Viability of Airborne Wind Energy in the United Kingdom

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ABSTRACT

To meet the worldwide requirements of carbon emission reduction, the European Council has set the UK a 15% energy target to come from renewable energy by 2020. The biggest renewable energy sources in the UK are bioenergy, wind, solar and hydro. The UK is located in prime geography, considered to be the best

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in Europe, for harvesting and over the last three decades, the number of wind farms has increased greatly. However, the interaction of wind speed and structural strength have limited the height of platform-based wind turbines to a maximum height of around 100 m.

Airborne Wind Energy (AWE) systems enable the extraction of more energy from the wind at elevated altitudes beyond 150 meters using a device termed a kite. A method is required to determine suitable locations for AWE system implementation. In this work, a regional feasibility study is conducted to establish an ideal suitable location to implement the AWE system. Extensive work has been carried out to assess the electricity costs and energy savings, area availability as well as regional airborne wind energy power densities at different regions within the UK. A standardised method has been developed to assess the viability of AWE in various geographical locations. It was found that Scotland was the most suitable location for the implementation of an AWE systems due to the high wind power density in this region and existing high costs of electricity thus greater potentials for energy cost savings.

Keywords: airborne wind energy, wind turbine

1 INTRODUCTION

To meet the carbon emissions reduction targets that set by the European Council and UK government, the use of renewable energy has been increased greatly over the last three decades in the UK. In 2016, a total of 17.3 million tonnes of oil equivalent of primary energy use was from renewable energy sources. Of these total renewable energy usage, bioenergy accounted for 72%, followed by 19% for wind, 5.5% for solar and 2.7% for hydro [1]. In 2016, 83.2 TWh electricity was generated from renewable energy sources and accounted for 24.5% of electricity generated in the UK [1]. Of the 83.2 TWh electricity, 37.4 TWh was from both the onshore and offshore wind farms [1]. Wind power generation increased since 1990s and by mid-June 2017, there are 7,613

wind turbines with a total installed capacity of over 15.6 gigawatts;
10,275 megawatts of onshore capacity and 5,356 megawatts of offshore capacity [2]. These made the UK as the world's sixth largest producer of wind power and leading country for offshore wind energy [2].

The forthcoming of wind farms installation growth could be disrupted, due to the UK government intends to close the Renewables Obligation to new onshore wind power projects on 1 April 2016 [3].

The cost of wind energy generation has reduced greatly since 1980. In recent years, the cost reductions have also started to slow down and in the near future this could almost come to a standstill [4]. The wind turbine costs have even risen between the years 2001–2009. This is a result of high demands for wind energy systems; rising cost of raw materials as well as some of the cost growth is down to refining the newer wind power systems and supply chain restrictions [5].

Despite of this, exploiting the energy from the wind has recently started to mature with technology to be now regarded as a competitive energy resource within the UK. Although it was essential for wind energy systems to improve in numerous key areas before it was regarded as a worthwhile supply of energy. The improvements comprised of investigating and creating materials such as carbon-fibre blade designs, forming and improving efficient wind energy conversion technologies, and enhancing wind energy reliability at the same time as decreasing maintenance expenses. It has become challenging to enhance the cost-efficiency of wind energy, unless there is an innovative jump in the technological method used to exploit the power in the wind.

One novel approach to make a fresh innovative jump in wind energy technology is to examine and utilise the winds at elevated altitudes (beyond 150m), where noticeably extra power is obtainable. It has already been established that ground-based wind energy is competitive in contrast to other energy resources when the cost of energy is excessive. Therefore, if AWE technology could enhance to the stage where it is competitive as well as cost-efficient at every energy cost, then the UK would significantly benefit.

AWE offers various remarkable qualities that may possibly guide the UK to a potential resolution for energy problems encountered. AWE is a way to have energy on request at isolated locations, as it lacks the dependency on an energy supply cable. AWE is accessible virtually in all places around the globe. In addition, the prospective for energy obtainability as well as the uniformity at which this energy can be extracted is extensive. It is also promising that the constant advancement in wind energy technology may drive AWE into being completely competitive with fossil fuels and hence this source of energy possibly will assist the UK government in meeting its objectives and targets.

Given that the UK government has set overarching renewable goals and the aspiration to improve renewable energy is so important for the economy, environment and energy security of the country, this paper investigates the feasibility of AWE as an alternative renewable energy generation option for satisfying the UK government renewable energy targets and enhancing energy security as well as protecting the environment.

The key aim of this study is to raise awareness of AWE technologies and the prospective benefits that AWE systems can offer the UK. The objective of this investigation is to perform a feasibility study to assess a suitable region within the United Kingdom to effectively implement an AWE system.

In this study, three criteria were used to assess a suitable region. The three criteria were (1) electricity costs and energy savings; (2) available area and (3) regional AWE power densities at different regions. In this paper, firstly the electricity costs and energy savings were assessed by sourcing the data from EDF Energy website and DECC document. The data of either electricity costs or energy savings was normalised on a scale out of 10, with the largest awarded a mark of 10. Secondly the area available was assessed by analysing the regional population densities and airline traffic densities. The data of either population densities or airline traffic densities were normalised on a scale out of 10, with the lowest awarded a mark of 10. Finally the regional airborne AWE densities at different regions were obtained by overlaying the international wind power density map to a Google Earth map of the UK regions, the information obtained was normalised on a scale out of 10, with the biggest power density region awarded a mark of 10.

2 HIGH ALTITUDE WIND RESOURCE THEORITICAL ANALYSIS

AWE systems and wind turbines are designed for capturing wind energy. There are numerous parameters affecting the wind energy captured - wind speed, air density, vertical wind speed variation, atmospheric boundary layer, capacity factor, global wind patterns and jet streams.

2.1 Power in the Wind

The vital part in harnessing the wind's power is to first understand the wind resource and the amount of energy it can present. The wind power varies with the density of air, the outlined surface area being considered and the wind velocity. The power obtainable from the wind P_{wind} (W) can be expressed as [6]:

$$P_{wind} = \frac{1}{2}\rho A v^3 \tag{1}$$

Where A (m^2) is the cross-sectional surface area of the wind being considered, v (m/s) is the wind velocity, and ρ (kg/m^3) is the density of the moving air. From equation (1), it can be seen that when contrasting wind power at ground-level against wind gathering at elevated altitudes, the two significant aspects are wind speed and density. Wind speed has a tendency to rise with altitude, whereas air density reduces with increased altitude.

Equation (1) demonstrates that wind velocity is particularly essential to the quantity of power generated, as power is a function of the wind speed cubed. It can be seen that eight times more power is produced if the wind velocity is doubled ($2^3 = 8$). Therefore, the huge reliance on wind velocity is the key driving aspect for researchers since they try to enlarge the production of wind power by questing to exploit the airstreams at elevated altitudes [6].

Wind energy production is considered high altitude at elevated heights; beyond what can typically be collected by a traditional ground-built wind turbine. Generally, ground-based wind turbines have a range between 100 to 150 m in tower height, therefore AWE can be considered at heights from above 150 m to approximately 16 km.

