011), using winds corresponding to the  
34 IPCC A1B (intermediate emissions) and B1 (low emissions) scenarios, indicated that there was  
35 likely to be a 3% increase in the mean available wave power for the A1B scenario along with a  
36 wider spread of incident wave heights but contrastingly, a 2% decrease for the B1 scenario.

37 The authors found an overall decrease in power conversion in both scenarios, however, which  
38 was attributed to the fixed performance characteristics (often presented as a power matrix) of  
39 WECs, leaving them unable to convert the additional power available under the A1B scenario.

40 The projected changes fall well with the uncertainty bounds associated with the input wind data,

1 and should, therefore, be regarded as highly uncertain. Other studies linking the variability in  
2 wave climate to the North Atlantic Oscillation (NAO) have yielded similar results (Mackay et al.  
3 2010).

#### 4 5 *2.2.5 Bioenergy*

6 The likely effects of climate change on bioenergy could fall into two areas. Firstly, the typical  
7 power generation cycle used in several bioenergy approaches is, in theory, sensitive to ambient  
8 temperature, with warmer cooling water or air reducing efficiencies. A study (Förster &  
9 Lilliestam 2010) based on a hypothetical nuclear plant located in central Europe, but applicable  
10 to any river-cooled thermal plant, showed that concurrent increases in river temperature and  
11 decreases in river flow could impact quite significantly on power production. This would apply  
12 similarly to coastal thermal plant, with a predicted rise in sea water temperatures reducing their  
13 cooling efficiencies.

14  
15 The second, and possibly more serious, consequence of climate change for biomass-fuelled  
16 generation is the impact on the growing cycle of biofuel crops. A report analysing maize  
17 production in the US suggests that an increase in the variation seen in temperature and  
18 precipitation would lead to subsequent variation in biofuel production (Hatfield & Singer 2011).  
19 Managing the uncertainty resulting from this is a key issue for the industry. (Bellarby et al. 2010)  
20 use a model to project changes in the suitability of different areas of the UK for growing different  
21 types of biofuel crops. The authors note that the model is fairly simple and the assumptions  
22 made create associated uncertainties, but indications are given that certain crops, such as  
23 willow, which are currently popular as biofuels in the UK, may become less suitable under future  
24 climate conditions. An additional factor to consider under changing climate is the migration of  
25 crop pests and pathogens (Bebber et al. 2013).

### 26 **2.3 Changes in extreme climate**

27 A major consideration for future climate change scenarios is the potential for increased  
28 frequency of extreme weather events, which could have major impacts on renewable generation  
29 infrastructure.

30  
31 Sea-level rises are a widely predicted impact of climate change. Co-fired or biomass plant that  
32 is coastally located could be subject to inundation during high tides. Tidal generators, whilst not  
33 dependent on climate factors, are potentially vulnerable to resource changes linked to sea-level  
34 rises. The potential for changes to the tidal constituents due to sea-level rise is described in  
35 (Pickering et al. 2012), and does indicate that if a large degree of sea-level rise were to occur,  
36 changes in tidal characteristics around the UK would be expected.

1 In very high wind conditions, wind turbines will stop producing power and in order to prevent  
2 damage. More frequent and persistent storms would increase the amount of 'lost' energy due to  
3 this process. The fatigue loading on the blades and tower structure would also be increased.  
4 The survivability of any technology located in a marine environment is a critical consideration in  
5 project planning. It was found in (Reeve et al. 2011) there is likely to be an increase in the  
6 occurrence of extreme waves at the Wave Hub site for the future scenarios. This is in  
7 accordance with the findings of (Perrie et al. 2004), which showed that climate change is likely  
8 to slightly increase the wave heights generated in large storms.

9  
10 Prolonged periods of precipitation onto saturated ground present a high flood risk to all assets  
11 and infrastructure, including renewable generation plant. For hydropower, extreme flooding can  
12 lead to the spillways exceeding their design limits, whilst run-of-river plant could suffer  
13 inundation. The opposite situation of more frequent extreme drought is also likely to affect river-  
14 cooled thermal plant and also, obviously, hydropower generation.

