ICE REPORT T1.1.1: AN OVERVIEW OF RENEWABLE ENERGY SUPPLY POTENTIAL

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ICE report T1.1.1:
An overview of renewable energy supply potential

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About ICE

Supported by Interreg VA France (Channel) England, the Intelligent Community Energy (ICE) project, aims to design and implement innovative smart energy solutions for isolated territories in the Channel area. Islands and isolated communities face unique energy challenges. Many islands have no connection to wider electricity distribution systems and are dependent on imported energy supplies, typically fossil fuel driven. The energy systems that isolated communities depend on tend to be less reliable, more expensive and have more associated greenhouse gas (GHG) emissions than mainland grid systems. In response to these problems, the ICE project considers the entire energy cycle, from production to consumption, and integrates new and established technologies in order to deliver innovative energy system solutions. These solutions will be implemented and tested at our unique pilot demonstration sites (Ushant island and the University of East Anglia's campus), to demonstrate their feasibility and to develop a general model for isolated smart energy systems elsewhere. The ICE consortium brings together researcher and business support organisations in France and the UK, and engagement with SMEs will support project rollout and promote European cooperation.

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1. Introduction

This report reviews available renewable energy technologies for remote communities, outlines appropriate methodologies for assessing the available resources, and identifies key constraints. A parallel report, 'T1.1.2 Policy Issues', describes the regulatory and policy factors expected to be relevant to the aims of the ICE project, focussing on those policies and regulations that affect the production, distribution and consumption of energy in the project regions. Together, the two reports fulfil task T1.1 of the ICE project.

The two sites selected as case studies for ICE are first Ushant (FR: Ouessant), an electrically isolated island community of a few hundred people off the coast of Northwest France, and second, the main campus of the University of East Anglia (UEA), a large teaching, research and residential facility serving more than 15,000 students in Eastern England. The energy systems of these sites appear to have few similarities. Ushant is electrically isolated, having no physical connection to mainland France. It is a publicly administered commune, meaning that proposed changes to its energy system are a matter for cooperative decision-making. The UEA campus is connected to the local gas and electricity distribution systems with sufficient capacity for its energy requirements now and in the future. It operates as a privately-owned site offering greater autonomy to energy decision makers.

However, the sites have two key factors in common in relation to their energy supplies. Firstly, both occupy relatively small geographical areas. The UEA campus is built on 130 hectares, while Ushant has an area of around 1,500 hectares, and both have clearly defined electrical boundaries: Ushant due to its isolation, and UEA due to its status as a managed campus. Secondly, both locations have strong incentives to make changes to their energy systems that require the use of innovative energy supply and/or energy management technologies. On Ushant, the current energy system is entirely reliant on fossil fuels shipped from mainland France for electricity, heat and transport, and its electricity system depends heavily on a single generation plant. The cost, security and environmental impacts of this arrangement are unsustainable. While the UEA campus is linked to the wider Great Britain (GB) electricity and gas networks, there is a strong incentive as a research university to lead on environmental issues, including through cleaner, more efficient energy systems as well as minimising the cost of providing energy services to staff and students. All UK universities have government mandated targets for carbon emission reduction (HEFCE, 2010).

An electrically isolated island energy system faces some unique challenges. The difficulty of meeting residents' energy needs without the benefit that comes with interconnection to larger electricity networks is compounded by the need to do so in a way that protects against unnecessary economic or environmental cost. However, recent years have seen advances in both energy supply technologies – primarily renewable energy conversion technologies – and demand-side technologies such as demand management, information technologies and energy storage. There is growing consensus about the merit of such 'smart grids' that can intelligently integrate both the generators and consumers of electricity, to deliver secure and sustainable energy from multiple sources.

This report identifies the available renewable technologies suitable for isolated communities and presents a framework for undertaking a resource assessment for each. A renewable energy resource assessment is conducted to quantify the amount of energy available at a site or sites and to estimate the amount of electricity or heat that can be extracted. The various sources of renewable energy have different issues regarding intermittency and predictability, and varying constraints affecting exploitation of the resource. The aim of this document is to enable stakeholders to easily compare the benefits and limitations of different technology types and to make decisions on which technologies they may wish to take forward.

2. Renewable Technology and Resource Quantification Overview

2.1 Overview

As part of the site selection process for any renewable energy deployment, an assessment process as outlined in Figure 2-1 is typically followed. The constraints on the deployment of each technology are first identified, enabling selection of suitable sites for detailed analysis. A full assessment of the raw resource is performed for the selected site(s), and device performance characteristics are then applied to predict the annual energy generation of the project, accounting for resource variation. Finally, capital expenditure and operational costs are incorporated to calculate the levelised cost of energy (LCOE), enabling an assessment of the financial viability of the project to be made.

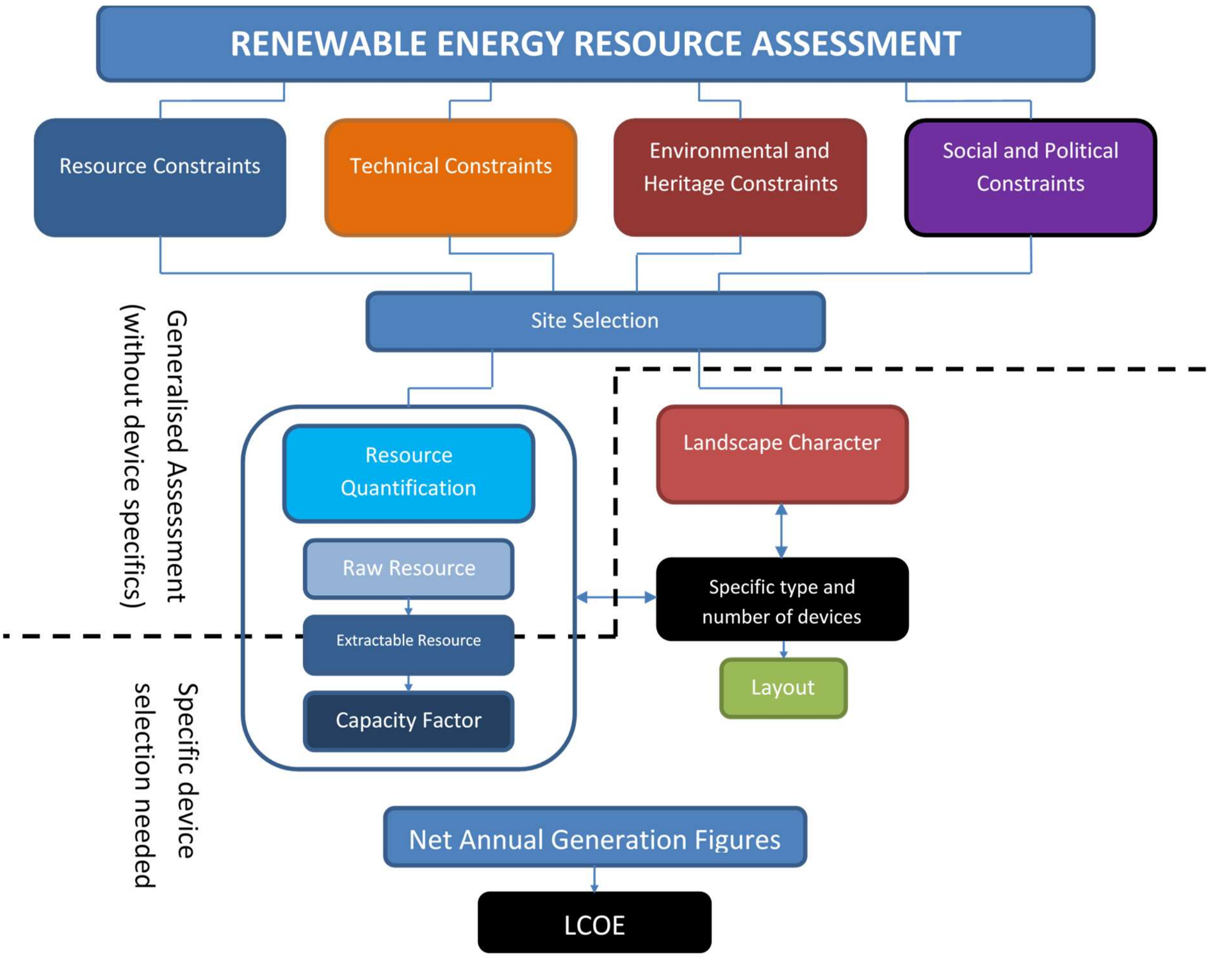

Figure 2-1: Flow chart describing the resource assessment process for renewable technologies, including the constraints to development.

2.2 Constraints affecting the deployment of technologies

2.2.1 Resource Constraints

Renewable energy technologies all require a naturally occurring resource. For most technologies this resource is variable and/or intermittent, with the exception of biomass generation which is dependent on reliable supplies of the raw material. The quantification of the raw resource is a key factor in assessing the deployment potential of a renewable technology. Determining the resource will usually involve a combination of numerical modelling and *in-situ* data collection. More intermittent resources, such as solar, wind and wave energy, require longer datasets to accurately calculate the resource availability than predictable resources such as tidal energy.

2.2.2 Technical Constraints

Technical constraints are practical restrictions on the technology, for example unsuitable terrain or lack of grid access. Areas that have the best availability of raw resource may not be suitable for technology deployment, for example if they are remote or lack appropriate infrastructure. Similarly, urban areas are likely to have practical limitations due to housing, roads, and other existing infrastructure. If there is insufficient demand for on-site energy usage, any electricity-generating renewable technology will require a grid connection of sufficient capacity or an alternative mechanism to mitigate offtake, such as electrical storage. All deployment sites will require suitable access for construction and maintenance.

2.2.3 Environmental and Heritage Constraints

Many sites with appropriate levels of raw resource fall within or close to areas of environmental or natural interest. These include:

- National parks
- Nature reserves
- Areas of scientific or natural interest
- Areas with protected flora or fauna
- Protected environments (e.g. wetlands, ancient forests)
- Landscape conservation areas
- UNESCO World Heritage Sites
- Other areas of cultural or natural significance

Countries and regions have classifications for protected or conservation areas with limits on development or requirements specific to the local jurisdiction. These may restrict the installation of renewable energy technologies and the required infrastructure. Many renewable technologies create ecological impacts (e.g. Copping et al., 2016; Wang & Wang, 2015; Hernandez et al., 2014), and environmental considerations must be considered in the planning of any development. The visual impact of renewable technologies may also be a factor, especially in areas of natural beauty or historic significance, and will be considered in project planning applications. The relevant legislation is discussed in the accompanying ICE report 'T1.1.2 Policy Issues'.

2.2.4 Social and Political Constraints

The installation of electricity generation technology may impact local stakeholders including residents, visitors and businesses, for example through visual impact, noise, or loss of amenity. Planning regulations may be in place to limit the locations where technologies can be sited. Relevant policies and legislation are discussed in ICE report 'T1.1.2 Policy Issues'.

2.3 Levelised Cost of Energy

The levelised cost of energy (LCOE) is the unit cost of energy produced over the lifetime of a project, including the initial capital expenditure (CAPEX), ongoing operational costs (OPEX) and decommissioning costs, calculated as:

$$LCOE = \frac{Costs\ over\ lifetime\ of\ a\ project}{Total\ amount\ of\ electrical\ energy\ generated}$$

This measure can be used to compare methods of energy generation types that may have very different modes of operation. For example, the costs of a gas power station are very different to that of a wind farm. The gas plant will have high ongoing costs in the form of fuel whereas a high proportion of the wind farm costs may be upfront. Calculating the expected LCOE for a project requires analysis of the planning, installation, operation, maintenance and decommissioning costs in addition to predicting the amount of energy that will be produced. The need for predictions of generation over project lifetimes means there are often large uncertainties in the calculations, particularly for untested technologies such as arrays of marine energy converters (BEIS, 2016). LCOE is therefore an inappropriate metric for comparing immature renewable technologies with established commercial technologies. A methodology for calculating LCO for storage technologies is provided by Pawel (2014).

3. Technology Types

3.1 Solar

3.1.1 Overview

There are two primary methods of solar energy conversion: the use of photovoltaic (PV) panels to generate electricity, and thermal heating. Examples of both systems are shown in Figure 3-1. Solar PV installations convert the Sun's radiation into electricity that can be used locally or fed into the grid. Solar thermal plants convert the solar radiation into heat that can be used for water, space heating or electrical generation. Significant falls in global prices in the last decade mean that solar panels are used extensively as a simple and low-cost renewable energy solution. Deployments range from small-scale installations on domestic rooftops to large commercial farms with capacities of hundreds of megawatts.

