Alderney future power supply scenarios – a literature review

ORE Catapult Development Services, commissioned by the States of Alderney Energy Team

Literature Review

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Contents

List of Abbreviations

Abbreviation	Definition
A	Ampere
ACRE	Alderney Commission for Renewable Energy
ACT	Advanced conversion technologies
AD	Anaerobic Digestor
AEL	Alderney Electricity Ltd
AR4	Allocation Round 4 (Contracts for Difference)
ATT	Advanced thermal treatment
CAGR	Cumulative Annual Growth Rate
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CfD	Contract for Difference
CTV	Crew Transfer Vessel
DNO	Distribution Network Operator
EV	Electric Vehicle
FiT	Feed in Tariff
FSCI	Fuel Supplies Channel Islands
GB	Great Britain
GE	General Electric
GWh	Gigawatt Hour
HV	High Voltage
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
ICE	Intelligent Community Energy
IEHT	Isle of Eigg Heritage Trust
IRENA	International Renewable Energy Agency
kV	Kilovolt
kVA	Kilovolt-Ampere
kW	Kilowatt
LCOE	Levelised Cost of Energy
LPG	Liquid Petroleum Gas
LV	Low voltage
MPI	Multipurpose Interconnectors
MW	Megawatt
MWh	Megawatt Hour
NM	Nautical Mile
O&M	Operation and Maintenance
ODSL	Offshore Renewable Energy Catapult Development Services
OTNR	Offshore Transmission Network Review
PPA	Power Purchase Agreement
PV & PVT	Photovoltaic & Photovoltaic Thermal
ROC	Renewable Obligation Certificates
SoA	States of Alderney
Solar PV	Solar Photovoltaic
SSEN	Scottish and Southern Electricity Networks
V	Voltage
W	Watt

WACC	Weighted average cost of capital

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EXECUTIVE SUMMARY

The Channel Island of Alderney's current energy system is wholly dependent on fossil fuels and is subject to global market price fluctuations. This literature review assesses relevant and available information on Alderney's energy system, provides an overview of available renewable generation and storage technologies and captures similar examples of remote islands which have transitioned to an independent renewable energy-based energy system.

The States of Alderney are currently developing an energy policy with short-, medium- and long-term objectives seeking to manage energy costs, supply, and decarbonisation. Feedback from a recent public consultation of the proposed Island Plan in October 2021 indicates considerable local support for the development of renewable energy. A significant challenge for the island is that the fuel tankers required for importing fuels will reach their end of life in the next 10 years. This will place significant cost on consumers, as will the weaning from fossil fuel energy production through loss of volume supply benefits and engine running efficiencies.

Alderney consumes approximately 6 GWh electricity per annum. Alderney Electricity Ltd run the electrical grid, which is approximately halfway through an extensive upgrade programme to enable safe and compliant switching of the network. There are geographical limitations as to where domestic renewable energy can be put onto the grid, currently capped at 300 kW, however the HV grid could accept up to a 5 MW feed. There have been previous discussions with 3rd parties for the potential to secure an interconnector between UK, Alderney and France however discussions have since halted.

Various land based and marine renewable energy technologies have been reviewed and have the potential to produce energy from Alderney's substantial renewable energy resources. Costs of certain technologies such as onshore wind, solar PV have reduced dramatically over the last decade; this combined with the high energy costs on the island may help facilitate future renewable energy projects. Tidal stream energy is of particular interest to the island. Alderney's have ownership of the seabed out to 3 NM and this is located next to Europe's second most energetic tidal resource. This could enable a new and lucrative revenue source in future for the island, as well as the potential to export GWhs of energy.

Other remote islands have begun to reduce their reliance on fossil fuels electricity generation, with some making substantial progress. These islands include the Isle of Eigg, the Shetland Islands, the Faroe Islands, the Isles of Scilly, and Ushant. Alderney can learn lessons from these to aid the development of their future energy system.

INTRODUCTION

The Channel Island of Alderney, a UK crown dependency and part of a group of Islands known as the Bailiwick of Guernsey is the northern most of the Channel Islands. Alderney is self-governed by the States of Alderney (SoA) which consists of an elected President and 10 States Members.

The island's current energy system is wholly dependent on fossil fuels and is subject to global market price fluctuations. It has an ageing shipping fleet, responsible for transporting and importing the required fuels, likely leading to further increased energy costs in future.