15  
16 Extremes of low temperature present a potential risk to wind turbine blades, causing icing (Pryor  
17 & Barthelmie 2010), and freezing of rivers would likely reduce hydropower output during critical  
18 cold spells when demand is at a peak. High temperatures present most risk to thermal plant  
19 operation, affecting cooling water/air temperatures and reducing efficiencies.

### 20 21 **3. Assessment and management of risks**

#### 22 ***3.1 Impact of changing mean on cost of energy***

23 This section addresses the potential for climate change to affect the cost of energy. Where  
24 possible, the most sophisticated and up-to-date probabilistic climate modelling framework for  
25 the UK provided by the UK Climate Impacts Programme (UKCP09) has been used here, along  
26 with some varying assumptions for baseline climate. UKCP09 offers a number of different ways  
27 of accessing and analysing data for future climate change scenarios at different levels of detail  
28 (UKCP09 2012).

##### 29 *3.1.1 Wind energy*

30 The wind speed data provided by UKCP09 is more limited than other variables, due to lower  
31 confidence in the models (Sexton & Murphy 2010). The range of changes in future surface wind  
32 speeds summarised in (Sexton & Murphy 2010) is relatively small and spans both positive and  
33 negative changes. Figure 6 shows some of the percentage changes in wind speeds in the  
34 2050s found from the 11 runs of the HadRM3 ensemble at the 50% probability level for a  
35 'medium' emissions scenario. To consider impacts on wind energy output, the wind speeds from  
36 UKCP09 have been used to derive baseline and future UK wind generation scenarios based on  
37 the locations of existing wind farms and their capacities. The future values of the levelised cost  
38 of energy (LCOE) from wind have then been derived using the method described in (DECC  
39 2012). The LCOE represents the unit cost of electricity over the lifetime of the generating assets

1 by discounting the capital expenditure, operational costs and annual energy production to net  
 2 present values. A key input to the LCOE calculation is the expected resource, and thus the  
 3 expected level of annual generation. By assuming fixed capital and operational costs in all  
 4 scenarios, and varying the resource as projected by the climate models, the impact of changing  
 5 resources on the LCOE can be ascertained. Given the uncertainty associated with the climate  
 6 projections, these figures are intended as an indication of possible changes rather than  
 7 definitive figures. It is important to highlight that this analysis is looking solely at energy  
 8 production and does not account for climate impacts on operational environments – for  
 9 example, increasing extreme winds causing higher maintenance requirements.

11 Table 1 shows the change in LCOE for groups of onshore capacity, and offshore capacity from  
 12 the Crown Estate Leasing Rounds 2 and 3. The baseline climate was created from the 1960-  
 13 1990 daily averages from the HadRM3 model. The direction of changes is highly uncertain,  
 14 typically positive at the 10% probability level and negative at the 90% level. The magnitude of  
 15 the changes is relatively small at the 50% probability level, but the more extreme changes are  
 16 more significant. The geographic spread of changes is such that the current northern bias is  
 17 further enhanced, with some slight decreases in LCOE in the future, whilst the south east of  
 18 England sees some future increases in LCOE as the wind output reduces.

20 **Table 1 Climate change impact on UK wind energy LCOE – change in £/MWh**

	Baseline Climate	Emission Scenario - 2050								
		Low			Medium			High		
		10%	50%	90%	10%	50%	90%	10%	50%	90%
Onshore Wind	84.31	5.24	<b>0.71</b>	-3.14	5.24	<b>0.71</b>	-2.93	5.51	<b>0.47</b>	-3.36
Offshore R2	115.69	9.64	<b>2.19</b>	-3.56	10.37	<b>2.5</b>	-3.56	10.37	<b>2.19</b>	-3.85
Offshore R3	117.30	6.51	<b>1.19</b>	-2.87	7.17	<b>1.49</b>	-2.87	7.17	<b>1.19</b>	-3.15
All Offshore	116.62	7.83	<b>1.61</b>	-3.17	8.52	<b>1.92</b>	-3.17	8.52	<b>1.61</b>	-3.45
All Wind	114.69	7.67	<b>1.55</b>	-3.19	8.31	<b>1.83</b>	-3.17	8.33	<b>1.53</b>	-3.47

