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Renewable Energy Generation



University of Wales Trinity Saint David
Independent Project - Level 6

Executive Summary

Bristol Airport, a prominent transportation hub in Southwest England, has seen substantial growth since its establishment in 1957, evolving into one of the UK's busiest airports. However, as air travel demand surged, so did the challenge of aligning operational needs with sustainability goals, including achieving their target of Net Zero operations by 2030.

Despite facing challenges such as the COVID-19 pandemic, Bristol Airport has shown resilience, emerging as the UK's fastest-recovering airport. Nevertheless, increased passenger numbers have led to higher energy consumption, amplifying the airport's carbon footprint. In response, Bristol Airport has launched renewable energy initiatives, transitioning its fleet to electric vehicles, and installing a 1.4 MW solar array. However, these efforts fall short of the goal to achieve twenty-five percent onsite renewable energy generation by 2025. As a result, the airport is actively seeking out additional solar sites.

This report proposes an alternative solution, involving evaluating energy generation using wind power. Wind turbines, capturing kinetic energy from aircraft jet blasts during take-off, present a hopeful opportunity for consistent and dependable power generation, supplementing solar energy production and lessening reliance on the grid. Additionally, with Bristol Airports elevated location, known for strong and consistent winds, wind power generation can be sustained even when aircraft movements are at a minimum.

Due to the delicate nature of aircraft guidance equipment utilised around an airfield, the feasibility of installing bladeless wind turbines instead of traditional bladed turbines has been investigated. As Traditional wind turbines have long rotating blades, they face challenges relating to interference with aircraft, Instrument Landing Systems (ILS), and wildlife, prompting the investigation of bladeless alternatives. Several bladeless wind turbines have been investigated, including Vortex Bladeless, Katrick Technologies' bladeless wind turbine, Halcium PowerPod, and Aeromine.

Comparative analysis revealed Katrick turbines as a top performer in energy generation, followed by Vortex, Aeromine, and Halcium PowerPods. Integration strategies include positioning Katrick turbines within ILS aerals and Vortex turbines in designated construction zones, maximising energy capture while minimising interference.

Next steps include testing for safe turbine placement, financial analysis for a cost-benefit assessment, and presentations to the Bristol Airport Board of Directors for approval. The proposed timeline spans testing and trials, financial analysis, and funding requests, aiming for phased implementation aligned with sustainability objectives.

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Glossary of Acronyms

AGL	Aeronautical Ground Lighting
ATM	Air Transport Movements
CO2	Carbon Dioxide
DDM	Difference in Depth of Modulation
DOM	Depth of Modulation
EV	Electric Vehicle
GP	Glide Path
GW	Gigawatt
HV	High Voltage
Hz	Hertz
ICAO	International Civil Aviation Organization
ILS	Instrument Landing System
LLZ	Localiser
MW	Mega Watt (unit of power)
NHS	National Health Service
PPE	Personal Protective Equipment
RPM	Revolutions per Minute
TW	Terawatt
VHF	Very High Frequency

1.0 Introduction

Bristol International Airport is located in Lulsgate Bottom, North Somerset, approximately 8 miles southwest of Bristol city centre (refer to Figure 1). The airport serves as a vital transportation hub for the Southwest of England and Wales, facilitating both domestic and international flights.

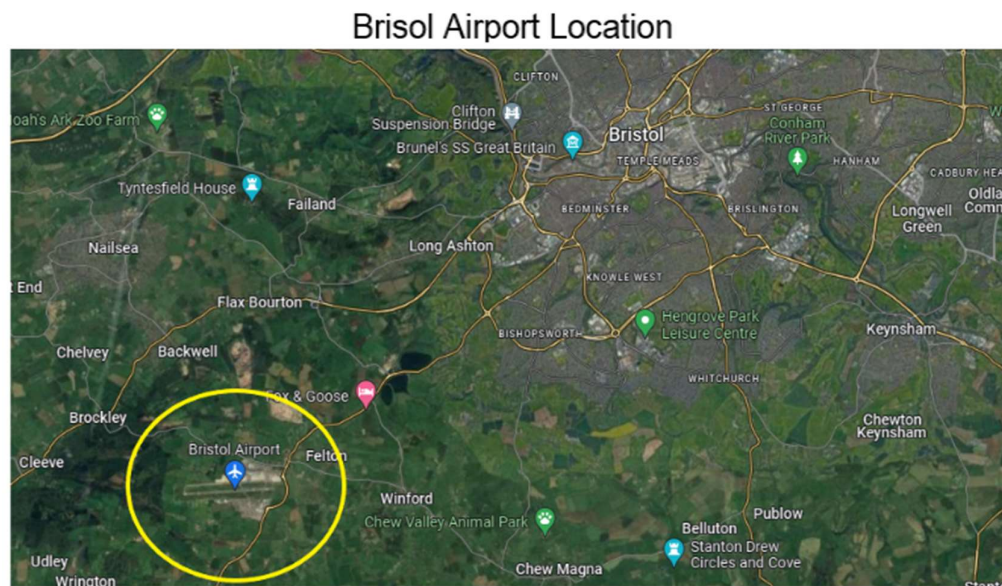


Figure 1 Bristol Airport Location (Google, 2024)

Opening in 1957, the airport has evolved to become one of the busiest airports in the UK. The Airport has one main terminal building that accommodates both domestic and international flights. It serves as a hub for several airlines and hosts a variety of carriers such as Easyjet, Ryanair, Jet2, and Tui.

Bristol Airport has one runway that can be used in two directions, east (90° – runway 09) and west (270° – runway 27) depending on wind direction. An aircraft will generally take off and land into the wind. Both runways (same piece of asphalt) are capable of handling various types of aircraft including helicopters and small aircraft, such as the two-seater Piper, up to larger passenger carrying aircrafts including the Airbus A320 and Boeing's luxurious 787 Dreamliner.

Over the past sixty-seven years, the airport has undergone significant expansions and renovations. A new terminal building was built in 2000 and further extensions to the east and west shortly followed several years later to meet the growing demand for air travel in the

region. Bristol Airport serves as a vital gateway for both business and leisure travellers, contributing to the connectivity of the Southwest of England and beyond.

However, the surge in demand for air travel, coupled with the airport's dedication to sustainability, with the removal of gas from the entire site and the increase of the Electric Vehicle (EV) fleet, has led to a substantial increase in the forecasted maximum electricity demand for the forthcoming decade.

This heightened demand poses a challenge for the airport to balance its operational needs with its environmental objectives. With Bristol Airport setting its own target of achieving Net Zero Operations by 2030, and in October 2022 the UK government and the International Civil Aviation Organization (ICAO) mandating a legally binding target of achieving Net Zero greenhouse gas emissions by 2050, this further emphasises the importance of mitigating the environmental impact of air travel and supporting the transition to sustainable practices. (Mithal and Rutherford, 2023)

This report has investigated how the impact of achieving Net Zero Operations will drastically affect the airports future maximum electrical capacity/maximum demand issues and proposes a solution to help reduce the impact on the electrical demand from the grid.

1.1 Site layout

Figure 2 shows the footprint of Bristol Airport's site (outlined in red). There's a car park to the north, with the terminal building adjacent. The aircraft stands and apron hug the terminal building, with taxiway access from the apron to the runway in the middle of the site. When taking off on runway 09, the aircraft will enter the runway from the west and take off to the east, and the opposite when using runway 27. To the south of the runway, there's the airport fire department, a maintenance area with several privately owned aircraft hangers, along with further car parking (Silver-zone parking) and car hire.

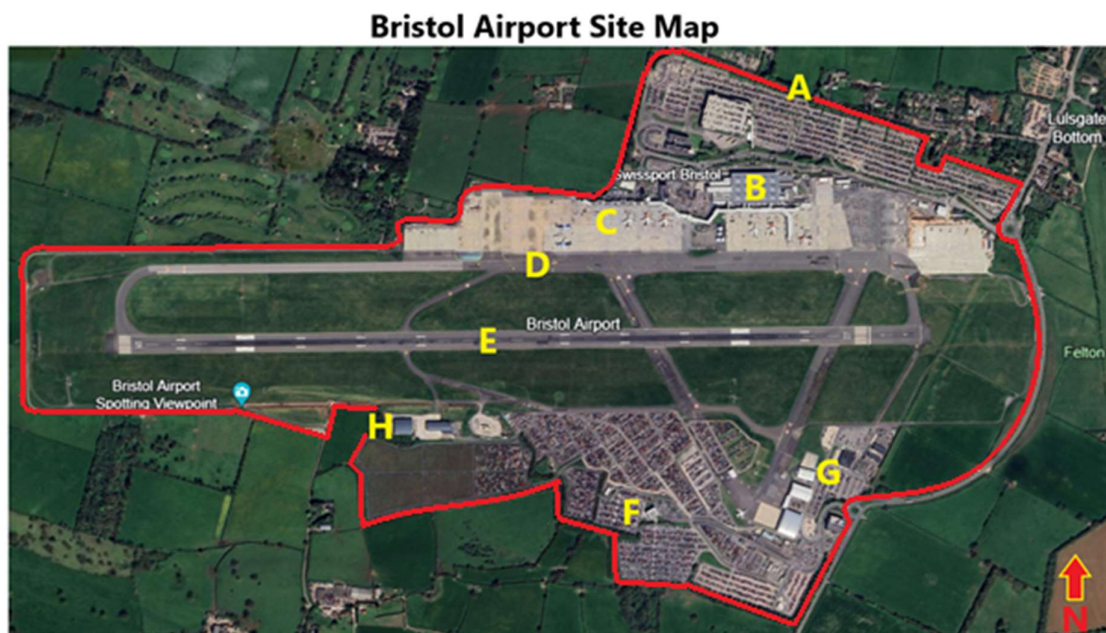


Figure 2 Bristol Airport Site Map (Google Earth, 2024)

- A. North-side car parking and multistorey carpark.
- B. Terminal building.
- C. Aircraft stands and Apron.
- D. Taxiways
- E. Runway (09 and 27)
- F. South-side car parking (Silver-zone)
- G. Car Hire
- H. Fire Department

2.0 Background

In 2018, Bristol Airport achieved its record passenger numbers, nearly reaching 8 million passengers for the year. But, as with many industries, the COVID-19 pandemic hit the aviation industry hard. The airport was virtually completely closed, apart from the extremely rare occasion when personal protective equipment (PPE) was flown in to assist the National Health Service (NHS). These were extremely dark times for the industry and for Bristol Airport in particular, as the airport was still having to be maintained and kept active for the rare arrival.

Following this unprecedented event, since reopening, Bristol Airport have become the fastest recovering airport in the UK with little over 85,000 air transport movements (ATM) scheduled in 2024 (refer to Figure 3). From boasting record high passenger numbers in 2018, with 80,000 ATM, to scraping just over 20,000 ATM during the pandemic, a record high of 9.8 million passengers were recorded in 2023, with a predicted 10.8 million passengers due in 2024. (BBC, 2022) (BRS, 2024)

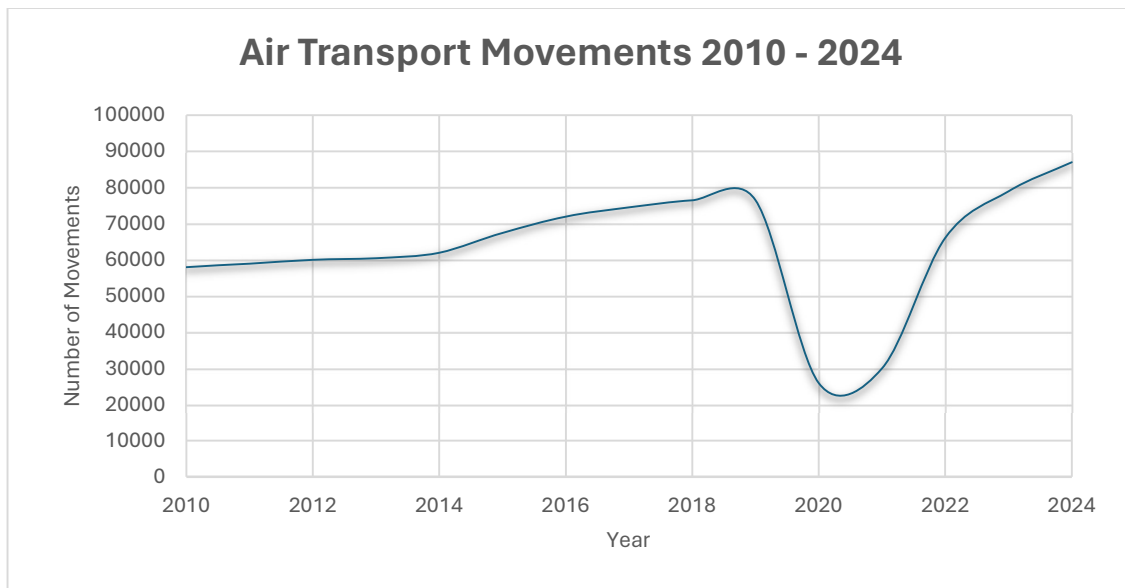


Figure 3 Air Transport Movements 2010-2024 (BRS, 2024)

With the airports increase in passenger numbers, comes the increase in energy consumption, and therefore increasing its carbon footprint.

To meet the 2030 net zero operational target, Bristol Airport has changed all their airside and landside vehicles from petrol/diesel to EV's. This in turn, has increased the airports demand for electricity. (BRS, 2024)

Figure 4 displays a notable increase in energy consumption for charging EV's between 2021 and 2022. This surge can be attributed to several factors, including the introduction of new electric vehicles across the site, the rise in passenger numbers, and the utilisation of electric buses for passenger transportation landside, and airside, to and from the terminal building and aircraft. Additionally, Figure 4 reveals a discernible trend in energy usage as more EV's are added to the fleet. With vehicles relying on air conditioning during warmer months and resorting to heating and lights during colder, darker months, EV charging is an increasing demand on the electrical supply.

Comparison of Energy used to charge Electric Vehicles (EV's) between 2021 and 2022													
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2021 Energy Used (kWh)	165	269	286	224	522	490	1706	1758	1764	3301	3762	2942	17189
2022 Energy Used (kWh)	2872	3912	5130	3289	3105	2548	2534	3617	3341	3080	3568	4815	41811

Figure 4 Energy used to Charge EV's between 2021 - 2022 (BRS, 2024)

In 2021, 17,189 kWh of energy was used to charge EV's, but in 2022 the energy used nearly tripled to 41,811 kWh (41.8MW).

To track the escalating electrical demand, Bristol Airport's Engineering department has devised a comprehensive model comparing maximum demand to maximum capacity (Figure 5). Collaborating closely with the development department, they've projected this model's trajectory up to 2033. The red line represents the historical electrical usage, closely mirroring the forecast thus far. Due to a minor setback in the completion of business partners' projects, the actual usage has temporarily lagged the projected step increase. However, it's anticipated to swiftly realign once these projects are finalised and integrated into the system.