Figure 3-1: Examples of solar energy installations: ground mounted PV installation (top); rooftop mounted solar thermal (bottom left); rooftop mounted PV (bottom right).

Solar energy is well-suited for deployment in remote communities due to the range of available scales of deployment and the low levels of infrastructure required. Solar installations will produce power effectively at most latitudes although locations further from the equator will generate less, especially in winter. It is a particularly effective technology for meeting demand which rises in the summer and drops in the winter; this may make it less suitable as the only source of power in communities with significant winter demand.

Resource quantification involves measuring or modelling the solar radiation reaching the site. Solar radiation can be measured from in-situ equipment or satellites, or it can be modelled using commercial software packages. For a known latitude, the number of daylight hours and the relative path of the sun are inherently predictable. Weather models and historical data can also be used to inform the likely amount of cloud cover, temperature and weather conditions. Data can be analysed across a range of timescales, from long-term project-length calculations of the total expected yield of an installation to short-term variability linking generation with demand throughout the day.

The size and orientation of the panels are fundamental to the levels of energy conversion. The line of the horizon and any features that will restrict direct sunlight should be considered, as well as any losses due to atmospheric conditions. Solar tracking systems are available that can increase electricity production by continually orienting the PV cells to the most appropriate angle and direction relative to the Sun. If the use of such a system is under consideration then this should be taken into account when calculating the resource.

Solar Photovoltaics

Photovoltaic (PV) materials produce an electrical current through the photoelectric effect when exposed to electromagnetic radiation; the materials used in solar cells are designed for optimal response to the frequencies of light most abundant in solar radiation. The electricity produced is direct current (DC) but with the use of a power inverter it can be converted into alternating current (AC) and delivered into an electrical grid or stored in batteries.

The first solar PV cell was developed in 1954, and solar cells have subsequently developed into a mainstream technology, grouped into first, second or third generation categories (IRENA, 2016).

- First generation solar cells are produced from crystalline silicon and constitute the majority of solar installations worldwide. They are relatively low cost and have been a well-established technology for 25 years.
- Second generation, or thin film, technologies use less material and have lower production costs than silicon wafer cells. Their low cost, light weight and flexible design makes them ideal for non-standard applications such as on offshore installations
- Third generation cells encompass several different types of new technologies currently being developed, including concentrating and organic PV cells.

Concentrating PV uses cells that are capable of converting a significantly larger amount of energy than they receive directly from the sun by focusing the radiation from a larger area onto a smaller cell, using lenses or mirrors. This allows more energy to be harnessed at lower cost (Baig et al., 2012).

The PV market has experienced average annual growth of over 40% globally for more than a decade. Improved manufacturing techniques have contributed to a significant drop in the cost of producing solar cells, with second generation thin film module prices at US$0.5/W in early 2016 (IRENA, 2016).

Low and Medium Temperature Solar Thermal

Heat generation accounts for a significant proportion of annual energy consumption, for example, in 2012 heating comprised 47% of total energy use in the UK (Connor et al, 2015). Instead of converting solar energy to electricity for electrical heat generation, solar radiation can be used directly for heating. In domestic and commercial settings this will involve either heating a medium (water or other fluids) for direct use or to be fed through heat exchangers to provide hot water, or the use of a solar air heating system for space heating.

There are other uses of low and medium temperature solar energy besides heating water and space, for example, solar ovens can be used for cooking or drying hence reducing the need for fossil fuels.

High Temperature Solar Thermal

Concentrated solar power (CSP) is a system where solar radiation is collected over a large area and concentrated upon a smaller focal point through reflection from parabolic mirrors. This heats a fluid which is used to create high temperature steam to drive a turbine as in a conventional thermal power station. This system requires accurate control of the collecting mirrors to ensure that the radiation is focused on the correct point.

Unlike solar panels, CSP generators are able to delay generation by up to several hours by storing the high temperature steam prior to generation. This provides a bulwark against intermittency. CSP stations require a large area to be covered with solar collectors and the erection of a tall central structure providing the focal point. They are best suited to locations with large areas of unused land such as deserts.

3.1.2 Constraints

Resource Constraints

The key parameters in quantifying the solar resource use different metrics to measure the amount of solar radiation received. These are:

- Direct normal irradiance (DNI): Solar radiation received per unit area by a surface perpendicular to the rays of the Sun.
- Global horizontal irradiance (GHI): Radiation received by a surface that is horizontal relative to the ground.
- Global tilted irradiance: Radiation received by a surface fixed at a particular incline, for example solar panels with a fixed incline.
- Diffuse horizontal irradiance (DHI): Radiation received by a horizontal surface after scattering by particles in the atmosphere.

Sites which receive the highest levels of solar radiation will be best suited to energy generation, for example desert environments with high intensity radiation and little cloud cover. Sites further from the equator will demonstrate greater seasonal variation due to longer days in the summer allowing more generation. Figure 3-2**Error! Reference source not found.** shows a map of global horizontal irradiation, illustrating the high levels of GHI received in the desert regions close to the Tropics, for example, the Sahara Desert and Great Australian Desert. However, annual radiation levels of over 1,000 kWh/m^2 are received at latitudes as high as northern Europe, demonstrating that solar energy is a viable resource over most of the globe. Clear skies and long days provide the optimal resource, however, solar irradiation is transmitted through clouds and solar cells will still be productive in overcast conditions. The effectiveness of generation without direct solar radiation will depend on the level of cloud cover and the sensitivity of the chosen solar cells.

The temperature of a PV cell will have a significant effect on its performance. The electrical efficiency has been shown to decrease with increasing temperature (Skoplaki & Palyvos, 2009). Air temperature and wind speed will also have an effect on the temperature of the cells, in addition to the internal electronics and other factors such as the building where the PV panel is sited.

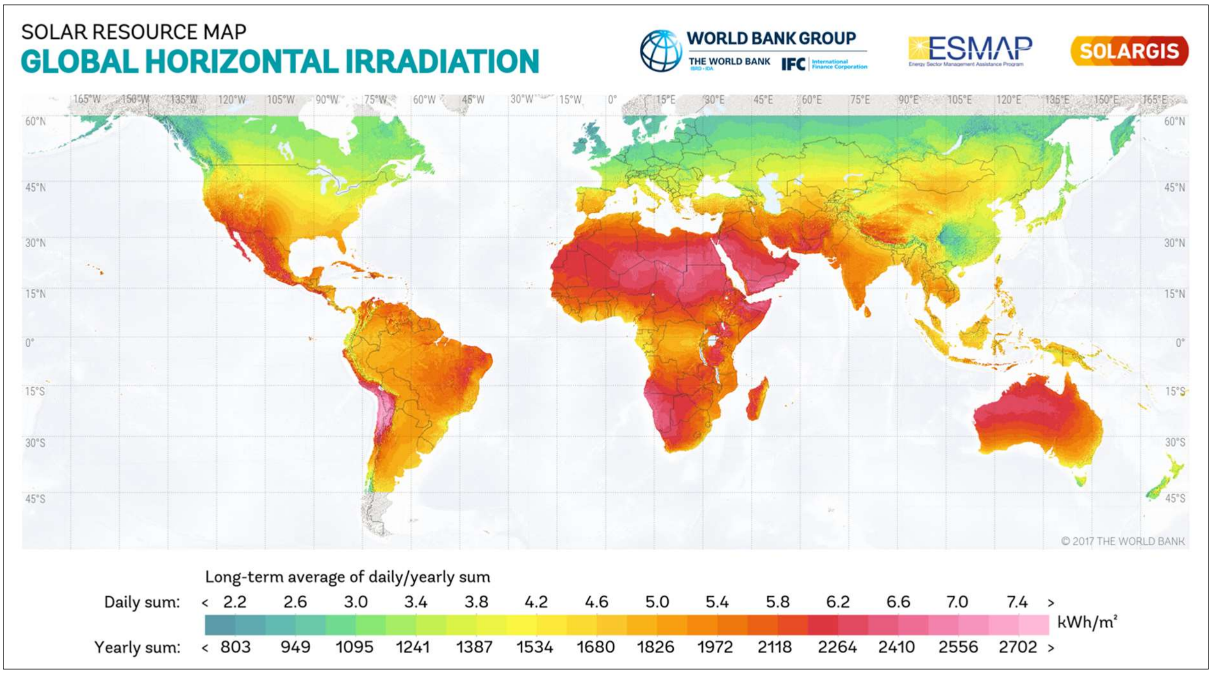

Figure 3-2: Map of global horizontal irradiation (source: SolarGIS, 2018)

Technical Constraints

Solar panels are typically installed on rooftops or at ground level, more rarely they can also be deployed as floating installations where conditions allow. Rooftop installations allow solar generation without additional land use. Ground level panels can be deployed in bespoke standalone sites or as mixed-use sites, for example with grazing livestock. Restrictions may be imposed by planning regulations to limit visual impacts or for other reasons. These will vary with the local regulatory regime.

Solar panels can be installed almost anywhere an electrical connection can be established. Small scale installations can be placed on domestic buildings with the power used internally, stored, or connected through single phase domestic supplies. Larger scale installations require dedicated connections to the grid or user base. Panels can also be deployed with relatively little infrastructure. Once installed, the plant does not need to be staffed or accessed daily, with access only required for ongoing maintenance and in case of failure.

The type and capacity of the grid connection may impose limits on the installation. For example, under UK regulations, small scale embedded generators (SSEGs) are limited to 16A on a single phase connection. This means that 3.68kW is the largest system that can be installed freely on most domestic buildings in the UK. Larger systems require the distribution network operator (DNO) to be notified and an application must be submitted for system studies and associated network reinforcement where necessary prior to connection (Energy Networks Association, 2014).

To ensure the optimum output, any rooftops or inclined surfaces where the panels are to be deployed in the northern hemisphere should be close to south facing (and conversely north facing in the southern hemisphere) to maximise the intensity and available time of solar irradiance.

Environmental and Heritage Constraints

The environmental impacts of solar technologies are usually localised to the development site and the negative impacts are usually minor when compared with other renewable generation technologies (Tsoutsos et al., 2005). The visual impact of solar cells may be considered unwelcome, especially in environmentally important or culturally protected areas, which may prevent planning permission being obtained. With careful positioning panels can be installed on rooftops while minimising visible change in comparison with the pre-existing roof. The installation of ground-mounted developments, especially large-scale farms, is more obtrusive and planning regulations should be studied to ensure that selected locations are suitable.

Solar cells contain chemical substances which could be hazardous to wildlife. Care should be taken to prevent damage to the solar cells, especially during installation or decommissioning. In normal conditions there are no operational emissions, and impacts on flora and fauna are small. Where solar installations are to be co-located with agricultural land use the effect on agriculture must be considered.

Social and Political Constraints

The planning regulations for the installation of solar panels vary by country and region. Domestic and smaller rooftop installations often do not require specific planning permission as long as the system is outside a conservation area. For example, in the UK rooftop panels with a capacity of less than 4kW can be installed without permission on non-listed buildings, and in France systems less than 3kW do not require a full planning application. Larger scale installations will usually have to obtain full planning permission. The regulatory considerations are explored in detail in the accompanying ICE report 'T1.1.2 Policy Issues'.

3.1.3 Methodology for quantifying resource

The first step in a resource assessment for a solar energy project is an analysis of solar irradiation data. Irradiation can either be measured by deploying appropriate measurement equipment such as a pyranometer (to measure solar radiation flux density) or pyrheliometer (to measure direct beam irradiance) at sites of interest, or collated from other sources. Solar radiation levels around the globe are available from several open source and commercial databases (e.g. Amillo et al., 2014; Page, 2001; Šúri & Hofierka, 2004) providing data collated from satellite measurement, weather stations and numerical models. Data collected on-site can be used to supplement and validate global models.

The collected data can be used to identify locations with the best raw resource. Areas which violate technical, environmental and social constraints will be discounted. The areas with the best resource from the remaining sites can then be taken forward for further analysis. Solar planning software tools such as PVSyst (Mermoud, 2014) and PVGIS (Huld et al., 2012) can be used to design solar installations and will provide predictions of the availability and intensity of solar radiation over time. Using a database of solar technologies, these tools can also enable power and cost calculations for the installation.

Small scale (rooftop) solar

Domestic and non-domestic buildings with flat roofs, or close to south facing pitched roofs (in the northern hemisphere), provide an ideal site for small scale solar. Providing the rooftop has an unobstructed view then it can be used to site panels to generate electricity or heat water. The number and layout of the panels will be subject to:

- Availability of suitable roof space
- Type and capacity of grid connection
- Planning restrictions
- Other technical or social constraints.

Large scale (ground-mounted) solar

Large scale ground-mounted projects will require more detailed site selection. Investigation of other local renewable energy projects can provide useful insight into the specific challenges involved with obtaining planning permission.