21  
 22 **3.1.2 Solar, hydro and wave energy**

23 In a similar manner to the previous results presented for wind, levelised costs were calculated  
 24 for solar, hydro and wave power using a method leveraged from (MacDonald 2010) and  
 25 described in full in (Burnett 2012). Baseline economic parameters are derived from a number of  
 26 sources: wave – (Allan et al. 2011); solar – (International Energy Agency 2010); and hydro –  
 27 (MacDonald 2010), all representative of the observed climate from 1960-1990. Future climate  
 28 change is applied using a range of UKCP09 outputs: hydro – weather generator; solar –  
 29 probabilistic framework; wave – HadRM3 wind speeds combined with the methodology  
 30 described in (Harrison & Wallace 2005) to derive wave height and period. As with the analysis  
 31 of the LCOE for wind energy, all other inputs to the calculation are kept constant across all  
 32 scenarios. The results are shown in Table 3. It should be highlighted that the baseline numbers  
 33 are calculated using more tentative assessments of capacity factor than the wind figures from  
 34 Table 1, and cover only a single emissions scenario.

1 **Table 2 Climate change impact on UK solar, wave and hydro energy LCOE – £/MWh**

	Baseline Climate	Emission Scenario - 2050								
		Low			Medium			High		
		10%	50%	90%	10%	50%	90%	10%	50%	90%
Hydro	<b>83.2</b>				97.9	<b>87.6</b>	77.4			
Wave	<b>193.0</b>				211.5	<b>198.4</b>	187.8			
Solar	<b>237.7</b>				239.2	<b>230.8</b>	222.4			

2

3 **3.2 Adaptation**

4 Adaptation to climate change can take many forms, depending on the severity and nature of the  
 5 changes that occur. (Mukheibir 2013) categorises types of adaptation into a range of different  
 6 responses, indicating factors including the timeframe, coverage and drivers of different  
 7 adaptations.

8

9 The highest likelihood scenarios appear to feature only small changes in wind energy output, so  
 10 short-term adaptation measures would thus appear to be unnecessary, and investment risk  
 11 related to climate change would seem to be low. Existing spatial patterns persist, and  
 12 reconfiguration of capacity locations would likely be unnecessary. The potential for long-term  
 13 adaptation to increasingly frequent high wind speeds could be built in to machine design – for  
 14 example, rather than shutting down completely in high winds, the blades gradually turn away  
 15 from the prevailing wind and reduce output (Enercon 2014). Similarly, many WECs are ‘tuned’  
 16 to produce their maximum output in the most frequent types of sea-state occurring where they  
 17 are located, and could be re-tuned to adjust to different prevailing conditions (Reeve et al.  
 18 2011).

19

20 Alteration of hydropower reservoir operating rules is likely to be necessary in a changing climate  
 21 ((Weyman & Bruneau 1991; Minville et al. 2010)). More major site-specific adaptations may be  
 22 necessary, for instance raising dam walls and enhancing spillway capacity to cope with  
 23 additional flood waters, or uprating turbine capacity (Harrison 2005; Duncan 2014). For  
 24 bioenergy, it may become necessary to change the type of crop used in order to obtain  
 25 maximum yield under different temperature and precipitation conditions.

26

27 The already significant variability in renewable output requires careful management by the  
 28 network operators to ensure demand is met. An increase in the short-term variability of  
 29 renewable output could lead to more extreme ‘good’ and ‘bad’ years, which could also have an  
 30 effect on perceived investment risks. This may be a particular issue for small scale or  
 31 community developments with only a single plant in their portfolio and limited scope to diversify.  
 32 In the case of an increase in variability, it would seem sensible to invest in two areas – improved  
 33 short and medium-term weather forecasting, and efficient and cost-effective storage facilities.  
 34 Forecasting of wind speeds is generally good in the very short term, but can be very difficult

1 over time periods greater than 2-3 days. Many storage technologies are in development and  
 2 may prove suitable to provide a (partial) 'buffer' to reduce the dependence on responsive fossil-  
 3 fuel plant as back-up generation. 'Virtual power plants' and demand management may also  
 4 provide similar facilities.