The density of air falls from 1.225 kg/m^3 at sea level to 0.413 kg/m^3 at an altitude of 10 km [7]. This suggests that the density at 10 km altitude is one third of the density at sea level; hence, the energy generated at a specified wind velocity at sea level would be 3 times more than the energy generated by an identical wind turbine situated at a 10 km altitude. Furthermore, it also seems that at reduced heights the impact of density variations with altitude is moderately little, given that the density falls to 1.111 kg/m^3 at an altitude of 1 km; which is equivalent to 9.1% below the sea level density. Hence, it appears that the change in air density is almost linear with height.

2.2 Wind Speed Variations

The variation and frequency of wind velocities at a specified location over the course of a year can be expressed by a probability density function. Previous research over the years has revealed that the Weibull distribution function $f(v)$ is very suited to fitting wind speed frequency distributions [8]. The distribution is established from two parameters (1) k, the shape factor that portrays the form of the distribution and (2) c, the scale factor that represents the wind velocity. The Weibull distribution can be expressed as [6]:

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left(-\left(\frac{v}{c}\right)^{k}\right) \tag{2}$$

Where v (m/s) is the wind speed

In addition to this, the cumulative probability distribution $F(v)$ is the probability of the wind speed not exceeding v and can be expressed as [6]:

$$F(v) = 1 - \exp\left(-\left(\frac{v}{c} \right)^k \right) \tag{3}$$

A special case of the Weibull function is the Rayleigh distribution where the shape factor k is assumed to be 2. Therefore, only the mean wind velocity $\bar{v}$ (m/s) is required when using the Rayleigh distribution. The Rayleigh distribution can be expressed as [6]:

$$f(v) = \frac{\pi}{2}\left(\frac{v}{\bar{v}^2} \right)\exp\left(-\frac{\pi}{4}\left(\frac{v}{\bar{v}} \right)^2 \right) \tag{4}$$

As with the Weibull distribution function, the cumulative distribution function $F(v)$ can be expressed as [6]:

$$F(v) = 1 - \exp\left(-\frac{\pi}{4}\left(\frac{v}{\bar{v}} \right)^2 \right) \tag{5}$$

Rayleigh and Weibull distributions are commonly utilised in wind industry as well as wind energy research to create fast approximations of possible yearly energy outputs of a wind turbine at a specified location. Researches have shown that the use of the distributions with actual site measured wind velocity data is generally satisfactory and they also make evaluations about the wind power potential of a site a lot easier [9, 10].

2.3 Wind Shear

A vital parameter in the characterisation of the wind resource is the wind shear present in the atmosphere. Wind shear, also known as wind gradient refers to the change in wind speed and direction over a fairly short period of time or distance. Wind shear can be split up into horizontal and vertical components that can be seen near fronts and jet streams. The variation of wind speed with elevation, which is known as vertical wind shear is considered to be a crucial design parameter in the wind energy industry. Vertical profiles of the wind speed are typically influenced by the friction against the surface of the earth. This conflict commonly results in wind velocities increasing with altitude.

Wind shear can generally affect two design parameters for horizontal axis wind turbines (HAWTs): it regulates the output of a turbine depending on the tower height and also has an impact on the lifespan of a rotor blade. HAWTs which are situated at elevated altitudes are generally subjected to strong winds and therefore can generate more power. Rotor blades deteriorate from the impact of cyclic loads, as a result of the changes in wind velocity between the higher and lower blades which consequently initiates a bending moment [6].

However, for AWE systems, wind shear predominantly influences the output. The functioning altitude of AWE systems can primary be altered fairly effortlessly, but functioning the system at greater heights has the drawbacks that flying devices have to operate at larger tether angles which increases the tension force on the tether. Furthermore, the effect of irregular loadings is less significant for AWE systems, as they usually have kite or wing spans that are considerably less in contrast to a rotor blade diameter of a HAWT with a comparable rating.

In regards to all types of wind energy applications, it is established that the instantaneous and seasonal variation of wind speed as a function of altitude are the most vital separate and distinctive issues which determine the vertical wind profiles: the variation of instantaneous profiles are deemed to represent the wind velocity over a period of seconds and is expressed by the similarity theory of boundary layers [10]. Whereas, the seasonal variation profiles refer to the long-term averages and should depend on a more empirical method, as they are associated to the statistics of occurrence of numerous influencing aspects, such as surface roughness [12].

The Hellman power law is frequently used in the wind industry to approximate the variation of wind velocities with altitude when there is no actual measured altitude profile available. The Hellman power law can be expressed as [13]:

$$v(z) = v_{ref}\left(\frac{z}{z_{ref}}\right)^{\alpha} \qquad (6)$$

Where α is the friction coefficient and it varies with the roughness of the terrain over which the wind is passing; $v(z)$(m/s) is the wind speed at height z (m); v_{ref} (m) is meteorological wind speed measured at the standard height z_{ref} (m) of 10m.

The Hellman power law exponent varies with the roughness of the terrain over which the wind is passing. The typical values of the friction coefficient are [13]:

- 0.10 for smooth hard ground or calm water.
- 0.15 for tall grass on level ground.
- 0.20 for high crops, hedges and shrubs.
- 0.25 for wooded countryside or many trees.
- 0.30 for small town with trees and shrubs.
- 0.40 for large city with tall buildings.

2.4 Atmospheric Boundary Layer

The available wind resource at ground-level is restricted as a result of many reasons. The contours of the terrain, as well as huge topographies like trees, mountains, structures, etc., generally obstruct the wind and decrease the site locations suitable for successful wind energy generation. Wind adjacent to the surface of the ground is furthermore influenced by the atmospheric boundary layer which is also known as the planetary boundary layer.

At high altitudes within the boundary layer, the geostrophic winds are unaffected by friction, but as height reduces frictional force reduces the speed until at the earth’s surface the speed is zero. It is established that the boundary layer can scale from a couple of hundred meters to 2,000 m in height, subject to the roughness of the land as well as the atmospheric conditions [14].

It is evident that greater mean wind speeds can be offered, if a wind energy system can exploit the winds which are not disturbed by the unfavourable lower section of the atmospheric boundary layer [15]. Therefore, the key benefit of using winds at elevated heights above 1 km is that wind generation technologies such as AWE systems can potentially harness the higher altitude wind power which is available.

The mean wind speed in Europe is roughly 3.5 to 4 m/s, at an altitude of 100 m [15]. This is generally within the grasp of a common ground-level wind turbine. However, it is shown that at 1 km in height, the mean wind speed is doubled in respect to the altitude at 100 m [16]. This signifies a big rise in wind power; seeing as, the power that can be extracted from the wind grows with the cube of the wind speed.

2.5 Global Wind Patterns and Jet Streams

It is clear that the mean wind speed remains to escalate even beyond the height of the atmospheric boundary layer [17]. This is as a result of an effect identified as a jet stream. Jet streams are known to be initiated from the mixture of atmospheric heating (by solar radiation) and the earth's rotation on its axis [18].