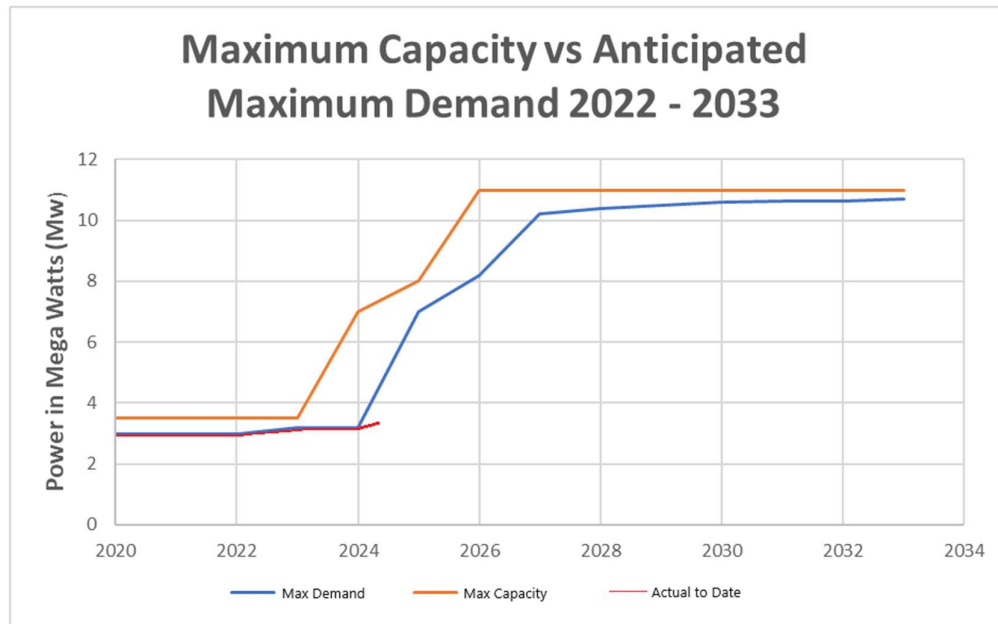


Figure 5 Maximum Capacity vs Anticipated Maximum Demand 2022-2033 (BRS, 2024)

To counteract this growing trend in electrical demand, Bristol Airport installed a 1.4MW Solar array during the summer of 2023 (Figure 6), which has generated 127,800kW over the 2023/24 winter period (Figure 7). (Withey, 2024)

Bristol Airport's New 1.4 MW Solar Array



Figure 6 Bristol Airport's New 1.4MW Solar array (BRS, 2024)

Figure 7 is a live screen shot of Bristol Airports new 1.4MW solar array's generation for the day, month, and year so far, taken on 19th of March 2024. This solar array went live on 29th of November 2024 and since then, has produced 127.8 MW's of electricity. The average daily

solar generation for the 2023/24 winter period was 1.14MW. During the hours of darkness, solar does not generate any power at all, and given the location of Bristol Airport, during the winter months, there are many days when the solar struggles to generate even low amounts of electricity.

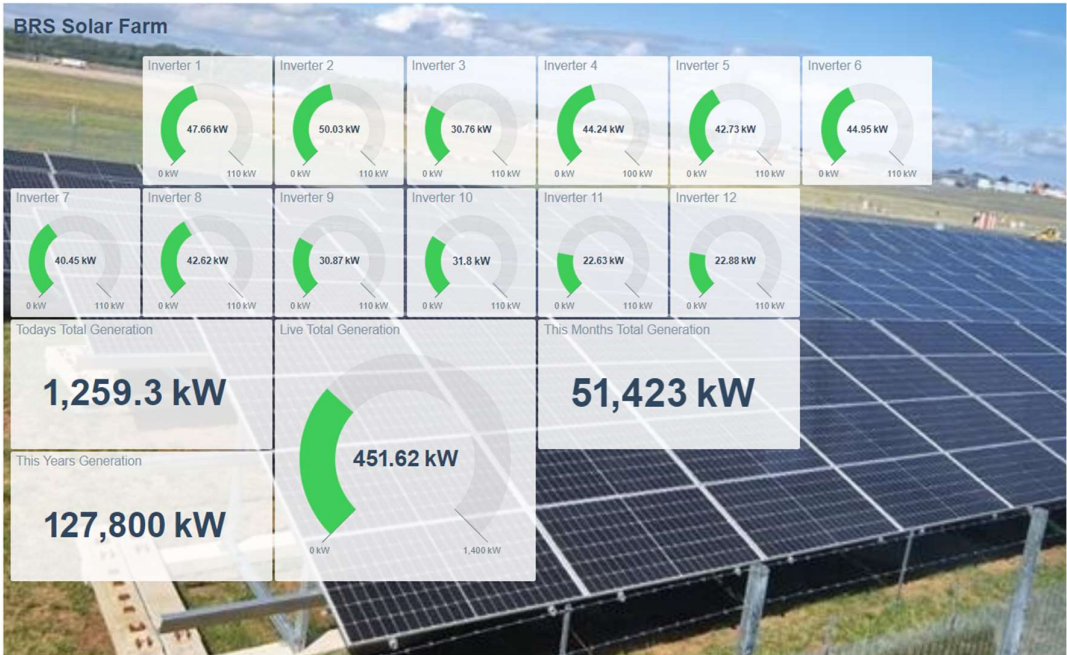


Figure 7 BRS Solar Farm Generation (Withey, 2024)

Figure 8 shows the Daily Electrical Generation produced by the new Solar Farm since going live, up until 17th of April 2024, with considerable drops in generation during the winter months.

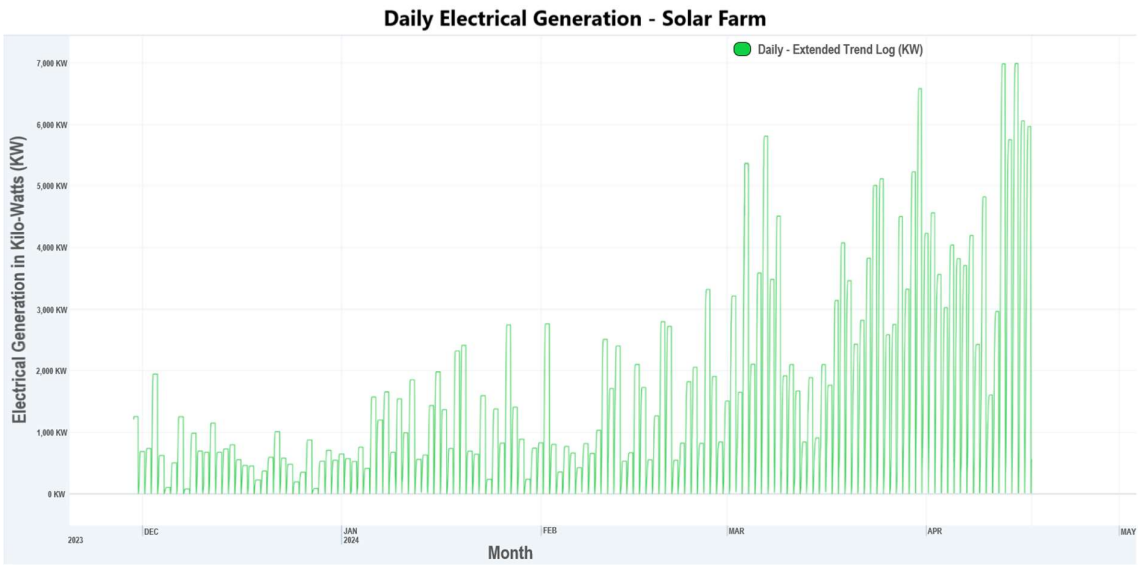


Figure 8 Daily Electrical Generation – BRS Solar Farm (Withey, 2024)

3.0 Problem Statement

While the maximum capacity model (Figure 5) suggests that Bristol Airport can maintain its operations within the eleven-megawatt limit for the next decade, it's important to highlight that this model has already integrated the projected average energy output from the new solar array, depicted in Figure 6. This integration implies limited space for further expansion of the main terminal building to accommodate additional passenger growth, given that recently, the board of directors authorised the airport permission to increase its capacity to cater for up to 12 million passengers and beyond. In addressing this challenge, Bristol Airport has set another goal of achieving twenty-five percent onsite renewable energy generation by the end of 2025. (BRS, 2024) This target aims to prevent the airport from surpassing its maximum capacity and underscores its commitment to sustainable energy practices.

Despite utilising numerous buildings' rooftops for solar generation and installing a new 1.4 mega-watt (MW) solar array, Bristol Airport falls short, achieving only twenty percent of its 2025 renewable energy target. As the maximum demand approaches the maximum capacity, exploring alternative options becomes imperative. By the end of 2025 transitioning into 2026, the airports Maximum Electrical Capacity will be 11 MW. To reach the 25% target, the airport must generate 2.75 MW of renewable energy. Despite the total site-wide generation, which includes the new 1.4 MW array, reaching 2.2 MW, there still exists a deficit of 0.55 MW.

3.1 New solar locations

In response to the successful outcomes observed from solar generation initiatives throughout the site, the board directed the implementation of an additional solar site.

Following this decision, the engineering and sustainability team engaged in discussions to identify areas suitable for potential solar development. Two promising locations were identified. However, this undertaking requires careful consideration of multiple factors.

First and foremost, the selected site must possess a clear south-facing aspect to optimise solar exposure and energy generation potential. Moreover, it is imperative that the site's positioning is carefully planned to mitigate any potential glint and glare that could interfere with aircraft operations during departure or arrival. Additionally, to ensure the safety and efficiency of flight paths, the site must be strategically located to avoid any obstruction along the direct flight path. Furthermore, practical logistics must be considered. The chosen site should be in close proximity to the airport's high-voltage (HV) ring infrastructure, enabling seamless integration into the electrical supply system.

The two potential areas identified for a future solar site were Option A (Figure 9) and Option B (Figure 12)

3.1.1 Site Option A

Option A is located to the south-east of the runway and right of the A38 road, as shown in Figure 9. This location is south of the flight path and with the panels also facing south, this should eradicate any glint and glare distracting aircraft/pilots.



Figure 9 Potential new Solar location Option A (Solarsense, 2024)

The yield

The yield	
PV Generator Energy (AC grid)	2,335,595 kWh
Grid Feed-in	2,335,595 kWh
Down-regulation at Feed-in Point	0 kWh
Own Power Consumption	0.0 %
Solar Fraction	0.0 %
Spec. Annual Yield	1,032.08 kWh/kWp
Performance Ratio (PR)	92.0 %
Yield Reduction due to Shading	1.1 %/Year
CO ₂ Emissions avoided	1,097,536 kg / year

Figure 10 Potential Yield of Site Option A (Solarsense, 2024)

Solarsense had carried out a simulation for site option A and estimated the potential results in yield and CO2 reduction (Figure 10). The simulation states that site option A is a robust solution for power generation, yielding an impressive 2.3 gigawatts of power annually and averaging just under 6.4 MW per day. Beyond its considerable energy output, this site option also champions environmental sustainability by significantly reducing carbon dioxide emissions by an estimated 1,097,536 kilograms per year. This substantial reduction underscores its efficiency in mitigating environmental impact, aligning with global efforts to combat climate change and foster a cleaner, greener future.

The simulation has generated a monthly forecast of energy production for site option A, providing a detailed projection of its anticipated output over the course of each month, depicted in Figure 11.

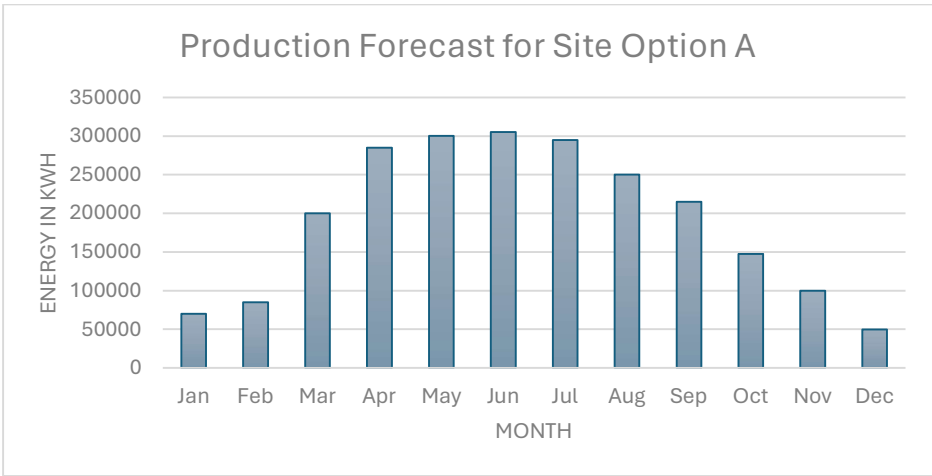


Figure 11 Production forecast for Site Option A (Solarsense, 2024)

The generation forecast depicted in Figure 11 shows a notable increase in energy production during the sunnier summer months, which is to be expected.

3.1.2 Site Option B

Option B is located to the north-east of the runway and right of the A38 road, as shown in Figure 12. This location is north of the flight path and with the panels facing south, a glint and glare assessment will need to be carried out to determine if glint and glare could be an issue for aircraft/pilots.



Figure 12 Potential new Solar location Option B (Solarsense, 2024)

The simulation suggests that even though Site Option B has a smaller footprint, it too offers a robust solution for power generation, with an annual output of 674 MW and an average daily output of 1.85 MW (Figure 13). Additionally, the simulation indicates a noteworthy reduction in carbon dioxide emissions, estimated at approximately 316,866 kilograms per year. These results underscore the potential of Site Option B to make a substantial contribution towards mitigating environmental impact.

The yield

The yield	
PV Generator Energy (AC grid)	674,313 kWh
Grid Feed-in	674,313 kWh
Down-regulation at Feed-in Point	0 kWh
Own Power Consumption	0.0 %
Solar Fraction	0.0 %
Spec. Annual Yield	970.33 kWh/kWp
Performance Ratio (PR)	91.3 %
Yield Reduction due to Shading	1.4 %/Year
CO ₂ Emissions avoided	316,866 kg / year

Figure 13 Potential Yield of Site Option B (Solarsense, 2024)

The simulation generated a monthly forecast of energy production for site option B, providing a detailed projection of its anticipated output over the course of each month, depicted in Figure 14, that also has a noticeable increase in generation during the sunnier/summer months with longer daylight hours.

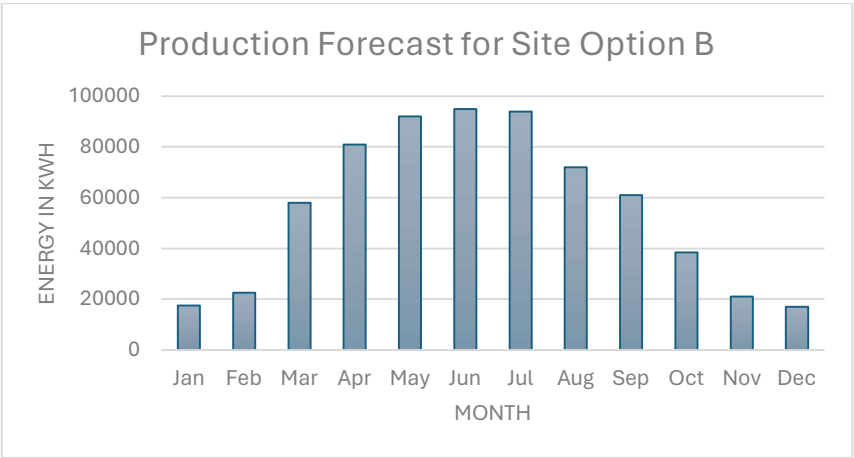


Figure 14 Production Forecast for Site Option B (Solarsense, 2024)

Despite the significant energy generation potential of both sites, which could substantially contribute to Bristol Airport's goal of achieving 25% onsite renewable energy generation by 2025 and reducing CO2 emissions, they are still subject to the limitations of no generation during night-time hours and reduced generation during the winter months.