5  
 6 The close coupling of all types of renewable energy and demand to weather patterns means  
 7 that the impacts of climate change on each factor cannot be considered in isolation. For  
 8 example, increasing ambient temperatures in summer could result in a greater requirement for  
 9 space-cooling which, when combined with a reduced mean wind resource, would require  
 10 alternative generation. Solar power may be more suitable for providing this energy, but the  
 11 concurrent generation and demand patterns would need to be studied to ascertain the precise  
 12 gap and the ability of solar to fill it. Such changes imply changes to overall capacity credits from  
 13 renewable technologies and analysis of combined supply and demand on an aggregate basis  
 14 would seem sensible.

15  
 16 **4. Discussion**

17 **4.1 Confidence in the science**

18 In general, confidence in the output of climate models among qualified scientists is very high,  
 19 but a clear understanding of the uncertainties and sensitivities is needed. On temperature, there  
 20 is agreement between models and a significant association between carbon dioxide emission  
 21 levels and trends in temperature change. The same level of confidence does not exist with  
 22 respect to other weather variables. In particular, surface-level wind speed is difficult to model on  
 23 a scale applicable to wind power generation. As discussed in previous sections, different  
 24 models give different results, and the direction of projected change is inconsistent. As  
 25 computing power increases, and consequently the resolution of models improves, higher  
 26 confidence may be achieved.

27  
 28 The current generation of modelling is, however, still valuable in providing a framework against  
 29 which to test the resilience of renewable energy systems to climate change. Table 3  
 30 summarises the potential impacts and the existing levels of confidence in the modelling of these  
 31 impacts. Considering the model outputs as possible future scenarios rather than a deterministic  
 32 future prediction allows testing of various aspects of the system against a range of plausible  
 33 future conditions.

34  
 35 **Table 3 Summary of confidence**

Specific impact	Volume of evidence	Agreement	Impact	Comments
Small changes in mean annual wind power output	Medium	Medium	Low	The range of changes suggested by many of the models are relatively low and will thus have a small impact

Decrease in summer hydropower production	Medium	Medium	Low-Med	Still a range of uncertainties in the modelling but there could be some reduction in summer production
Increase in winter hydropower production	Medium	Medium	Low-Med	Dependent on ability of scheme to utilise extra flow, but could be some increase in production
Enhancement of existing north-south solar production differences	Low	None	Low	Single study, scale of changes very minor
Small changes in mean annual wave energy production	Low	None	Low	Wave energy currently contributes only a small amount to the energy system, so impacts of changes in output are minimal
Sea level rise leading to changes in tidal energy production	Low	None	Unknown	Not currently quantified, but some evidence that sea-level rise could change tidal flow patterns
Reduced wind power due to extreme high winds (turbines stop producing)	Low	None	Low	Small risk of occurrence within the ranges currently predicted
Increased failure of wind turbines due to extreme high winds	Med	Low	Med	Some evidence but specific impacts are difficult to ascertain
Increased failure of wind turbines due to blade icing in extremely low temperatures	Med	Med	Low	The occurrence of such events is likely to remain very low
Reduced access to offshore wind turbines (and wave/tidal energy devices) due to increased storms	Low	None	Low	It is likely that adaptations to maintenance strategies will be possible in the event of reduced access

1

## 2 **4.2 Research gaps and priorities**

3 Obviously, given the lack of confidence in the projections of future wind speeds, and the clear  
4 intention to increase the use of wind power generation in future, research on the physics,  
5 dynamics and modelling of wind conditions is critical. Increasing understanding will also drive  
6 improvements in forecasting, which is imperative to assist with managing variability. Wind

1 models provide direct input to wave models, and thus improvements in the skill of wind  
2 modelling will also have a positive impact on the success of wave models. These are important  
3 not only for analysing wave energy generation potential, but also loading conditions, reliability  
4 and accessibility parameters for other offshore renewables.

