



THE UNIVERSITY *of* EDINBURGH

## Edinburgh Research Explorer

### A Climate Change Report Card for Infrastructure: Energy: Renewable Generation

**Citation for published version:**

Cradden, LC, Agarwal, A, Burnett, D & Harrison, G 2016, *A Climate Change Report Card for Infrastructure: Energy: Renewable Generation*. Living with Environmental Change (LWEC) Partnership, Swindon.  
<<http://www.nerc.ac.uk/research/partnerships/ride/lwec/report-cards/infrastructure-source10>>

**Link:**

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

**Document Version:**

Publisher's PDF, also known as Version of record

**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.



**A Climate Change Report Card for Infrastructure**

**Working Technical Paper**

**Energy: Renewable Generation**

**Lucy C Cradden, Atul Agarwal, Dougal Burnett and Gareth P Harrison**

**Institute for Energy Systems  
University of Edinburgh**

## Table of contents - Energy: Renewable Generation

Highlights and Key Messages .....	3
Generation .....	3
Extreme conditions .....	<b>Error! Bookmark not defined.</b>
Introduction .....	3
Potential impacts of climate change.....	4
Renewable electricity generation mix in the UK .....	4
Climate impacts on renewable resources.....	6
Wind Power.....	6
Hydropower .....	8
Solar power .....	11
Wave power.....	11
Bioenergy .....	12
Other climate impacts on renewable generation.....	13
Extremes .....	13
Assessment and management of risks .....	14
Impact of changing mean on cost of energy .....	14
Wind energy.....	14
Solar, hydro and wave energy .....	16
Adaptation .....	17
Broader drivers and interactions .....	19
Confidence in the science .....	19
Research gaps and priorities.....	22
References .....	23

## ***Highlights and Key Messages***

### **Key messages**

- In general, the confidence assigned to projections of future climate change impacts on renewable generation output is low. Particularly at the local scales relevant to renewable energy, it is very difficult to assign certainty (or uncertainty) to the results of models.
- Even when there is moderate confidence in modelling skill, there is still a limited amount of confidence in emissions scenarios, and it is possible that other influences such as socio-economic factors, will have a far greater impact on renewable energy development than climate change alone.
- Consideration of climate change impacts on renewable energy without also modelling socio-economic impacts, misses the potential to study the interaction between climate and society and the combined influence on future infrastructure investment and development.

### **Specific impacts on generation and technologies**

- For wind power, there is low-medium confidence in the climate modelling skill, particularly with regard to the direction of change in wind speed – increasing or decreasing. Most models agree that the scale of the impacts on mean wind speed, and thus on wind power generation, is likely to be quite small.
- Hydropower has a complex relationship with a number of different interacting climate variables. Several models combining the different climate factors with future changes suggest reductions in river flows, which would reduce production, particularly in summer.
- The solar power resource is already unevenly distributed around the UK, and appears likely to become more so in future, with the resource increasing most significantly in the south, and possibly reducing slightly in northern areas.
- Modelling of future wave power resources is low in confidence, given the large degree of uncertainty in various aspects of the model. The impact of any changes on the power system as a whole is likely to be minimal, given the small amount of generation capacity planned. Increasing frequency and strength of extreme wind conditions would have a high impact on wind power generation, leading to increased machine downtime - due to both shut-downs and failures.
- Both extreme flooding and drought would have a high impact on for hydropower plant, with design conditions being exceeded in the case of floods and reduced output in the case of drought.

### ***Introduction***

An increasing amount of renewable generation is being connected to the UK electricity network in order to address emission reduction targets in an attempt to mitigate climate change, and energy security needs as traditional fossil fuel reserves become depleted delivering at least partial insulation from fluctuating global energy prices. Many of the sources of renewable electricity are sensitive to increases and

decreases in the mean and variability of a range of climatic parameters, and are thus vulnerable to climate change.

A large proportion of future energy needs are expected to be met by wind power, which is, obviously, sensitive to changes in wind speed and direction. Other major sources of renewable electricity include hydropower, which depends on a balance of rainfall and evapo-transpiration (a function of temperature and humidity, among other things), and solar power, which relies on incident radiation and cloud cover.

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

### ***Potential impacts of climate change***

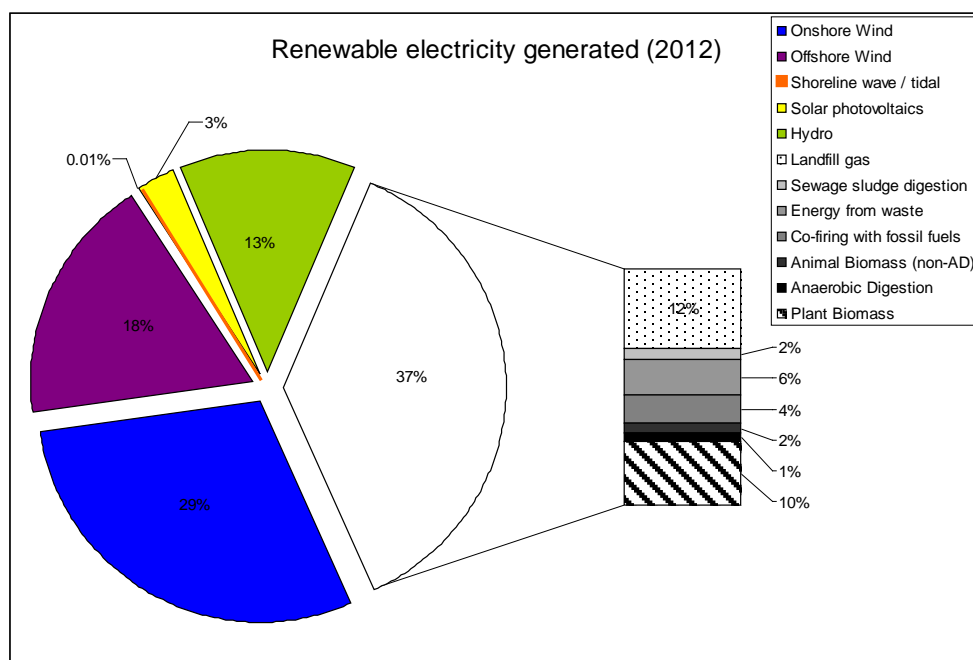
#### **Renewable electricity generation mix in the UK**

Figure 1 shows the contribution of each type of generation to the total electricity produced from renewable sources in 2012 (DECC 2013a). Hydropower is a mature technology, having been deployed on a large scale in the post-war 1950s and 60s, mainly in Scotland and hilly areas of Wales, and represented 13% of the total. More recent developments tend to be smaller, 'run of river' schemes which do not involve creating large dams, but as with the older projects they are most commonly situated in mountainous regions of Scotland.