These twisty strong streams of high-speed winds are typically situated at around 7 to 16 km above sea level, and often reach a peak between 8 to 12 km [17]. The wind velocity of a jet stream can reach up to 10 times the wind speed at ground-level. There are two jet streams, i.e. polar and subtropical jet stream, in both the northern and southern hemisphere.

As a result of these jet flows in each hemisphere, any wind which exceeds the atmospheric boundary layer has a tendency to increase in speed progressively as the altitude rises, until it makes contact with a jet stream. Hence again, the power that can be obtained from the wind rises from the increasing wind velocity. The significance of exploiting additional power at bigger capacities per system is that it will have an effect of reducing the price per kWh of energy generated, which highlights the potential of utilising this energy within the UK.

The ecological researchers Christina Archer and Ken Caldeira used almost 30 years of atmospheric data to produce a global atlas of wind velocity variations and wind consistencies [17]. The statistics are presented by the researchers in a wind power density format (kW/m^2), which is useful for approximating the prospective amount of energy available at a location. The measured watt per square meter format considers the effect of variations in both the air density at various heights and the wind speed.

It has been demonstrated that 50% of the time within the entire UK, it is possible to achieve a wind power density of 5 kW/m^2; assuming that an AWE system is situated at an optimal altitude [17]. Whereas, at a height of 80 m which is the typical tower height of HAWTs, the UK wind power density is 0.5 kW/m^2 50% of the time. This implies that 50% of the time there is a reward of 10 times the power production by situating a wind application at a greater altitude.

2.6 Capacity Factor

An essential aspect to take into consideration within wind power generation is the uniformity of the wind. Uniformity of the wind supply at a given location is evaluated by a capacity factor, which is the percentage of the energy truly obtained by a wind turbine comparative to what could be acquired, assuming that it is constantly functioning at full capacity. It is very common for most ground level locations to have capacity factors of no more than 35% [19]. The estimated capacity factor is higher at higher altitudes than at lower altitudes, i.e., 64% at elevated altitudes of 4.6 km and 85% at elevated altitudes of 4.6 km in Nottingham, UK [20]

These huge capacity factors at high altitudes are considered to be particularly essential, as they not only present the extra energy which can be generated, but they also give reassurance for big energy firms who require uniform power to supply the grid with electricity. The use of uniform wind energy means that reliance on energy storage or alternative energy production facilities can be reduced. In addition to this, support can also be provided to fulfil energy generation interruptions, which on the other hand can increase the percentage of energy that is provided to the electricity grid from wind resources.

The overall quantity of wind energy available furthermore is question of concern, as researchers have suggested that wind power is roughly 100 times the power used by all human civilization [21]. The overall sum of human thermal power usage is considered to be approximately 10^{13} W [22], whereas the entire power deemed to be dissipated in winds is roughly 10^{15} W [23]. Therefore, almost all of the energy demand worldwide can simply be met by extracting 1% of this huge wind resource.

Reflecting on the huge scope of the wind resource as well as the extreme surges in the capacity factor and wind power density at elevated altitudes, helps to demonstrate the current attractiveness as to why researchers and firms are developing varieties of different airborne innovations designed to extract energy from this vast resource.

3. EVALUATING THE POTENTIAL OF AWE TECHNONOGY

Majority of the benefits of AWE that were revealed previously are very creditable and there is very little dispute about them. Nevertheless, these advantages are not adequate enough to establish the technology’s potential. For AWE to reap the overall benefits, the technology needs to compete against other sources of energy production.

In consideration to the advantages stated earlier for utilising the wind as a resource, it is evident that AWE can demonstrate its technological and economic potential by being capable of competing with traditional wind exploiting techniques.

The fundamental stage in evaluating a modern wind technology is commonly to determine the efficiency of which the available energy in the wind can be extracted, known as the power coefficient. Therefore, the target for traditional wind turbines is to reach the alleged Betz Limit, first introduced by the German engineer Albert Betz in 1919. Betz Limit is acknowledged as the theoretical maximum for extracting wind energy from a given area [24].

As shall be justified later in this study, with AWE systems it is not as straightforward to identify the area to harness the wind energy. Whist there could be sufficient information available to contrast the efficiency of AWE systems against traditional wind turbines, considering only the efficiency is not enough factor to determine a verdict. As soon as the quantity of energy derived from a given resource is identified, it thereafter can be established the expense to make use of this resource (cost effectiveness). For example the cost per swept area for a horizontal axis wind turbine is used to evaluate the cost effectiveness of electricity production by horizontal axis wind turbine.

A frequent benchmarking or ranking tool used in energy economics to assess the cost-effectiveness of different energy generation technologies is the Levelized Cost of Energy (LCOE). This method reflects the lifetime generated energy and costs to estimate a price per unit of energy generated [25]. LCOE can give beneficial information on the feasibility of a project, especially when constant feed-in tariffs (FITs) are available. A renewable energy technology (RET) investor is then merely concerned with the yearly energy generation and less interested in seasonal or daily patterns.

Under present market conditions the economic feasibility of an electricity generating system can be established relatively accurate from determining the resultant LCOE. Hence, by contrasting AWE systems against traditional wind turbines based on the LCOE provides a better perception than merely contrasting energy concentrations, capacity factors or potential efficiencies.

Over the years, there has been a quantity of standard tools developed for estimating the LCOE for traditional wind turbines at a specified location and the majority of researchers approve on the same techniques. The performance of a wind turbine is typically signified by the power curve that relates the wind velocity with the energy output [6].

Alleged Weibull distributions are used to portray the yearly wind velocity distribution at a site position with a specified mean wind velocity (section 2.2). Wind shear exponents approximate the gain in wind velocity from an increase in altitude (section 2.3) and therefore estimate the wind velocity at a turbine hub height from the wind velocity at for example 15 meters in height. These explained tools are commonly deemed adequate for a basic approximation, but to design actual wind turbine farms involves more precise measurements as well as calculations to be carried out. Attempting the same analysis for AWE systems presents numerous questions and the majority of which are not currently remedied in literature regarding AWE systems.

Therefore to evaluate the capability of AWE systems as a renewable energy supply, an effective simulation model needs to be devised considering the distinctive characteristics of the system.

Hence, it is vital for the renewable energy sector to settle on standard methodologies so that AWE systems can be marketed to prospective investors and the availability of valid simulation models can be beneficial in allowing tactical planning of this technology to be performed.

4 AWE ENERGY SYSTEM BENEFITS AND DIFFICULTIES

In the event of the UK deciding to implement an AWE technology, means that it is essential to comprehend the benefits and difficulties which could be encountered from the various methods of airborne wind energy systems. Currently there are three reputable inventions used to harvest AWE: (1) the kite, (2) balloon and (3) rotorcraft innovations. Each individual method has benefits and difficulties. It is considered that there are a number of benefits that all of these AWE technologies share over non-renewable fuels or present ground-level wind power.

It has been verified that the exploitation of wind energy has very small effect on the environment in contrast to fossil fuels [26]. The production of wind energy does not participate in releasing destructive emissions into the atmosphere in addition to the waste products, apart from the materials and energy needed to construct the system itself. For the society, this is considered to be one of the main appealing aspects of wind energy. It has been found that there is insignificant impact on the climate by implementing an AWE extraction system at a scope equivalent to the sum of the entire worldwide energy consumption [17].