5  
6 It is necessary to focus research on designing adaptable and resilient machines for future  
7 conditions. The provision of increasingly reliable estimates for design and resource parameters  
8 will allow machine designers to factor in climate change, but the range of uncertainties must be  
9 clearly communicated.

10  
11 The cost of climate change and the associated level of risk is currently only able to be  
12 estimated. Combining the many levels of uncertainty within the climate data, the engineering  
13 models and the economics is a complex task which has not been sufficiently addressed as yet.

## 14 15 **6. Conclusions**

16 The impact of climate change on renewable energy generation is a developing area of study for  
17 the engineering community. Understanding the potential for different future climates to change  
18 the magnitude and pattern of available energy is particularly important as investment in  
19 renewables grows, and the technologies form a more substantial part of the electricity system.  
20 The current generation of models discussed here show some impacts, generally in the low-  
21 medium range of severity. The confidence in the models, however, is quite low, and a number  
22 of specific areas of uncertainty have been highlighted that require further research and analysis.

23  
24 Some of the key issues that have been identified are: that increased extreme wind events would  
25 potentially have a medium degree of impact, causing more wind turbine failures, but despite a  
26 reasonable volume of evidence the agreement regarding specific outcomes is low; sea-level  
27 rise could have an effect on tidal energy generation but, as yet, the lack of specific analysis  
28 means the impact is entirely unknown; there is a medium level of agreement surrounding  
29 projected hydropower changes, but the impact of the changes is in the low-medium category.

30  
31 There is a conceivable investment risk associated to climate change, and thus the development  
32 of robust technology and processes to manage and adapt to future scenarios is imperative.  
33 Using different future climate scenarios in an analysis of LCOE for different technologies  
34 indicates relatively small potential changes due to modelled changes in energy production,  
35 which are likely to be less significant than other uncertain factors affecting the cost of energy.  
36 The cost of more subtle changes, such as an increased frequency of extreme events, requires  
37 further evaluation.

## 38 39 **Acknowledgements**



1 The authors gratefully acknowledge the support of the Engineering and Physical Sciences  
2 Research Council in funding the Adaptation and Resilience in Energy Systems (ARIES) project.

3

#### 4 **References**

5 Allan, G. et al., 2011. Levelised costs of Wave and Tidal energy in the UK: Cost  
6 competitiveness and the importance of “banded” Renewables Obligation Certificates.  
7 *Energy Policy*, 39(1), pp.23–39. Available at:  
8 <http://linkinghub.elsevier.com/retrieve/pii/S0301421510006440>.

9 Anon, *Climate Change Act 2008 (c.27)*, London, UK: The Stationery Office.

10 Babtie Group Ltd., 2002. *Climate Change Impacts on the Safety of British Reservoirs*, Available  
11 at: [http://www.britishdams.org/reservoir\\_safety/defra-reports/200201Climate change](http://www.britishdams.org/reservoir_safety/defra-reports/200201Climate%20change%20impacts%20on%20the%20safety%20of%20British%20reservoirs.pdf)  
12 [impacts on the safety of British reservoirs.pdf](http://www.britishdams.org/reservoir_safety/defra-reports/200201Climate%20change%20impacts%20on%20the%20safety%20of%20British%20reservoirs.pdf).

13 Bebber, D.P., Ramotowski, M.A.T. & Gurr, S.J., 2013. Crop pests and pathogens move  
14 polewards in a warming world. *Nature climate change*.

15 Bellarby, J. et al., 2010. The potential distribution of bioenergy crops in the UK under present  
16 and future climate. *Biomass and Bioenergy*, 34(12), pp.1935–1945. Available at:  
17 <http://www.sciencedirect.com/science/article/pii/S0961953410002667> [Accessed March  
18 24, 2014].