Initially, sites that are likely to contravene local planning or distributer guidelines should be discounted. It should be noted that any grid connection may also need planning permission. When a site has been identified as suitable then a full calculation of the potential can be undertaken. Software tools (e.g. PVSyst and PVGIS) enable input of the site's annual radiation statistics and the size and layout of any buildings and will calculate the estimated electrical output.

The design of the site will be guided by:

- Available suitable space
- Proximity to high capacity, high voltage grid architecture
- Any technical limitations of the site
- Planning guidelines
- Capacity of regional grid
- Financing, i.e. the cost of installation and operation along with any rules of funding for the project.

Predicted project outcomes can be optimised by altering the type, number and size of panels, the layout, and angle of inclination. The inclusion of a tracking system will increase the performance of the array, however, it may involve a larger upfront cost and require additional maintenance.

3.1.4 Calculation of energy produced

The amount of energy generated will depend on the size and type of installation. Once a potential design for an installation has been identified the total annual yield can be calculated. This will depend on the solar cells used, since the efficiency of solar panels varies with type. The software packages mentioned above will provide energy generation calculations for the specific system installed.

3.2 Tidal

3.2.1 Overview

The tides have long been utilised as a source of power, with widespread operation of tidal mills recorded in the Middle Ages and earlier (Charlier & Menanteau, 1997). Tidal energy has been used to generate electricity for over five decades; La Rance Tidal Power Plant, the first commercial tidal power station, came online in France in 1966 and is still operational today. Tides are caused by the forces of gravitational attraction and relative motions between the Earth, Moon and Sun. This makes them a highly predictable energy source, with the only variability from astronomical predictions due to local weather conditions and geographical features of the shoreline and seabed. Worldwide, there is estimated to be over 1TW of exploitable resource close to the coast (Kempener & Neumann, 2014).

Two aspects of the tidal resource can be exploited for energy conversion: the tidal stream, where the kinetic energy of the tidal current is used to drive a turbine directly, and the tidal range, which utilises the potential energy from the height differential due to the rise and fall of the tides. Examples of both forms of tidal energy conversion are shown in Figure 3-3.

In the last twenty years, the tidal energy industry has focused primarily on tidal stream technology. Single demonstrator devices have been successfully deployed at test and demonstration sites, for example OpenHydro, ScotRenewables SR2000, Andritz Hydro Hammerfest HS100 and Atlantis AR1000 at the European Marine Energy Centre (EMEC) in Orkney, Scotland (EMEC, 2018a), SeaGen-S in Strangford Lough (Atlantis Resources Ltd, 2018a) and Sabella D10 off Ushant (Paboeuf et al., 2016). The first multi-device arrays were deployed in 2016, with MeyGen operating a 6MW array of four turbines in the Inner Sound off the north coast of Scotland (Atlantis Resources Ltd, 2018b) and Nova Innovation operating three 100MW turbines in the Shetland Islands (Nova Innovation, 2018). A detailed overview of the status of the tidal industry including a description of existing and planned technologies, future potential, industry drivers and barriers is available from the International Renewable Energy Agency (Kempener & Neumann, 2014).

Figure 3-3: Examples of tidal power technology: OpenHydro turbine deployed at EMEC (Source: OpenHydro, 2018) (top left); Sabella D10 turbine (Source: Open Ocean, 2015) (top right); La Rance tidal power plant (bottom).

Tidal Stream

Tidal stream energy conversion uses the horizontal movement of water driven by the ebb and flood of the tides to drive a turbine and generate electricity. Tidal stream turbines typically require mean flow velocities greater than $1ms^{-1}$, therefore potential developments sites will be in locations with accelerated flows, either due to a large tidal range or constrained in channels or around headlands. The available power in the flow is proportional to the cube of the velocity multiplied by the density.

Seawater has a density approximately 1000 times that of air, therefore tidal turbines can generate power equivalent to wind turbines from lower velocities and with significantly reduced blade diameters.

A range of turbine designs have been proposed and tested, including horizontal and vertical axis turbines, oscillating hydrofoils, Archimedes screw devices and Venturi devices. A full list has been compiled by EMEC (2017a). In recent years horizontal axis turbines have emerged as the dominant style for large (>500kW) installations (Zhou et al., 2014), and have accounted for most full-scale demonstrator deployments of single devices and arrays.

Tidal Range

Tidal range power utilises conventional low-head hydropower technology to exploit the difference in water level between high and low tide. A head of water, caused by the difference in water level over a tidal cycle, is created across a barrier through the use of sluice gates and then released to drive turbines and generate electricity. Tidal range power stations can be configured to generate on the flood or ebb tide, giving two periods of approximately 6 hours of generation per day, or as a two-way generation system utilising both the flood and ebb tides, giving four shorter periods of generation per day.

Barrage tidal power stations involve the construction of a barrier across an area with a large tidal range, typically a river estuary or bay. This results in a total blockage of the estuary, except for lock gates to allow the passage of shipping, and the sluice gate and turbine chambers. The potential environmental impacts are therefore significant and have been extensively studied for a proposed development in the Severn Estuary, UK (DECC, 2010) and following construction of the La Rance barrage in France (Retiere, 1994).

A proposed alternative to barrage construction is the use of tidal lagoons, whereby an artificial reservoir is constructed either at the shoreline or offshore in an area with significant tidal range. Lagoons operate in the same way as barrages, but without the full blockage effects and therefore with lower environmental impacts. Although no lagoons have been constructed to date, an independent UK Government review concluded that lagoons could play a cost-effective role in the UK's future energy mix (Hendry, 2016). Plans for the world's first tidal lagoon in Swansea Bay, South Wales, are at an advanced stage but await a final decision on the marine licence (Tidal Lagoon Power, 2018).

3.2.2 Constraints

Resource Constraints

The key resource parameters in determining the suitability of a site for tidal stream energy are the flow velocity and its variability over a tidal cycle. Sustained periods of flow above the speed required for generation are essential for a project to produce significant energy. The directionality of the flow is important; some turbine designs have a yaw capability and will continually align themselves with the flow, while others are fixed and will operate less efficiently if the flow direction is not in line. Directional characteristics of the flow will vary from approximately bi-directional, for example in a constrained channel, to elliptical or asymmetrical, with significant variations between the ebb and flood tides. Tidal range requires a site with a large vertical displacement between high and low tide. The rated power of a development is proportional to the square of the head of water available, therefore a site with a 7m tidal range will have double the generation potential of a site with a 5m range.

The tidal signal comprises a series of tidal constituents known as harmonics, each due to a different astronomical motion between the Earth, Moon and Sun. For a detailed understanding of the tidal resource at a specific site, a full harmonic analysis must be performed based on either measured or modelled data, using software such as UTide (Codiga, 2011). Depending on the location, some sites are dominated by the diurnal (24-hour) cycle and others by the semi-diurnal (12-hour) cycle. The flow regime is additionally influenced by the spring-neap cycle of approximately 14 days, where spring tides see higher than average flows and tidal ranges, and neap tides lower than average.

The tides are strongly influenced by local geographical features in nearshore regions, which can result in potentially significant variations in flow speed and direction across a proposed site. Resource analysis must therefore address the spatial variability of the flow, either through measurement at multiple locations or numerical modelling.

Technical Constraints

Tidal energy converters require a site with energetic flow. This presents several technical challenges for installation and maintenance which should be accounted for in assessing the feasibility of a development.

Tidal turbines are typically installed with either gravity-based foundation structures or drilled monopile foundations. Gravity foundations comprise a support structure held in place on the seabed by its own weight and onto which the turbine nacelle is installed. Monopile foundations involve the supporting structure being secured in a hole drilled into the seabed, thus providing a strong and stable base for the turbine. The geological constitution and any slope of the seabed will be important in finding a suitable location for deployment with either foundation type (Heath et al., 2017). Large vessels with dynamic positioning and suitable lifting equipment are required for most installations. Tidal turbines are designed to work with minimal intervention but will require periodic and corrective maintenance, and a strategy for regular access and recovery must therefore be established.

Individual turbine specifications will determine the flow speeds in which they can operate. The cut-in velocity defines the current velocity at which the turbine will start to generate, and the rated velocity the velocity at which maximum generation will occur. Since the maximum velocities are well understood for tidal sites, most tidal turbines do not have a cut-out velocity, above which the device is constrained. The Sabella D10 turbine, for example, is rated to cut-in at $0.4ms^{-1}$ and operate in velocities up to $4ms^{-1}$ (Paboeuf et al., 2016).

Environmental and Heritage Constraints

A tidal energy project will affect the surrounding marine environment, and the potential impact on marine life, the physical environment and other water users must be assessed prior to commissioning a project. An environmental impact assessment is likely to be required to determine effect of the project on the environment, as discussed in section 2.2.3.

A particular consideration is the effect of a tidal installation on fish and marine mammals. The installation activities, movement of turbine blades, increased turbulence, noise and other aspects of a tidal project may have a detrimental effect on the marine fauna. Certain areas may have particular sensitivities, e.g. feeding grounds with an abundance of marine life, and may therefore need to be discounted as potential sites.

The effect on fishing, navigation and other water users should be considered when selecting a site for development. With tidal stream developments, the choice of device, e.g. floating, bottom-mounted, surface piercing, will influence constraints on other water users. Sites of historical interest such as shipwreck locations must also be avoided, not only in the positioning of devices but also in planning cable routes to shore.

Social and Political Constraints

The specific planning process for tidal energy projects will vary depending on jurisdiction. The 'owner' of the seabed, marine management agencies, electrical network operators, local communities and national governments may all be involved in the planning and consenting process. The regulatory process is described in the accompanying ICE report 'T1.1.2 Policy Issues'.

3.2.3 Methodology for quantifying resource

Resource assessment methodologies for tidal stream energy are codified by the International Electrotechnical Commission in the IEC-TS 62600-201 standard (IEC, 2015a). Additional standards and protocols for tidal resource assessment have been produced by industry and research organisations, including the EquiMar protocols (Ingram et al., 2011) and the European Marine Energy Centre (EMEC) guidelines (Legrand, 2009).

The first stage of a resource assessment is a pre-feasibility study to characterise the tidal conditions across the area of interest, identify any major constraints and enable selection of potential sites for development. This can be done at a relatively coarse resolution prior to a more detailed analysis of the site(s) identified as having development potential.

A full assessment of the resource will initially involve identifying key site characteristics including water depth, tidal range, flow velocities, bathymetry and seabed geology. If a specific tidal turbine has been selected for the project then the specifications of the turbine, such as the hub height, should be considered when quantifying the resource, otherwise site characteristics for a horizontal axis turbine can be assumed (Legrand, 2009). The tidal resource will need to be quantified with a combination of harmonic analysis, to identify key tidal constituents, numerical modelling and analysis of measured data.

Flow measurements at a site can be acquired using flow meters, acoustic profilers, high frequency (HF) radar and other measurement equipment. Each measurement technique has certain advantages, and a combination of equipment may be needed to acquire a full set of site data. Flow meters such as acoustic Doppler velocimeters (ADVs) use high sampling frequencies to capture tidal flows and turbulence at individual locations. Acoustic Doppler current profilers (ADCPs) sample the current velocities through the water column, providing a vertical profile of flow variation with depth. HF Radar installations enable surface current velocities to be measured over a wider area through the use of shore-based transmission and receiving stations, and results have been shown to correlate well with surface measurements from ADCP point measurements (Ren et al., 2015). To complement measurement programmes, hydrodynamic numerical models are can be used to simulate tidal flows across the area of interest, either using a 2D grid to provide depth-averaged output, or 3D, accounting for variation with depth. As with any numerical simulation, the accuracy of the output relies on the inputs provided, model set-up and boundary conditions. Model output should be verified and validated with in-situ data before being used in calculations for a project.

Guidelines on the level of detail required for each stage of the resource assessment vary a little with source, but the EMEC guide, as an example, recommends:

- Regional assessment: Harmonic analysis identifying two main constituents acquired from the water level time series from public or commercial sources; hydrodynamic models with a resolution of <5km; no field survey is required.
- Pre-feasibility site assessment: Harmonic analysis identifying a minimum of four constituents derived from flow velocities; hydrodynamic model with a resolution of <500m; a minimum two-day field survey is recommended.
- Full-feasibility site assessment: Harmonic analysis identifying at least twenty constituents; hydrodynamic model with a resolution <50m; a minimum one-month field survey is recommended.
- Design development assessment: In addition to the full-feasibility study, a further three months of field survey is recommended.

The availability of any previous hydrodynamic models covering the areas of interest should be investigated, especially for the first stage regional assessment. Full site assessment will usually require a bespoke model to be established (unless the site has been investigated previously) with a suitably fine resolution. It is recommended that models provide a minimum of 30 days data for the first stage and three months to one year for the more detailed analyses.