3.2 Alternative Approach

Solar generation is a well-established approach for curbing carbon emissions and yielding significant power output during daylight hours. However, solar generation faces a notable drawback as no energy is produced during the hours of darkness. To address this limitation and support Bristol Airport in managing its maximum electrical capacity, continuous electricity generation throughout the day and night would be advantageous. A twenty-four-hour generation approach becomes especially crucial during night-time hours when the solar array remains inactive, ensuring a consistent and uninterrupted power supply to meet the airport's demands.

Countries such as Denmark have been utilising wind powered renewable generation since 1991 when the country installed the world's first offshore wind farm. Since that time, the quantity of operational offshore wind turbines in Denmark has steadily risen, with additional installations currently in progress. (Statista, 2024)

Denmark's energy landscape is predominantly influenced by wind power, with wind energy playing a pivotal role in its power mix. As of 2023, wind power constituted a significant portion, surpassing 57 percent, of the nation's total electricity generation (refer to Figure 15). This substantial reliance on wind energy underscores Denmark's commitment to renewable energy and its success in harnessing the abundant wind resources available in its geographical region.(Statista, 2024)

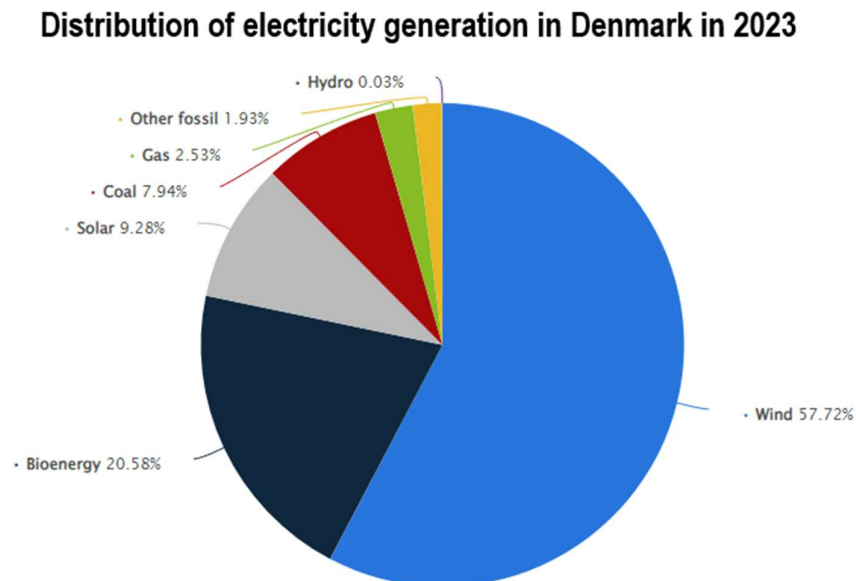


Figure 15 Distribution of Electricity Generation in Denmark in 2023 (Statista, 2024)

Due to its location, Bristol Airport encounters some very poor weather conditions and encounters high wind speeds. Between 2021 and 2023, the average wind speed at Bristol Airport was 11.75 mph, with an average gusting wind speed of 34.75 mph (refer to Figure 16) (Windfinder, 2024). Harnessing this wind energy using a wind turbine would generate electricity twenty-four hours a day.

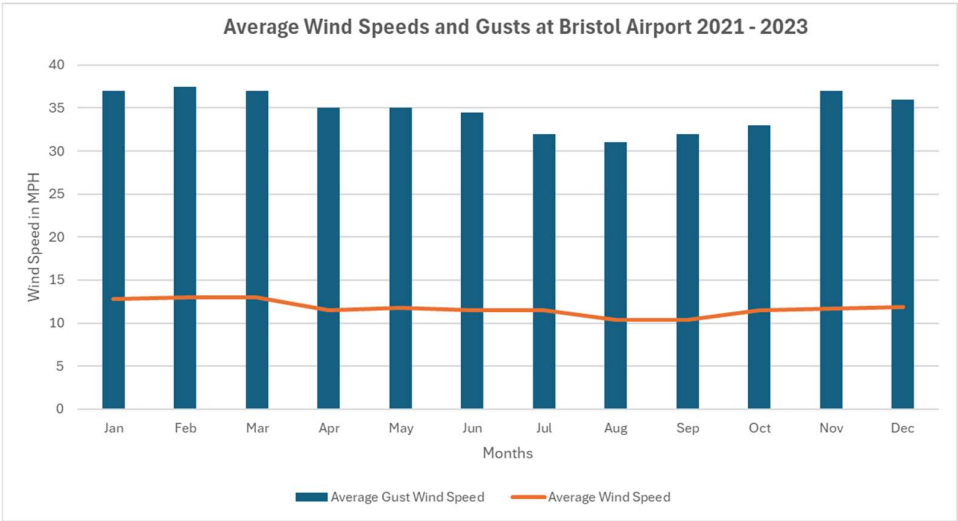


Figure 16 Average Wind Speeds at Bristol Airport 2021 - 2023 (Windfinder, 2024)

Although solar power has its merits, like predictability and suitability for distributed generation, wind power presents distinct advantages. Wind is a more efficient power source than solar. Compared to solar panels, wind turbines release less CO₂ to the atmosphere, consume less energy, and produce more energy overall and have the capacity to generate electricity in night-time or during overcast conditions. (Green, 2020)

Even though Bristol Airports location is perfect for wind powered renewable generation, it does have days during the summer months when the wind does drop off slightly. Unfortunately, this would be the time of year when the airport would be at its busiest and electrical demand would be high due to the increase energy demand to serve food and beverages to passengers and cool the terminal building with air conditioners and chillers.

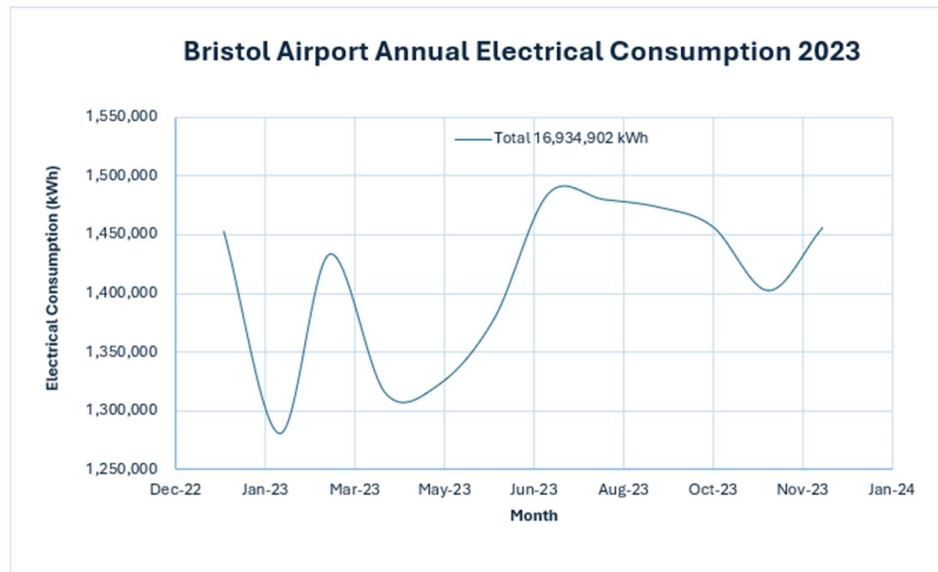


Figure 17 Bristol Airport Annual Electrical consumption 2023 (BRS, 2024)

As Figure 17 shows, there is a noticeable surge in electricity consumption during the summer months with additional smaller peaks occurring around Christmas and during the school holidays in February.

During the summer months, there could be over a million passengers a month passing through the terminal (refer to Figure 18), each wanting hot food and drinks such as burgers, full English breakfasts, or coffee, putting a high demand on the electrical supply.



Figure 18 Bristol Airport Passenger Numbers 2023 (BRS, 2024)

With this increase in passenger numbers comes an increase in air traffic movements. As stated in section 2.0 and Figure 3, in 2024 over 85,000 air transport movements have been scheduled. Each time an aircraft takes off, it requires a phenomenal amount of force to accelerate along the runway and leave the ground to become airborne. When an Airbus A320 aircraft (an aircraft used by many of Bristol Airports' carrier business partners) starts to roll, it will apply full thrust from both of its CFM international CFM56-5B engines. Each one of these engines can produce 30,000lbf (pounds of force) of thrust, which is equivalent to sixty-four Tesla model 3- performance models (0-60 in 3.1seconds) in power and can potentially push this wind flow to travel approximately 450 meters, equivalent to four and a half football pitches in length (refer to Figure 19). (CFM, 2024) (EV Database, 2024)

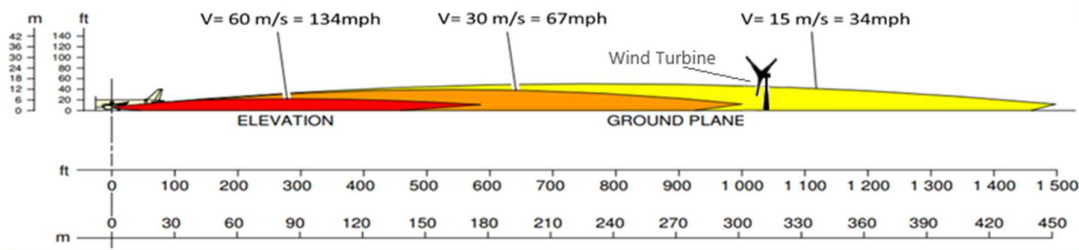


Figure 19 Airbus A320 Engine Exhaust Velocities (Airbus, 2023)

It is proposed that Bristol Airport can seize this opportunity to harness the kinetic energy dissipated into the atmosphere by these engines and convert it into electricity using a wind turbine.

4.0 Wind Turbines

A wind turbine is a device that converts the kinetic energy of the wind into mechanical energy, which can then be used to generate electricity. It typically consists of a tall tower with large blades attached to a rotor at the top. As the wind blows, it causes the blades to rotate, spinning the rotor. The rotor is connected to a generator, which converts the rotational energy into electrical energy. Wind turbines come in various sizes, from small turbines used for residential or rural applications to large utility-scale turbines used in wind farms to generate electricity for communities or power grids. They are a renewable energy technology that harnesses the natural power of the wind to produce clean and sustainable electricity.

The majority of land-based wind turbines typically boast a capacity ranging from two to three megawatts (MW), (although, this would depend heavily on the size of the wind turbine and average wind speed Figure 20) enabling them to generate more than 6 million kilowatt hours (kWh) of electricity annually. This quantity is adequate to satisfy the electricity needs of approximately 1,500 typical households. (Ettoumi, 2011)

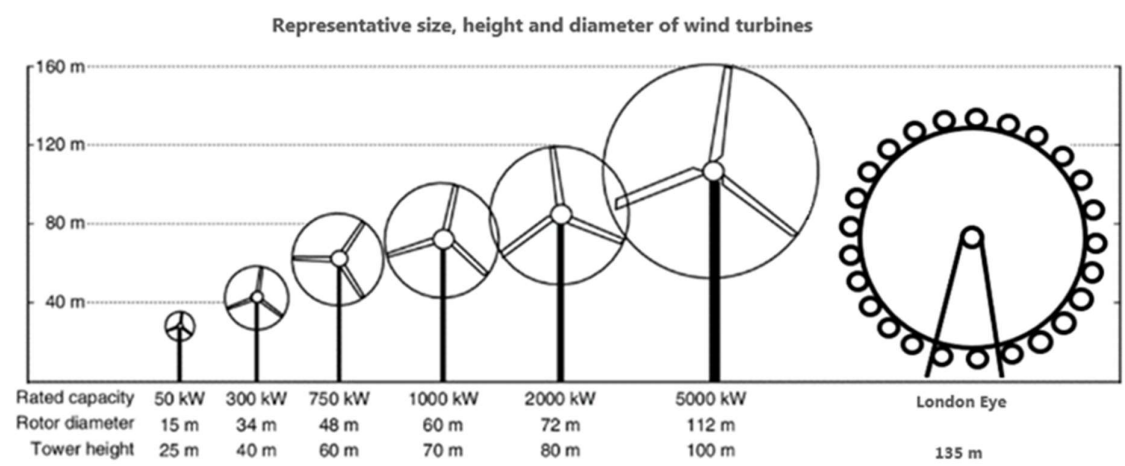


Figure 20 Representative Size, Height, and Diameter of Wind Turbines (Ettoumi, 2011)

According to recent data released by National Grid, just over 26% of the United Kingdom's electricity is now derived from wind power, refer to Figure 21. This marks a significant increase from the 7% reported in 2013, highlighting the rapid growth of wind power capacity in the UK. (GE, 2024)

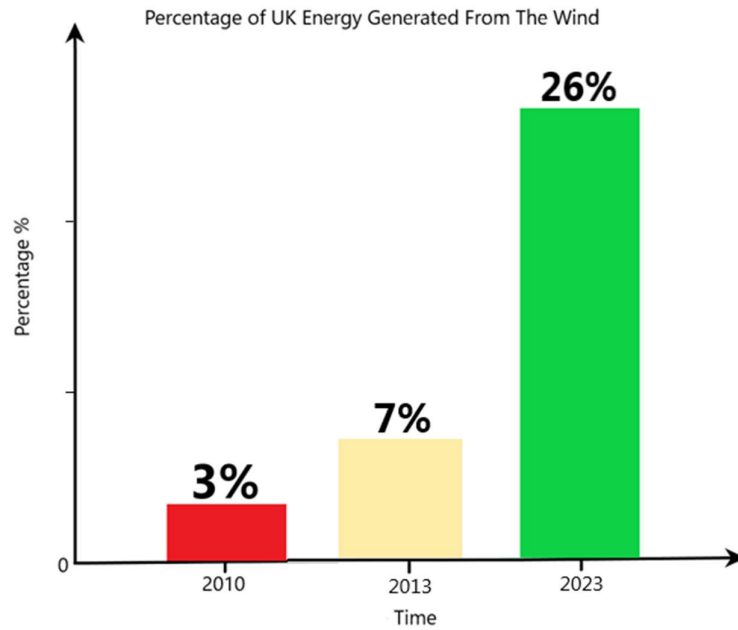


Figure 21 Percentage of UK Energy Generated from The Wind (GE, 2024)

Since the year 2000, the UK has made significant strides in renewable electricity generation, particularly from wind and solar sources (Figure 22 and Figure 23).

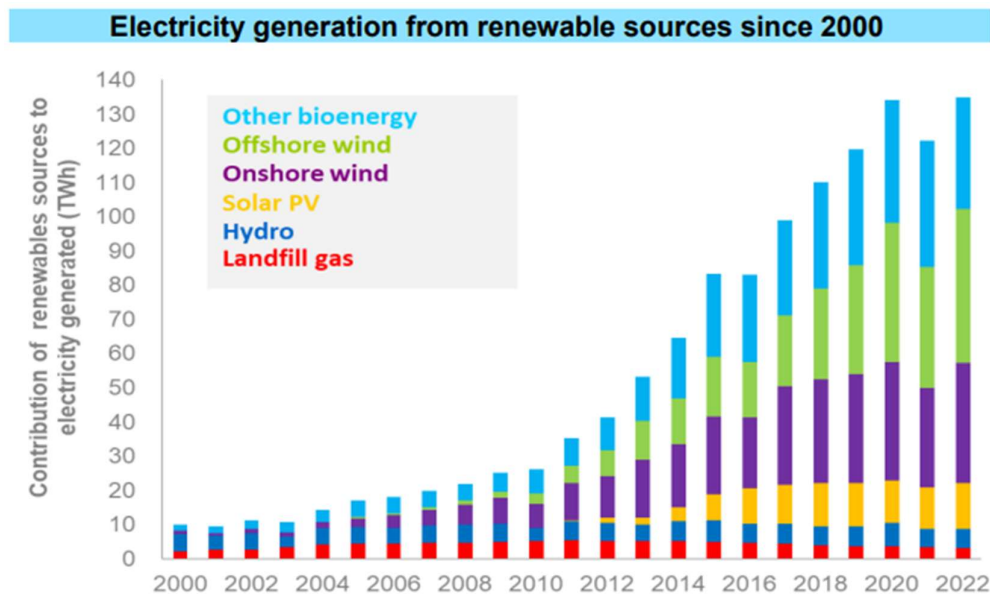


Figure 22 Electricity Generation from Renewable Sources since 2000 (ONS, 2023)

By 2024, the country has amassed an impressive 231.5 terawatt hours (TWh) of energy from wind, showcasing substantial investment and development in wind power infrastructure. In

comparison, solar renewable electricity generation has also contributed significantly but to a lesser extent, totalling 37.9 terawatt hours (TWh) over the same period (refer to Figure 23).