19 Burnett, D., 2012. *Climate change and renewable energy portfolios*. University of Edinburgh.  
20 Available at: <http://hdl.handle.net/1842/6245>.

21 Burnett, D., Barbour, E. & Harrison, G.P., 2014. The UK Solar Energy Resource and the Impact  
22 of Climate Change. *Solar Energy*, In Press.

23 Carter, D.J.T. & Draper, L., 1988. Has the north-east Atlantic become rougher. *Nature*.

24 Cradden, L., Harrison, G. & Chick, J., 2012. Will climate change impact on wind power  
25 development in the UK? *Climatic Change*, 115(3-4), pp.837–852 LA – English. Available  
26 at: <http://dx.doi.org/10.1007/s10584-012-0486-5>.

27 Crook, J.A. et al., 2011. Climate change impacts on future photovoltaic and concentrated solar  
28 power energy output. *Energy Environ. Sci.*, 4(9), pp.3101–3109. Available at:  
29 <http://dx.doi.org/10.1039/C1EE01495A>.

30 DECC, 2014a. *DUKES 2014 Chapter 6 - Renewable Sources of Energy*, London. Available at:  
31 [https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/337684/cha](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/337684/cha)  
32 [pter\\_6.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/337684/cha).

33 DECC, 2012. *Electricity Generation Costs*, Available at:  
34 <https://www.gov.uk/government/publications/decc-electricity-generation-costs-2013>.

35 DECC, 2015. *Energy Trends Section 6 – Renewables*, Available at:  
36 [https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/415998/ren](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/415998/ren)  
37 [ewables.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/415998/ren).

38 DECC, 2014b. Renewable energy planning database monthly extract (May 2014). Available at:  
39 <https://www.gov.uk/government/statistics/renewable-energy-planning-database-monthly>  
40 [extract](https://www.gov.uk/government/statistics/renewable-energy-planning-database-monthly).