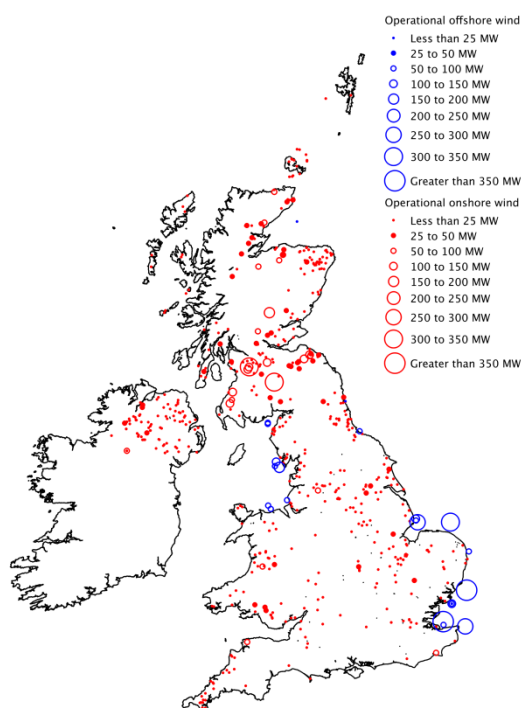
Onshore wind turbines are also a relatively mature technology, having increased their share from around 1-2% of all electricity production in the late 1990s to around 10-12% today. Offshore wind really only gained momentum in the last 4-5 years, but now represents around 5-7% of the total electricity produced. The distribution of installed wind power capacity around the UK can be seen in Figure 2. In total, on- and offshore wind produced nearly half of all renewable electricity in 2012.

Solar power, despite being a fairly mainstream technology in other parts of northern Europe, such as Germany, has been relatively uncommon in the UK. The high capital cost of photo-voltaic (PV) panels, the large areas that they require, and the anecdotal belief that the UK is 'not sunny enough', perhaps contribute to this. Wave and tidal power produced only a tiny percentage of the renewable electricity generation in 2012. The technologies for these are still very much in their infancy, with most of the power generated being the result of testing brand-new devices.

Bio-energy comes from a number of different sources. In 2012, it contributed 37% of the total renewable generation, and of this, around one third each were landfill gas and plant biomass.



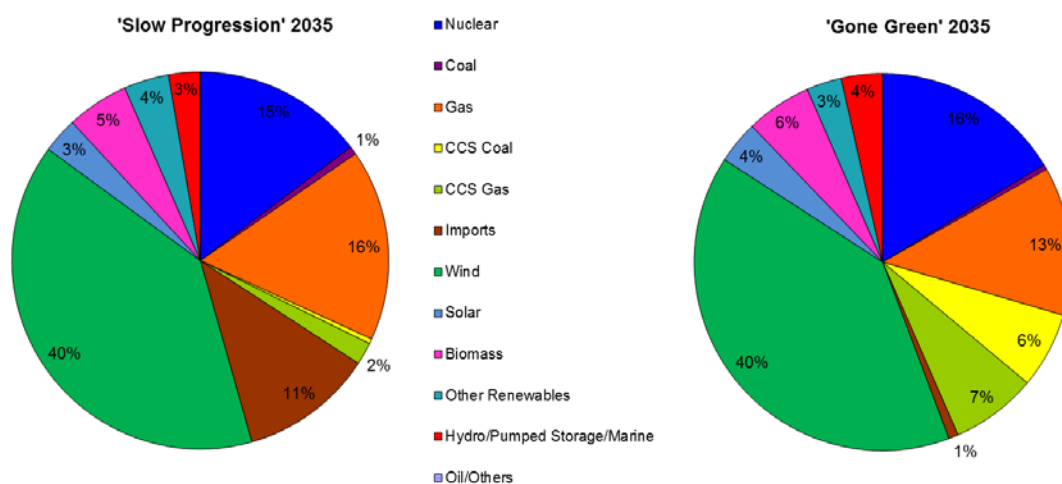
**Figure 1 Relative contribution of different renewable technologies**



**Figure 2 Operational wind farms (October 2013)**

In total, renewables produced around 11.5% of the total electricity generated in 2012, increasing from under 3% in 2000 (DECC 2013b). Aiming to meet emission reduction targets would suggest that that share of the total generation will increase further in the coming decades. Determining the future contribution of renewables very precisely is an impossible task, but National Grid have developed four 'pathway' scenarios representing possible generation mixes up until the 2050s in order to model future demand and network requirements (National Grid 2014). An indication

of the possible proportions of generation attributed to each type of fuel can be obtained. For example, shown in Figure 3, in the 'slow progression' scenario for the 2030s, wind contributes 40% of the total generation, whilst around 15% comes from the combined total of biomass, hydro, marine, solar PV and 'other renewables'. In the 'gone green' scenario for the 2030s, the proportion of wind is again around 40%, with the combined total of biomass, hydro, marine, solar PV and 'other renewables' coming in at 17%. In all cases, the contribution of wind power to the national electricity supply is clearly expected to increase significantly, whilst solar and biomass also increase from the 2012 baseline, but not quite so dramatically. The change in contribution of the hydro/marine/pumped storage category is much less, perhaps indicating a lack of confidence in new marine energy technologies and a limited capacity for new hydropower.



**Figure 3 National Grid Future Energy Scenarios – contributions to generation in 2035 (National Grid 2014)**

### Climate impacts on renewable resources

Many of the renewable technologies are inherently dependent on climate factors; that is, their power output is directly related to a specific climate variable. For example, wind power production is almost entirely dictated by wind speed. The bio-energy technologies are slightly different, as they often have some climate dependencies but do not necessarily have such a direct relationship with a single meteorological parameter. Bearing this in mind, each technology will be discussed separately in this section.

### Wind Power

#### *Mean wind speeds, distribution and temporal variability*

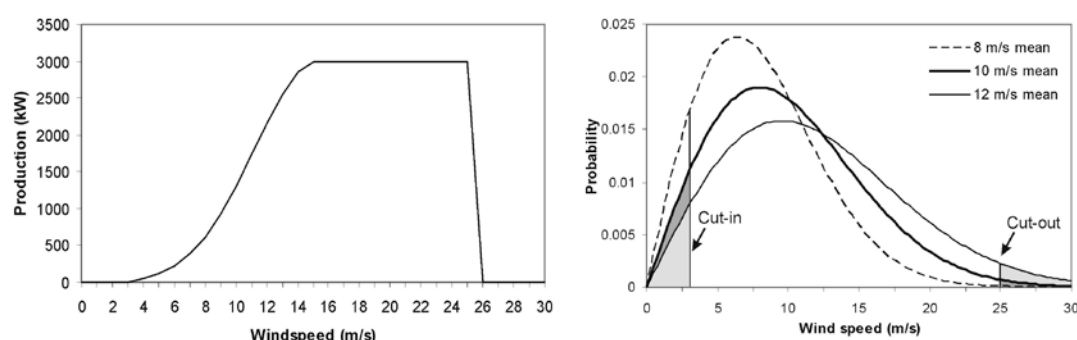
As already stated, wind power production depends very strongly on wind speed, and to a lesser extent, the direction in which it is blowing. Wind turbines are based on fundamental physics which state that the power density available from the wind ( $P$ ,  $W/m^2$ ) is a function of the wind speed ( $U$ ,  $m/s$ ), such that:

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

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

power availability. Changes that affect the mean wind speed in a particular location would therefore be expected to influence the power generation and possibly the finances of a wind farm.