UK Electricity Generation from Renewable Sources Since 2000 (TWh)

	2000	2010	2020	2021	2022
Onshore wind	0.9	7.2	34.7	29.2	35.2
Offshore wind	-	3.1	40.7	35.5	45.0
Solar PV	-	0.0	12.5	12.1	13.3
Hydro	5.1	3.6	6.9	5.4	5.7
Landfill Gas	2.2	5.2	3.5	3.3	3.1
Other Bioenergy	1.7	7.0	36.0	36.7	32.7
Total Renewables	9.9	26.2	134.3	122.2	135.0

Figure 23 UK Electricity Generation - Renewable Sources Since 2000 (TWh) (ONS, 2023)

In the year 2022, renewable electricity generated from wind sources (both onshore and offshore) amounted to 80.2 terawatt-hours (TWh), while solar energy contributed only 13.3 TWh. This highlights the growing importance of both wind and solar energy in the UK's renewable energy landscape, with wind power dominating the renewable electricity generation sector. Therefore, it is proposed that Bristol Airport enhances its electricity generation by complementing solar cell generated electricity with electricity produced by wind turbines.

4.1 How a Wind Turbine works

With a generic land-based wind turbine, most commonly seen on top of hills/mountains, wind passes over the turbine blades, making them turn, which turns the central shaft. A gear box then shifts this slow rotation into a speed that's high enough to spin a generator. The generator converts the energy from the wind into green electricity and feeds this into the grid. This is depicted in Figure 24.

Components of a Wind Turbine

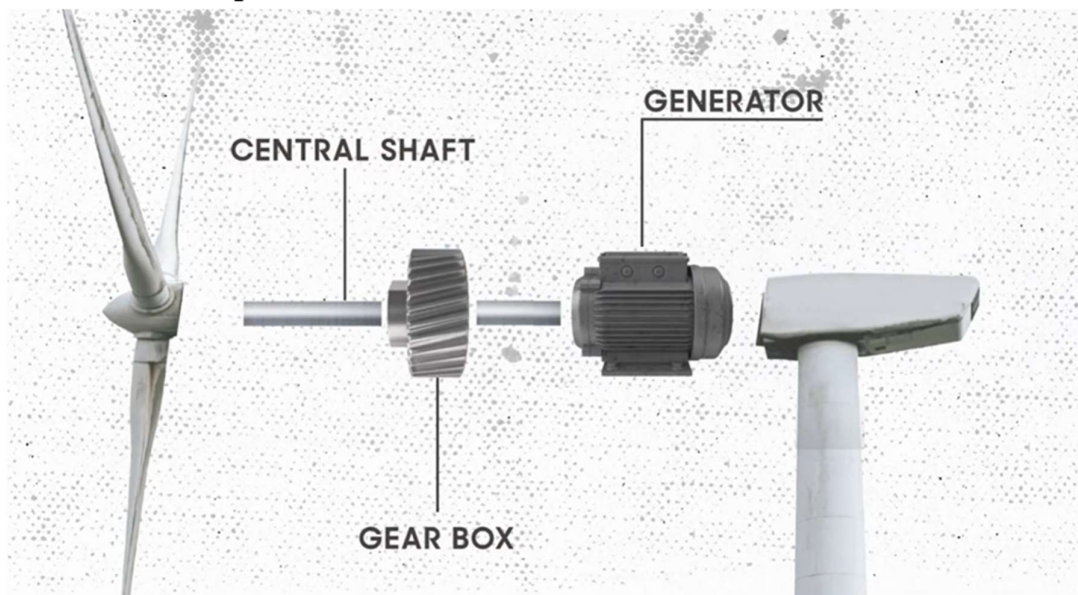


Figure 24 Components of a Wind Turbine (GE, 2024)

The strategic geographic location of the UK makes it exceptionally conducive to wind-powered electrical generation, with forty percent of Europe's wind passing over its small group of islands. Figure 25 depicts a sample wind map of Western Europe, highlighting regions such as Scandinavia, the UK, Ireland, and the Atlantic coastline of Europe as having the most advantageous wind conditions for wind energy development/generation.

Wind Map of Western Europe

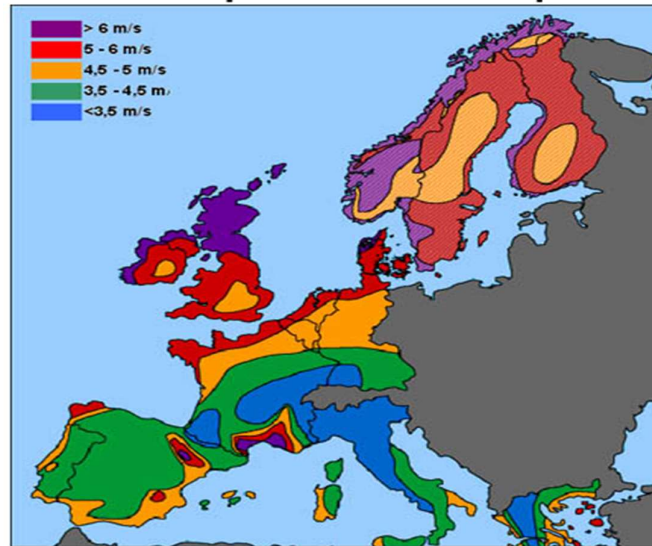


Figure 25 Wind Map of Western Europe (Hulshorst, 2008)

Wind remains a consistent resource all year-round, with its peak strength typically occurring during the darker/colder winter months, aligning with the increased electricity demand of the UK public, when there is heightened usage of heating and lighting. This inherent attribute provides wind-based renewable electrical generation with a distinct advantage over solar energy. This advantage is particularly significant given the UK and Ireland's reputation as one of the wettest and rainiest countries in Europe, where the presence of rain clouds often impedes sunlight, impacting solar energy generation potential (refer to Figure 26).

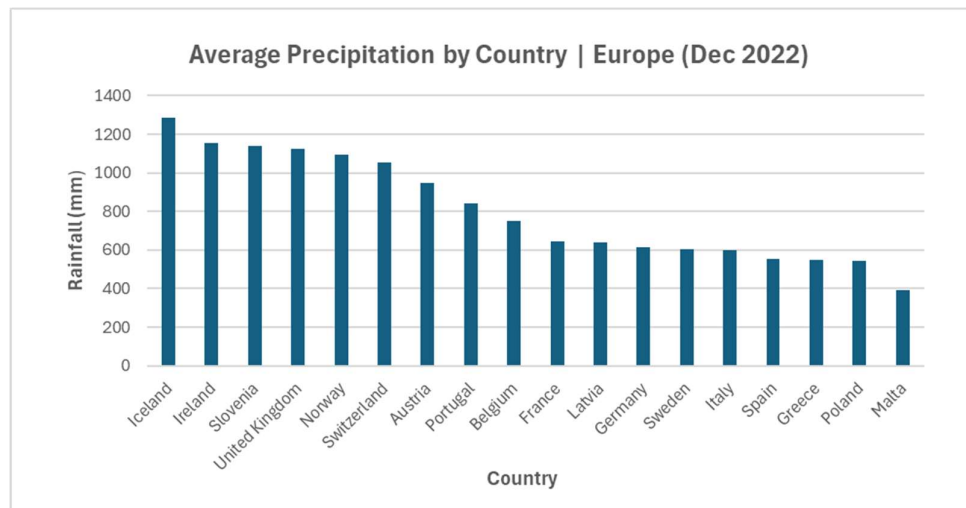


Figure 26 Average Precipitation by Country(Economics, 2023)

Unsurprisingly, Iceland does use wind turbines, but to a limited extent. Despite having abundant geothermal and hydroelectric resources, Iceland has started to explore wind energy as an additional renewable energy source. An obstacle lies in the fact that conventional tall wind turbines would rapidly become uncontrollable with Iceland's extremely strong winds, rendering their current utilisation impracticable. The average wind speed in Iceland stands at 40 miles per hour, with gusts reaching up to 112 miles per hour, particularly on stormy winter days. (Stenhouse, 2017)

In 2023, EU wind generation achieved a new record high, reaching 475 TWh, a notable increase from 420 TWh recorded in 2022 (refer to Figure 27). This marked an impressive growth of 55 TWh, equivalent to a 13% rise, representing the largest absolute increase on record. This surpasses the previous highest generation increase of 47 TWh reported in 2019. Despite a recent slowdown in wind capacity additions, 2023 witnessed record new wind installations totalling 17 GW. Wind generation is subject to significant annual fluctuations due to variances in wind conditions. Notably, in 2023, the capacity factor for wind experienced an increase owing to favourable wind conditions, resulting in a more substantial rise in generation. (Brown and Jones, 2024)

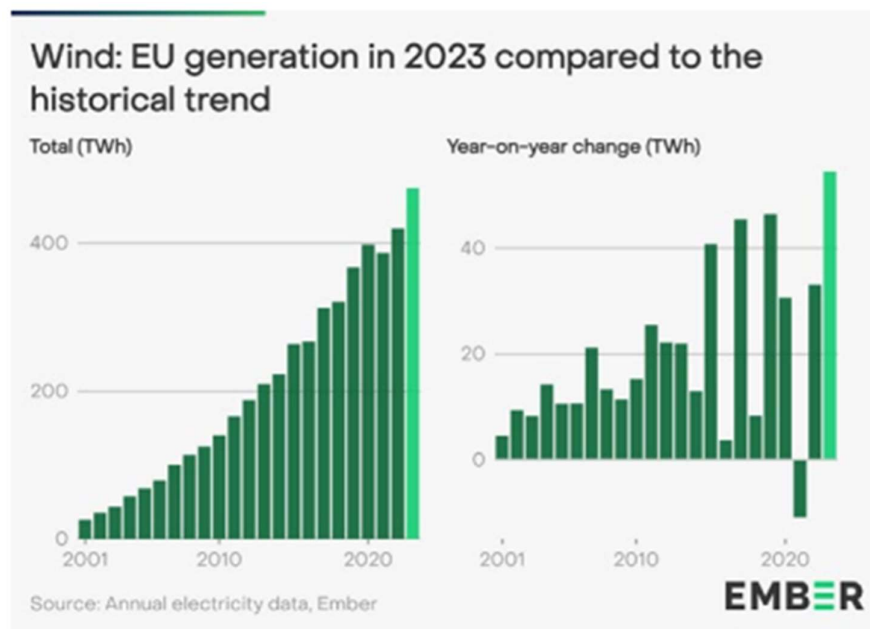


Figure 27 EU Generation in 2023 compared to Historical Trend (Brown and Jones, 2024)

As Figure 27's year-on-year change depicts, wind power generation can experience significant annual fluctuations due to variations in wind patterns. In 2023, the capacity factor for wind rose due to favourable wind conditions, resulting in a notable increase in generation. This marks the second consecutive year of growth following a decline in generation in 2021, which was the first decrease ever recorded (-11 TWh). (Brown and Jones, 2024)

4.2 Limitations and Considerations

Even though generating electricity using a wind turbine, from the jet blast of an aircraft seems straight forward, there are several factors to take into consideration:

4.2.1 Location on airfield:

The available space for installing a wind turbine within the airfield is highly constrained, primarily due to the laminar and directional airflow generated by the jet blast of aircraft. Figure 28 and Figure 29 provide visual representations of a jet blast's impact, showcasing the airflow patterns resulting from aircraft taking off from runway 27 and 09, respectively. These depicted areas of influence have been designated as Catchment Zones A and B for ease of reference. Additionally, Figure 30 presents an aerial overview of the entire airfield, highlighting both potential areas for wind turbine installation, as labelled.

Jet Blast from Airbus A320 at Catchment Zone A

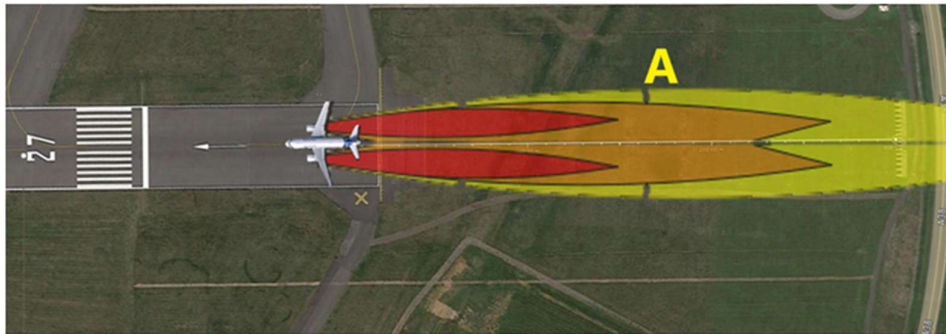


Figure 28 Jet Blast from Airbus A320 at Catchment Zone A (Google, 2024)

Jet Blast from Airbus A320 at Catchment Zone B

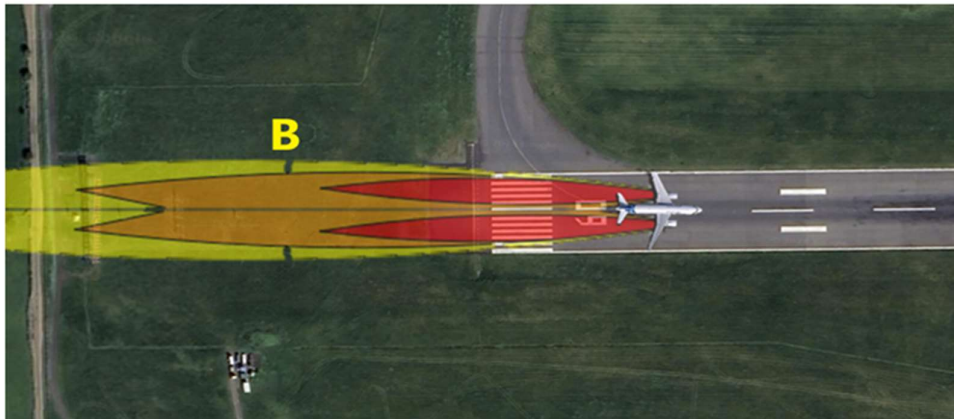


Figure 29 Jet Blast from Airbus A320 at Catchment Zone B (Google, 2024)

Aerial Overview of Entire Airfield - Highlighting Catchment Zones A and B



Figure 30 Aerial Overview of Entire Airfield Highlighting Catchment Zones (Google, 2024)

4.2.1.1 Area A

Examining Area A reveals a relatively flat terrain with occasional undulations (Figure 31 and Figure 32), offering extensive exposure to environmental elements. This openness presents a notable advantage in harnessing wind energy on a regular basis, even in the absence of aircraft arrivals or departures. Given the highly directional nature of jet blast phenomena, Area A stands to capture a significant portion of the energy expelled during take-off, while also intercepting some of the turbulent airflow generated by landing aircraft. It is important to note that any equipment/object installed within either Catchment Zone A or B, must be frangible¹.