Along with these benefits, wind is harvested at elevated altitudes in a tri-dimensional space and has greater wind power densities. Therefore when contrasting AWE to traditional ground-level wind energy production, there might be rather little land footprint. It has been estimated that a kite airborne wind power farm with several adequately spaced out kite systems, can generate roughly 7 to 13 times the value obtained by wind towers [27].

As AWE systems generate wind energy at elevated altitudes, it is considered to be harmless to bats and birds which is very dissimilar from ground-level wind energy systems which are known to slaughter birds. Hence AWE technologies would have more acceptances to the community in contrast to traditional ground-level wind turbines. Additionally, since AWE systems are positioned and operated at elevated altitudes, so they appear to be very little and therefore have the advantage of shrunken visual effect on the public eye.

A fourth benefit which may be offered from AWE technologies is energy generation transportability. Given that there are no constraints of huge costly foundations and towers, AWE systems may possibly be put into operation at provisional locations for short-term periods. Furthermore, these systems might become very valuable in cases where the power is cut off from the electricity grid; therefore the system can be used as a disaster relief effort or an emergency supply of power for an unexpected catastrophic situation.

Moreover, due to the fact that AWE is obtainable worldwide, suggests that these AWE devices at high altitude may possibly be positioned fairly near to cities. Hence the convenience of the remote heights, which the technology reaches, might be beneficial to help bring the AWE resource closer to consumers. Clearly this aspect of the AWE technology system might help to prevent electrical as well as infrastructure losses that are commonly compulsory for transmission of energy over long distances. In addition, the energy security for the community and the airborne system itself may possibly be improved in comparison with ground-level systems. Since the system is out of reach to most ground-level threats and shorter transmission lines mean that there is reduced cable exposure to prospective ground-level vandals.

Overall, the most significant benefit of an airborne device is the supply of wind being extensively available locally. This is considered to be a huge advantage seeing that presently there is a big desire within the community to decrease the UK reliance on imported oil. However it is seen that this is likewise a national security problem, taking in to account that the less the UK relies on imported energy from countries, the more stable the economy grows to be together with an increase in the availability of energy within the country.

Difficulties for some AWE technologies in contrast to ground-level wind turbines are the mechanisms, which intensify the amount of complexity of the system, for example hovering wind-rotors. Furthermore, now that the technology has advanced for stronger and lighter tether cables airborne wind energy systems are presently more applicable than they have been previously. However unfortunately stronger and lighter tether lines are still not broadly available, and hence continue to be rather costly [28]. These features cause airborne systems to be more complex and, hence increase the cost to operate in comparison with a straightforward ground based wind system.

Another challenge which could arise for the AWE industry is a conflict or legal questions surrounding the ownership and use of high-altitude airspace. In the USA, for example it is deemed that airspace greater than 150 m above ground level is categorised as navigable space or a public highway for aviation [29, 30]. Therefore developers who wish to operate airborne systems in this high-altitude airspace would probably require special privileges to occupy it for that reason and would want to be legally safeguarded against the disrupting air traffic. This could mean that airborne wind farm designers would be required to lease navigable airspace from the government, which is similar to the leasing system that currently exists for offshore wind farms.

Furthermore, AWE developers may require some partial property privileges, for land directly beneath the airspace leased, to facilitate tethering the AWE system to the ground and running transmission lines to deliver generated power to the electricity grid. Thus it appears that AWE operators hypothetically would require two distinct leases, i.e. one with a private landowner as well as one with the government, to install and operate an AWE system at high altitudes over any given plot. This in reality could initiate a fascinating dispute between property-owners, governments and developers over the balance of public and private property privileges in navigable airspaces.

Ultimately, AWE systems may also initiate a requirement for “spatial airspace planning” arrangements comparable to marine three-dimensional schemes that currently manage deep-sea zones [30]. Therefore, zoning of navigable airspace regions for AWE systems would permit governments to assign particular airspace regions for AWE innovations whilst conserving other areas as air travel paths.

A major issue with clean energy resources, such as solar and wind energy, is the irregularity of the energy flow. This implies that at some point in time zero energy can be generated, no matter if the system is located in the best position. Even for AWE systems, some researchers have advised that good sites could still generate no energy at least 5% of the time [17, 31]. Furthermore, energy irregularity is a big issue for electric utility firms, as any savings in expense which an AWE system can offer can be severely decreased as a result of firms using fossil fuel power plants or implementing huge energy storage batteries to function as a standby power resource for wind energy interruptions.

Lightning strikes are considered to be another concerning aspect with operating an airborne system at high altitude. To help diminish this issue it seems that an airborne system would have to be either landed for the period of the lightning storm or constructed with protection to endure the lightning strike. This could effectively be accomplished: however the energy supply could become inconsistent in addition to a rise in the complexity and cost of the system to be capable of withstanding a lightning strike [32].

In summary, it appears that the difficulties in relation to the development of an AWE system are important and give rise to some significantly new challenging property and regulatory problems that would need to be resolved for such an industry to thrive.

However, it seems that by merging and utilising present technologies will assist in overcoming some of these complications. The benefits of operating a high density wind energy resource at elevated heights offers *remarkable* returns to persons who are able to creatively conquer the difficulties and to create an airborne system which is competitive. At present, there are numerous firms and researchers around the world which are attempting to do just that [33].

5 AVAILABILITY OF AWE IN THE UK

It is common to use wind power density (kW/m^2) to approximate the amount of wind energy available at a location. The wind power density includes the effect of variations in both the air density at various heights and the wind speed.

The optimal power density that wind technologies at elevated heights can harness by positioning at altitudes with the most ideal winds as shown in Fig. 1 [17]. The left side of Fig. 1 demonstrates the optimum attitude for an AWE technology and similarly, on the right side is the wind power density that is available at that optimal altitude. These illustrations enable a planner to first establish the prospective output of an AWE system at a given site, and subsequently establish the ideal operating height of the technology where the greatest potential exists.

More detailed ground level wind power densities in the UK is shown in Fig. 2, and it appears that there is a further contrast of the potential of an AWE system against a traditional ground based wind turbine. The crucial aspect is that the wind power density at high attitude as shown in Fig. 1 is approximately 3 – 5 kW/m^2, no less than 50% of the time within the entire UK.

However, in Fig. 2 for the wind at ground level, i.e. 50 m above ground in hills and ridges, the mean wind power density is in the range from 0.4 to 1.8 kW/m^2 [34]. The greater wind power densities shown in Fig. 2 are available in the northern parts of the UK, i.e. Scotland. The wind power densities in Figs.1 and 2 verify that AWE systems have the potential to at least produce double wind energy value than traditional wind turbines, since the wind power densities are two times the amount of what is available at ground level.

6 REGIONAL FEASIBILITY STUDY OF AN AWE SYATEM

To assess the individual regions within the UK that shall deliver the most effective possibility of success, a decision matrix was created, in which eleven regions were graded on three criteria which are the electricity cost and energy savings, area availability, and obtainable high altitude wind energy within a regional vicinity.