Wind turbines, due to further complexities of the laws of physics, can extract a maximum of 56% of this available power – known as the Betz limit (Manwell, et al., 2002). In practice, the expected power produced by a turbine at a given incoming wind speed can be calculated using a ‘power curve’. A typical power curve for a Vestas V90 3MW wind turbine is shown in (Vestas Wind Systems A/S. 2004) (left), indicating that, for example, the turbine will start producing power when the wind speed reaches around 3 m/s, will produce around 50% of its rated capacity at 10 m/s and will reach its full rated power at 15 m/s. The turbine will cut out and stop producing power at speeds greater than 25 m/s to prevent damage to the turbine in these very high wind speeds.



**Figure 4 Power curve (left) and wind speed distribution (right) (Harrison et al. 2008)**

The proportion of time that the wind at a particular location is blowing at a given speed is shown in a typical distribution, presented in the right-hand panel of Figure 4. A change in the characteristic distribution shape will lead to a different sum total of energy generated over a given period of time. For example, if the ‘tail’ of the distribution was to shift further out to the right, more extremely high wind speeds within the ‘cut-out’ region of the turbine power curve might be expected.

Variability at a short time scale is typically the most problematic aspect of managing wind generation output, and so any increase in the degree of variation could be detrimental. Conversely, obviously, a reduction in variation would probably be considered a beneficial change. The seasonal pattern currently follows expected consumer demand – i.e. lower in summer and higher in winter. The consequences of a change in the seasonal pattern would be judged in the context of any concurrent changes in demand patterns. For instance, an increase in output in winter would be advantageous if electric heating were to become more prevalent, whilst a decrease in summer output would be detrimental if air conditioning were more commonly used.

#### *Climate modelling evidence for future changes in mean, distribution and variability*

Extensive work has been carried out by Pryor et al. (2005a, 2005b) looking at potential impacts of climate change on wind speeds in the Baltic Sea area. There are some indications of a potential strengthening in winter wind speeds, but a key message is that the results are considered to be highly uncertain. In a later review of



climate change impacts specifically related to wind energy (Pryor and Barthelmie 2010), the same authors conclude that on the basis of the evidence in the literature, the future changes projected with current models are unlikely to have a discernable effect on wind power generation.

Looking specifically at climate change impacts on wind energy in the UK, two studies (Harrison et al 2008; Cradden et al. 2012), using two independent models found some evidence of a strengthening seasonal wind speed pattern – increases in winter, decreases in summer – that could lead to impacts on the expected power output in these seasons. The authors stated similar concerns as Pryor and Barthelmie regarding the high degree of uncertainty in the results. Similar differences were found between model simulations of current climate and actual measurements as between simulations of current and future climate. This indicates a low degree of confidence that changes observed in the future simulations are statistically significant.

#### *Spatial distribution and variability*

An interesting aspect of future changes in wind speeds might relate not just to average resources, but to the spatial patterns of the resource. From day-to-day, spatial distributions of wind speeds depend on the weather systems affecting the country, with the dominant patterns leading to higher average wind speeds in northerly and westerly areas of the UK. This dominant pattern is driven by a storm track bringing in areas of low pressure from the Atlantic, which tend to follow broadly similar paths across the country.

A shift in the storm track paths or in the strength of the driving forces would lead to a change in the spatial distribution of wind speeds around the country. The expected generation from the existing wind farm configuration as shown in Figure 2 would change, with perhaps different areas of the country having more suitable resources. This could result in a different evolution of optimal wind turbine sites over the coming century, and this would be potentially wasteful in terms of the requirement to decommission existing sites and reposition infrastructure. There is some evidence to suggest that the paths of incoming Atlantic storms may change under future climate change scenarios – ‘a shift in the storm track’ (Jiang and Perrie 2007).

#### **Hydropower**

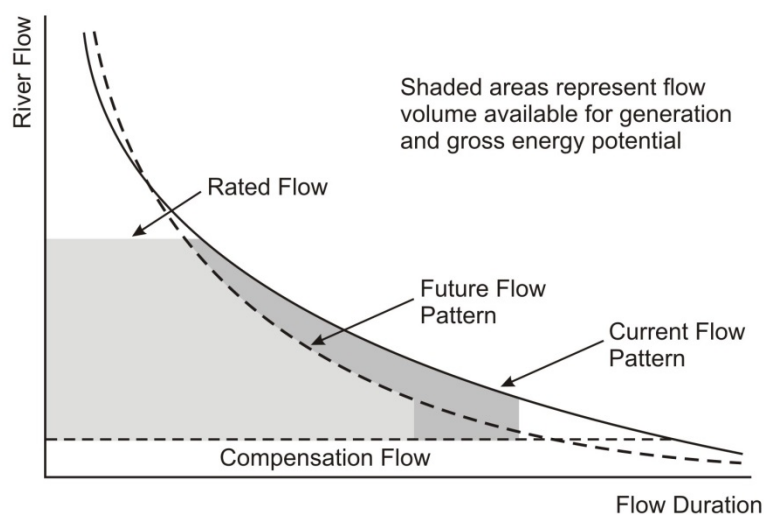
Among all of the renewable technologies hydropower has been most extensively assessed largely due to its major global contribution to energy supply. Hydropower exploits the potential energy of water falling over a vertical height (or head) with the available power (W) given by:

$$P = \rho g H Q$$

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

The design of hydro schemes (particularly run-of-river and to a lesser extent storage relies on a form of cumulative probability distribution: the flow duration

curve. The production at a hydro scheme is limited by its maximum (rated) and minimum flows through the turbines together with specified flow rates that bypass the scheme (compensation flow, typically the 90<sup>th</sup> or 95<sup>th</sup> percentile flow). Figure 5 gives an example of a flow duration curve showing a potential change between current and future flow regimes. The shaded areas indicate the gross energy potential which changes with the flow patterns.



**Figure 5 Example flow duration curve and energy generation for current and future climate**

The flow in the river at any instant is determined by the catchment area as well as the water balance, a function of precipitation, evapotranspiration and any water entering or leaving long term storage. Changes in the volume and timing of precipitation will therefore serve to alter river flows. The literature highlights a tendency for catchments to ‘amplify’ changes in precipitation with substantially greater changes in river flow (Mukheibir 2013). In part this relates to the level of soil moisture with saturated soils promoting faster runoff. The composition of precipitation also has a substantial impact with snow cover playing a major role in regulating winter and spring flows in many hydro-rich catchments around the world: whether precipitation falls as rain or snow and the extent of melt depend very strongly on temperature.

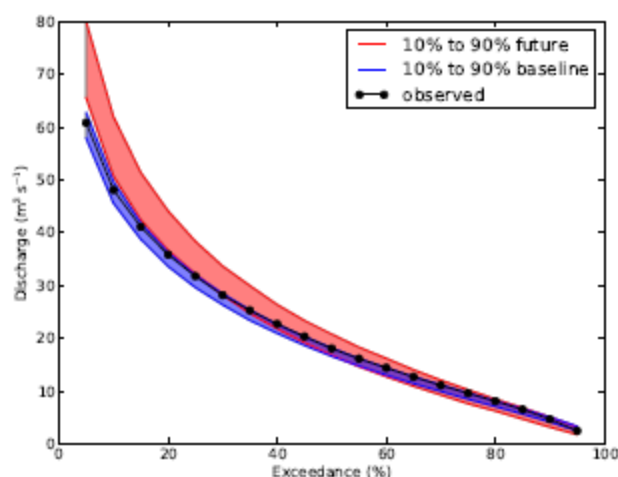
Evapotranspiration also plays a major role, particularly in warmer climates. Potential evapotranspiration is a complex function of temperature, radiation, humidity, wind speed and other variables. In a warmer climate the rate of evaporation will increase along with the ability of the atmosphere to hold the water. Actual evapotranspiration depends not only on the potential but also the availability of moisture in soils and water bodies. Evidence from climate models suggests substantial seasonal changes in soil moisture levels.