Catchment Zone A - Terrain



Figure 31 Catchment Zone A - Terrain (Google Earth, 2024)

¹ Frangible refers to a material or structure that is designed to break or collapse easily upon impact, typically to minimise damage or injury. In the context of aviation, frangible structures are often used for objects like approach lighting systems and signs. These structures are engineered to break apart upon contact with an aircraft, reducing the risk of severe damage to the aircraft and its occupants in the event of a collision. Frangible materials are carefully selected and designed to balance durability with the ability to absorb impact energy and disintegrate safely when necessary.

Catchment Zone A - Terrain (Horizontal Aspect)

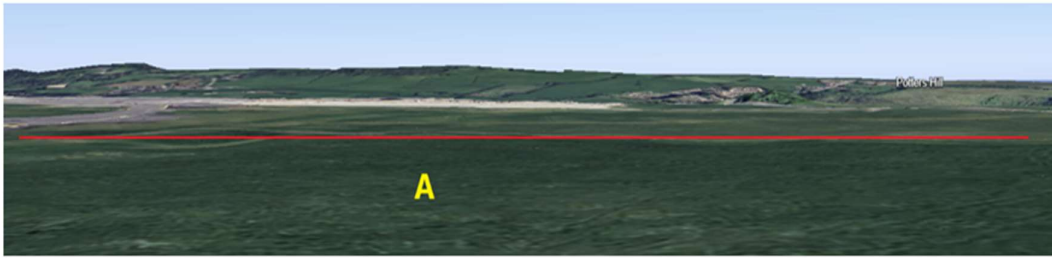


Figure 32 Catchment Zone A – Terrain (Horizontal Aspect) (Google Earth, 2024)

During the take-off phase, aircraft typically ascend into the wind for optimal aerodynamic performance. Extensive monitoring of wind direction and runway usage over the past decade has revealed that runway 27 has been utilised approximately 76% of the time (Figure 33 and Figure 34). This statistic presents another notable advantage for Area A compared to Area B, as the prevailing runway usage indicates that three-quarters of the time, aircraft would direct their jet blast towards this specific location. Consequently, Area A stands to benefit significantly from the consistent exposure to jet blast energy during aircraft take-offs, further highlighting its favourable position for wind turbine placement.

Percentage (%) of Used Runway (27 - 09) from 2013 - 2023

2013 - 2023	Westerly (27)	Easterly (09)
Average	76%	24%

Figure 33 Percentage of Used Runway (27-09) from 2013-2023 (BRS, 2024)

Percentage (%) of Used Runway (27 - 09) from 2013 - 2023

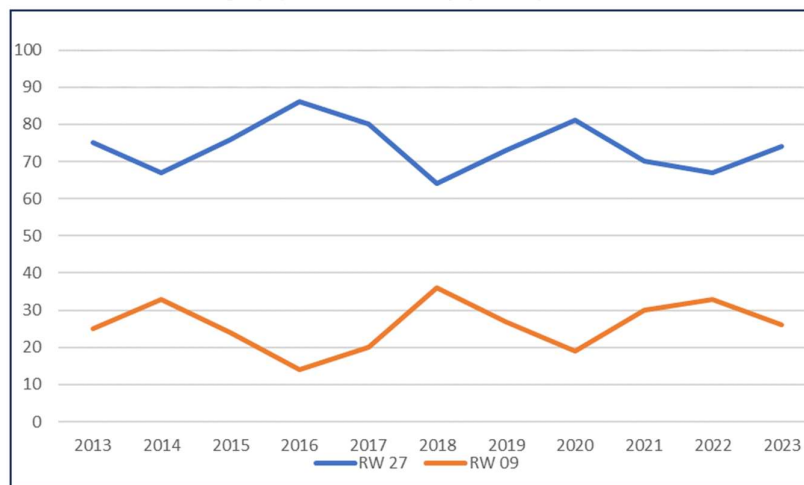


Figure 34 Graph of Percentage of Used Runway (27-09) from 2013-2023 (BRS, 2024)

4.2.1.2 Area B

Upon closer examination of Area B, a noticeable elevation change in the landscape is evident (Figure 35 and Figure 36), which poses a potential challenge for wind turbine placement. This significant drop in terrain suggests that the majority of the jet blast generated during aircraft take-offs may overshoot any wind turbine installed within this area. Furthermore, this dramatic decline in elevation could hinder the ability of a wind turbine to capture easterly winds during periods of minimal aircraft activity. As a result, the topographical features of Area B may limit the effectiveness of wind energy capture and utilisation, particularly in instances where wind direction and aircraft movements intersect.

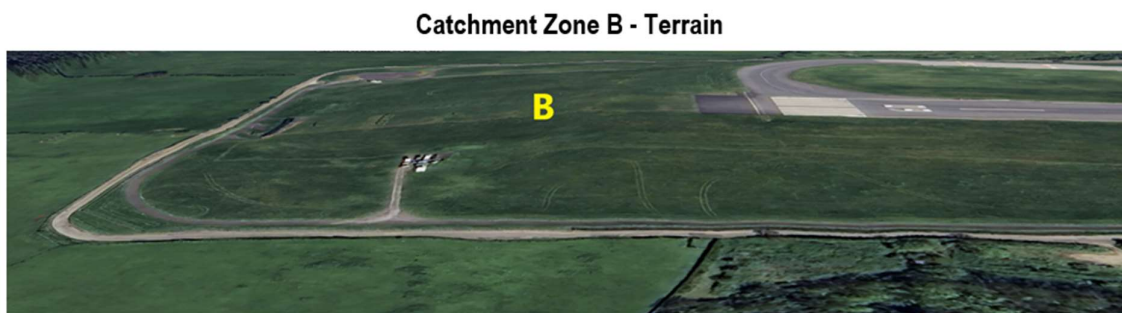


Figure 35 Catchment Zone B – Terrain (Google Earth, 2024)

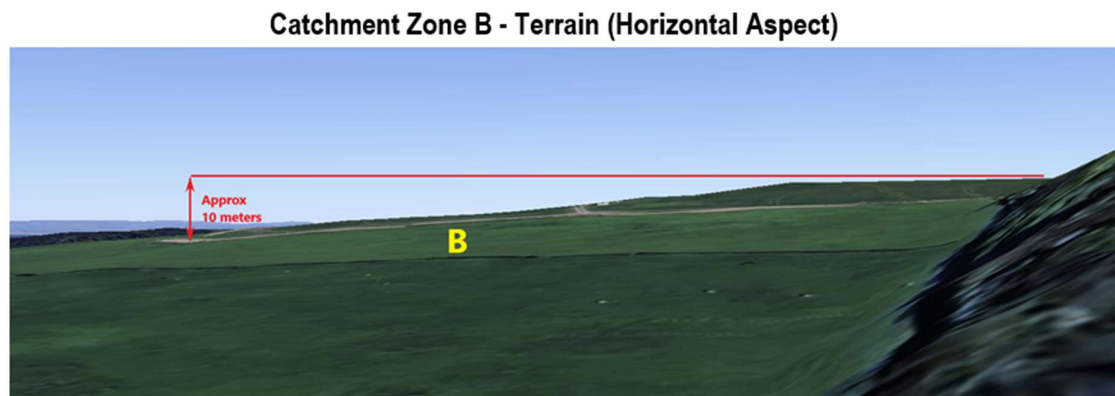


Figure 36 Catchment Zone B – Terrain (Horizontal Aspect) (Google Earth, 2024)

4.2.2 Rotating blades in the flight path as an aircraft is landing:

In typical circumstances, this scenario might be deemed impractical. However, due to the fact that the force of an Airbus A320's jet blast diminishes at an altitude of approximately 15 meters (depicted in Figure 19), it becomes feasible for a wind turbine to harness the winds generated by these blasts. In order to harness the winds generated by the jet blast, the central shaft of the turbine should be elevated to approximately 10 meters. Additionally, with a blade length of five meters, this configuration ensures sufficient clearance for incoming aircraft during landing manoeuvres.

Taking into account the angle at which aircraft approach for landing, typically around 3 degrees, they would still have an altitude of 26 meters as they pass over the turbine blades (refer to Figure 37). This altitude spans from the touchdown zone to the vicinity of the Instrument Landing System (ILS) (refer to Figure 38). This difference in height is critical for maintaining a safe distance between the landing aircraft and the rotating wind turbine blades, ensuring operational safety.

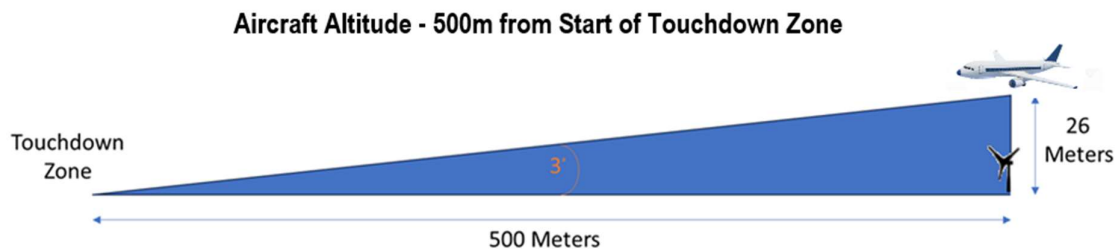


Figure 37 Altitude 500m to Start of Touchdown Zone (3DExport, 2024)(Lewis, 2024)



Figure 38 Distance between Start of Touchdown Zone and ILS (Google, 2024)

4.2.3 Interfering with the Instrument Landing System (ILS):

Introduced in the late 1930s, the Instrument Landing System (ILS) remains the most accurate approach navigational aid for pilots. It offers both horizontal and vertical guidance to a runway, enabling precise landings even without visual contact with the runway. This dual guidance capability makes an ILS approach a precision approach. Comprising two main components, the Localiser (LLZ) provides lateral guidance, while the Glide Path (GP), commonly known as the Glide Slope, offers vertical trajectory guidance. (Maaz, 2022)

Disrupting either of these components could have a considerable effect on the landing of arriving aircraft. While Catchment Zone A does not interfere with the runway 27 ILS Glide Path, it falls within the line of sight of the runway 27 ILS Localizer's beam/signal (refer to Figure 39).



Figure 39 Runway 27 – ILS Localiser Signal (Google, 2024; Lewis, 2024)

Figure 40 illustrates the typical ILS Localiser beam/signal omitted. The localiser omits two frequencies, each either side of the red centreline. Placing obstacles within these beams/signals' path of an airfield's ILS Localiser can disrupt its functionality. However, by evenly distributing the same number of obstacles on both sides of the centre of the beam, the disruption to the beam or signal will be balanced. Consequently, aircraft will still be able to accurately read the signal and safely land.

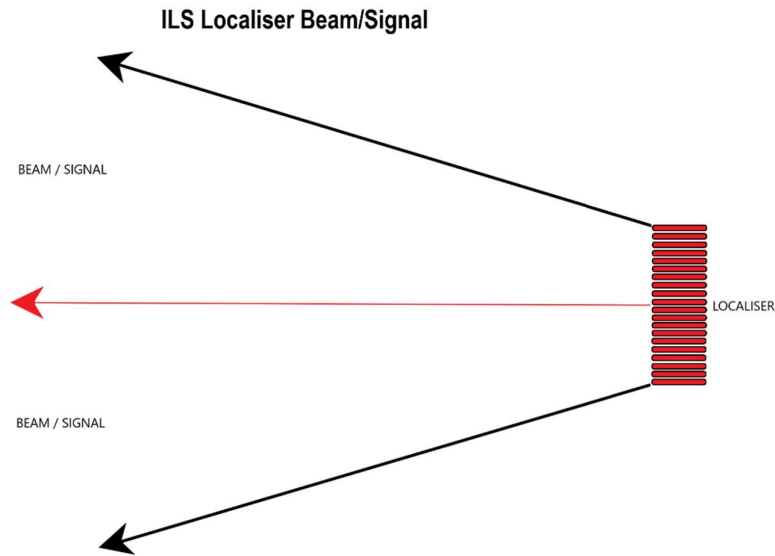


Figure 40 ILS Localiser Beam/Signal (Lewis, 2024)

When obstacles are unevenly distributed, with more obstacles on one side than the other, it results in an unequal disruption to the beam or signal, as depicted in Figure 41. This inconsistency can lead to difficulties for an aircraft to properly interpret the signal during landing. As a result, the pilot may encounter challenges or uncertainties when attempting to guide the aircraft for landing, potentially compromising the safety of the landing procedure and the passengers onboard. (Smith, 2024)

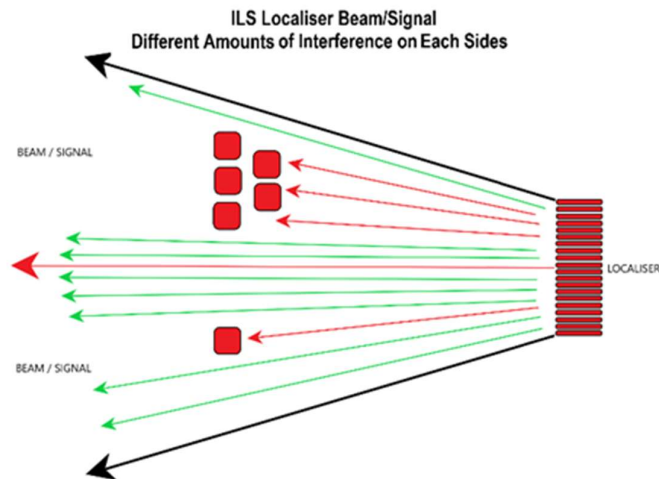


Figure 41 ILS Localiser Signal Different amounts of Interference (Smith, 2024)

Therefore, maintaining symmetry in obstacle placement relative to the ILS Localiser's beam is crucial to ensure accurate and reliable signal reception for safe landings, shown in Figure 42 and Figure 43.