Measured current data should be acquired for the sites of interest including transect surveys to establish the variation across the site, and longer term (at least 15-30 days) static surveys. Data should be analysed with 2-10 minute intervals and provided in 0.5-1m vertical bins. Current speeds should be provided as three directional components (east, north and vertical) for each time step to enable directional analysis.

3.2.4 Calculation of energy produced

The specific turbine characteristics will determine the amount of power that can be extracted from the tidal flow. Turbine developers will produce a power curve showing the relationship between the flow speed and electrical power output. Flow outside of the operational speed limitations should be discounted. Using this power curve, the power generation throughout the tidal cycle can be calculated and extended to monthly and annual periods. The losses caused by varying direction of flow, wave motions, turbulence, wake effects and shadowing from other turbines may also have been investigated by the turbine developer and can be incorporated into power calculations. A power performance assessment of the Sabella D10 turbine using data collected from a 2015 deployment is presented by Paboeuf et al (2016).

3.3 Wave

3.3.1 Overview

Wave energy converters (WECs) convert the kinetic energy of the wave motion into electricity. The technology is still in the development and testing phase and the sector has not yet converged on a specific device type. A wide range of WEC designs have been designed and sometimes developed, utilising many different methods of energy conversion. Devices can be designed to operate either onshore, in the nearshore region (~10-20m depth), or offshore (~50-100m depth). The principle device types are as follows, with examples shown in Figure 3-4:

- **Point absorber**: A device that is small relative to the wavelength of the waves, and able to absorb energy from an incident wave front much wider than its own dimensions. These typically comprise a floating buoy which moves freely with the waves relative to a fixed base. Electricity is generated via a linear generator, hydraulic turbine or pump system due to the relative motion between the buoy and the static mooring.
- **Linear Attenuator**: A long, hinged, floating structure aligned parallel to the direction of the incident waves. It absorbs the energy of the waves along its length, generating electricity due to the relative motions of the different sections of the device driving hydraulic turbines at the hinges.
- **Oscillating surge device**: A floating or seabed-mounted device that uses the horizontal surge motion of the waves to rotate a pivoted flap, generating electricity through hydraulic turbines or pump systems.
- **Oscillating water column (OWC)**: A floating or shoreline structure comprising an enclosed chamber which is open to the sea at the bottom and the air at the top. A bi-directional turbine is installed in the upper opening. Waves cause the water level within the chamber to rise and fall, continually forcing air out of the chamber and then drawing it back in, driving the turbine to generate electricity.
- **Rotating mass**: A floating body containing a rotating mass pendulum. The device is designed to move with the heave, surge and sway motions of the waves causing the mass within to rotate. This rotational motion is captured and used to drive a generator.

An up-to-date list of proposed wave energy converter designs is provided by EMEC (2017b).

Research and development in wave energy has been ongoing since the 1970s, and the industry has seen a number of full-scale prototype devices developed and tested. EMEC has hosted a range of devices including Pelamis, Aquamarine's 'Oyster' and Wello's 'Penguin' (EMEC, 2018b). In the SouthWest UK, Fred Olsen's 'BOLT II Lifesaver' device was tested at the FaBTest site for two years from 2012 (FaBTest, 2015). However, the industry has faced a number of setbacks in recent years including the high-profile failure of companies including Pelamis and Aquamarine. It has been recognised that an increased focus must be placed on early stage and component testing to increase the reliability of devices and bring down costs (Ocean Energy Forum, 2016).

Figure 3-4: Examples of wave energy devices: the onshore Pico Plant OWC in the Azores (source: Pico OWC, 2006) (top left); the nearshore Wavestar device with point absorber floats (source: Wavestar, n.d.) (top right); the offshore Fred Olsen 'BOLT II Lifesaver' (bottom).

3.3.2 Constraints

Resource Constraints

Ocean waves can be classified as either higher frequency wind waves, generated locally by transference of energy from wind to the water, or lower frequency swell waves, generated by distant wind events, which have propagated away from their region of generation. A typical sea state may comprise both wind and swell waves, and an understanding of the underlying sea states is an important part of the resource assessment process. Different devices will be designed to operate most efficiently in specific conditions, so the wave characteristics at a site will inform the choice of device. Particularly, the directionality of sea states must be considered as some devices will only operate across a limited range of wave directions.

The variability of the wave resource must be considered when assessing a site. In addition to short-term variability, most sites will see seasonal variability, with larger sea states occurring during stormier winter months, and inter-annual variability. Some sites are also more exposed to storm events which may require the device to be shut down for survival. It is important from a reliability perspective to understand the loads that are likely to be experienced by the devices during the most extreme conditions.

Technical Constraints

The technical issues surrounding a wave energy project will be dependent on the type of device. However, all wave energy devices will be installed in areas of energetic wave climates, and consideration must therefore be given to weather windows for installation and operations and maintenance activities. Access to appropriate port facilities must be considered.

Floating devices will require mooring systems designed to suit the device motion, water depth and seabed conditions. Seabed-mounted devices are likely to require drilled foundations, similar to those used for tidal turbines. The bathymetry and seabed slope must be assessed and incorporated into the site planning process.

Power export to the grid requires an onshore grid connection and associated infrastructure. The cable route to shore must be planned to avoid areas with highly mobile sediment or seabed canyons, and appropriate protection for the cable route, such as rock armouring, considered.

Environmental and Heritage Constraints

Wave energy converters may have an impact on marine life, commercial fishing, shipping and other water users in the immediate vicinity of the devices and may also cause wider far-field impacts on the physical environment. Unless deploying at a pre-consented test site, it is probable that an environmental impact assessment will be needed to determine the scope of the effects of the project, the level of acceptability and potential mitigation.

Fish and marine mammals may be affected by noise from the device, electromagnetic radiation and moving parts. However, device foundations and other subsea infrastructure can act as artificial reefs and play a role in attracting marine fauna (Inger et al., 2009).

With wave energy devices being primarily floating or surface-piercing devices, often with extensive underwater mooring cables, most wave energy developments will require an exclusion zone to prevent the risk of collision and entanglement to other marine traffic. This will have consequences for commercial fishing and may lead to re-routing of shipping lanes.

By removing energy from the sea, the wave climate in the lee of the devices will be affected (Millar et al., 2009), with consequences for sedimentary processes. This may have impacts on beaches and coastline morphology, with implications for marine life and recreational activities. A report from the charity Surfers Against Sewage (2009) detailed the potential impact of WECs on recreational water users.

Visual impacts are likely to be a lesser concern than for other forms of renewable energy due to the likely distances offshore for most deployments. However, this may be a consideration along sections of coastline preserved for their heritage value or where there are protected seabed areas.

A full overview of potential environmental impacts of wave energy can be found in Copping et al. (2016).

Social and Political Constraints

The specific planning process for wave energy projects will vary by jurisdiction. The body responsible for ownership of the seabed, marine management agencies, electrical network operators, local communities and national governments may all be involved in the planning and consenting process. The regulatory process is described in the accompanying ICE report ‘T1.1.2 Policy Issues’.

3.3.3 Methodology for quantifying resource

An international standard for wave energy resource assessment has been developed by the IEC in IEC-TS 62600-101 (IEC, 2015b), and other guidance documents and protocols are available from sources such as EquiMar (Ingram et al., 2011) and EMEC (Pitt, 2009).

The initial stage of a resource assessment process involves a high-level regional assessment of wave conditions. This will typically utilise output from coarse resolution global wave models or existing data records to enable potential development sites to be identified and investigated further. A detailed resource assessment for a proposed site will be performed using *in-situ* recorded data and higher resolution numerical modelling.

The most commonly used wave measurement device is a wave buoy, a moored, floating instrument which follows the motion of the waves and measures the sea surface displacement with a combination of an accelerometer, compass and GPS tracker. The displacement data will be processed on-board the buoy to produce a frequency domain variance density spectrum, which allows calculation of key summary parameters such as significant wave height, mean period and direction. An advantage of wave buoys is that data can be transmitted back to shore in real-time. An alternative measurement device is an upward-facing ADCP, which produces equivalent output but usually lacks data transmission capabilities. For wider spatial coverage, radar systems such as HF and X-band radar can be used, but operational limitations reduce the accuracy of these measurements in comparison to direct measurement methods (Wyatt et al., 2011).

Nearshore wave models such as SWAN (Booij et al, 1999), TOMAWAC (Benoit et al., 1996) and MIKE21 (Warren and Bach, 1992) can be used to propagate sea states across a geographical grid, accounting for energy losses due to nearshore and shallow water physical processes. These allow spatial assessments of the resource across potential sites to be made. To increase confidence in their outputs, numerical models should be used in combination with measured datasets within the model domain for calibration and validation studies.

Site characteristics can be summarised in a scatter diagram, as shown in Figure 3-5. This presents the percentage occurrence of combinations of wave heights and periods, allowing the most frequently occurring and extreme sea states to be identified. For a more in-depth understanding, and to inform the engineering design for the site, analysis of wave spectra will provide information about the range of energies contained in the waves and can be used with information about specific devices to identify whether sites are viable for energy generation. Extreme value analysis can be applied by fitting measured or modelled data to a specific distribution and attempting to predict the likelihood of long-term extreme events. The 10-year, 50-year and 100-year maximum wave heights are important for assessing the survivability of devices and components.

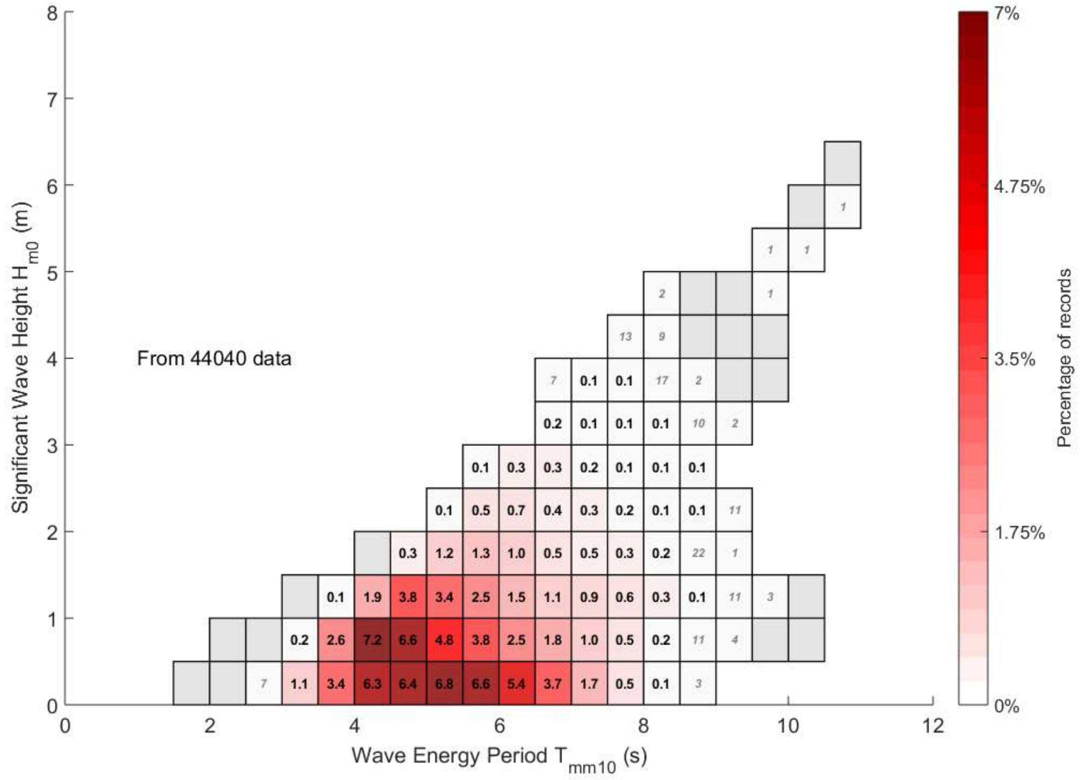

Figure 3-5: Scatter diagram showing the relationship between significant wave height and energy period at the FaBTest wave energy test site, produced by University of Exeter (Parish & Hardwick 2012).

3.3.4 Calculation of energy produced

The available wave power can be derived from the measurement data and spectral analysis following the process described by the EquiMar protocols (Ingram et al., 2011). When assessing a site for deployment of a specific device, the developer power matrix can be used. This describes the predicted device power production for different combinations of wave heights and periods and can be used in combination with the site scatter diagram to predict potential annual power production.