The sheer number of climatological mechanisms that regulate river flow suggests that hydropower is vulnerable to a changing climate. Much of the literature on climate impact on hydropower is for overseas locations with large hydropower facilities and relative importance for energy supply, particularly North America (e.g., Weyman and Bruneau 1991; Minville et al. 2009) and Africa (e.g., Reibsame et al. 1995; Harrison and Whittington 2002). In the UK as a whole hydro now has a more

modest role hence few studies in contrast to substantial amounts of climate impact studies focussed on hydrology (e.g. Fowler and Kilsby 2007), water resource systems (Fowler et al. 2007) and reservoir safety (Babtie Group 2002). A key finding from international studies is that the sensitivity of hydropower production to changes in climate increases significantly as the amount of storage declines; this would imply that the larger storage-based hydropower would be inherently less susceptible than smaller low-head run-of-river schemes elsewhere.

Harrison (2005) examined the impact on a potential low-head mini-hydro scheme on the River Teviot in the Scottish Borders. Using a simple software suite simplified from Harrison and Whittington (2002), the catchment hydrology, scheme operation and economics were modelled. The use of the UKCIP02 scenarios for 2020 suggested that use of uniform changes underestimates the extent of change with substantially larger drops in summer flows than increases in winter flows. The characteristics of the scheme resulted in summer production falling by over 20% and a negligible increase in winter production. In production terms, the turbine capacity limit means that virtually no additional power is produced during the winter relative to current conditions. However, the significant drops in summer flows mean that the scheme is idle for more of the season and consequently summer production drops by over a fifth. Fortunately, the larger potential in winter means that annual production is impacted to a lesser degree although the drop is still appreciable.

A more recent study by Duncan (2014) applied the UKCP09 Weather Generator to sophisticated hydrological models of five representative catchments in Scotland. Examining the flow probabilities for baseline (1961-1990) and the 2050s (2040-2069), the range of flows bounded by the 10% and 90% probabilities are shown in Figure 6 for the River Ewe. Observed data was found to be in line with modelled baseline flow duration curves, giving confidence that the weather generator and hydrological model will produce plausible flow duration curves for future climate. It is also clear that there is an increase in magnitude of flows at the higher percentiles and a significant decrease in baseflows. This would be consistent with other findings that increased storm events will drive large storm response while greater evapotranspiration will reduce summer low flows. The impact on a hypothetical 16 MW hydro scheme was also modelled with results indicating that capacity factors would drop with significant falls in the summer. Slightly higher capacity factors are seen in winter albeit constrained by the turbine rating and design flow.



**Figure 6 Flow duration curves for River Ewe for baseline and 2050s climate (Duncan, 2014)**

### **Solar power**

Solar energy is the most abundant renewable energy source available on Earth. It presently counts for a relatively small proportion of generated energy, but growing concerns over climate change have helped stimulate a marked growth in implementation over recent years and is expected to dramatically increase as solar technologies mature and costs significantly reduce.

Solar energy can be affected by changing cloud cover characteristics (Crook et al. 2011; Pan et al. 2004). Human activity can cause a change in atmospheric particles (aerosols) that in turn impact cloud cover by increasing (or decreasing) the volume of cloud condensation nuclei. Solar irradiance levels reaching the surface of the earth are dependent on cloud cover, and will therefore be impacted by climate change.

The impact of climate change on solar energy has been explored to some degree. Gueymard and Wilcox (Gueymard and Wilcox 2011) investigate the long term solar resource in the U.S. and highlight the seasonal changes in the solar resource. Pan *et al.* (Pan et al. 2004) uses a regional climate change model with results suggesting that seasonal irradiance in the US may decrease by up to 20% by the end of the 2040s.

Burnett et al. (2014) characterises the UK solar resource to provide a detailed assessment of the baseline climate which is combined with UKCP09 probabilistic output to allow the effect of Climate Change to be explored and to estimate the future UK solar resource at a regional and local scale. In brief, the results show an overall increase in resource over the UK, especially in more southern and south-westerly locations. However, there will be increased seasonal variability in many areas, more notably in southern regions. It is expected that present regional differences in solar resource will be further increased in the future with most southerly regions getting sunnier and benefiting from increased solar energy resource in summer, while the relatively poor northerly resources will decrease slightly. In winter most regions will witness increased cloud cover and slightly reduced solar energy resource.

The expectation is that all types of solar energy system will be affected: solar photovoltaics (PV), solar water heating and solar thermal generation, of which the first two are relevant to the UK. Differences between technologies will occur given the differing spectral absorbance characteristics between solar water heating panels and PV cells of differing types. Additionally, their response to changing temperature differs: PV panel efficiency degrades as ambient temperatures rise while solar water heating efficiency improves.

### **Wave power**

Wave energy converters (WECs) rely on wind generated waves for their operation. As the name suggests these waves are formed by the interaction of the wind with the ocean surface. Waves observed at a location have a seemingly random appearance because they are, in fact, a large number of harmonic waves of different amplitudes, periods, directions and phases interacting with each other (Holthuijsen

2007). These individual waves may be generated great distances away from the location of the observer, from which it may be inferred that the wave climate of a region is more complex than the simple interaction of local winds with the water surface. For example, the wave climate on the western coast of the UK is greatly influenced by waves, especially swell, generated in the middle and the western regions of the North Atlantic.

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

$$P = 0.49H_s^2T_e$$

The wave climate is likely to change as a direct consequence of changes in wind patterns. The increase in the roughness of waves in the North Atlantic has been discussed for over three decades (e.g. Neu 1984; Carter and Draper 1988). It is reasonable to expect that these variations in the marine climate, whether climate change driven or otherwise, will have some effect on electricity generation by WECs.

A study of the Wave Hub site in Cornwall (Reeve et al. 2011), forced with wind corresponding to the IPCC A1B (intermediate emissions) and B1 (low emissions) scenarios, suggested that there was likely to be an overall decrease in the wave power conversion by WECs by 2-3%. It indicated that there was likely to be a 2.95% increase in the mean available wave power for the A1B scenario along with a wider spread of incident wave heights and a 2.27% decrease for the B1 scenario. The decrease in power conversion was attributed to the fixed performance characteristics (often presented as a power matrix) of WECs because of which they may not be able to convert the additional power. Other studies linking the variability in wave climate to the North Atlantic Oscillation (NAO) have yielded similar results (Mackay et al. 2010).

### Bioenergy

The likely effects of climate change on bioenergy could fall into two areas. The first is related to the fact that the typical thermal power generation cycle is, in theory, sensitive to ambient temperature. Higher ambient temperatures would raise the temperature of the 'cold sink' part of the typical Rankine cycle which describes the generation of steam from combustion of a fuel, i.e. the cooling water or air will have a higher temperature and be less effective as a coolant. Thus, increasing temperatures might be expected to reduce the efficiency of all steam-driven thermal power plants including biomass combined heat and power, energy from waste. A study (Förster and Lilliestam 2010) based on a hypothetical nuclear plant located in central Europe, but applicable to any river-cooled thermal plant, showed that concurrent increases in river temperature and decreases in river flow could impact quite significantly on power production. Given that the UK's current characteristic weather is cooler and wetter than central Europe, it might be expected that future changes might push production patterns towards those currently experienced in hotter, drier climates.