Each individual criterion was set an equal weight, and the processes applied to establish the grades for the individual criterion are defined in the following sections. For this study, eleven regions were chosen. However, by applying the methodology developed in this study, other site locations can be evaluated. Therefore, AWE system developers could apply these stages as a standard means of discovering and evaluating appropriate site locations for their system.

6.1 Electricity Cost and Energy Savings

The UK regional potential energy and cost saving required two substantial aspects to be considered (1) the cost of electricity and (2) the regional energy requirements. The grade weighting within the cost and energy cretria was divided into 30% for the regional electricity requirements and a bigger weighted grade of 70% for the cost of electricity, as it participates more directly into the price savings per kWh of electricity created.

The cost of electricity within regional areas of the UK was the first aspect to consider, as bigger regional electricity prices could directly result in bigger cost saving for regions which implement an AWE system. Therefore, the regions that have larger electricity costs were correspondingly fixed higher marks. The estimated mean cost of electricity for individual regions was obtained from EDF Energy [35].

The electricity cost for individual regions was noted and the grade given to the cost of energy was estimated from normalising the cost figures on a scale out of 10, with the highest electricity cost region presented a mark of 10 points. The points of individual regions are shown in Table 1.

The regional electricity requirements were the second aspect to consider, as the quantity of energy being consumed by a region signifies the amount of energy the AWE system can be restored with renewables. This is founded on economies of scale, as bigger wind farm systems are inclined to be more cost efficient per watt-hour generated. Bigger wind farm systems are furthermore appealing as they can offer a bigger influence on the reliance of foreign oil, as well as assisting to improve the national security. Hence, the regions which exploit more yearly electricity are awarded bigger marks. The total UK annual electricity consumption for the years 2015 was obtained from the *DECC Sub-national electricity and gas consumption statistics* [36].

To achieve the energy savings grade, the entire yearly energy usage (GWh) for the year 2015 was noted. Next, the regional energy usage was normalised on a scale out of 10, with the largest energy usage region awarded a mark of 10 points. The points of individual regions are shown in Table 1.

6.2 Area Availability

In order for an AWE system to be successful, it is essential to ensure that there is sufficient space available to install and operate the device. This is considered to be predominantly vital in the premature phases of system development and testing, as time is required to enhance the safety and reliability of the device. Hence, a bigger safety barrier area is necessary for experimental program machines.

The aspects to consider in regards to area availability are (1) how active is the air traffic in the regional area and (2) how much ground space is available in the regional area? Solutions to these questions were evaluated by using information maps relating to regional air traffic as well as the population density. The grade for area availability was established from two aspects (1) the regional density of airline traffic and (2) the regional population density.

Preferably, developers of AWE systems would like to deploy a system direct or nearby a site location which they are supplying energy to. A beneficial way to assess the likelihood of discovering an appropriate site, with adequate space is to use the estimated population densities of regions where the system is to be implemented. Therefore, regions with high population densities will have lower possibilities of available space for the system. In addition, they are also inclined to have higher costs of leasing the land. This resulted in the lowest marks being awarded to regions with extremely high population densities.

The 2011 regional population densities of the UK was reported by the *Office for National Statistics* [37]. The estimated population densities for the individual regions were noted and marks were awarded on a scale of 0 – 10. Table 2 demonstrates the scale which was employed.

The grade weighting within the area availability group was divided into 40% for the regional airline traffic density and a higher weighted grade of 60% for the regional population density, as it is more advantageous to have energy generation systems situated closer to the consumer. The points of individual regions are shown in Table 3.

When an AWE system is in operation, it is essential to ensure that there is adequate air space available in the location of operation, as these devices are most effective at altitude heights which conflict with airplanes or helicopters. Thus, it is considered that regions with high airline traffic density are less expected to gain consent to be deployed.

A computer software *Airline Route Mapper* was used to contrast the airline traffic densities between the different regions [38]. This application tool displays the airline flight paths of over 700 international airlines. A screen-print was captured of the airline flight paths over the UK, and the image was overlapped on Google Earth as shown in Fig. 3 [39].

The pictures were then organised in sequence from high airline traffic density to less airline traffic density. This was carried out with a visual assessment and regions with big airports as well as a large amount of airline traffic were graded less.

Next, the regions were placed into one of the six classes presented in Table 3 and marked correspondingly.

6.3 Regional Airborne Wind Energy Density

The final classification in the AWE feasibility decision matrix is the obtainable high altitude wind energy within the different regions. The *Global Assessment of High-Altitude Wind Power* study, is used to establish the regional grades [17].

The obtainable wind power density at the individual regions was established by, overlaying the international wind power density map (Fig. 1) over a Google Earth map of the UK regions being assessed. An example of the 50th percentile wind power density amplified and overlapped onto a Google Earth view of the UK is shown in Fig. 4.

A suitable assessment of the obtainable wind power densities for each region was established by contrasting the colours of the regions on the Google Earth map with the power density key, shown in Fig. 5.

The power density values were noted for the individual percentiles (50th, 68th, and 95th) and the marks were acquired from normalising the information on a scale out of 10 points; with the biggest power density regions awarded 10 points. Therefore, each individual region was presented three separate grades; one for each percentile. The grade weighting was the same for each of three grades in the obtainable wind power density classification. The points of individual are shown in Table 4.

It is observed from Fig. 4, that wind power densities in the UK have a tendency to be at great in north regions, and the power densities start to reduce towards the south and the east. The biggest grades awarded in this classification are interpreted as a direct price saving in regards to an AWE system, in view of the fact that a system could deliver more power per unit in regions that have the biggest power density scores.

When developing an AWE system, it is essential to elect beneficial site locations that can deliver the greatest possibility of achievement. Hence, the aim of this assessment was to offer a standardised technique to contrast the different regions within the UK and identify the regional site location that would mostly benefit from an airborne wind energy system.

It is considered that a good grade on this assessment does not essentially ensure victory, and neither does a terrible grade suggest that an AWE system could not deliver a huge advantage to that region. The individual regions could have numerous requirements and difficulties which should have to be figured out before deploying an AWE system. This part of the study shall distinguish as well as emphasise the major aspects that have to be reflected upon in selecting the most ideal site locations.

7 RESULTS ANALYSIS AND DISCUSSION

When developing an AWE system, it is essential to elect beneficial site locations that can deliver the greatest possibility of achievement. In this study, eleven regional locations were assessed, the regional availability of AWE as shown in Table 5.

7.1 Cost and Energy Savings

The top five regions in the classification of cost and energy savings are: Scotland, North West, Wales, South West, and North East. These five regions have relatively big electricity costs, and furthermore have extremely huge energy usage amounts which shrink the energy usage of many of the littler regions. In despite the fact that the cost of electricity was weighted extra compared to the energy usage aspect, it is clear that the energy usage aspect has a powerful influence on the grade for this classification.

It will be very advantageous to situate an AWE system in areas with the best cost and energy savings classification, as this will deliver a bigger effect on the price savings as well as the renewable energy usage (despite the fact that the region only uses one system) than other areas would.