3.4 Wind

3.4.1 Overview

Wind power is generated by air flow through turbines, which can range in size from the small domestic-scale to multi-MW commercial-scale structures. Smaller turbines are typically used for domestic or small-scale off-grid generating systems, while larger turbines will be grid-connected and often installed in arrays of multiple devices, forming a wind farm. The industry converged on a three-bladed, horizontal axis turbine design (the 'Danish Concept' turbine), although vertical axis and two-bladed horizontal axis turbines can still be seen. Examples are shown in Figure 3-6.

Figure 3-6: Examples of commercial wind turbines: Siemens SWT-2.3-101 horizontal axis turbine (source: Siemens, 2018) (top left); MHI Vestas offshore wind turbine (source: MHI Vestas, 2018) (bottom left); Quiet Revolution qr6 vertical axis turbine (source: Quietrevolution, n.d.) (right).

Power has been successfully harvested from the wind for millennia, with early structures consisting of rotating sails connected mechanically to simple machinery for milling grain or pumping water. The use of such structures to generate electricity from the wind began in the 1880s and grew in the early decades of the 20th century, especially in rural areas where connection to distribution grids was not yet possible. However, development accelerated following the oil crisis of 1973, with wind farms increasingly being deployed around the world from the 1980s. Improvements to power electronics, blade design and manufacturing processes have enabled ever larger and more efficient turbines to be developed. At the end of 2016 there was an estimated 487GW installed capacity of wind energy with 28 countries having more than 1GW installed (GWEC, 2016a).

Since the early 1990s, wind farms have also been developed offshore, enabling exploitation of the stronger and more consistent wind resource over the sea. Although there are greater technical challenges and greater costs relating to installation, power export and operations and maintenance, the offshore industry has seen significant growth in the last decade, with 14.4GW installed worldwide by the end of 2016, primarily in Europe (GWEC, 2016b). The next development for the industry is likely to be floating offshore wind turbines, allowing access to deeper water and thus considerably increasing the economic viability of many more sites. Prototypes are already being tested, for example the Hywind project in Scotland (Statoil, 2017).

Wind energy is reaching the point of being cost-competitive with fossil fuel and nuclear generation, with the British Hornsea 2 and Moray offshore projects, for example, due to start generating in 2022/23 at £57.50 per MWh (RenewableUK, 2017a), and French onshore wind LCOE standing at €76 per MWh in late 2016 (RenewablesNow, 2016).

3.4.2 Constraints

Resource Constraints

The mean wind speed at turbine hub height will provide a basic assessment of the feasibility of a site to support wind generation. More detailed analysis should examine the consistency of wind speed, storm frequency, directionality, wind shear, turbulence and whether there is any regularity to the wind system, for example regular occurrences of stronger winds in the afternoon. The ideal site will have a consistent wind speed close to the rated velocity for the proposed turbine.

The resource may be assessed through measurement or modelling. Monitoring campaigns, using tower-mounted or ground-based monitoring equipment will provide the most accurate data for a site of interest. When using modelled data, the associated uncertainties should be considered. Coarse scale models may not accurately account for local features, especially in complex terrain and near to coastlines. Although useful to identify areas of interest, in many cases global and regional wind models will not provide sufficient data for a full resource quantification.

Technical Constraints

Any wind energy development, with the exception of small individual turbine installations, will require electrical grid access. The proximity and ease of access for a grid connection to the site will have an effect on the cost and feasibility of development. Larger farms will require a high voltage connection to the distribution grid and the access to grid infrastructure and any required development along the access route should be taken into account when siting a project. Offshore developments will face similar challenges to the wave and tidal industries with the routing of power export cables. Variations in regulatory regimes can dictate whether upfront connection costs are met by network operators or by the windfarm developer. Where the former is responsible the developer will pay for later use of the network, while where it is the latter this can represent a substantial addition to capital costs. The accompanying ICE report 'T1.1.2 Policy Issues' discusses these regulations in more detail.

Wind turbines are large structures, for example a typical 1.5MW turbine (e.g. Vestas V63) has a rotor diameter of 63.6m and is installed on a tower 60m high (Wind Power, 2017). To install and maintain these turbines requires site access for large vehicles and equipment. Remote locations with poor road infrastructure may prove difficult (and expensive) to access and hence may not be feasible for development. Offshore installations will require appropriate jack-up barges for pile-driving and turbine installation.

The risk of collapse of correctly installed modern wind turbines is considered low (Robinson et al., 2013). However, it remains best practice to ensure that they are installed a safe distance from infrastructure such as buildings, roads and railways. The UK Ministry of Housing, Communities and Local Government guidance recommends that turbines are sited no closer than the fall-over distance (hub height plus blade length) plus 10% to buildings (Ministry of Housing, Communities & Local Government, 2015) and the UK Highways Agency guidance is that turbines are no close than the lesser of the height plus 50m or the height plus 50% from the highway (Department for Transport, 2013). Similar limits are suggested for railways, waterways and power lines. There is no nationally-set minimum distance of separation between housing and wind turbines (Smith, L., 2016). Guidelines from the local authorities in the region of the site will define the limits for specific developments and local councils are able to enforce restrictions in their areas of influence.

Terrain should be suitable for the installation of turbines. Geographically unsuitable areas may include forests, marshland and areas prone to flooding, among others. While the presence of these geographical features does not preclude the installation of wind turbines, it is likely that they will add further complexity to the project and therefore add to the cost. Wind developments in the UK can be required to avoid damage and to make changes which enhance local environments as conditions of planning consent. In France wind farms must undergo a full planning process that ensures that they comply with noise guidelines and safety regulations. The geology of the site should be analysed to understand the geotechnical constraints on installation of the turbines. The soil and rock conditions will dictate the size and type of foundations required.

Environmental and Heritage Constraints

A full environmental impact assessment should be carried out for all but the smallest wind energy installation as part of the consenting process. Key impacts include noise from the turbines, the 'flicker' effect from rotating turbine blades, hydrological impacts on local water courses due to installation, and impacts on local flora and fauna. The risk to birds from wind turbine developments can be significant (e.g. Drewitt and Langston, 2006), and the presence of endangered species in the vicinity of a development may lead to refusal of planning consent.

Areas of cultural or historical significance, and designated sites such as national parks, will have restrictions on any allowed development, primarily due to the visual impact of turbines.

Social and Political Constraints

The installation of wind turbines is a subject of much debate between developers, authorities and local stakeholders. The impact (or perceived impact) of the development may elicit considerable opposition, and the site selection should take this into account. Planning regulations vary by locality and planning consent will usually be required for any permanent structures. However, there may be exceptions, for example, in the UK permission is not always required for small scale domestic turbines (Smith, 2016).

The accompanying ICE report 'T1.1.2 Policy Issues' discusses the regulations in more detail.

3.4.3 Methodology for quantifying resource

There are currently no published international standards for wind resource assessment, although aspects are covered in the IEC 61400 standards for wind turbines, including IEC 61400-1:2005+AMD1:2010 CSV: Wind turbines - Part 1: Design requirements (IEC, 2014) and IEC 61400-12-1:2017: Power performance measurements of electricity producing wind turbines (IEC, 2017). The development of a wind resource assessment document (IEC 61400-15: Assessment of Wind Resource, Energy Yield and Site Suitability input conditions for wind power plants) is ongoing, meanwhile the MEASNET (2016) guidance document on site-specific wind conditions is widely used.

The first stage of a wind resource assessment is the identification of potential sites with appropriate levels of resource, usually performed with global or regional wind models. Wind speed and power data are available from a range of sources at local, regional and global scales with varying levels of resolution and accuracy. Care should be taken when using modelled data to ensure that the level of uncertainty and inaccuracy are within acceptable parameters. An example of such output is shown in Figure 3-7.

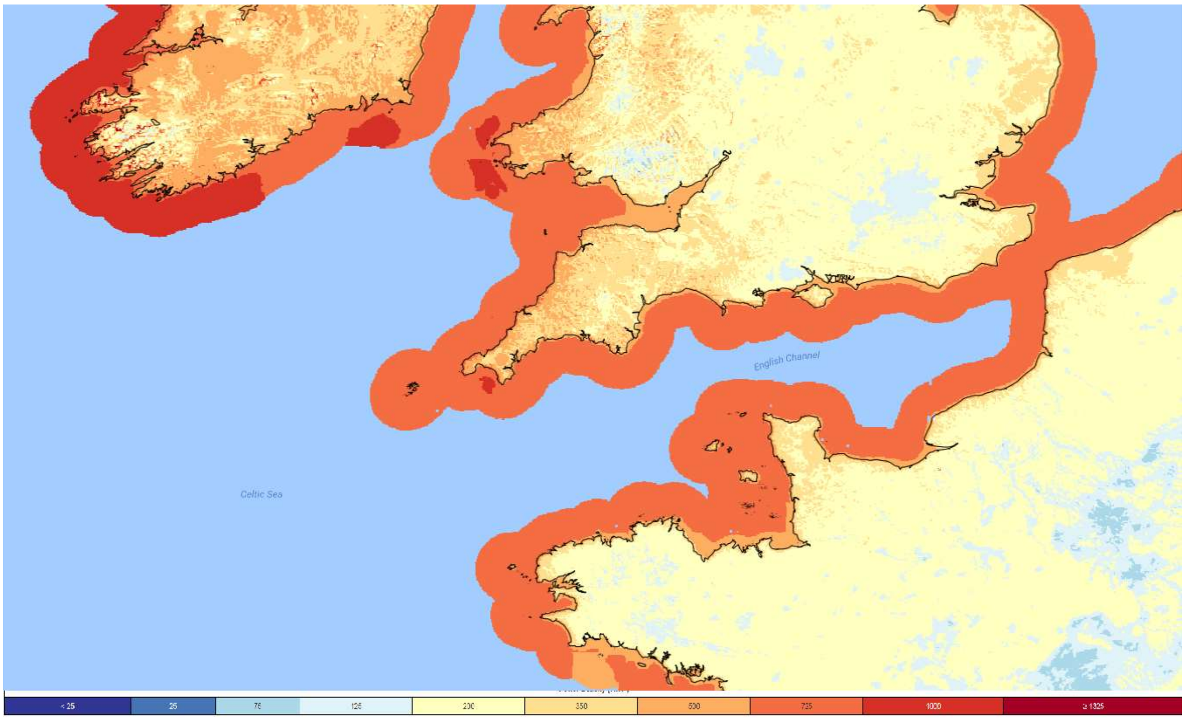

Figure 3-7: Aggregated mean wind power density (W/m^2) at 50m in the southern UK and northern France (source: Global Wind Atlas, 2017).

When sites of interest have been identified then detailed characterisation of the wind resource can be undertaken. *In-situ* wind data can be collected by installing a monitoring tower and/or using ground-based monitoring devices. To accurately understand the resource, wind measurements should be taken at a range of heights above the ground. Recording with anemometers requires installation of a mast (with likely planning constraints) with instruments attached. The simplest anemometers comprise a propeller or set of cups attached to an axle that can rotate in the wind. More technical instruments include hot wire, laser and ultrasonic designs with the advantage of being able to sample at much higher frequencies. Ground- or sea surface-based remote sensing systems such as SoDAR and LiDAR systems can be operated with little site preparation required. SoDAR and LiDAR systems work by emitting pulses of high frequency sound (SoDAR) or infra-red light (LiDAR) and measuring the signal reflected off particulates in the air. The Doppler shift in the reflected signal caused by movement of the air is measured to enable wind speed calculation. The advantage is that they can measure wind speeds throughout a vertical column above the device (and in the case of scanning LiDAR systems over an area) from its fixed location. It is recommended that a minimum of one year of wind data is collected prior to constructing a wind farm (Brower, 2012).

Ten minute-averaged wind speeds are commonly used in assessing the wind resource, although instantaneous data are also necessary to compute values of turbulence and maximum gusts. The wind data should be analysed to see the vertical profile of wind speed, particularly across the height of the rotor area. Analysis of the distribution of wind speed values allows assessment of the potential output of a wind farm over time. Statistical methods can be applied to the recorded or modelled wind data to estimate the extreme values (largest gusts) that could occur at a site. The largest values that could be expected to be exceeded on a 10-year, 50-year and 100year period should be calculated. The level of confidence in these extreme values will largely depend on the length of the measured dataset.

To extrapolate short-term site data to long-term predictions, a method known as 'measure, correlate, predict' (MCP) is applied. This correlates the short-term (~1 year) site measurement data with the equivalent record from a long-term permanent monitoring site which may be some distance from the proposed development. The correlation coefficients acquired are then used to make longer-term predictions for the site of interest.