The States of Alderney's Policy and Finance Energy Team have commissioned Offshore Renewable Energy Catapult Development Services Ltd to complete an island energy systems literature review and scoping study report establishing the potential hybrid 'mix' of power supply and storage technologies which, exist or are being developed, and that would meet the island's strategic energy system objectives of:

- Minimising cost of energy
- Reducing or mitigating energy supply risks, and
- Minimising or eliminating the use of carbon emitting energy sources

The scoping study will identify 3 future power supply mix scenarios for the short-term (5-10 years), medium-term (10-20 years) and long-term (20+ years) and consider both renewable energy generation technologies as well as energy storage options for the island. Guided by the strategic energy system objectives outlined above and considering constraints including cost, environmental impact, carbon emission reductions and impacts on the character of Alderney, high level energy system scenarios will be identified.

Renewable energy generation technologies to be considered include Solar Photovoltaic (Solar PV) and Solar Thermal, Wind, tidal stream, air source and ground source heat pumps, biomass and energy storage technologies including pumped, batteries and hydrogen. Interconnector options will also be considered as part of this study.

As a precursory activity for the scoping study this literature review assesses relevant available information on Alderney's energy system, available renewable resources on the island and overview of available renewable generation and storage technologies. The literature review will also summarise relevant islands energy system case studies where once fossil fuel reliant islands have shifted their energy system to more sustainable, renewable sources of energy production.

Background

The Channel Island of Alderney, a UK crown dependency and part of a group of Islands known as the Bailiwick of Guernsey is the northern most of the Channel Islands. The Island of Alderney is self-governed by the States of Alderney (SoA) which consists of an elected President and 10 States Members. Routine government is performed by three principal committees Policy and Finance, General Services, and Building and Development Control. These three committees are run by States Members and each work under a different mandate and have a separate budget. Certain 'transferred services' namely policing, customs and excise, airport operations, health, education, social services, childcare and adoption are the delegated responsibility of the States of Guernsey.

Alderney (Figure 1) is located 10 miles to the west of the Normandy peninsular of France and 55 miles south of

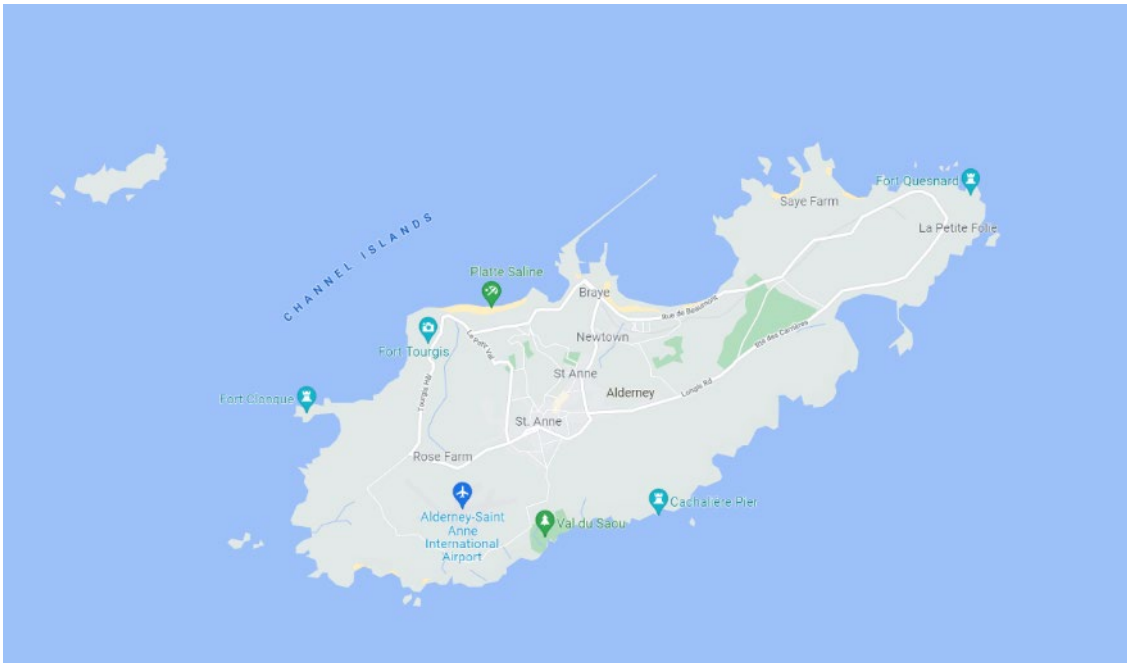

Figure 1. Map of Alderney [184]

the English coast. The island is approximately 3 square miles and has a population of 2,030 [1].