7.2 Area Availability

In the classification of area availability, the five regions which established the greatest grades are: Wales, Scotland, North East, Yorkshire, and South West. These five regions are likely to have a larger chance of discovering an appropriate area on the ground to locate an AWE system. In addition these locations could also offer an extra sensibly sized area of safety in comparison to many of the regions in heavily populated locations.

These five areas are considered have more of a chance to acquire consent to utilise the airline space and to function an AWE system at the optimum altitude height for energy production. The isolation and land which is obtainable within these areas could furthermore participate in lowering the prices related to land use.

As a result of the area availability being so crucial for the operation of an AWE system, many of the regions with the worst grades in this classification may encounter a number of conflicts for the operation of AWE systems in their location. Due to this, it is substantial to be aware of the regions that established the worst grades in this classification.

The four regions with the lowest grades in this classification are: London, South East, West Midlands and East England. The following list of choices would probably have to be reflected upon by these four regions to effectively be capable of implementing and operating an AWE system:

- Implement a creditable sea type of an AWE system off the coast.
- Discover a gap in the airline traffic flight paths.
- Identify a site position (distant from big airports) which might comprise of airline traffic at larger altitude heights, and therefore a system could be operated at smaller altitude height.

- Get the CAA to produce air space for the operation of an airborne wind energy system.

Unfortunately these individual choices may offer problematic issues, in addition to larger added prices and hazards.

7.3 Regional AWE Power Density

Regional AWE power density is the last classification that was assessed. The five regions with the highest grades are Scotland, North East, North West, Yorkshire and Wales. It is acknowledged that the greatest AWE power densities in the UK is in the north, and it is can be visually seen that the wind power steadily decreases for regions further south and east.

The AWE power is specifically valid for these areas, due to the fact that a big grade here suggests that it might directly transform into cost efficiencies for a system. The operation of every AWE system within these areas are more than likely to deliver considerably more power per generating system in comparison to other areas, as a result of the greatest grades being awarded in this classification. The outcome at these regions would comprise of smaller prices for the necessary upfront infrastructure, in addition to smaller charges in regards to the operation and preservation costs per kWh of electricity generated.

7.4 Best Regional Area of AWE Feasibility Grades

The regions that received the highest top three total combined grades are Scotland, North West and Wales as shown in Fig. 6. South West Ranked 6th overall is also included for comparison, given that it had two reasonable classification grades.

It is observed that these best three regions have the highest grades in either one or two out of the three classifications. Therefore, this can make either one of the three regions a suitable choice to implement an AWE system. The best three regions stand in comparison to South West which was graded satisfactory in two classifications, however this region had an extremely small grade in the regional AWE power density class. The low AWE power density in the South West resulted in its comparatively lower total score and thus its sixth overall raking position.

Scotland was awarded the greatest total grade due to this region scoring very good in each of the classifications. This region established the best grade in two out the three classifications. Scotland established the best regional AWE power density mark, which was bigger than the second place regional AWE power density mark for North West.

8 CONCLUSIONS

In this study, the implementation of regional AWE feasibility was assessed. A regional feasibility decision matrix was developed as a standardised method to help compare and contrast the different regions within the UK. It was found that the region of Scotland established itself as being the best suitable site location for implementation of an AWE system, as high scores were awarded for the power density, area availability as well as the electricity cost and energy savings.

This study suggested that within the Scottish region the cost of system will translate into being cheaper due to the high power densities. There is satisfactory ground and air space to operate the system as well as provide a good safety boundary for deployment and testing of the system. Lastly, the location would benefit more by having a bigger reduction in their electricity bills from the implementation of the system, as electricity costs and consumption within the area is high.

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Figure Captions List

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Table 1	UK regional electricity costs and consumption marks

Table 2 Classification of population density marks

Table 3 UK regional population density and airline traffic density marks

Table 4 UK regional AWE power density marks

Table 5 UK regional AWE feasibility results

Table 1 UK regional electricity costs and consumption marks

UK Region	Cost of Electricity p/kWh	Energy Usage GWh	Cost of Electricity Normalised	Energy Usage Normalised
London	14.14	39654	0.9	10.0
North West	15.20	32104	7.6	7.4
East Midlands	14.41	21478	2.6	3.7
Yorkshire	14.97	23338	6.2	4.3
Wales	15.57	16146	10.0	1.8
West Midlands	14.68	24172	4.3	4.6
Scotland	15.43	26100	9.1	5.3
East England	14.36	27272	2.3	5.7
South West	15.25	24598	8.0	4.7
North East	15.25	11626	8.0	0.2
South East	14.50	39255	3.2	9.9
Classification Weight			70%	30%

Table 2 Classification of population density marks

Population Density /person·km^{-2}	Mark
<100	10
100 – 199	9
200 – 299	8
300 – 399	7
400 – 499	6
500 – 599	5
600 – 699	4
700 – 799	3
800 – 899	2
900 – 999	1
>1000	0

Table 3 UK regional population density and airline traffic density marks

UK Region	RPD[1] /person·km^{-2}	ATD[2]	RPD Normalised	ATD Normalised
London	5199.7	Intense	0	0
North West	497.9	Medium Low	6	8
East Midlands	290.1	Medium	8	6
Yorkshire	342.7	Medium Low	7	8
Wales	147.4	Medium Low	9	8
West Midlands	430	Medium High	6	4
Scotland	67.2	Low	10	10
East England	305.8	Medium High	7	4
South West	222	Medium Low	8	8
North East	302.2	Medium High	7	4
South East	452.2	High	6	2
Classification Weight			60%	40%

Note: 1. RRD is the regional population density.

2. ATD is the airline traffic density.

Table 4 UK regional AWE power density marks

UK Regional	50th kW/m^2	68th kW/m^2	95th kW/m^2	50th N[1] kW/m^2	68th N[1] kW/m^2	95th N[1] kW/m^2
London	3.0	1.2	0.5	3.3	5.0	5.0
North West	5.0	2.0	0.5	10.0	10.0	5.0
East Midlands	3.0	1.0	0.5	3.3	5.0	5.0
Yorkshire	5.0	1.0	0.5	10.0	5.0	5.0
Wales	4.0	1.0	0.5	6.7	5.0	5.0
West Midlands	3.0	1.0	0.5	3.3	5.0	5.0
Scotland	5.0	2.0	1.0	10.0	10.0	10.0
East England	3.0	1.0	0.5	3.3	5.0	5.0
South West	3.0	1.0	0.5	3.3	5.0	5.0
North East	5.0	2.0	0.5	10.0	10.0	5.0
South East	3.0	1.0	0.5	3.3	5.0	5.0
Classification Weight				33.3%	33.3%	33.3%

Note: 1. N is the abbreviation of Normalised.