The second, and possibly more serious, consequence of climate change for biomass-fuelled generation is the effect that changes in weather parameters might have on the growing cycle of biofuel crops.

The impacts arise from a number of factors. Firstly, there is evidence that crop yields will improve in elevated levels of atmospheric CO<sub>2</sub>. Changes in solar radiation will directly influence the available energy for photosynthesis. Rainfall and temperature are critical for determining soil moisture levels that are key to yields. In addition rainfall and temperature levels are key in the ripening and drying processes, affecting harvest timing and also crop moisture levels, with high levels detrimental to the calorific value of crops. Temperature is also important in regulating growth with frost depth and frequency an important factor in mortality and yield.

A report analysing maize production in the US suggests that an increase in the variation seen in temperature and precipitation would lead to subsequent variation in biofuel production (Hatfield and Singer 2011). Managing the uncertainty resulting from this is a key issue for the industry. Bellarby *et al.* (2010) use a model to project changes in the suitability of different areas of the UK for growing different types of biofuel crops. The authors note that the model is fairly simple and the assumptions made create associated uncertainties, but indications are given that certain crops, such as willow, which are currently popular as biofuels in the UK, may become less suitable under future climate conditions. An additional factor to consider under changing climate is the migration of crop pests and pathogens (Bebber et al. 2013).

Much of the analysis produced to date has focussed on specific energy crop yields, with limited information on impacts on secondary bioenergy (wastes and residues), wider supply chains or economic impacts. An increasing amount of biomass currently being used for UK energy production is sourced from overseas. As such, the impact of climate change on the physical supply of material from overseas as well as issues raised by the 'food versus fuel' debate will be relevant.

## **Other climate impacts on renewable generation**

### **Extremes**

A major consideration for future climate change scenarios is the potential for increased frequency of extreme weather events. All infrastructure, including renewable energy plant, is vulnerable to extreme wind speeds, extended or reduced periods of precipitation and very high or low temperatures.

Sea-level rises are a widely predicted impact of climate change that could have a direct effect on some areas of renewable generation. Co-fired or biomass plant that is coastally located could be subject to inundation during high tides. An additional factor to consider for coastal thermal plant is the predicted rise in sea water temperatures, reducing the cooling efficiencies of the plant. Tidal generators, whilst not dependent on climate factors, are potentially vulnerable to resource changes linked to sea-level rises. The potential for changes to the tidal constituents due to sea-level rise is described in (Pickering et al. 2012), and does indicate that if a large degree of sea-level rise were to occur, changes in tidal characteristics around the UK would be expected. Additional factors affecting tidal generators might be changing meteorological drivers for ocean currents and temperature changes.

In very high wind conditions, wind turbines will stop producing power and turn away from the prevailing direction in order to prevent damage to the machine. More frequent and more persistent storms would increase the amount of 'lost' energy due to this process. The fatigue loading on the blades and tower structure would also be increased in this situation. Stormy conditions over the sea which cause large swell waves present a danger to wave and tidal energy devices in exposed locations, again, with increased frequencies and more prolonged events causing greater damage and loss of generation.

When rainfall (or snowmelt) rate exceeds the rate of drainage, flooding will occur. Prolonged periods of precipitation (either rain, or snow which later melts quickly) onto saturated ground present a high risk to all assets and infrastructure, including renewable generation plant. For hydropower, extreme flooding can lead to the spillways exceeding their design limits, whilst run-of-river plant will suffer inundation. The opposite situation of more frequent extreme drought conditions are also likely to affect thermal plant that uses cooling water from rivers most seriously, and also, obviously, hydropower generation will be affected.

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

Survivability of any marine energy technology, i.e. wave energy converters and offshore wind and tidal turbines, in the marine environment is a critical consideration in project planning. It was found in (Reeve et al. 2011) there is likely to be an increase in the occurrence of extreme waves at the Wave Hub site for the future scenarios. This is in accordance with the findings of (Perrie et al. 2004), which showed that climate change is likely to slightly increase the wave heights generated in large storms.

### ***Assessment and management of risks***

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

This section addresses the potential for climate change to affect the cost of energy. The most sophisticated and up-to-date probabilistic climate modelling framework for the UK is provided by the UK Climate Impacts Programme (UKCP09). They offer a number of different ways of accessing and analysing data for future climate change scenarios at different levels of detail (UKCP09 2012) for a range of potential applications. Where possible, UKCP09 data has been used here to carry out the future analyses, but varying assumptions for baseline climate have been applied and are described further in the cited references.

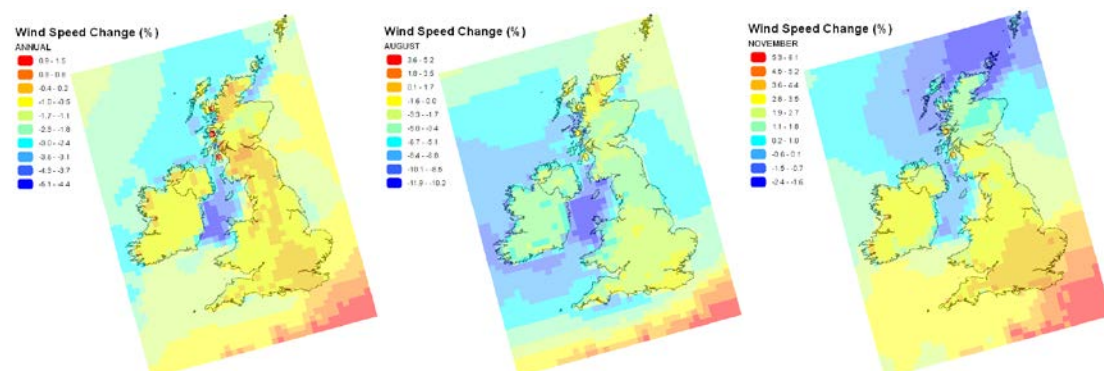
#### **Wind energy**

For wind speeds, the provision of data by UKCP09 is more limited than other variables, due to lower confidence in the output (Sexton and Murphy 2010). Two possible sources are available:

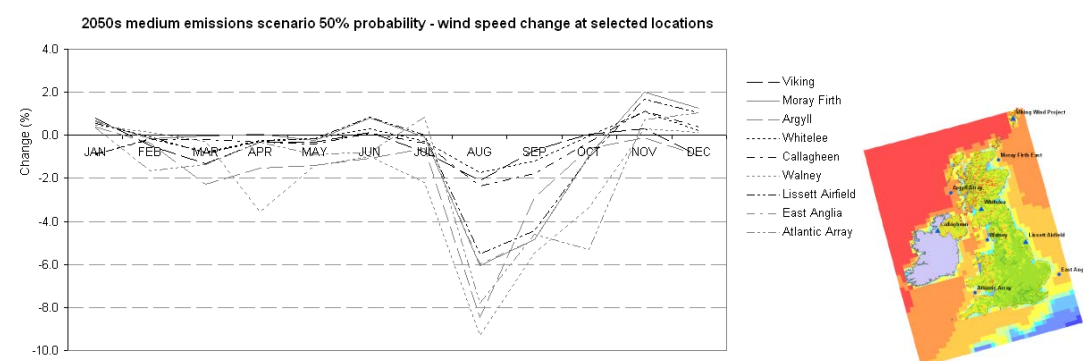
- monthly cumulative distribution functions (CDFs) of projected change under different emissions scenarios for individual points on the 25km resolution UK grid;
- output from an 11-member ensemble run of the HadRM3 regional climate model which provides spatially coherent daily and monthly mean wind speeds for baseline and future scenarios over the whole UK grid