3.4.4 Calculation of energy produced

A power curve, produced by turbine manufacturers, provides the relationship between wind speed and power output for a specific turbine. Generation is limited to wind speeds between a cut-in speed, below which there is insufficient energy to facilitate generation, and a cut-out speed, above which the turbine is shut down to prevent damage. The theoretical maximum energy that can be captured by a wind turbine due to Betz' Law is 59.3%; in practice, most modern wind turbines can capture between 25-40% of the wind energy in peak conditions (Hau, 2013). Using the power matrix provided by the turbine manufacturer, predicted wind speeds, and accounting for any mechanical and electrical losses, predictions can be made of the annual energy output.

3.5 Waste and Biomass

3.5.1 Overview

Conversion of waste or biomass into useful energy is a way of valorising materials that would otherwise have negligible or negative value. For the ICE project, three scenarios for valorisation have been considered:

- Local Direct Scenario - Direct conversion of locally-generated waste or biomass into electrical energy;
- Local Indirect Scenario - Conversion of locally-generated waste or biomass into intermediate fuels that can displace conventional fuels, including fuels used for electricity generation;
- Regional Indirect Scenario - Conversion of regionally-generated waste or biomass into intermediate fuels that can be transported and used for local electricity generation or other uses.

All of these scenarios also have the potential to generate heat in a combined heat and power (CHP) context, which can help reduce reliance on fossil fuel imports.

Local Direct Scenario

A grid-scale biomass generating plant is a thermal power station that uses waste products, for example domestic waste or by-products from other industrial processes, or bio-matter, such as wood or other energy crops, as fuel or to produce bio-gas, either of which can be combusted to generate heat. As in a typical thermal power station this is used to create pressurised steam that can drive a generator.

Several new processes, with smaller plant sizes, have been developed to cater for localised distributed generation from wastes. These typically burn the bio-gas directly in an internal combustion engine, to generate mechanical and thence electrical energy. The modular Flexibuster plant developed by SEaB is an example, shown in Figure 3-8.

Figure 3-8: The modular Flexibuster bio-gas plant (source: SEaB Energy, 2016)

Local Indirect Scenario

Certain waste or biomass materials can also be converted chemically into fuels. A long-established example of this is the production of 'wood alcohol' (methanol) from woody wastes. Methanol can be burned in conventional internal combustion engines to generate electricity, albeit with some minor engine modifications to ensure material compatibility with methanol. It can also be easily stored (as a liquid at ambient temperature and pressure) to provide useful energy storage.

A number of newer processes have been developed to convert different wastes into useful fuels. One example is the Plaxx process (Figure 3-9) which can convert mixed plastic wastes, for example from the domestic waste stream, into a diesel-like fuel. This can be burned in conventional diesel engines without requiring any engine modification. Plaxx has been engineered into a modular format to allow easy deployment.

Figure 3-9: The Plaxx RT7000 processor for converting mixed plastics into fuel (source: Recycling Today, 2017)

Regional Indirect Scenario

Some processes for valorisation of waste or biomass cannot realistically be engineered at small scale, and these typically need to draw on a regional resource base. Biomass can be converted into bio-diesel and large process plants to generate bio-diesel have been constructed across the world. Bio-diesel itself is not of interest to ICE since it is already integrated into the conventional fuels infrastructure.

However, valorisation of the glycerol waste stream coming from bio-diesel plants could be of interest. Glycerol can be burned in conventional diesel engines, with only minor engine modifications, to generate electricity with very low emissions. Some processing of raw glycerol is needed to create fuel-grade material, but this could in principle be performed in a relatively small refining plant (in the region of 10,000 T/year). This could be located in the local area, importing raw glycerol from a regional bio-diesel plant, to provide a renewable fuel that can be used for power generation or other uses.

3.5.2 Constraints

Resource Constraints

The availability of biomass resource and its cost, whether produced locally or imported, will be key in predicting whether a plant is viable in a remote community. An assessment of price risk for the fuel and continued fuel access over the lifetime of the project is a specific requirement specific for this technology. Taking account of the scenarios presented above, the following resource data are needed to assess possible resource constraints:

- Arisings of domestic, packaging, food, agricultural and mariculture/seaweed wastes that could be feedstock to a Flexibuster plant;
- Arisings of mixed plastic wastes (components of domestic and packaging waste streams) that could be feedstock to a Plaxx plant;
- Arisings of woody wastes that could be converted to methanol;
- Availability of raw glycerol from a regional bio-diesel plant.

Technical Constraints

Each of the waste and biomass processing options imposes its own requirements in terms of infrastructure. In terms of output/grid connectivity, there are two possibilities:

- The process plant generates electricity directly and is situated at a convenient point for grid connection;
- The process plant generates a fuel that can be burned in an existing diesel plant (for electricity generation or other uses) and requires a tankering service to distribute fuel to users.

In terms of feedstock supply, there are three possibilities:

- Domestic and commercial wastes can be collected and diverted using the existing refuse collection infrastructure, so no additional infrastructure is needed;
- Agricultural and mariculture/seaweed wastes would need dedicated services to consolidate and transport arisings to the process plant, potentially using facilities that are already available for agricultural and maricultural activities;
- Regionally sourced materials (e.g. raw glycerol) would require infrastructure to transport them to the process plant, including road transport, port handling and shipping services.

3.5.3 Methodology for quantifying resource

Given the range of options potentially available, a two-stage methodology is appropriate:

1. Identification of the scale of arisings available or potentially available, in the categories listed above. This will allow the most attractive process options to be identified;

2. More detailed arisings data can then be collected, including seasonality, trends, risks etc.

3.6 Energy Storage

The intrinsic variability of some renewable energy technologies means that the periods of peak generation are frequently unaligned with the times of peak demand. Without a means of storing the energy generated there is a risk that generators will need to be curtailed or the energy dumped. As the renewable resource costs nothing (with the exception of biomass) it is financially beneficial to generate whenever possible. This can be addressed through the use of energy storage solutions.

Energy storage technologies enable load levelling between the periods of generation and high demand, allowing renewable energy generated at off-peak times to be used on the grid at peak times and reducing the need to curtail generation. Energy storage can also be used to meet spikes in demand, where demand increases beyond current generation. Using energy from storage reserves enables this demand to be met without the need to cold start an extra power station. The response from energy storage plants is typically very fast; sudden or unexpected demand spikes can be met quickly, minimising any disruption to the grid (Denholm, 2010).

The main technologies for energy storage are:

- **Mechanical storage**: These systems convert the electrical energy into mechanical potential energy, for example, pumped hydro electrical pants, compressed air systems, or flywheels.
- **Electrical storage**: Capacitor based systems store electrical charge and can be used to hold electrical energy to be used at a later time.
- **Electrochemical storage:** Battery systems store electrical energy as chemical potential energy. There are many different types of chemical battery which can be utilised to hold energy, with the most common being lithium-ion. A full overview of battery storage options can be found in IRENA (2015).
- **Hydrogen storage**: These systems use electrical energy to generate hydrogen from water. The hydrogen can be stored long-term, transported to another location, or used when required in fuel cells or combustion engines.

4. Applicability to Countries of Interest

4.1 France

Electricity generation in France is dominated by nuclear power, which accounted for 72.3% of electricity generation in France in 2016, with renewables and fossil fuels producing 19.2% and 8.5% respectively (RTE Open Data, 2018). A series of interconnectors between France and its European neighbours enables other countries to access the large nuclear baseload generated in France. Similarly, France can consume excess power from the rest of Europe, particularly if there is surplus wind generation in Northern Europe or Spain (IEA, 2016).

Electricity tariffs are regulated by the French government through the Commission de Regulation de L'Energie (CRE). All consumers have access to the same tariffs, including those on remote islands and overseas departments. The extra cost to generate and distribute energy to remote parts of the country is subsidised by a levy on energy bills.

France benefits from rich and diverse renewable resources. Wind speeds along the Atlantic coastline and in mountain foothills are well suited for wind energy generation and there is an excellent solar resource, particularly in the south. The north and west coasts provide opportunities to exploit the emerging wave and tidal technologies, as evidenced by the growing number of demonstration projects in the planning and development stages (Ocean Energy Systems, 2016).

4.2 UK

Electricity generation in the UK is more diverse than in France, with 54.5% generation in 2016 from fossil fuels (42% natural gas, 9% coal), 21% from nuclear and 24.5% from renewables (Energy UK, 2018). From a renewables perspective, the UK has a similarly diverse range of resources, including one of the highest global tidal energy resource potentials. The UK is a global leader in offshore wind with 5.36GW of operational capacity in June 2017, and a further 15.94GW with planning permission or under construction (RenewableUK, 2017b). Figure 4-1 shows locations of UK renewable energy generation.

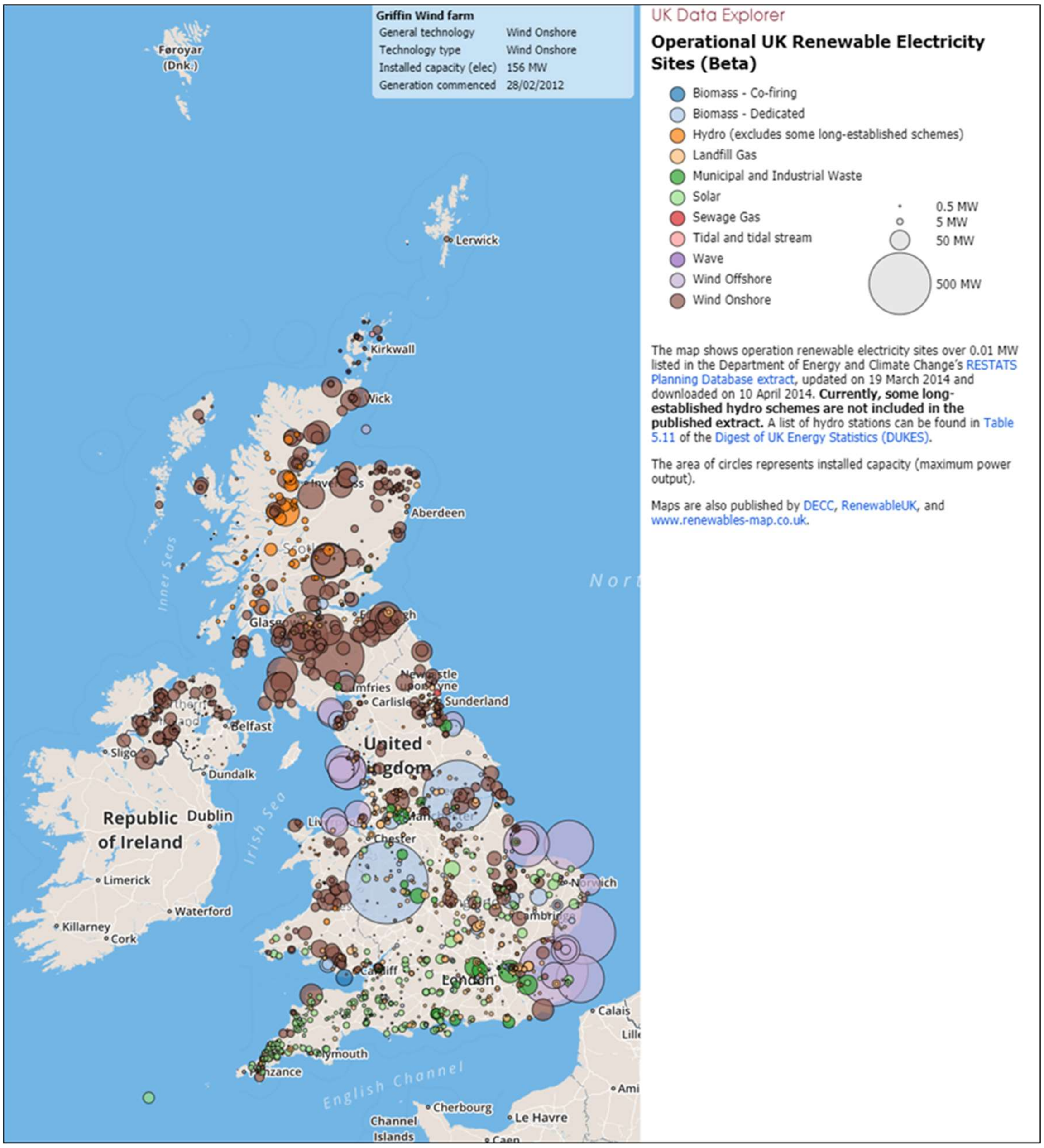

Figure 4-1: Map of UK renewable energy installations in 2014 (source: UK Data Explorer, 2014).