- 1 Duncan, N.J., 2014. *Mapping Scotland's Hydropower Resource*. University of Edinburgh.
- 2 Enercon, 2014. Enercon - Control System. Available at: <http://www.enercon.de/en-en/754.htm>.
- 3 Förster, H. & Lilliestam, J., 2010. Modeling thermoelectric power generation in view of climate  
4 change. *Regional Environmental Change*, 10(4), pp.327–338 LA – English. Available at:  
5 <http://dx.doi.org/10.1007/s10113-009-0104-x>.
- 6 Fowler, H.J. & Kilsby, C.G., 2007. Using regional climate model data to simulate historical and  
7 future river flows in northwest England. *Climatic Change*, 80(3-4), pp.337–367.
- 8 Fowler, H.J., Kilsby, C.G. & Stunell, J., 2007. Modelling the impacts of projected future climate  
9 change on water resources in north-west England. *Hydrology and Earth System Sciences*,  
10 11(3), pp.1115–1126.
- 11 Gueymard, C.A. & Wilcox, S.M., 2011. Assessment of spatial and temporal variability in the US  
12 solar resource from radiometric measurements and predictions from models using ground-  
13 based or satellite data. *Solar Energy*, 85(5), pp.1068–1084. Available at:  
14 <http://www.sciencedirect.com/science/article/pii/S0038092X11000855> [Accessed March  
15 25, 2014].
- 16 Harrison, G.P., 2005. Climate Change in Scotland: Impact on Mini-Hydro. In *Proc. 5th*  
17 *International Conference on Hydropower (Hydropower '05)*.
- 18 Harrison, G.P., Cradden, L.C. & Chick, J.P., 2008. Preliminary Assessment of Climate Change  
19 Impacts on the UK Onshore Wind Energy Resource. *Energy Sources, Part A: Recovery,*  
20 *Utilization, and Environmental Effects*, 30(14-15), pp.1286–1299. Available at:  
21 <http://www.tandfonline.com/doi/abs/10.1080/15567030701839326>.
- 22 Harrison, G.P. & Wallace, A.R., 2005. Sensitivity of wave energy to climate change. *Energy*  
23 *Conversion, IEEE Transactions on*, 20(4), pp.870–877.
- 24 Harrison, G.P. & Whittington, H.B.W., 2002. Susceptibility of the Batoka Gorge hydroelectric  
25 scheme to climate change. *Journal of Hydrology*, 264(1), pp.230–241.
- 26 Hatfield, J.L. & Singer, J.W., 2011. Climate change: What to expect and how will it affect  
27 feedstock production options? In R. Brown, D. Karlen, & D. Johnson, eds. *Sustainable*  
28 *Biofuels for Advanced Biofuels*. *Soil and Water Conservation Society*. pp. 349–360.  
29 Available at:  
30 [http://www.swcs.org/documents/resources/Chapter\\_21\\_\\_Hatfield\\_\\_Climate\\_Chang\\_6A49](http://www.swcs.org/documents/resources/Chapter_21__Hatfield__Climate_Chang_6A49)  
31 [A597A0988.pdf](http://www.swcs.org/documents/resources/Chapter_21__Hatfield__Climate_Chang_6A49A597A0988.pdf).
- 32 Holthuijsen, L.H., 2007. *Waves in oceanic and coastal Waters*, Cambridge University Press.
- 33 International Energy Agency, 2010. *Projected Costs of Generating Electricity 2010*, OECD  
34 Publishing. Available at:  
35 [http://www.iea.org/publications/freepublications/publication/projected\\_costs.pdf](http://www.iea.org/publications/freepublications/publication/projected_costs.pdf).
- 36 Jiang, J. & Perrie, W., 2007. The Impacts of Climate Change on Autumn North Atlantic  
37 Midlatitude Cyclones. *Journal of Climate*, 20(7), pp.1174–1187. Available at:  
38 <http://dx.doi.org/10.1175/JCLI4058.1>.
- 39 MacDonald, M., 2010. UK electricity generation costs update. *Mott MacDonald*, (June).  
40 Available at:  
41 <http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:UK+Electricity+Generatio>  
42 [n+Costs+Update#0](http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:UK+Electricity+Generatio).