The range of changes in surface wind speeds projected in the UKCP09 model summarised in (Sexton and Murphy 2010) are relatively small, and for the most part, span both positive and negative changes. Figure 7 shows some of the percentage changes in wind speeds in the 2050s found from the 11 runs of the HadRM3 ensemble at the 50% probability level for a 'medium' emissions scenario. August and November have been identified as having the most extreme changes, and are shown alongside the change in the annual mean. In terms of the spatial differences in wind speed changes, Figure 8 illustrates that the model is predicting the most severe decreases in wind speeds in August with some more modest increases in November, with a similar pattern appearing to affect most sites.

To translate the changes in wind speed into impacts on wind energy output, the wind speeds from the 11-run HadRM3 ensemble have been used to derive baseline and future UK wind generation scenarios based on the locations of existing wind farms and their capacities. The future values of the levelised cost of energy (LCOE) from wind have then been derived using the method described in (DECC 2012).



**Figure 7 Wind speed change (%) for 2050s medium emissions scenario with 50% probability**



**Figure 8 Climate change impact on wind speeds at geographically spaced locations**



The overall impact of the wind speed changes on the LCOE is shown in Table 1. The figures are broken down into groups representing the current onshore capacity, offshore capacity from the Crown Estate Leasing Round 2, and the Crown Estate Leasing Round 3. It can be seen that the direction of changes is highly uncertain, being typically positive at the 10% probability level and negative at the 90%. The magnitude of the changes is relatively small at the 50% probability level, but the more extreme changes are more significant. The geographic spread of changes is such that the current northern preference is further enhanced, with some slight decreases in LCOE in the future whilst the south east of England sees some future increases in LCOE as the wind output reduces.

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

	Baseline Climate	Emission Scenario								
		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

### Solar, hydro and wave energy

A simple study to assess the sensitivity of wave energy to changes in wind (Harrison and Wallace 2005) revealed that variations in the mean annual wind speed had an effect on not only the significant wave height and energy period (and therefore power), but also on other aspects related to the performance of wave energy projects. The summary from (Harrison and Wallace 2005), which used the Pelamis wave energy converter as a case study are presented in Table 2:

**Table 2 Summary of results from (Harrison and Wallace 2005) relating wave energy project performance with changes in mean annual wind speed.**

Measure	Annual mean wind speed change			
	-20%	-10%	10%	20%
Mean $H_{m0}$ (m)	1.73	2.19	3.27	3.88
Mean $T_e$ (s)	5.00	5.63	6.88	7.50
Mean wave power (kW/m)	27.5	49.5	134.4	205.6
Mean output (kW)	134.4	183.8	279.4	322.5
Production (GWh/yr)	1.18	1.61	2.45	2.83
Load Factor (%)	17.9	24.5	37.3	43
Time at idle (%)	48.7	41	29.7	25.7
At capacity (%)	0.9	2.4	8.2	12.2
IRR (%)	2.45	6.18	12.16	14.63

Unit cost (p/kWh), 8% discount rate	9.43	6.89	4.54	3.93
Unit cost (p/kWh), 15% discount rate	14.68	10.74	7.06	6.12

In a similar manner to the previous results presented for wind, levelised costs were calculated using a method leveraged from (Mott MacDonald 2010) and described in full in (Burnett 2012) for solar, hydro and wave power. Baseline values are derived from a number of sources (wave: (Allan et al. 2011), solar: (International Energy Agency 2010) hydro: (Mott MacDonald 2010)) and future climate change applied using UKCP09 outputs (hydro – weather generator, solar – probabilistic framework, wave – using HadRM3 wind combined with the methodology described in (Harrison and Wallace 2005)). The results are shown in Table 3. It should be highlighted that the baseline numbers are calculated using more tentative assessments of capacity factor than the wind figures from Table 1, and cover only a single emissions scenario.

**Table 3 Climate change impact on UK solar, wave and hydro energy LCOE – change in £/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			

### Summary

In this section, some tentative assessment of the potential for climate change to influence the levelised cost of renewable energy has been presented. It must be highlighted that the timescales considered from the point of view of climate modelling are quite long – perhaps 30-40 years from now – and there is generally low confidence in the results. Investment decisions are typically made on the basis of shorter periods of around 20-30 years and thus climate change is unlikely to have an impact on investment decisions, at least until the modelling skill at shorter timescales is improved. Other influences, for example, the wider political context, are likely in the short term to have much greater impact. The introduction of policy mechanisms that incentivise renewable generation could have a larger effect on the financial viability of a development than (uncertain) changes in climate variables.

It is important to note that socio-economic influences on renewable energy cannot be considered in isolation from climate change. For example, sudden obvious changes in climate (or lack thereof) over the coming decades could influence the prioritisation of renewables development relative to more carbon-intensive energy sources. The combined effect of this is likely to be more important for investment decisions than climate variables alone.

### Adaptation

Adaptation to climate change can take many forms, depending on the severity and nature of the changes that occur. Mukheibir (2013) categorises types of adaptation

into a range of different responses, indicating factors including the timeframe, and coverage and drivers of different adaptations.

It is impossible to say for certain what the future will look like, and so the potential for adaptation to future conditions can be built in to the machine design – for example, new wind turbine designs have less severe responses to extremely high wind speeds and rather than shutting down completely, will gradually turn away from the prevailing wind and reduce output gradually. This reduces yield losses associated with high wind conditions (Enercon 2014). Similarly, many WECs are ‘tuned’ to produce their maximum output in the most frequent types of sea-state occurring where they are located. Re-tuning the control system to different prevailing conditions may be necessary under climate change scenarios (Reeve et al. 2011). Alteration of hydropower reservoir operating rules is likely to be necessary in a changing climate (Weyman and Bruneau, 1991, Minville et al, 2009).

More major site-specific adaptations may be necessary in the case of hydropower, for instance raising dam walls and enhancing spillway capacity to cope with additional flood waters or uprating the capacity of turbines (Harrison, 2005; Duncan 2014). Similarly, for bioenergy, it may become necessary to change the type of crop used in order to obtain maximum yield under different temperature and precipitation conditions.

The already significant variability in renewable output requires careful management by the network operators to ensure demand is met. In the case of an increase in this variability due to climate change effects, it would seem sensible to invest in two areas – improved short and medium-term weather forecasting, and efficient and cost-effective storage facilities. Forecasting of wind speeds is generally good in the very short term, but can be very difficult over time periods greater than 2-3 days. Research is required to improve the modelling skill in this area. Many storage technologies are in development and may prove suitable to provide a ‘buffer’ to reduce the dependence on responsive fossil-fuel plant as back-up generation. ‘Virtual power plant’ and demand management may also provide similar facilities.