Table 5 UK regional AWE feasibility results

UK Region	CES[1] CG[4]	AA[2] CG[4]	AWE PD[3] CG[4]	Total Grade	Position
London	12.1	0.0	14.8	26.9	11
North West	25.2	22.7	27.8	75.6	2
East Midlands	9.8	24.0	14.8	48.6	7
Yorkshire	18.7	24.7	22.2	65.6	5
Wales	25.1	28.7	18.5	72.3	3
West Midlands	14.7	17.3	14.8	46.8	8
Scotland	26.5	33.3	33.3	93.2	1
East England	11.0	19.3	14.8	45.2	10
South West	23.3	26.7	14.8	64.8	6
North East	18.8	19.3	27.8	65.9	4
South East	17.3	14.7	14.8	46.8	9

Note: 1. CES is the cost and energy savings.

2. AA is the area availability.

3. AWE PD is the regional AWE power density.

4. CG is the classification grade.

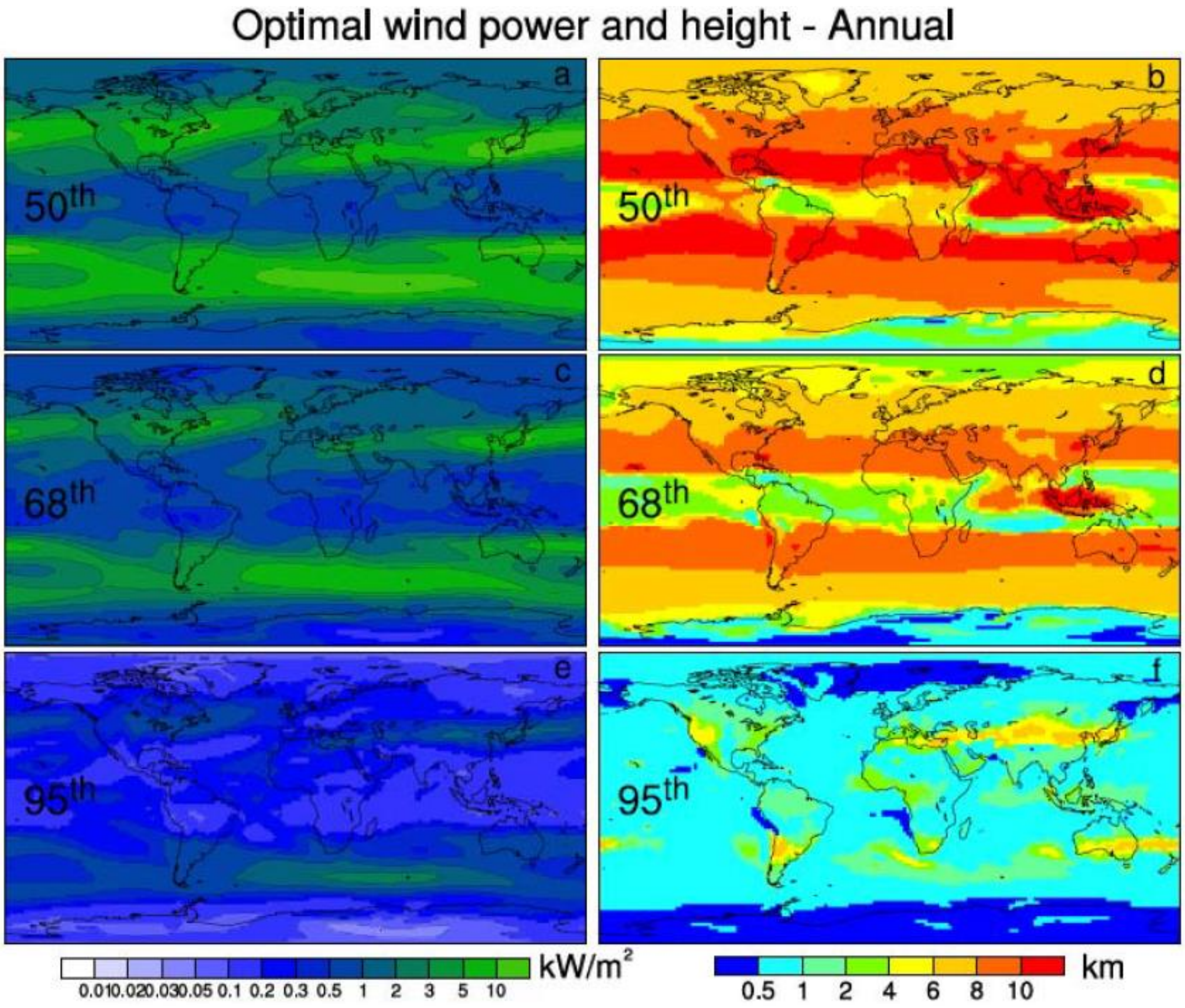

Fig. 1 Percentiles of wind power density (kW/m^2) and height (km) during 1979-2006 [17]

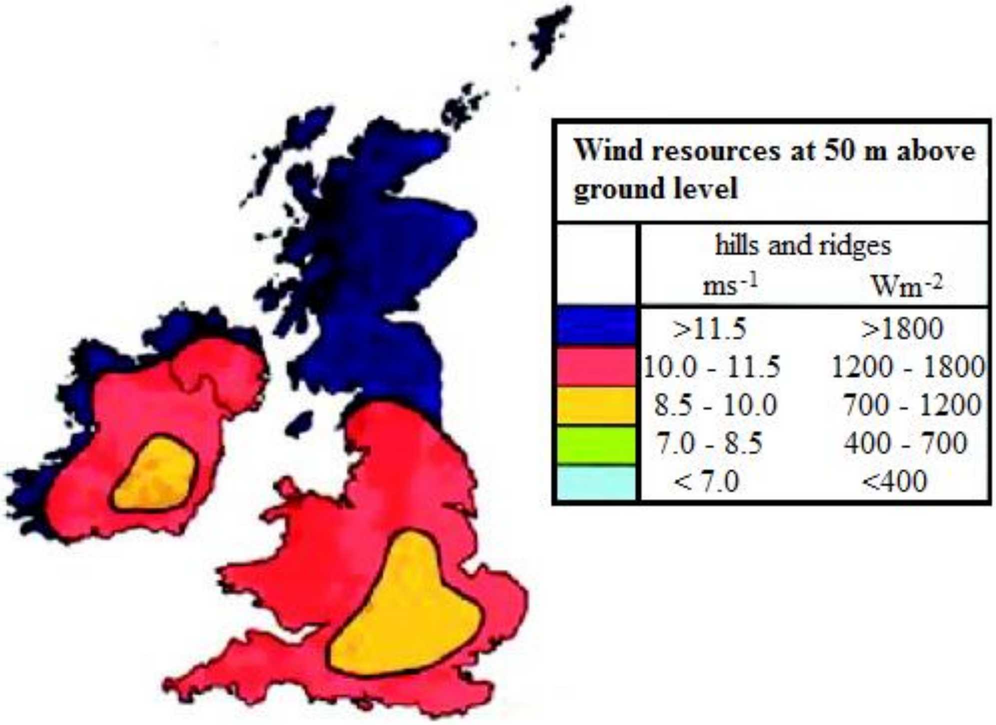

Fig. 2 Map of UK wind power densities at a height of 50 m above ground level [34]