5. Applicability to Focal Sites

5.1 Ushant / Ouessant

Ushant is an island off the North West coast of France (Figure 5-1) with approximately 850 residents living in 488 homes in 2009 (Sogreah Consultants, 2009). The main industry is tourism which can temporarily expand the local population with over 100,000 visitors travelling to the island each year, primarily in the summer season. The island is currently powered by four diesel generators supplying up to 4.1MW. During 2015 a Sabella D10 1.1MW tidal turbine (initially limited to 250kW) supplied power to the island (Paboeuf et al., 2016). It is planned to return to operation in the spring of 2018 at full capacity. In 2017 a 50kW solar array was installed on the island sports hall building, and further solar generation is planned (SDEF, 2018). The island aims to have 70% of electrical generation from renewable technologies by 2020 and 100% renewable generation by 2030, stated in a meeting with the mayor of Ushant, local officials and the ICE project team (Palluel, D. personal communication, November 2017). Due to the environmental protections in place on the island and the reliance on the summer tourist industry, it is likely that some renewable technologies may not be suitable for widespread deployment on or around the island, however, solar, wind, biomass and further tidal technologies could all be explored to increase the level of renewable generation and to diversify the island's energy mix. Heating technologies and energy efficiency may also be useful contributors to improving energy security on the island.

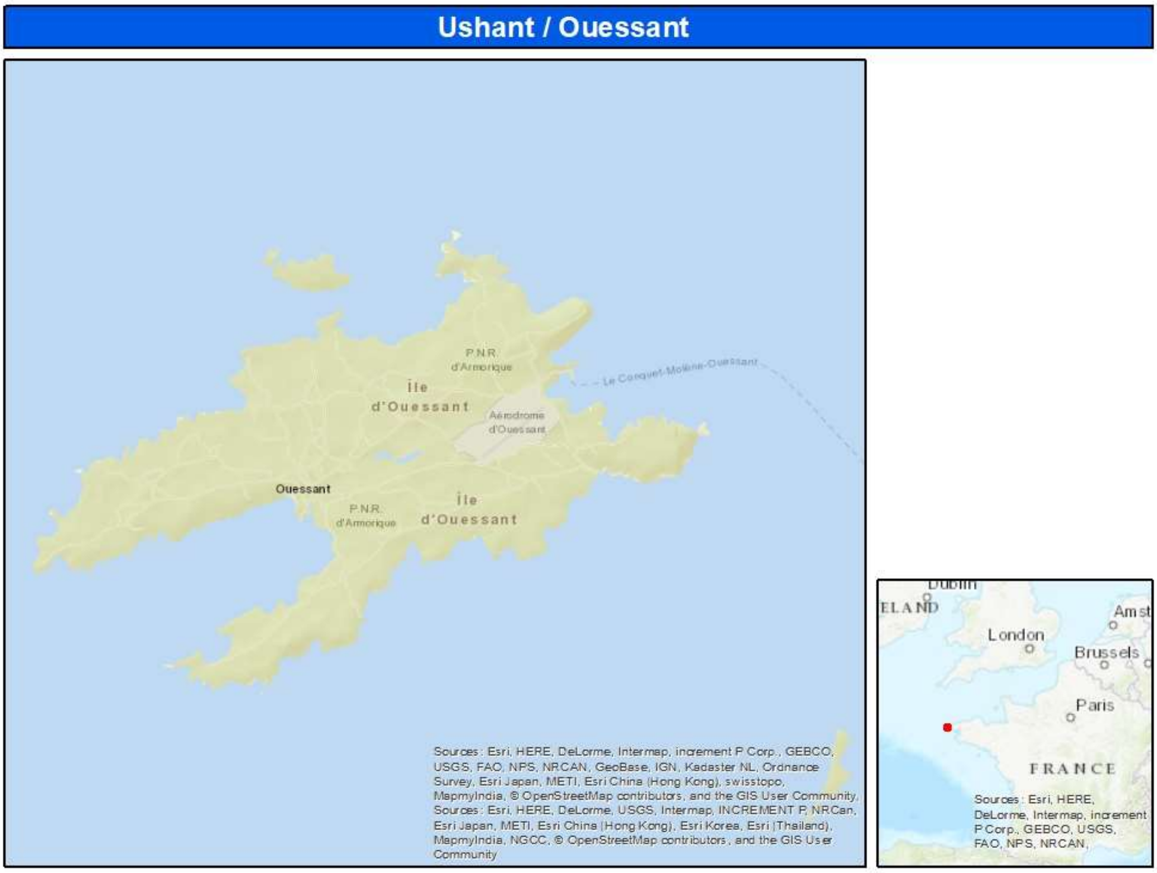

Figure 5-1: The island of Ushant and it location off the Northwest coast of France.

5.2 University of East Anglia Campus

The University of East Anglia is a campus university situated close to Norwich in Norfolk, in the East of the UK (Figure 5-2). The university has approximately 20,000 students and 4,000 staff, of which approximately 4,500 are resident on the campus for more than half the year. The campus has 250kW of solar generation capacity installed on building rooftops, as well as three CHP units providing 5.7MW electrical generation and 5.9MW of heat. The campus plan is for 1MW of solar to be installed by 2020, and there has been research into installing a 1MW biomass generator.

The campus is not coastal and thus there is no marine resource potential, however additional solar and biomass generation will be considered, plus the potential for wind energy.

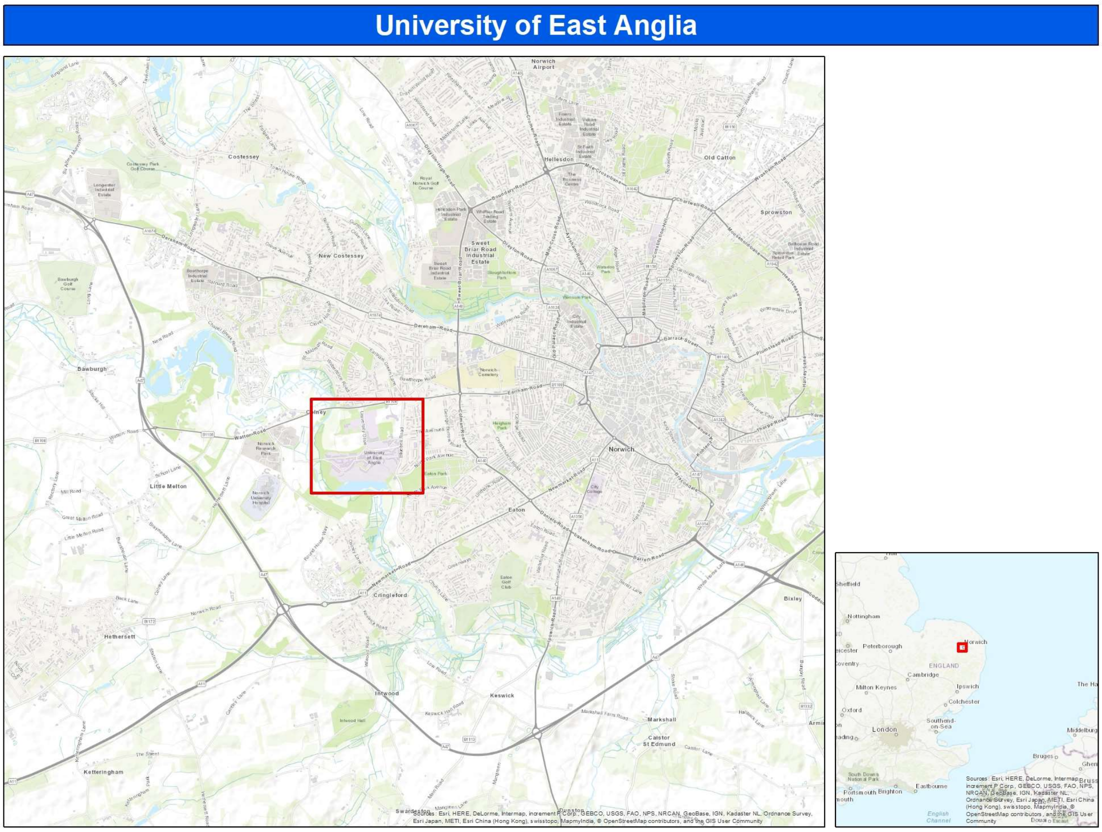

Figure 5-2: The location of the University of East Anglia campus in Norwich, in the East of the UK.

6. Conclusions

This document has reviewed the available renewable technologies with a view to further site specific assessment of individual potential to be investigated on Ushant and at the UEA Campus. This document has identified the key constraints relating to the resource, technology, environment and regulation. As an exposed island, Ushant is well-placed to benefit from solar, tidal, wind and biomass energy. While wave energy may be an option for the future, it is not sufficiently commercially developed to be considered as part of the energy mix at this time. On the UEA Campus, solar and biomass technologies are likely to be the most effective, with the possibility of wind energy if planning constraints permit and should the university be interested in this after consideration of any local concerns. Full assessments for these technologies for both sites will be presented in ICE report T1.4. However, with the exception of biomass all these resources are intermittent, with varying levels of predictability. Energy storage solutions are thus likely to play an important role in smoothing the power supply and ensuring resilience, though this is more of a concern with the off-grid island of Ushant. These issues will be addressed in detail in ICE report T1.2.

References

Amillo, A. G., et al., 2014. A new database of global and direct solar radiation using the eastern meteosat satellite, models and validation. *Remote Sensing*, 6(9) pp8165-8189.

Atlantis Resources Ltd, 2018a. *SeaGen-S 2MW*. [online] Available at: https://www.atlantisresourcesltd.com/wp/wp-content/uploads/2016/08/SeaGen-Brochure.pdf [Accessed 24/1/18].

Atlantis Resources Ltd, 2018b. *MeyGen*. [online] Available at: https://www.atlantisresourcesltd.com/projects/meygen/ [Accessed 24/1/18].

Baig, H., Heasman, K.C. & Mallick, T.K., 2012. Non-uniform illumination in concentrating solar cells. *Renewable and Sustainable Energy Reviews*, 16, pp5890-5909.

BEIS, 2016. *Electricity Generation Costs*. Department for Business, Energy and Industrial Strategy, London, UK.

Benoit, M., Marcos, F. & Becq, F., 1996. Development of a third generation shallow-water wave model with unstructured spatial meshing. *Proc. 25th International Conference on Coastal Engineering*, 2nd-6th Sept 1996, Orlando, Florida, USA.

Booij, N., Ris, R.C. & Holthuijsen, L.H., 1999. A third-generation wave model for coastal regions - 1. Model description and validation. *Journal of Geophysical Research – Oceans*, 104 pp7649-7666.

Brower, M., 2012. *Wind resource assessment: a practical guide to developing a wind project*. John Wiley & Sons, Hoboken, New Jersey.

Charlier, R.H. & Menanteau, L., 1997. The saga of tide mills. *Renewable and Sustainable Energy Reviews*, 1(3), pp171-207.

Codiga, D.L., 2011. *Unified Tidal Analysis and Prediction Using the UTide Matlab Functions*. Technical Report 2011-01. Graduate School of Oceanography, University of Rhode Island, RI, USA.

Connor, P. M., Xie, L., Lowes, R., Britton, J. & Richardson, T., 2015. The development of renewable heating policy in the United Kingdom. *Renewable Energy,* 75, pp733-744.

Copping, A., Sather, N., Hanna, L., Whiting, J., Zydlewski, G., Staines, G., Gill, A., Hutchison, I., O'Hagan, A., Simas, T., Bald, J., Sparling C., Wood, J., & Masden, E., 2016. *Annex IV 2016 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World*. IEA OES Annex IV.

DECC, 2010. *Severn Tidal Power Feasibility Study Conclusions and Summary Report*. HM Government Department of Energy and Climate Change, London, UK.

Denholm, P., Ela, E., Kirby, B. & Milligan, M., 2010. *The Role of Energy Storage with Renewable Electricity Generation. Technical Report NREL/TP-6A2-47187*. National Renewable Energy Laboratory, Golden, Colorado, USA.

Department for Transport, 2013. *The Strategic Road Network and the Delivery of Sustainable Development*. Department for Transport, London, UK.

Drewitt, A.L. & Langston, R.H.W., 2006. Assessing the impacts of wind farms on birds. *IBIS International Journal of Avian Science*, 148(s1), pp29-42.

EMEC, 2017a. *Tidal developers*. [online] Available at: http://www.emec.org.uk/marine-energy/tidal-developers/ [Accessed 1/12/17].

EMEC, 2017b. *Wave developers*. [online] Available at: http://www.emec.org.uk/marine-energy/wave-developers/ [Accessed 25/1/18].

EMEC, 2018a. *Tidal clients*. [online] Available at: http://www.emec.org.uk/about-us/our-tidal-clients/ [Accessed 24/1/18].

EMEC, 2018b. *Wave clients*. [online] Available at: http://www.emec.org.uk/about-us/wave-clients/ [Accessed 25/1/18].

Energy Networks Association, 2014. *Distributed Generation Connection Guide*. Energy Networks Association, London, UK.