In the case of wind power, which might be expected to contribute most of all the renewables to the future electricity system, the highest likelihood scenarios appear to feature only small changes in wind speeds and thus fairly small changes in wind energy output would be expected. Short-term adaptation measures would thus appear to be unnecessary. The existing spatial pattern of higher generation potential in the north and west of the UK appears, within the UK HadRM3 model at any rate, to persist and thus major adjustments to the configuration of capacity would not be required in future. However, this is not the only model, and as indicated, the uncertainty is very high.

Given the high degree of uncertainty associated with climate change projections, it would be prudent to consider adaptation in a wider sense, and ensure the system is designed to have sufficient adaptive capacity to deal with a range of different scenarios. Even the direction of projected change, for example, in wind speed is currently unclear and thus developing a system with in-built capacity to cope with a range of possibilities is necessary. Although it would not, obviously, be possible to consider every eventuality, sufficient flexibility to cope with reasonable changes

would make the system more robust. Understanding the sensitivity of the system to changes in different parameters is the first step in this process.

### ***Broader drivers and interactions***

#### *Renewable energy planning*

The decisions on locations/sizes of renewable energy developments tend to rest in a negotiation between developer and local authority planning departments. The developer will choose a site that has good resources, reasonably priced infrastructure access and perhaps consider eliminating sites based on evidence for extreme events, e.g. flooding. They will then approach the local authority for planning permission and try to reach agreement on a specific site configuration. This should, in theory, result in the lowest cost sites being developed most quickly. However, the time-frame over which the resources at a site are considered in order to calculate costs are short, relative to the consequences of slower changes in climate.

#### *Community development of renewables*

The short-term risk associated with climate change is small. Changes in the long-term mean resources are expected to occur on very large time-scales, and thus investment risk, for example, by more vulnerable community developers, is not likely to be impacted by this particular factor. In the case of wind power, interannual variability in output is already known to be quite significant, and will be factored into any sensible financial risk analysis. Beyond the 20-25 year expected lifetime of a wind farm, more subtle changes associated with climate change can be reassessed before further investment.

A factor that might be more significant is the impact of an increase in the short-term variability of a site. This could lead to more extreme 'good' and 'bad' years in terms of financial success, increasing investment risks for developers. This may be a particular issue for small scale or community developments with only a single plant in their portfolio with limited scope to diversify risk across different investments.

#### *Demand interdependence*

The close coupling of both renewable energy and demand to weather patterns means that the impacts of climate change on each factor cannot be considered in isolation. For example, increasing ambient temperatures in summer could result in a greater requirement for space-cooling which, when combined with a reduced mean wind resource, would require alternative generation. Solar power may be more suitable for providing this energy, but the concurrent generation and demand patterns would need to be studied to ascertain the precise gap and the ability of solar to fill it. Such changes imply changes to overall capacity credits from renewable technologies. While not a panacea, energy storage, in sufficient capacities, could reduce the strength of the (already complex) relationship between demand and output from renewables and provide the system with more flexibility.

### ***Confidence in the science***

#### *Climate science and modelling*

In general, confidence in the output of climate models among qualified scientists is very high, but a clear understanding of the uncertainties and sensitivities is needed to reach this judgement. On temperature, there is agreement between models and a significant association between carbon dioxide emission levels and predicted trends in temperature change. The same level of confidence does not exist with respect to other weather variables, however. In particular, surface-level wind speed is a difficult parameter to model on a scale that is applicable to wind power generation. As discussed in previous sections, different models give different results, and the direction of change is inconsistent even within different runs of a single model. As computing power increases, and consequently the spatial resolution of models improves, higher confidence may be achieved.

An additional consideration in terms of confidence is the choice of emissions scenarios and how they are applied in the models. The IPCC provide a set of emissions scenarios for modellers that have been designed to reflect a range of future possibilities for technology, economic growth and political and social opinion (see (IPCC 2014)). The differing socio-economic conditions assumed give rise to different emissions levels and rates of stabilisation. The UKCP09 outputs which have been drawn upon heavily in this article do attempt to capture a spectrum of scenarios ranging from 'low' to 'high' emissions levels, but do only cover two of the four IPCC 'storylines' for future conditions, and not all scenarios are captured in all of the outputs (UKCP09 2012). The results of any climate modelling story should be considered in the context of the plausibility and representativeness of the scenarios used. The current generation of modelling is, however, still valuable in providing a framework against which to test the resilience of renewable energy systems to climate change. Considering the model outputs as possible future scenarios rather than a deterministic future prediction allows testing of various aspects of the system against a range of plausible future conditions.

### ***Summary of confidence in specific impacts***

<b>Specific impact</b>	<b>Volume of evidence</b>	<b>Agreement</b>	<b>Impact</b>	<b>Comments</b>
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	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	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 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 under these conditions)	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

--	--	--	--	--

***Research gaps and priorities******Climatology and meteorology***

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

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

***Engineering***

The issue of adaptation is key to managing the impacts of climate change. It is necessary to focus research on designing adaptable and resilient machines for future conditions. The provision of increasingly reliable estimates for design and resource parameters from the climate science community will allow machine designers to factor climate change, but the range of uncertainties must be clearly communicated. Considering the energy system as a whole, addressing the capacity of the system to deal with progressive changes, and concentrating development on more 'flexible' solutions such as efficient storage technology and short-term balancing mechanisms, would create a more robust infrastructure.

***Policy and economics***

The cost of climate change and the associated level of risk is currently only able to be estimated. Combining the many levels of uncertainty within the climate data, the engineering models and the economics is a complex task which has not been sufficiently addressed as yet. Modelling future economic and policy decisions requires the use of scenarios that effectively integrate many different influencing factors, including climate change alongside issues such as regulation, societal and political landscapes (which may also themselves be directly related to climate change). All of these factors, including climate, are subject to large degrees of uncertainty, making the task particularly difficult. Based on the existing models for climate impacts on renewable energy, the influence of changes to specific climate variables relating to renewable energy output will be relatively small in comparison to some of the wider social and political factors which are key to investment and development.