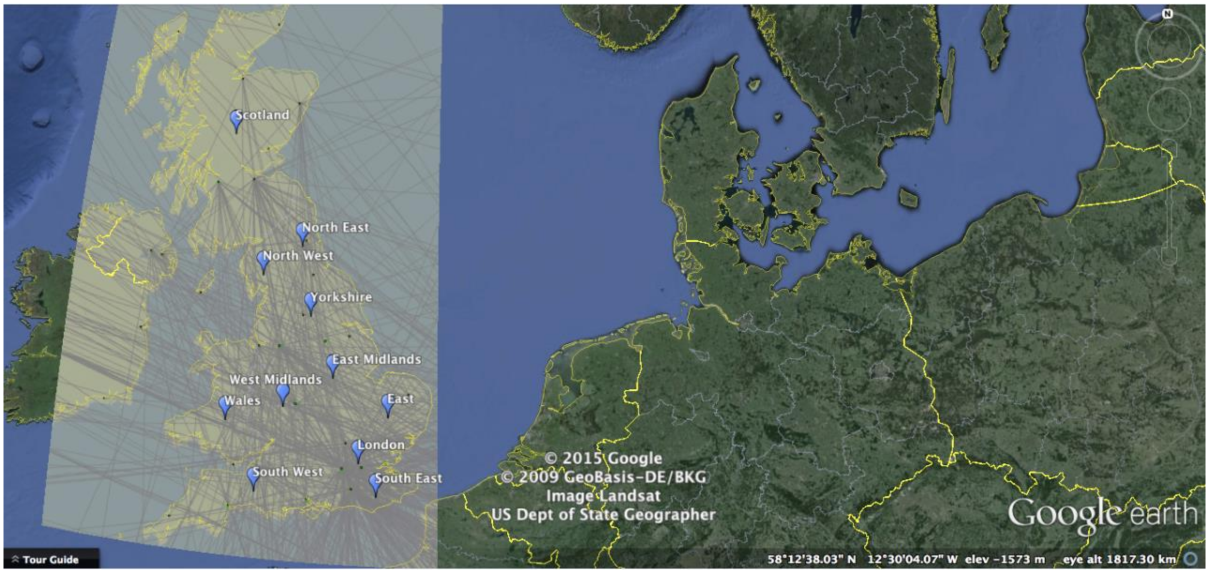

Fig. 3 Airline flight paths overlapped on Google Earth map of the UK

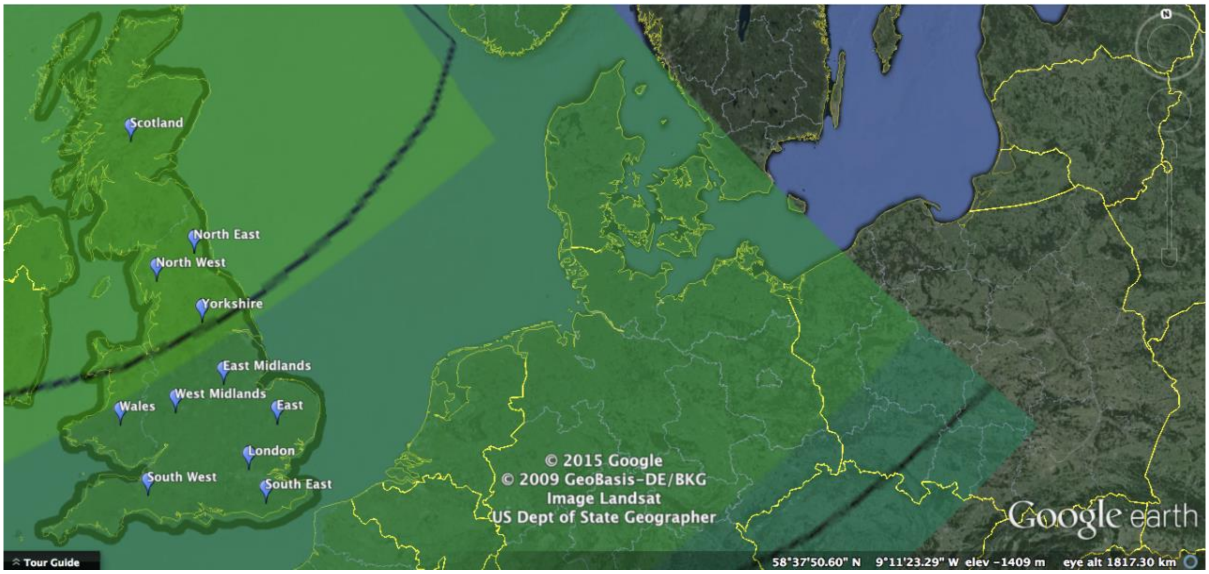

Fig. 4 50th percentile wind power density overlapped onto the Google Earth map of the UK

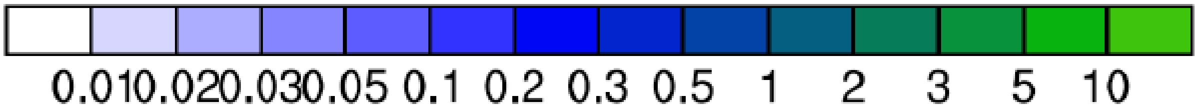

Fig. 5 Key for wind power densities (kW/m^2) [17]

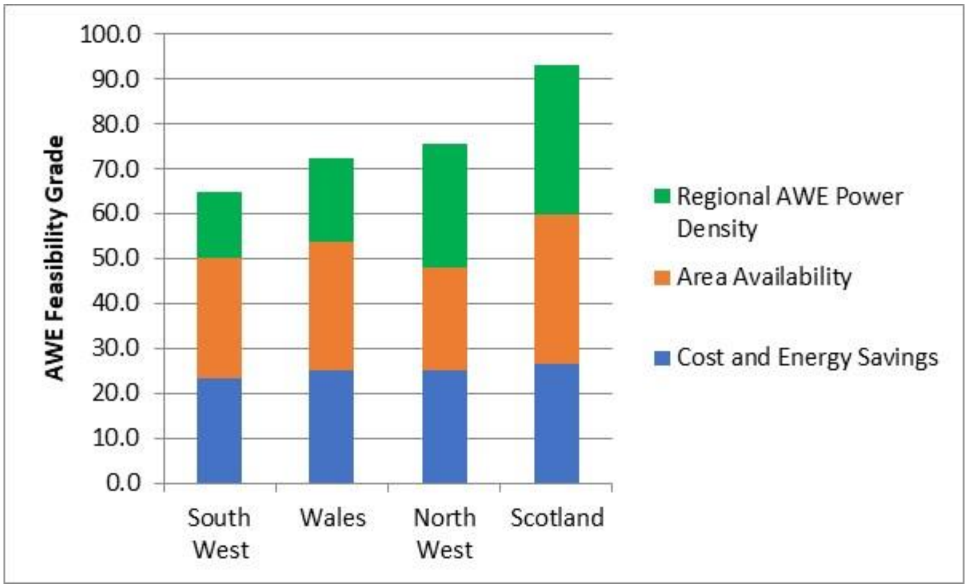

Fig. 6 The leading regional AWE feasibility grades