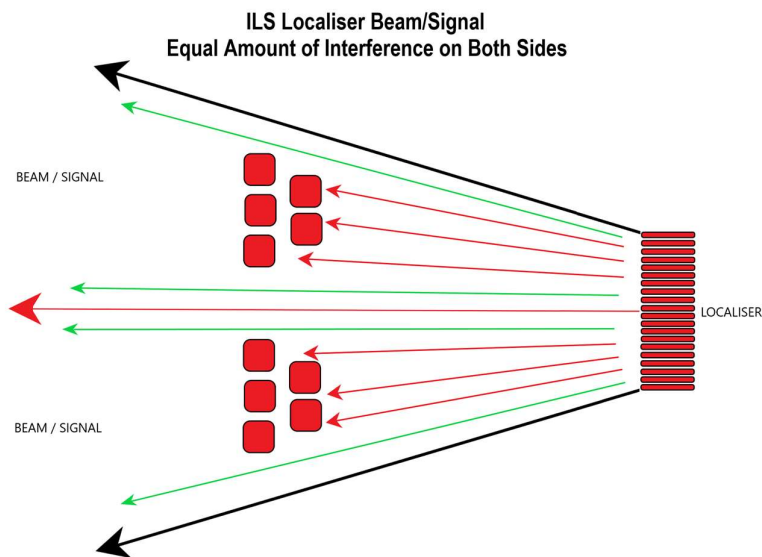


Figure 42 ILS Localiser Signal Equal Amount of Interference (Lewis, 2024; Smith, 2024)

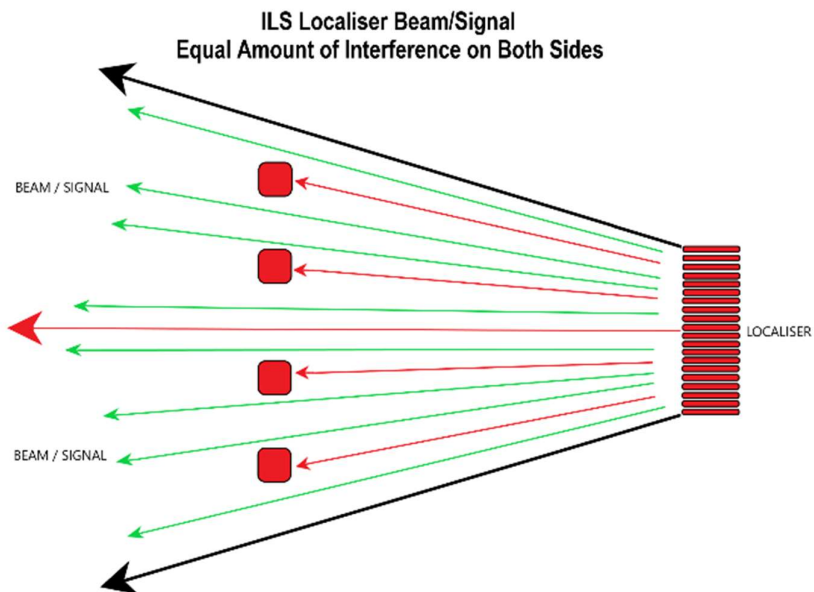


Figure 43 ILS Localiser Signal Equal Amounts of Interference (Lewis, 2024; Smith, 2024)

Even though the evenly distributing of obstacles within this area will disrupt the signal evenly, overly congesting this area can have a detrimental effect on the signal's integrity.

4.2.4 Wind Turbine Blades oscillating frequency interference

If a rotating blade of a wind turbine oscillates at a frequency similar to that of an ILS Localiser's signal frequency, it could result in significant disruptions for landing aircraft. The ILS Localiser emits a precisely calibrated signal to provide lateral guidance for aircraft during approach and landing. This signal is critical for pilots to maintain correct alignment with the runway and ensure a safe landing. Pilots calibrate the ILS system by selecting a specific frequency. The localiser component of the system functions within the VHF (Very High Frequency) band. A total of more than 40 channels are designated for localiser operations within the ILS system.

The localiser of the ILS consists of two lobes, one on each side of the runway centreline, overlapping precisely at the centreline and transmitted towards aircraft approaching for landing. To distinguish between the lobes, the right lobe is modulated to 150 Hz, while the left lobe is modulated to 90 Hz (Figure 44). This modulation allows the aircraft's ILS receiver to identify the lobe it is flying in. As the aircraft moves away from the centreline, the depth of modulation (DOM) increases, resulting in a difference in depth of modulation (DDM). The DDM is converted to an angular displacement by the aircraft receiver, indicating to the pilot the necessary correction direction. Simplifying the concept, if the aircraft receives, for instance, 20% of the 90 Hz signal and 5% of the 150 Hz signal, there is a frequency difference of 15%, guiding the pilot to adjust the aircraft's position accordingly. (Maaz, 2022)

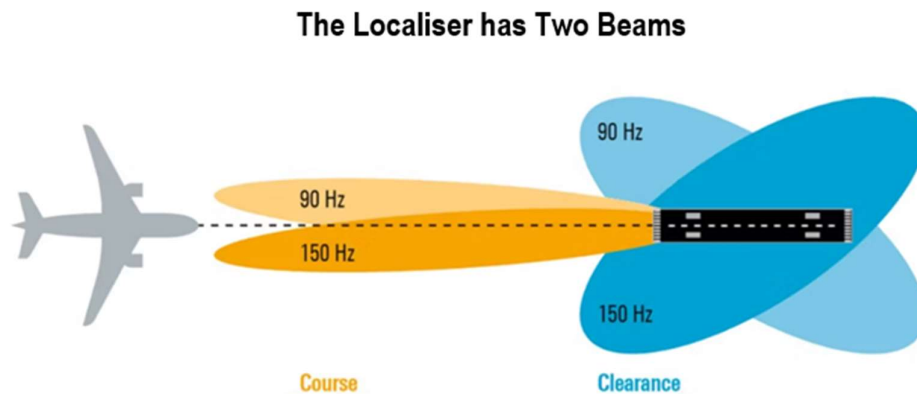


Figure 44 The Localiser has Two Beams (Maaz, 2022)

When a wind turbines' blade rotates at a frequency that coincides or closely matches the frequency of the ILS Localiser's signal, it can interfere with the reception and interpretation of the signal by the aircraft's navigation equipment. This interference can manifest as signal distortion, signal loss, or misleading signal readings for the aircraft's onboard systems.

As a result, pilots may experience difficulties in accurately tracking the ILS guidance, leading to challenges in maintaining proper alignment with the runway during approach and landing.

This could potentially compromise the safety and precision of the landing procedure, increasing the risk of incidents or accidents.

Therefore, it is imperative to assess and mitigate any potential frequency interference between wind turbine operations and critical navigation aids like the ILS Localiser to ensure the safety and efficiency of aircraft operations during landing.

The oscillating frequency of wind turbine blades can be controlled through a process called damping. Damping systems within the turbine adjust the pitch angle of the blades in response to changes in wind speed and direction. When wind blows, sensors detect these changes and signal the control system to adjust the pitch angle of the blades. By altering the angle, the turbine can modulate the resistance to the wind, thereby dampening the oscillations and regulating the frequency of the blade movement. This control mechanism ensures that the turbine operates within safe and efficient parameters, optimising energy generation while minimising structural stress and optimising the efficiency and safety of energy generation.

Although frequency damping in wind turbines is not directly related to assisting with interruptions to an ILS localiser signal, the importance of maintaining clear and reliable communication between the localiser and aircraft navigation systems remains paramount for safe and accurate landings. (Yang et al., 2023)

The rotational speed of a wind turbine is not measured in hertz (Hz), but typically measured in RPM (Rotations per Minute), and represents the number of complete rotations the blade makes in one minute. On average, a wind turbine spins at a rate of 15-25 RPM. (Hutt, 2022)

For example, if a wind turbine rotates at 20 RPM, the frequency in hertz would be:

$$Frequency\ Hz = \frac{Rotational\ Speed\ RPM}{60}$$

$$Frequency\ Hz = \frac{20}{60} = 0.33\ Hz$$

Although the resulting rotational frequency of 0.33Hz will not directly interfere with the 90Hz and 150Hz signals produced by the ILS, there is still a possibility for a wind turbine's rotational frequency to create interference, particularly if it exhibits a harmonic relationship with the

frequency of the ILS signal. In such scenarios, the rotating blades of the turbine could induce vibrations or air fluctuations that might impact the stability or clarity of the signal. Nevertheless, contemporary wind turbine designs and advanced signal processing technologies are usually engineered to mitigate such interference. To ensure the integrity of the ILS signal, it is recommended that if a wind turbine is installed in the vicinity of the localiser, it should be positioned behind the localiser to eliminate any potential disruption to the ILS signal. (Smith, 2024)

4.2.5 Being damaged or even blown away by the jet blast

As depicted in Figure 19, at full power, the exhaust blast of an aircraft can typically reach speeds of 130 mph, extending up to 180 meters beyond the aircraft. To put these values into perspective, it's helpful to consider the Saffir-Simpson Hurricane Intensity Scale, depicted in Figure 45. At the extreme end of the scale is Category 5, characterised by winds exceeding 150 mph. In such conditions, residential and industrial structures would suffer roof failure, while weaker structures would likely collapse entirely. Mobile homes, utility buildings, and objects like trees would sustain extensive damage or be completely destroyed. Remarkably, at take-off thrust levels, the Airbus A320's jet blast approaches wind speeds associated with a Category 5 hurricane, highlighting the immense force and potential for destruction it carries.

> HURRICANE WIND SPEED		
>> SAFFIR-SIMPSON SCALE		
CATEGORY	WIND SPEED (MPH)	DAMAGE
1	74-95	SOME
2	96-110	EXTENSIVE
3 MAJOR	111-129	DEVASTATING
4 MAJOR	130-156	CATASTROPHIC
5 MAJOR	157+	CATASTROPHIC

Figure 45 Saffir-Simpson Hurricane Intensity Scale (Liggit, 2020)

Therefore, existing within the jet blast catchment zone presents severe safety hazards to individuals, vehicles, and structures, making it imperative to maintain a clear area around an aircraft during take-off and landing. To safeguard the wind turbine's integrity, it is recommended that any installation occurs at a safe distance from the aircraft to minimise the risk of damage or destruction, while remaining close enough to capture the kinetic energy produced by the jet blast.

As illustrated in Figure 26, Iceland had the greatest average precipitation across all the whole of Europe during December 2022, suggesting that renewable energy via wind would be more beneficial than solar, but due to Iceland's prevailing weather conditions, including robust winds, this poses a unique challenge for traditional wind turbine setups. These forceful and erratic winds can create significant obstacles for standard wind turbines, potentially resulting in issues like turbine over speeding or loss of control. Consequently, deploying conventional wind turbines in such environments becomes increasingly impractical.

5.0 Wind Turbine Options

5.1 Generic Wind Turbine

Several limitations were raised in section 4.2 for erecting a generic wind turbine (depicted in Figure 46) within either of the Catchment zones. These limitations included:

- The height of the wind turbines structure could cause interference with landing aircraft,
- The structure being damaged by jet blast if erected too close,
- Potential interference to ILS created by the rotating blades.

Other disadvantages of a generic wind turbine to be taken into consideration are:

- Due to the size of these structures, if a turbine collapses, it falls with enormous force, potentially injuring or killing anyone nearby. A structure of this size falling within either catchment zone could cause tremendous damage to nearby aviation instrumentation or equipment,
- Large wind turbines can interfere with radar systems, reduce visibility, and could lead to aircraft accidents,
- Rotating blades kill a lot of birds. One study estimates that wind turbines kill more than 1.1 million birds each year. (Elstad, 2024)

Generic Wind Turbine



Figure 46 Generic Wind Turbine (Andrew, 2019)

Therefore, several bladeless wind turbine alternative options have been investigated.

5.2 Bladeless Wind Turbines

Bladeless wind turbines are a relatively new technology that represent a cutting-edge advancement in the realm of renewable energy technology, offering a promising avenue for the future. Unlike traditional wind turbines with rotating blades, these innovative turbines utilise a novel design that eliminates the need for large, spinning structures. Instead, bladeless turbines harness wind energy through oscillating or vibrating mechanisms, revolutionising the way wind power is captured and converted into electricity. This emerging technology not only has the potential to increase energy efficiency but also addresses concerns such as noise pollution, visual impact, and bird collisions associated with conventional wind turbines. As research and development in this field continues to progress, bladeless wind turbines hold significant promise for transforming the renewable energy landscape and fostering sustainable energy solutions on a global scale. (Elstad, 2024)

5.2.1 Vortex Bladeless

The Vortex bladeless wind turbine is ingeniously simple in design, facilitating straightforward manufacturing, installation, and operational processes (depicted in Figure 47).

Vortex Bladeless Wind Turbines in Testing



Figure 47 Vortex Bladeless Wind Turbines in Testing (Vortex, 2024)

Consisting of a fixed base and a cylindrical mast, the turbine oscillates freely in a direction perpendicular to the wind's flow, connected by a carbon rod. This design ensures that the

internal components never collide, yet effectively interact to generate electricity from wind energy. The movement and components of the Vortex Bladeless is depicted in Figure 48.

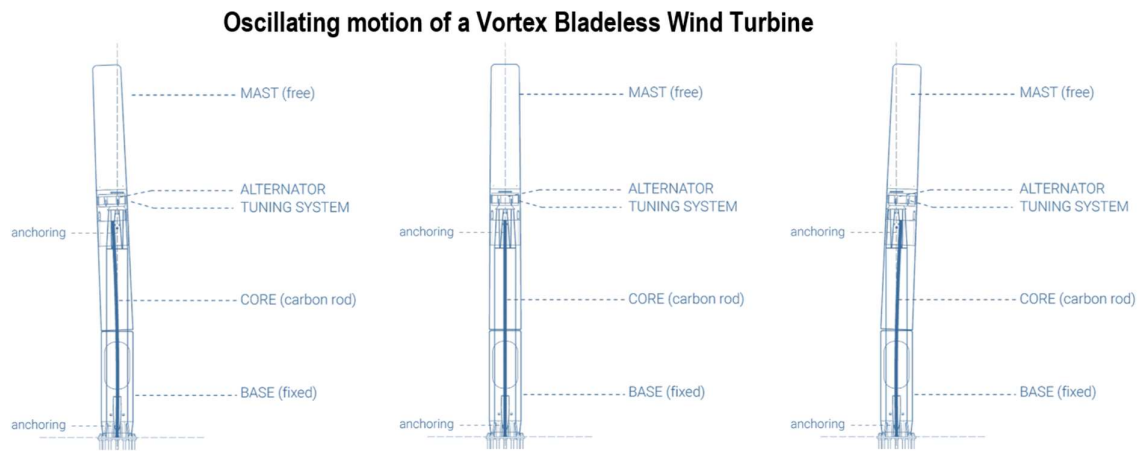


Figure 48 Oscillating motion of a Vortex Bladeless Wind Turbine (Vortex, 2024)

When comparing the Vortex Bladeless Wind Turbine with a conventional wind turbine, the absence of moving parts translates to significant savings in mechanical maintenance costs. Without sweeping blades, the bladeless turbine poses less threat to wildlife such as birds and bats. Vortex turbines offer the potential for reduced manufacturing and maintenance expenses owing to their simplified design with fewer moving parts compared to traditional design. Additionally, they can capture energy from turbulent winds more efficiently than traditional turbines, making them suitable for more diverse geographical locations. (Vortex, 2024)

When comparing the Vortex Bladeless turbines to Solar generation, it can be noted that; unlike solar panels, Vortex turbines can generate electricity day and night as long as there is wind, providing a more consistent power supply. When installed within the catchment zone of an aircraft's jet blast, every time an aircraft takes off, day or night, electricity will be generated. While solar panels require large land areas for installation, Vortex turbines can be placed on smaller plots of land, making them more suitable for locations with limited space. (Vortex, 2024)

Even though there are very minimal moving parts on the Vortex Bladeless wind turbine, the turbine still oscillates and could potentially create harmonics and cause interference to the ILS system. Therefore, for the Vortex Bladeless wind turbines to be installed within catchment zone A, it is recommended that a construction zone behind the ILS Localiser be investigated further (refer to Figure 49).

By installing Vortex Turbines at Bristol Airport, these turbine would complement solar energy generation, allowing for a diversified renewable energy portfolio.