## References

- Allan, Grant, Michelle Gilmartin, Peter McGregor, and Kim Swales. 2011. "Levelised Costs of Wave and Tidal Energy in the UK: Cost Competitiveness and the Importance of 'banded' Renewables Obligation Certificates." *Energy Policy* 39 (1). Elsevier: 23–39. doi:10.1016/j.enpol.2010.08.029.
- Bellarby, Jessica, Martin Wattenbach, Gill Tuck, Margaret J. Glendining, and Pete Smith. 2010. "The Potential Distribution of Bioenergy Crops in the UK under Present and Future Climate." *Biomass and Bioenergy* 34 (12): 1935–45. doi:10.1016/j.biombioe.2010.08.009.
- Burnett, D. 2012. "Climate Change and Renewable Energy Portfolios". University of Edinburgh. <http://hdl.handle.net/1842/6245>.
- Burnett, D., E. Barbour, and G. P. Harrison. 2014. "The UK Solar Energy Resource and the Impact of Climate Change." *Solar Energy* In Press.
- Carter, D J T, and L Draper. 1988. "Has the North-East Atlantic Become Rougher." *Nature*.
- Cradden, LucyC., GarethP. Harrison, and JohnP. Chick. 2012. "Will Climate Change Impact on Wind Power Development in the UK?" *Climatic Change* 115 (3-4). Springer Netherlands: 837–852 LA – English. doi:10.1007/s10584-012-0486-5.
- Crook, Julia A, Laura A Jones, Piers M Forster, and Rolf Crook. 2011. "Climate Change Impacts on Future Photovoltaic and Concentrated Solar Power Energy Output." *Energy Environ. Sci.* 4 (9). The Royal Society of Chemistry: 3101–9. doi:10.1039/C1EE01495A.
- DECC. 2012. *Electricity Generation Costs*. <https://www.gov.uk/government/publications/decc-electricity-generation-costs-2013>.
- . 2013a. *Digest of United Kingdom Energy Statistics (DUKES)*. London. [https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/279523/DUKES\\_2013\\_published\\_version.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/279523/DUKES_2013_published_version.pdf).
- . 2013b. "RESTATS: Electricity Growth." <https://restats.decc.gov.uk/cms/electricity-growth/>.
- Enercon. 2014. "Enercon - Control System." <http://www.enercon.de/en-en/754.htm>.
- Förster, Hannah, and Johan Lilliestam. 2010. "Modeling Thermoelectric Power Generation in View of Climate Change." *Regional Environmental Change* 10 (4). Springer-Verlag: 327–338 LA – English. doi:10.1007/s10113-009-0104-x.



- Gueymard, Christian A., and Stephen M. Wilcox. 2011. "Assessment of Spatial and Temporal Variability in the US Solar Resource from Radiometric Measurements and Predictions from Models Using Ground-Based or Satellite Data." *Solar Energy* 85 (5): 1068–84. doi:10.1016/j.solener.2011.02.030.
- Harrison, G P, L C Cradden, and J P Chick. 2008. "Preliminary Assessment of Climate Change Impacts on the UK Onshore Wind Energy Resource." *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* 30 (14-15): 1286–99. doi:10.1080/15567030701839326.
- Harrison, G P, and A R Wallace. 2005. "Sensitivity of Wave Energy to Climate Change." *Energy Conversion, IEEE Transactions on* 20 (4): 870–77. doi:10.1109/TEC.2005.853753.
- Harrison, Gareth P, and Robin A Wallace. 2005. "Climate Sensitivity of Marine Energy." *IEEE Transactions on Energy Conversion* 20 (4): 870–77.
- Hatfield, J.L., and J.W. Singer. 2011. "Climate Change: What to Expect and How Will It Affect Feedstock Production Options?" In *Sustainable Biofuels for Advanced Biofuels. Soil and Water Conservation Society*, edited by R. Brown, D. Karlen, and D. Johnson, 349–60. [http://www.swcs.org/documents/resources/Chapter\\_21\\_\\_Hatfield\\_\\_Climate\\_Change\\_6A49A597A0988.pdf](http://www.swcs.org/documents/resources/Chapter_21__Hatfield__Climate_Change_6A49A597A0988.pdf).
- Holthuijsen, Leo H. 2007. *Waves in Oceanic and Coastal Waters*. Cambridge University Press.
- International Energy Agency. 2010. *Projected Costs of Generating Electricity 2010*. Projected Costs of Generating Electricity. OECD Publishing. doi:10.1787/9789264084315-en.
- IPCC. 2014. "SCENARIO PROCESS FOR AR5." AR5. [http://sedac.ciesin.columbia.edu/ddc/ar5\\_scenario\\_process/](http://sedac.ciesin.columbia.edu/ddc/ar5_scenario_process/).
- Jiang, Jing, and William Perrie. 2007. "The Impacts of Climate Change on Autumn North Atlantic Midlatitude Cyclones." *Journal of Climate* 20 (7). American Meteorological Society: 1174–87. doi:10.1175/JCLI4058.1.
- MacDonald, Mott. 2010. "UK Electricity Generation Costs Update." *Mott MacDonald*, no. June. <http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:UK+Electricity+Generation+Costs+Update#0>.
- Mackay, Edward B L, AbuBakr S Bahaj, and Peter G Challenor. 2010. "Uncertainty in Wave Energy Resource Assessment. Part 2: Variability and Predictability." *Renewable Energy* 35 (8). Elsevier Ltd: 1809–19. doi:10.1016/j.renene.2009.10.027.

- Manwell, J.F., J.G. McGowan, and A.L. Rogers. 2002. *Wind Energy Explained: Theory, Design and Application*. Chichester: J. Wiley & Sons.
- Mukheibir, Pierre. 2013. "Potential Consequences of Projected Climate Change Impacts on Hydroelectricity Generation." *Climatic Change* 121 (1). Springer Netherlands: 67–78 LA – English. doi:10.1007/s10584-013-0890-5.
- National Grid. 2014. *UK Future Energy Scenarios*. Warwick, UK. <http://www2.nationalgrid.com/uk/industry-information/future-of-energy/future-energy-scenarios/>.
- Neu, H J A. 1984. "Interannual Variations and Longer-Term Changes in the Sea State of the North Atlantic from 1970 to 1982." *Journal of Geophysical Research* 89 (4): 6397–6402.
- Pan, Zaitao, Moti Segal, Raymond W Arritt, and Eugene S Takle. 2004. "On the Potential Change in Solar Radiation over the US due to Increases of Atmospheric Greenhouse Gases." *Renewable Energy* 29 (11): 1923–28. doi:10.1016/j.renene.2003.11.013.
- Perrie, Will, Jing Jiang, Zhenxia Long, Bechara Toulany, and Weiqing Zhang. 2004. "NW Atlantic Wave Estimates and Climate Change." In *Eighth International Workshop on Wave Forecast and Hindcast*. North Shore, Hawaii.
- Pickering, M.D., N.C. Wells, K.J. Horsburgh, and J.A.M. Green. 2012. "The Impact of Future Sea-Level Rise on the European Shelf Tides." *Continental Shelf Research* 35 (March): 1–15. doi:10.1016/j.csr.2011.11.011.
- Pryor, S.C., and R.J. Barthelmie. 2010. "Climate Change Impacts on Wind Energy: A Review." *Renewable and Sustainable Energy Reviews* 14 (1): 430–37. doi:10.1016/j.rser.2009.07.028.
- Reeve, D E, Y Chen, S Pan, V Magar, D J Simmonds, and A Zacharioudaki. 2011. "An Investigation of the Impacts of Climate Change on Wave Energy Generation: The Wave Hub, Cornwall, UK." *Renewable Energy* 36 (9): 2404–13. doi:http://dx.doi.org/10.1016/j.renene.2011.02.020.
- Sexton, David M. H., and James Murphy. 2010. *UKCP09: Probabilistic Projections of Wind Speed*. <http://ukclimateprojections.metoffice.gov.uk/media.jsp?mediaid=87876&filetype=pdf>.
- UKCP09. 2012. "UKCP09 Summary Table." *UK Climate Projections*. <http://ukclimateprojections.metoffice.gov.uk/22533>.
- Vestas Wind Systems A/S. 2004. "Vestas V90-3.0 MW Product Brochure". Rinkøbing: Vestas.