Energy UK, 2018. *Electricity generation*. [online] Available at: https://www.energy-uk.org.uk/energy-industry/electricity-generation.html [Accessed 25/1/16].

FaBTest, 2015. *Pioneering wave technology device launched in Falmouth heads for the US*. [online] Available at: http://fabtest.com/sites/default/files/FaBTest%20success%2023%203%2015.pdf [Accessed 25/1/18].

Global Wind Atlas, 2017. *Global Wind Atlas*. [online] Available at: https://globalwindatlas.info/ [Accessed 25/1/18].

GWEC, 2016a. *Global Wind Report: Annual Market Update 2016*. Global Wind Energy Council, Brussels, Belgium.

GWEC, 2016b. *Offshore Wind*. [online] Available at: http://www.gwec.net/wp-content/uploads/2017/05/Global-Offshore-2016-and-Beyond.pdf [Accessed 19/12/17].

Hau, E., 2013. *Wind turbines: fundamentals, technologies, application, economics*. Springer, Berlin.

Heath, J., Jensen, R. P., Weller, S., Hardwick, J., Roberts, J., Johanning, L., 2017. Applicability of geotechnical approaches and constitutive models for foundation analysis of marine renewable energy arrays. *Renewable and Sustainable Energy Reviews*, 72, pp191-204.

HEFCE, 2010. *Carbon reduction target and strategy for higher education in England*. Higher Education Funding Council for England, Bristol, UK.

Hendry, C., 2016. *The Role of Tidal Lagoons*. [online] Available at: https://hendryreview.files.wordpress.com/2016/08/hendry-review-final-report-english-version.pdf [Accessed 24/1/18].

Hernandez, R.R., Easter, S.B., Murphy-Mariscal, M.L., Maestre, F.T., Tavassoli, M., Allen, E.B., Barrows, C.W., Belnap, J., Ochoa-Hueso, R., Ravi, S. & Allen, M.F., 2014. Environmental impacts of utility-scale solar energy. *Renewable and Sustainable Energy Reviews*, 29, pp766-779.

Huld, T., Muller, R. & Gambardella, A., 2012. A new solar radiation database for estimating PV performance in Europe and Africa. *Solar Energy*, 86, pp1803-1815.

IEA, 2016. *Large scale electricity interconnection: Technology and prospects for cross-regional networks*. International Energy Agency, Paris, France.

IEC, 2014. *IEC 61400-1:2005+AMD1:2010 CSV Consolidated version. Wind turbines - Part 1: Design requirements*. International Electrotechnical Commission.

IEC, 2015a. *IEC TS 62600-201:2015 Marine energy - Wave, tidal and other water current converters - Part 201: Tidal energy resource assessment and characterization*. International Electrotechnical Commission.

IEC, 2015b. *IEC TS 62600-101:2015 Marine energy - Wave, tidal and other water current converters - Part 101: Wave energy resource assessment and characterization*. International Electrotechnical Commission.

IEC, 2017. *IEC 61400-12-1:2017 Wind energy generation systems - Part 12-1: Power performance measurements of electricity producing wind turbines.* International Electrotechnical Commission.

Inger, R., Attrill, M.J., Bearhop, S., Broderick, A.C., Grecian, W.C., Hodgson, D.J., Mills, C., Sheehan, C., Votier, S.C., Witt, M.J. & Godley, B.J., 2009. Marine renewable energy: potential benefits to biodiversity? An urgent call for research. *Journal of Applied Ecology*, 46(6), pp1145-1153.

Ingram, D., Smith, G.H., Bittencourt-Ferreira, C. & Smith, H. (eds.), 2011. *Protocols for the Equitable Assessment of Marine Energy Converters*. University of Edinburgh, School of Engineering Publishers, Edinburgh, UK.

IRENA, 2015. *Battery Storage for Renewables: Market Status and Technology Outlook*. International Renewable Energy Agency, Abu Dhabi, UAE.

IRENA, 2016. *The Power to Change: Solar and Wind Cost Reduction Potential to 2025*. International Renewable Energy Agency, Abu Dhabi, UAE.

Kempener, R. & Neumann, F., 2014. *Tidal Energy Technology Brief*. International Renewable Energy Agency, Abu Dhabi, UAE.

Legrand, C., 2009. *Assessment of Tidal Energy Resource*. BSI, London, UK.

MEASNET, 2016. *Evaluation of site-specific wind conditions, version 2*. [online] Available at: http://www.measnet.com/wp-content/uploads/2016/05/Measnet_SiteAssessment_V2.0.pdf [Accessed 25/1/16].

Mermoud, A. & Wittmer, B., 2014. *PVsyst User's Manual*. [online] Available at: http://www.pvsyst.com/images/pdf/PVsyst_Tutorials.pdf [Accessed 19/12/17].

MHI Vestas, 2018. *MHI Vestas Offshore Wind leads offshore wind debate at AWEA 2016*. [online] Available at: http://www.mhivestasoffshore.com/mhi-vestas-offshore-wind-leads-offshore-wind-debate-awea-2016/ [Accessed 25/1/18].

Millar, D.L., Smith, H.C.M. & Reeve, D.E., 2007. Modelling analysis of the sensitivity of shoreline change to a wave farm. *Ocean Engineering*, 34, pp884-901.

Ministry of Housing, Communities & Local Government, 2015. *Planning for renewable and low carbon energy: introduction*. [online] Available at: https://www.gov.uk/guidance/renewable-and-low-carbon-energy#wind-turbines [Accessed 25/1/18].

Nova Innovation, 2018. *Shetland Tidal Array*. [online] Available at: https://www.novainnovation.com/tidal-array [Accessed 24/1/17.

Ocean Energy Forum, 2016. *Ocean Energy Strategic Roadmap: Building Ocean Energy for Europe*. Ocean Energy Forum, Brussels, Belgium.

Ocean Energy Systems, 2016. *Annual Report*. [online] Available at: https://report2016.ocean-energy-systems.org/ [Accessed 25/1/18].

Open Ocean, 2015. *Sabella Connects the First French Tidal Turbine*. [online] Available at: http://www.openocean.fr/en/news/2015/09/22/sabella-connects-the-first-french-tidal-turbine/ [Accessed 24/1/18].

OpenHydro, 2018. *Projects*. [online] Available at: http://www.openhydro.com/Projects [Accessed 24/1/18].

Paboeuf, S., Sun, P.Y.K., Macadré, L.-M. & and Malgorn, G., 2016. Power Performance Assessment of the Tidal Turbine Sabella D10 Following IEC62600-200. *Proc. 35th International Conference on Ocean, Offshore and Arctic Engineering*, American Society of Mechanical Engineers, Busan, South Korea, June 19–24, 2016.

Page, J.K., Albuisson, M. & Wald, L., 2001. The European solar radiation atlas: a valuable digital tool. *Solar Energy*, 71(1), pp81-83.

Parish, D. and Hardwick, J. 2011, updated 2016 “Falmouth Bay Test Site: Description of site Characteristics and Eligible Test Installations”. Technical Report, FaBTest

Pawel, I., 2014. “The Cost of Storage – How to Calculate the Levelized Cost of Stored Energy (LCOE) and Applications to Renewable Energy Generation. *Energy Procedi*a, 46, pp68-77.

Pico OWC, 2006. *OWC Pico Power Plant*. [online] Available at: http://www.pico-owc.net/gallery.php?cat=42&id=226&wnsid=8e59c45a7d6d10b995906dddfa282af3 [Accessed 25/1/18].

Pitt, E., 2009. *Assessment of Wave Energy Resource*. BSI, London, UK.

Quietrevolution, n.d. *The qr6 Vertical Axis Wind Turbine*. [online] Available at: https://www.quietrevolution.com/ [Accessed 25/1/18].

Recycling Today, 2017. *Recycling Technologies awarded for Plaxx oil*. [online] Accessed 25/1/18].

Ren, L., Nash, S. & Hartnett, M., 2015. Observation and modeling of tide- and wind-induced surface currents in Galway Bay. *Water Science and Engineering*, 8(4), pp345-352.

RenewablesNow, 2016. *French wind power costs EUR 76 per MWh – study*. [online] Available at: https://renewablesnow.com/news/french-wind-power-costs-eur-76-per-mwh-study-550594/ [Accessed 19/12/17].

RenewableUK, 2017a. *Offshore wind prices tumble in record-breaking auction results – cheaper than nuclear and gas*. [online] Available at: http://www.renewableuk.com/news/362971/Offshore-wind-prices-tumble-in-record-breaking-auction-results--cheaper-than-nuclear-and-gas-.htm [Accessed 19/12/17].

RenewableUK, 2017b. *Offshore Wind Project Timelines*. [online] Available at: http://c.ymcdn.com/sites/www.renewableuk.com/resource/resmgr/publications/RUK17_Offshore_Timeline_v4.pdf [Accessed 26/1/18].

Retiere, C., 1994. Tidal power and the aquatic environment of La Rance. *Biological Journal of the Linnean Society*, 51, pp25-36.

Robinson, C.M.E., Paramasivam, E.S., Taylor, E.A., Morrison, A.J.T. & Sanderson, E.D., 2013. *Study and development of a methodology for the estimation of the risk and harm to persons from wind turbines*. Health and Safety Executive, UK.

RTE Open Data, 2018. *Production nationale annuelle par filière (2012 à 2016)*. [online] Available at: https://opendata.rte-france.com/explore/dataset/prod_par_filiere/?sort=-annee [Accessed 25/1/18].

SDEF, 2018. *Future solar power plants in Ushant driven by SDEF*. SDEF.

SEaB Energy, 2016. *Flexibuster*. [online] Available at: https://seabenergy.com/products/mb400/ [Accessed 25/1/18].

Siemens, 2018. *Onshore Geared Wind Turbine SWT-2.3-101*. [online] Available at: https://www.siemens.com/global/en/home/markets/wind/turbines-and-services/swt-2-3-101.html [Accessed 25/1/18].

Skoplaki, E. & Palyvos, J.A., 2009. *On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations*. Solar Energy, 83, pp614-624.

Smith, L., 2016. *Planning for onshore wind, Briefing Paper Number 04370*. House of Commons Library, London, UK.

Sogreah Consultants, 2009. *Etude de faisabilite d’une operation de maitrise de l’energie et de developpement des energies renouvelables sur les iles de Molene at Ouessent*. Sogreah, Lyon, France.

SolarGIS, 2018. *Solar resource maps of World*. [online] Available at: https://solargis.com/products/maps-and-gis-data/download/world [Accessed 26/1/18].

Statoil, 2017. *World's first floating wind farm has started production*. [online] Available at: https://www.statoil.com/en/news/worlds-first-floating-wind-farm-started-production.html [Accessed 19/12/17].

Surfers Against Sewage, 2009. *Guidance on environmental impact assessment of offshore renewable energy development on surfing resources and recreation*. Surfers Against Sewage, St Agnes, UK.

Šúri, M. & Hofierka, J., 2004. A New GIS-based Solar Radiation Model and Its Application to Photovoltaic Assessments. *Transactions in GIS*, 8(2), pp175-190.

Tidal Lagoon Power, 2018. *Planning*. [online] Available at: http://www.tidallagoonpower.com/projects/swansea-bay/planning/ [Accessed 27/1/18].

Tsoutsos, T., Frantzeskaki, N. & Gekas, V., 2005. Environmental impacts from the solar energy technologies. *Energy Policy*, 33(3), pp289-296.

UK Data Explorer, 2014. *Operational UK Renewable Electricity Sites*. [online] Available at: http://ukdataexplorer.com/renewables/ [Accessed 26/1/18].

Wang, S. & Wang, S., 2015. Impacts of wind energy on environment: A review. *Renewable and Sustainable Energy Reviews*, 49, pp.437-443.

Warren, I.R. & Bach, H.K., 1992. MIKE 21: a modelling system for estuaries, coastal waters and seas. *Environmental Software*, 7, pp229-240.

Wavestar, n.d. *Projects*. [online] Available at: http://wavestarenergy.com/projects [Accessed 25/1/18].

Wind Power, *The*, 2017. *V39/500 (Vestas)*. [online] Available at: https://www.thewindpower.net/scripts/fpdf181/turbine.php?id=169 [Accessed 19/12/17].

Wyatt, L.R., Green, J.J. & Middleditch, A., 2011. HF radar data quality requirements for wave measurement. *Coastal Engineering*, 58, pp327-336.

Zhou, Z., Scuiller, F., Charpentier, J.F., Benbouzid, M. & Tang, T., 2014. An up-to-date review of large marine tidal current turbine technologies. *Proc. International Power Electronics and Application Conference and Exposition*, Shanghai, China, 5-8 Nov 2014.