Proposed Construction zone behind 27 ILS Localiser

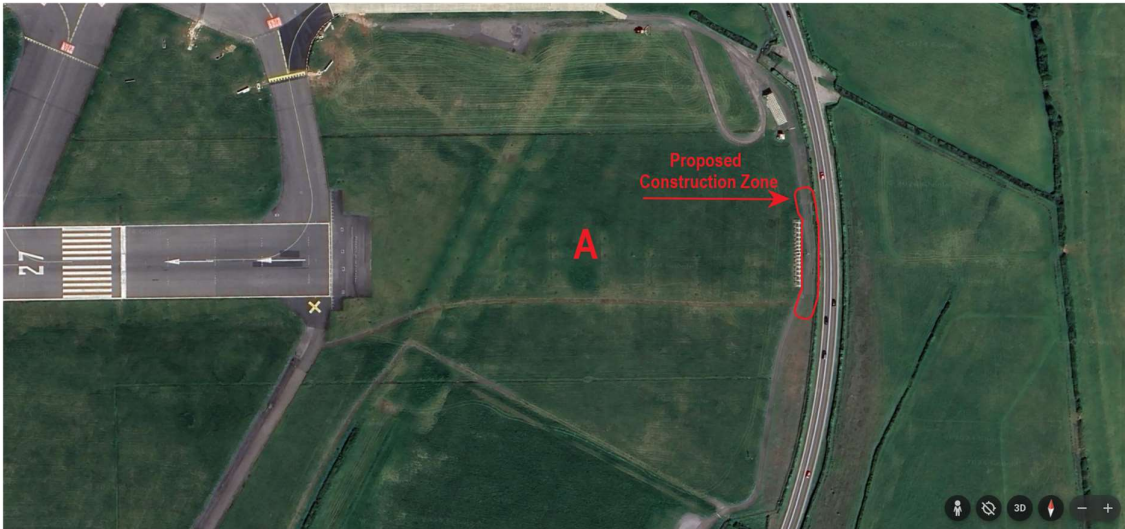


Figure 49 Proposed Construction Zone behind 27 ILS Localiser (Google Earth, 2024)

5.2.2 Katrick Technologies

Katrick Technologies' innovative Wind Panel breaks away from conventional wind turbines by forgoing rotational mechanisms to harness wind energy. Their design features oscillating aerofoils that traverse the entire duct (depicted in Figure 50), effectively capturing wind energy from low-level turbulent and gusty winds. This dynamic movement allows the technology to swiftly adapt to sudden fluctuations in wind speeds typically encountered in ground-level conditions.



Figure 50 Katrick Technologies Bladeless Wind Turbine (Ketrick, 2024)

Unlike traditional wind turbines, Katrick Technologies' bladeless wind turbine employs a distinctive design that eliminates the need for large spinning blades (refer to Figure 50). Instead, it harnesses wind energy through oscillation and resonant frequencies, resulting in a more compact and bird-friendly solution. This groundbreaking design addresses several drawbacks associated with traditional wind turbines, including noise pollution, visual impact, and potential harm to wildlife.

In comparison to solar energy, Katrick Technologies' bladeless wind turbine offers distinct advantages. Solar power relies on sunlight and is therefore limited to daylight hours, and as with all wind turbines, wind energy can be harnessed day and night, making it a more consistent and reliable source of renewable energy. Additionally, this bladeless wind turbine's compact design makes it suitable for a wide range of locations, including urban and residential areas where space may be limited. Several options for positioning the Katrick Wind turbine are depicted in Figure 51 and Figure 52.

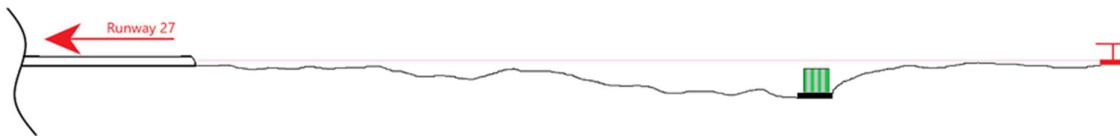


Figure 51 Katrick Turbine - Catchment Zone A (Lewis, 2024)

In Figure 51, the Katrick turbine is installed within the dips of the terrain within Catchment Zone A. Therefore, limiting the potential impact on the ILS signal. Although this is an advantage, installation cost would be higher as ducts for cables would need to be installed to transfer electricity from the turbine to the high voltage network. Additionally, by installing the turbine here, a lot of the wind energy would pass over the turbine and get missed.



Figure 52 Katrick Turbine Installed between ILS Aerials (Lewis, 2024)

Figure 52 shows the turbine installed between the aerals of the ILS. When installing these turbines between the ILS aerals, testing would need to be carried out to ensure no harmonics are produced. Shielded cabling, filters and active harmonic control may also be required to protect against interference towards the ILS. Nineteen units could be installed here between the twenty aerals of the ILS. (Bristol Airport's 27 ILS Localiser Figure 53). (Csanyi, 2011; Lewis, 2024)



Figure 53 Bristol Airports 27 ILS Localiser (Lewis, 2024)

In contrast, rotary motions are most effective at higher elevations (above 10 meters) where the wind exhibits more laminar characteristics. With fewer abrupt changes in wind speeds and directions, the rotational action of wind turbine blades efficiently captures a greater amount of wind energy. (Ketrick, 2024)

Overall, Katrick Technologies' bladeless wind turbine represents an innovative and eco-friendly alternative to traditional wind turbines, offering enhanced efficiency, reduced environmental impact, and greater flexibility in deployment compared to solar energy.

5.2.3 Halcium PowerPod

The Halcium PowerPod is a bladeless wind turbine designed to harness wind energy in a highly efficient and innovative manner. This cutting-edge technology offers several advantages over traditional wind turbines and solar energy. Figure 54 shows the five different colour option available, allowing the customer to integrate the PowerPod into its surroundings.



Figure 54 Halcium PowerPod (Halcium, 2024)

Unlike traditional wind turbines, the Halcium PowerPod does not have any external moving parts. Instead, the blade is contained entirely within the stationary shell, making it safe for kids, pets, and wildlife. This eliminates noise pollution, reduces visual impact, and mitigates potential harm to wildlife, making it an environmentally friendly option.

Airflow is gathered from all directions (depicted in Figure 55), with the aim of channelling it through the exterior of the pod and directing it towards an internal circular blade. The outer shell remains stationary, securely fixed in position. Thanks to its design, the pod can harness wind from any angle, adapting to changes or even multiple wind directions simultaneously. In contrast, conventional turbines under such conditions are prone to breaking, potentially hurling blades at high velocities. (Halcium, 2024)



Figure 55 PowerPod 360° Intake (Halcium, 2024; Lewis, 2024)

As with all wind turbines, the PowerPod can generate electricity from wind energy day and night, providing a more consistent and reliable source of renewable energy compared to solar.

The versatile compact design of the Halcium PowerPod makes it ideal for installation in various locations, including urban and residential areas where space may be limited. This versatility in deployment makes it an excellent option for decentralised energy production. (Halcium, 2024)

As illustrated in Figure 56, the PowerPod can also be installed within the dips of the terrain of catchment zone A, but as with the Katrick turbine, the same negative characteristics occurs. The jet blast will travel over the turbine and the issues of addition ducting/groundworks cost remain.

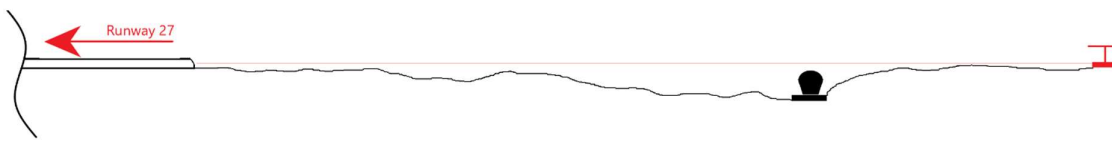


Figure 56 PowerPod – Catchment Zone A (Lewis, 2024)

As with the Katrick Turbine, installing the PowerPod within the ILS aerals is also an option, as depicted in Figure 57.

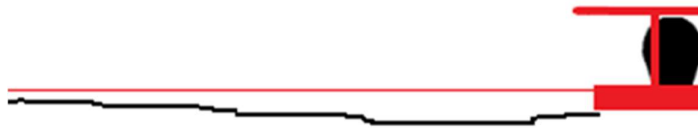


Figure 57 PowerPod Turbine Installed between ILS Aerials (Lewis, 2024)

For the PowerPod to be installed between the ILS aerals, all cables would need to be shielded to reduced the potential of interference to the ILS signal. Even though the PowerPod has no external moving part, with an internal rotating circular blade, testing would need to be carried out to ensure that any harmonic interference/distortion produced is mitigated using electronic devices such as filters or active harmonic control techniques. (Csanyi, 2011)

5.2.4 AeroMine

Aeromine wind turbines represent an innovative form of renewable energy technology designed to capitalise on the kinetic energy of the wind to produce electricity sustainably. Unlike traditional wind turbines with rotating blades, Aeromine turbines employ motionless wind energy systems (Figure 58). This unique approach eliminates visible moving components, ensuring a quiet operation that minimises disturbances to wildlife habitats. (Aeromine, 2024)

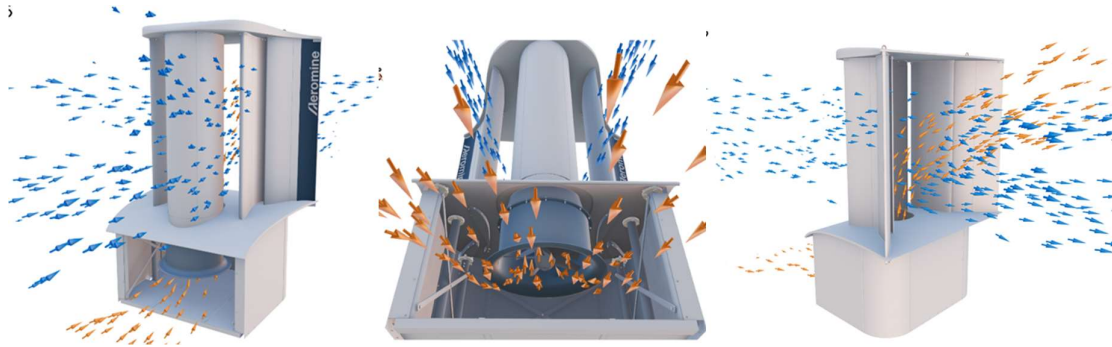


Figure 58 Aeromine Wind Turbine (Aeromine, 2024)

Additionally, the absence of moving parts reduces maintenance demands, contributing to long-term reliability and cost-effectiveness. A benefit of Aeromine wind turbines lies in their flexibility regarding placement. These turbines offer versatility, capable of integration into building structures or functioning as independent units. This versatility mirrors that of solar panels, facilitating deployment in diverse environments, including constrained spaces or regions with limited sunlight availability. As with all wind turbines, Aeromine wind turbines also have the advantage of being able to operate in cloudy or dark conditions, providing a distinct advantage over solar energy. (SNL, 2020; TMS, 2024)

The Aeromine wind turbine was originally designed to sit on top of a building and take advantage of wind hitting the side of a building and travelling up and into the bottom of the unit (as depicted in Figure 59 and Figure 60). Although, to capture the energy from a jet blast, the positioning of this unit would need to be slightly different. (SNL, 2020)



Figure 59 Aeromine Turbines on Roof of Building (Aeromine, 2024)

Air travelling through the Aeromine Turbine

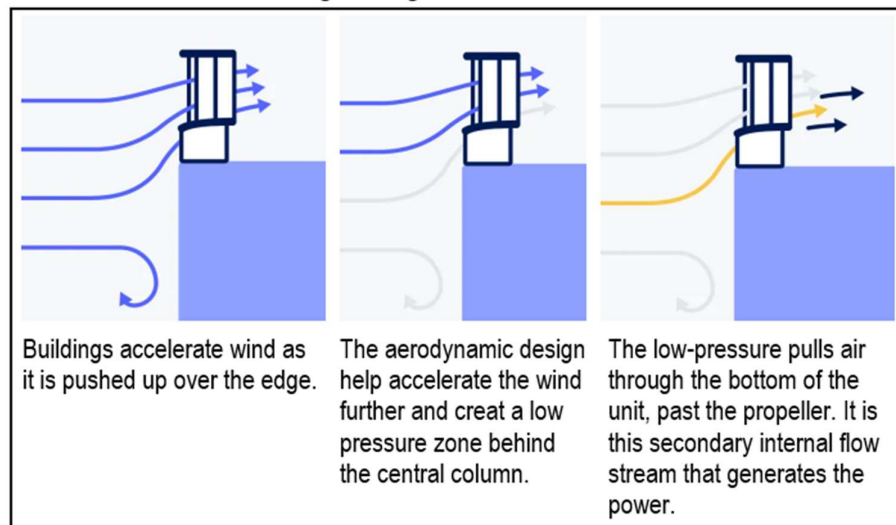


Figure 60 Air travelling through the Aeromine Turbine (Aeromine, 2024)

To harness the energy of an aircrafts jet blast, the proposed solution for the Aeromine turbine involves positioning the turbine behind the 27 ILS Localiser, as illustrated in Figure 61. This setup entails the installation of a modified blast ramp/wall, strategically designed to guide the airflow into the turbine. By directing the previously untapped energy towards the turbine, this innovative approach aims to capture and utilise the kinetic energy that would otherwise go to waste.



Figure 61 Aeromine on Structure – behind 27 Localiser (Lewis, 2024)

With the Aeromine positioned behind the 27 ILS Localiser, there will be little to no interference to the ILS signal. Although, testing would need to be carried out to ensure that no harmonic interference/distortion was being produced.

To capture the strongest winds of the jet blast (refer to Figure 19) the base of the Aeromine would need to sit at a height of 10 meters (at a distance 300 meters behind an aircraft). With the Aeromine sitting at four and a half meters in height, this would give an overall height of just below 15 meters. Given that an aircraft would have an altitude of twenty-six meters at this point (refer to Figure 37), there would be eleven meters clearance. (Aeromine, 2024; Lewis, 2024)

As with all wind turbines the Aeromine benefits from continuous 24/7 electrical generation. However, in contrast to the other three alternative bladeless wind turbines, the Aeromine can only achieve its peak performance and operate at its full capacity from a singular direction.

5.3 Comparison of Alternative Bladeless Wind Turbines

In comparison, the examination of four distinct bladeless wind turbine options reveals a diverse landscape of innovative technologies with unique features and advantages to assist Bristol Airport with their electrical capacity model, by capturing kinetic energy from an aircrafts jet blast and the high winds encountered at the airport, and converting it into electricity.

When assessing the electricity generation of each turbine (Figure 62) in their optimal positions, the Katrick Wind Turbine emerges as the top performer, capable of producing 4.5 MW of electricity within a 24-hour timeframe. In contrast, the Halcium PowerPod generates the least amount of electricity, yielding only 0.45 MW within the same timeframe.

Turbine	Generation per Unit per Hour (kW)	Generation of Units Located between ILS Aerials (kW)	Number of Units located between ILS Aerials	Generation of Units Located behind ILS Localiser (kW)	Number of Units Located behind ILS Localiser (50 Meters)	Total Generation per Day (kW)
Vortex Bladeless	4	N/A	N/A	80	20	1,920
Katrick	10	190	19	N/A	N/A	4,560
PowerPod	1	19	19	N/A	N/A	456
Aeromine	5	N/A	N/A	50	10	1,200

Figure 62 Comparison between of Turbine Outputs (Lewis, 2024)

The Vortex Bladeless Wind Turbine impresses with its ingeniously simple design, offering straightforward manufacturing, installation, operational processes and ability to erect multiple turbines in a small area. Its lack of moving parts not only leads to significant savings in maintenance costs but also reduces the threat to wildlife. Additionally, Vortex turbines demonstrate efficient energy capture from turbulent winds, enhancing their suitability for diverse geographical locations. With an average daily generation of up to 1.9 MW (for 20 units), the Vortex Bladeless wind turbine offers excellent power generation 24/7. However, potential harmonic interference to critical systems like the ILS requires careful consideration before installation.