- 1 Mackay, E.B.L., Bahaj, A.S. & Challenor, P.G., 2010. Uncertainty in wave energy resource  
2 assessment. Part 2: Variability and predictability. *Renewable Energy*, 35(8), pp.1809–  
3 1819. Available at: <http://linkinghub.elsevier.com/retrieve/pii/S0960148109004534>.
- 4 Manwell, J.F., McGowan, J.G. & Rogers, A.L., 2002. *Wind Energy Explained: Theory, Design  
5 and Application.*, Chichester: J. Wiley & Sons.
- 6 Minville, M. et al., 2010. Behaviour and performance of a water resource system in Qu{é}bec  
7 (Canada) under adapted operating policies in a climate change context. *Water resources  
8 management*, 24(7), pp.1333–1352.
- 9 Mukheibir, P., 2013. Potential consequences of projected climate change impacts on  
10 hydroelectricity generation. *Climatic Change*, 121(1), pp.67–78 LA – English. Available at:  
11 <http://dx.doi.org/10.1007/s10584-013-0890-5>.
- 12 National Grid, 2014. *UK Future Energy Scenarios*, Warwick, UK. Available at:  
13 [http://www2.nationalgrid.com/uk/industry-information/future-of-energy/future-energy-  
scenarios/](http://www2.nationalgrid.com/uk/industry-information/future-of-energy/future-energy-<br/>14 scenarios/).
- 15 Neu, H.J.A., 1984. Interannual Variations and Longer-Term Changes in the Sea State of the  
16 North Atlantic from 1970 to 1982. *Journal of Geophysical Research*, 89(4), pp.6397–6402.
- 17 Pan, Z. et al., 2004. On the potential change in solar radiation over the US due to increases of  
18 atmospheric greenhouse gases. *Renewable Energy*, 29(11), pp.1923–1928. Available at:  
19 <http://www.sciencedirect.com/science/article/pii/S0960148103003549> [Accessed March  
20 25, 2014].
- 21 Perrie, W. et al., 2004. NW Atlantic Wave Estimates and Climate Change. In *Eighth  
22 international workshop on wave forecast and hindcast*. North Shore, Hawaii.
- 23 Pickering, M.D. et al., 2012. The impact of future sea-level rise on the European Shelf tides.  
24 *Continental Shelf Research*, 35, pp.1–15. Available at:  
25 <http://www.sciencedirect.com/science/article/pii/S0278434311003578> [Accessed March  
26 20, 2014].
- 27 Pryor, S.C. & Barthelmie, R.J., 2010. Climate change impacts on wind energy: A review.  
28 *Renewable and Sustainable Energy Reviews*, 14(1), pp.430–437. Available at:  
29 <http://www.sciencedirect.com/science/article/pii/S1364032109001713> [Accessed January  
30 27, 2014].
- 31 Pryor, S.C., Barthelmie, R.J. & Kjellström, E., 2005. Potential climate change impact on wind  
32 energy resources in northern Europe: analyses using a regional climate model. *Climate  
33 Dynamics*, 25(7-8), pp.815–835 LA – English. Available at:  
34 <http://dx.doi.org/10.1007/s00382-005-0072-x>.
- 35 Pryor, S.C., Schoof, J.T. & Barthelmie, R.J., 2005. Empirical downscaling of wind speed  
36 probability distributions. *Journal of Geophysical Research: Atmospheres*, 110(D19), p.n/a–  
37 n/a. Available at: <http://dx.doi.org/10.1029/2005JD005899>.
- 38 Reeve, D.E. et al., 2011. An investigation of the impacts of climate change on wave energy  
39 generation: The Wave Hub, Cornwall, UK. *Renewable Energy*, 36(9), pp.2404–2413.  
40 Available at: <http://www.sciencedirect.com/science/article/pii/S096014811100111X>.
- 41 Riebsame W E et al., 1995. Complex River Basins. In K. M. Strzepek & J. B. Smith, eds. *As  
42 climate changes: international impacts and implications*. Cambridge University Press.

1	Sexton, D.M.H. & Murphy, J., 2010. <i>UKCP09: Probabilistic projections of wind speed</i> , Available
2	at: <a href="http://ukclimateprojections.metoffice.gov.uk/media.jsp?mediaid=87876&amp;filetype=pdf">http://ukclimateprojections.metoffice.gov.uk/media.jsp?mediaid=87876&amp;filetype=pdf</a> .
3	UKCP09, 2012. UKCP09 Summary Table. <i>UK Climate Projections</i> . Available at:
4	<a href="http://ukclimateprojections.metoffice.gov.uk/22533">http://ukclimateprojections.metoffice.gov.uk/22533</a> .
5	Vestas Wind Systems A/S., 2004. Vestas V90-3.0 MW Product Brochure.
6	Weyman, S. & Bruneau, P., 1991. Potential impacts of global climatic evolution on the optimal
7	scheme of a hydroelectric complex. <i>Hydrology for the Water Management of Large River</i>
8	<i>Basins</i> , pp.245–256.
9	
10	
11	
12	<b>Figure and table captions (images as individual files separate to your MS Word text file).</b>
13	Figure 1 Relative contribution of different renewable technologies
14	
15	Figure 2 Operational wind farms (October 2013)
16	
17	Figure 3 Typical wind speed distributions
18	
19	Figure 4 Example flow duration curve and energy generation for current and future climate
20	
21	Figure 5 Flow duration curves for River Ewe for baseline and 2050s climate (after Duncan,
22	2014)
23	
24	Figure 6 Wind speed change (%) for 2050s medium emissions scenario with 50% probability
25	
26	Table 4 Climate change impact on UK wind energy LCOE – change in £/MWh
27	
28	Table 5 Climate change impact on UK solar, wave and hydro energy LCOE – £/MWh
29	
30	Table 6 Summary of confidence
31	