Katrick Technologies' Bladeless Wind Turbine introduces a groundbreaking design that eliminates large spinning blades, addressing various drawbacks associated with traditional turbines. This innovation offers advantages in noise reduction, visual impact, and wildlife protection. Moreover, its compact design and versatility in deployment make it a compelling alternative to both traditional wind turbines and solar energy. Boasting the highest output of all four options, with a daily generation potential of little over 4.5 MW (for 19 units), the Katrick Technologies wind turbine offers a viable alternative option to solar. Further investigation into the potential of installing within the ILS Localiser Aerials is required to ensure the units do not interfere with the ILS signal.

The Halcium PowerPod stands out for its bladeless design, ensuring safety for wildlife and minimising noise pollution. Its 360-degree intake capability enables efficient wind energy capture from any direction, enhancing its adaptability to changing wind patterns. While offering continuous energy generation day and night, the PowerPod's compact and versatile design makes it suitable for decentralised energy production. However, the PowerPod has the lowest electrical generation of all four turbines. With an average daily electrical generation of just under 0.5 MW from a combined nineteen units, the PowerPod falls short to the other alternative bladeless wind turbine options.

The Aeromine wind turbine presents a unique motionless wind energy system, eliminating visible moving components and ensuring quiet operation. Its flexibility in placement, resembling that of solar panels, allows for deployment in diverse environments. However, while benefiting from continuous electrical generation, the Aeromine's peak performance is limited to a singular direction, distinguishing it from other bladeless wind turbine options. With an average daily electrical generation of 1.2 MW, it too falls short of the alternative options. Along with a lower output, the cost of installing an additional structure and blast wall could cause costs to escalate compared to installing other products.

Overall, each bladeless wind turbine option represents a unique step forward in the realm of renewable energy technologies, showcasing their individual strengths and considerations. Moreover, these innovations have the potential to harness the considerable energy currently dissipated into the atmosphere from an aircraft's jet blast, further enhancing their environmental impact and sustainability.

6.0 Further Investigation

It is proposed that further investigation is carried out to determine how implementation of bladeless wind turbines at Bristol Airport to harness the kinetic energy from aircraft jet blasts could benefit the airports electrical demand and contribute towards the airport's sustainability goals and targets by reducing its carbon footprint.

It is recommended that further investigation is carried out on the installation of both Katrick Bladeless and Vortex Bladeless turbines. By harnessing the distinct advantages of each technology, there is the potential for significant electrical generation. With an estimated average daily electrical generation output of 6.5 MW, this dual-turbine strategy could substantially enhance the airport's renewable energy capacity and help bridge the 0.55 MW shortfall of the 2.75 MW (25% renewable energy generation by 2025) target stated in section 3.0.

The integration of Katrick Bladeless turbines within the 27 ILS Localiser, strategically positioned between the aerals, offers an innovative solution. This placement optimises energy capture while minimising potential interference with critical systems. Meanwhile, the installation of Vortex Bladeless turbines in the designated construction zone capitalises on the technology's efficient energy capture from turbulent winds.

Together, these bladeless wind turbine systems would not only contribute to Bristol Airport's sustainability goals but also offer a reliable and consistent source of renewable energy. The synergy between Katrick Bladeless and Vortex Bladeless turbines demonstrates the potential for Bristol Airport and other infrastructure projects to leverage multiple renewable energy technologies for enhanced performance and environmental stewardship.

The applicability of this technology transcends Bristol Airport's confines, offering potential implementation across airports worldwide. Thus, it emerges as not only tailored to Bristol Airport, but as a scalable and adaptable solution poised to advance sustainability endeavors within the global aviation sector.

6.1 Next Steps

6.1.1 Testing and Trials

- Conduct testing to determine safe distances for turbine placement to avoid damage from jet blasts while capturing kinetic energy effectively.
- Trial installations of bladeless wind turbines to assess their performance and ensure compatibility with airport infrastructure.
- Test for any potential interference with the Instrument Landing System (ILS) signal and mitigate accordingly.
- Katrick Technologies have agreed to attend site at Bristol Airport, to carry out testing during August, when the number of Air Traffic Movements is at its highest. A further test during the winter of 2024/25 is to be carried out with an agreed date to be confirmed following the completion of the initial summer test.
- Evaluate CO2 savings of each tested turbine and compare to solar equivalent.

6.1.2 Financial Analysis

- Prepare a comprehensive cost-benefit analysis comparing energy generation and installation costs of bladeless wind turbines versus traditional energy sources.
- Estimate the payback period for the investment in bladeless wind turbines, considering energy savings and potential revenue generation.

6.1.3 Presentation to Board of Directors

- Present findings and recommendations to the Bristol Airport Board of Directors at a monthly Project Investment Board (PIB) meeting, providing a detailed comparison of energy generation, CO2 savings, costs, and additional environmental benefits associated with bladeless wind turbine technology.
- Seek approval for further implementation steps based on the presented analysis.
- Request financial resources to cover the costs of feasibility studies, further testing, and potential implementation of the Renewable Energy Generation Project.

6.1.4 Timeline

- Phase 1 (Testing and Trials): 9 months
- Phase 2 (Financial Analysis and Presentation): 2 months
- Phase 3 (Funding Request and Approval): 2 months

Implementing bladeless wind turbines at Bristol Airport has the potential to significantly contribute to the airport's sustainability objectives and reduce its environmental impact. Through careful investigation, testing, and financial analysis, the aim is to determine the feasibility and benefits of integrating this innovative technology into the airport's infrastructure. It is believed that this initiative aligns with Bristol Airport's commitment to sustainability and its goal of achieving net-zero emissions.

Conclusion

Bristol International Airport's journey towards sustainability amidst its growing role in regional and international air travel, underscores a critical need for innovative energy solutions. Despite weathering challenges such as the COVID-19 pandemic, the airport remains steadfast in its commitment to reducing its carbon footprint and achieving Net Zero Operations by 2030. As part of its renewable energy initiatives, the airport has made strides in transitioning to electric vehicles and implementing solar arrays. However, the ambitious target of generating twenty-five percent of onsite energy from renewables by 2025 necessitates exploring alternative approaches.

The prospect of harnessing wind energy, particularly through wind turbines powered by an aircraft's jet blast, presents a promising avenue for Bristol Airport. Leveraging its strategic geographical location characterised by consistent winds, wind turbines offer continuous electricity generation that complements existing solar initiatives and reduces reliance on conventional grid sources. However, the deployment of wind turbines within an airport environment comes with unique challenges that require careful consideration and innovative solutions.

One key consideration is the location of wind turbines within the airfield, balancing the advantages of prevailing wind direction with the constraints posed by directed airflow during aircraft operations. Additionally, potential interference with critical systems like the Instrument Landing System (ILS) raises safety concerns, emphasising the importance of precise placement and harmonic management to ensure uninterrupted signal reception for aircraft. Moreover, the force of aircraft jet blast poses risks to turbine integrity, requiring meticulous planning to ensure safe installation distances. Incorporating frangible materials into a turbines design is essential to further enhance safety by minimising potential hazards in the event of a collision.

In navigating these challenges, a comprehensive exploration of bladeless wind turbine options emerges as a promising strategy for Bristol Airport. Technologies such as the Vortex Bladeless, Katrick Technologies, Halcium PowerPod, and Aeromine offer innovative solutions to mitigate environmental impacts while maximising energy generation. Among these options, the Katrick Bladeless turbine stands out as a top performer in renewable generation, offering significant potential for electricity generation when strategically integrated with other turbine technologies.

To progress further, it is proposed that Bristol Airport must conduct rigorous testing, trials, and financial analysis to evaluate turbine placement, performance, and cost-effectiveness.

Presenting findings and recommendations to the Board of Directors will be crucial for securing support and resources for implementation. By embracing bladeless wind turbines and fostering collaboration between engineering, sustainability, and development teams, Bristol Airport can lead the way in sustainable aviation practices while continuing to serve as a vital transportation hub in the Southwest of England and Wales.

The integration of bladeless wind turbines represents a transformative opportunity for Bristol Airport to advance its sustainability objectives and reduce its environmental impact. Through strategic planning, innovative technology adoption, and collaborative decision-making, the airport can pave the way for a cleaner, greener future in aviation while maintaining its position as a premier gateway for travellers in the region and beyond.

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References

- 3DExport (2024) *Low poly cartoon airbus a320 airplane*. Available at: <https://3dexport.com/3dmodel-low-poly-cartoon-airbus-a320-airplane-268231.htm> (Accessed: 14 April 2024).
- Aeromine (2024) *Aeromine*. Available at: <https://aeromine technologies.com/> (Accessed: 5 May 2024).
- Airbus (2023) 'Airport Operations and Aircraft Characteristics'. Available at: https://aircraft.airbus.com/sites/g/files/jlcbta126/files/2023-12/ac_a320_1223.pdf (Accessed: 19 May 2024).
- Andrew, J.-M. (2019) 'Fundamentals of Wind Turbines'. Available at: www.windsystemsmag.com/fundamentals-of-wind-turbines/ (Accessed: 20 March 2024).
- BBC (2022) 'Bristol had "fastest recovery" of any UK airport'. 25 August. Available at: <https://www.bbc.co.uk/news/uk-england-gloucestershire-62673202> (Accessed: 27 April 2024).
- Brown, S. and Jones, D. (2024) *European Electricity Review 2024*. Available at: <https://ember-climate.org/insights/research/european-electricity-review-2024/#supporting-material> (Accessed: 14 April 2024).
- BRS (2024) 'Bristol Airport Internal Sharepoint'. Available at: Official Sensitive (Accessed: 25 February 2024).
- CFM (2024) *THE CFM56 ENGINE FAMILY*. Available at: <https://www.cfmaeroengines.com/engines/cfm56/> (Accessed: 13 April 2024).
- Csanyi, E. (2011) 'Principles for Controlling Harmonics'. Available at: <https://electrical-engineering-portal.com/principles-for-controlling-harmonics> (Accessed: 5 April 2024).
- Economics, T. (2023) *Average Precipitation by Country | Europe*. Available at: <https://tradingeconomics.com/country-list/precipitation?continent=europe> (Accessed: 14 April 2024).
- Elstad, S. (2024) *Are Bladeless Wind Turbines the Future of Wind Energy?* Available at: https://greenerideal.com/guides/renewable-energy/bladeless-wind-turbines-the-future-of-wind-energy/#google_vignette (Accessed: 28 April 2024).
- Ettoumi, F.Y. (2011) *A Neural Network Solution for Extrapolation of Wind Speeds at Heights Ranging for Improving the Estimation of Wind Producibile*. Available at: https://www.researchgate.net/figure/Representative-size-height-and-diameter-of-wind-turbines-5_fig1_274533972 (Accessed: 21 March 2024).

EV Database (2024) *Electric Vehicle Database - Tesla Model 3 Performance*. Available at: <https://ev-database.org/uk/car/1322/Tesla-Model-3-Performance#:~:text=Total%20Power%20%2A%20377%20kW%20%28506,hp%29%20Total%20Torque%20%2A%20487%20lb-ft> (Accessed: 13 April 2024).

GE (2024) *How do wind turbines work?* Available at: www.goodenergy.co.uk/how-do-wind-turbines-work/ (Accessed: 18 March 2024).

Google (2024) 'Google Maps'. Available at: www.maps.google.co.uk (Accessed: 20 March 2024).

Google Earth (2024) *Google Earth*. Available at: <https://earth.google.com/web/@51.38134007,-2.73522883,178.36676759a,195.42447854d,35y,-3.19911501h,90t,360r/data=OgMKATA> (Accessed: 21 March 2024).

Green, E. (2020) 'WIND VS. SOLAR — WHICH POWER SOURCE IS BETTER?'. Available at: <https://elemental.green/wind-vs-solar-which-power-source-is-better/#:~:text=Wind%20is%20a%20more%20efficient%20power%20source%20than,electricity%20per%20kWh%20as%20about%2048%2C704%20solar%20panels>. (Accessed: 28 April 2024).

Halcium (2024) *PowerPod*. Available at: <https://www.halcium.com/> (Accessed: 6 May 2024).

Hulshorst, W. (2008) *SMALL-SCALE WIND ENERGY*. Available at: <https://www.altenergymag.com/article/2008/06/small-scale-wind-energy/440/> (Accessed: 28 April 2024).

Hutt, N. (2022) 'How Fast Do Wind Turbines Spin? (20 RPM, on average)'. Available at: <https://renewablesystems.org/how-fast-do-wind-turbines-spin/#:~:text=The%20average%20wind%20turbine%20spins,at%20a%20rate%20of%2015-25%20RPM>. (Accessed: 28 April 2024).

Ketrick (2024) *We are Katrick Technologies*. Available at: <https://www.katricktechnologies.com/> (Accessed: 5 May 2024).

Lewis, I. (2024) 'Own Work'.

Liggit, A. (2020) *Above-normal Atlantic hurricane season expected by NOAA for 2020*. Available at: <https://wjla.com/weather/stormwatch7-weather-blog/above-normal-atlantic-hurricane-season-expected-by-noaa-for-2020> (Accessed: 28 April 2024).

Maaz, A. (2022) *Instrument Landing Systems: Everything You Need To Know About ILS*. Available at: <https://simpleflying.com/instrument-landing-systems-complete-guide/> (Accessed: 14 April 2024).

Mithal, S. and Rutherford, D. (2023) *ICAO'S 2050 NET-ZERO CO2 GOAL FOR INTERNATIONAL AVIATION*. Available at: <https://theicct.org/publication/global-aviation-icao-net-zero-goal-jan23/> (Accessed: 27 April 2024).

ONS, O.F.N.S. (2023) *UK ENERGY IN BRIEF 2023*. Available at: https://assets.publishing.service.gov.uk/media/6581cb5aed3c34000d3bfbfc/UK_Energy_in_Brief_2023.pdf (Accessed: 13 April 2024).

Smith, S. (2024) 'ILS Localiser Beam/Signal Analysis'. Available at: www.nats.aero (Accessed: 14 April 2024).

SNL, S.N.L. (2020) 'AEROMINE'. Available at: <https://labpartnering.org/storage/attachments/AeroMINE%20SAND2020-2901%20M.pdf> (Accessed: 5 May 2024).

Solarsense (2024) 'Bristol Airport PV Options'. Available at: www.solarsense-uk.com (Accessed: 20 March 2024).

Statista, R.D. (2024) *Distribution of electricity generation in Denmark in 2023*. Available at: <https://www.statista.com/statistics/1235360/denmark-distribution-of-electricity-production-by-source/#:~:text=Denmark%27s%20power%20mix%20is%20largely%20shaped%20by%20wind,leading%20producers%20of%20solar%20and%20wind%20power%20worldwide.> (Accessed: 28 April 2024).

Stenhouse, E. (2017) 'IceWind: Iceland's Solution For Wind Energy'. Available at: <https://www.evolving-science.com/environment-energy-water-and-waste-management/icewind-iceland%E2%80%99s-solution-wind-energy-00150> (Accessed: 28 April 2024).

TMS, T.M.S. (2024) 'Aeromine Wind Turbines: A Guide for Consumers'. Available at: <https://www.turbomachinerysolutions.com/aeromine-wind-turbine/> (Accessed: 5 May 2024).

Vortex (2024) 'Vortex Bladeless'. Available at: <https://vortexbladeless.com/> (Accessed: 28 April 2024).

Windfinder (2024) *Annual wind and weather statistics for Bristol Airport*. Available at: https://www.windfinder.com/windstatistics/bristol_lulsgate (Accessed: 13 April 2024).

Withey, R. (2024) 'Solar Generation at Bristol Airport'.

Yang, C., Xiao, L., Chen, P., Cheng, Z., Liu, M. and Liu, L. (2023) 'An analytical frequency-domain model of aerodynamic mass and damping of floating wind turbines'. *Wind Energy* 26(11), pp. 1140–1164. doi: 10.1002/we.2861.