The island's current energy system is wholly dependent on fossil fuels and is subject to global market price fluctuations. It has an ageing shipping fleet, responsible for transporting and importing the required fuel, potentially leading to further increased costs in future. The current energy system produces significant carbon emissions and has a large carbon footprint at a time when the developed nations are transitioning to net zero greenhouse gas emissions to combat the effects of climate change [2].

The States of Alderney's Energy Team have commissioned Offshore Renewable Energy Catapult Development Services (ODSL) to complete a future island energy system literature review and scoping study to establish the potential hybrid 'mix' of power supply technologies which, exist or are being developed, and that would meet the island's strategic energy system objectives of:

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The Island of Alderney

The Channel Island of Alderney, a UK crown dependency and part of a group of Islands known as the Bailiwick of Guernsey is the northern most of the Channel Islands. It is located 10 miles to the west of the Normandy peninsular of France and 55 miles south of the English coast. The island is approximately 3 square miles and has a population of 2,030 [1]

The island has two main transport hubs; Alderney Airport located to the southwest of the island which has airlinks with Southampton in the UK and the neighbouring Channel Island of Guernsey. Braye Harbour, located to the north of the Island is protected by a breakwater originally built in 1847. The harbour is used for passenger services as well as weekly freight services and the importation of fuel oil for the island. There is a small network of roads which circle and inter-link the entire island although use of vehicular transport is limited on the island.

The island of Alderney is situated 10 miles west of the Normandy peninsular of France, and its land mass naturally constrains the movement of water by the tides through the “Alderney Race” or “Raz Blanchard”. This natural phenomenon causes extreme tidal flows through the Alderney Race and results in it being one of Europe’s most significant tidal stream practicable resources estimated between 2-2.7 GW [3]. In addition to this favourable location the States of Alderney also hold seabed rights out to the 3 NM territorial limit. This places the island in a unique position, with the potential to reap economic benefits through the extraction and exporting of tidal stream generated electricity in addition to revenue generation from leasing areas of seabed within the 3nm limit to project developers. As a result, the Alderney Energy team have indicated that tidal stream energy development should be considered a priority given the revenue generation potential for the island.

Energy Policy

There is currently no dedicated Energy Policy for Alderney. The SoA have set out a vision and outlined energy goals in the Alderney Island Plan 2021. A public consultation of the proposed Island Plan was issued in October 2021. Initial feedback suggests that almost 90% of respondents consider renewable energy a top priority in future planning for the island.

The proposed energy goals in the 2021 Island plan are:

To promote ways in which our Island can play its part in reducing the carbon footprint and finding ways of reducing energy costs for individuals and organisations.

- **Clean** - Increase the amount of clean energy used (Clean energy = clean air).
- **Green** - Develop a strategy to encourage the use of green energy by households and commercial premises (Green energy = natural sources).
- **Renewable** - Encourage the use of constantly replenishable resources with associated storage technologies to reduce the Island's dependence on fossil fuels. (Renewable energy = recyclable sources).
- **Feed-in** - Find ways to allow renewable domestic (within the home) energy sources to input into the grid with the aim to reduce costs for all energy users on island.

Of note are the recent tensions between the UK and France in relation to fishing rights because of Brexit and which have escalated throughout 2021. The Channel Islands license and regulate their own territorial waters. Under the post-Brexit Trade and Cooperation Agreement signed between the UK and the EU French fisherman must be able to demonstrate a history of having fished within Jersey and Guernsey (including Alderney) waters to be able to request future licensed access. This resulted in retaliatory blockading of St Helier harbour in May 2021 and threats that power to the interconnector powering Jersey and Guernsey would be cut [4]. The fishing rights issue has since been resolved however, this threat has psychologically undermined the energy security provided by the Channel Islands' interconnector to France and has potential impacts on Guernsey Electricity Ltd (Guernsey's Electricity utility company) plans for its own direct interconnector to France. Contrarily and to the possible benefit of Alderney, it has led to a common objective of improving the independence of energy supply in the Channel Islands who are now in early-stage discussions for a Channel Island energy strategy and possible Channel Island Grid development.

As per the introduction section above the SoA Energy Team are tasked with developing an energy policy for Alderney and as such are seeking to develop, short (5-10 years), medium (10-20 years) and long term (20+ years) strategies whereby energy costs, supply risk and decarbonising are all considered. Delivery of any Alderney Energy Policy would be the responsibility of the SoA.

Renewable Energy Regulation

The Alderney Commission for Renewable Energy (ACRE) is responsible for licensing and regulating the operation, deployment, use or management of all forms of renewable energy in the Island of Alderney and its territorial waters [5]. It was established by the States of Alderney through the Renewable Energy (Alderney) Law 2007 and requires all forms of renewable energy on the island and its territorial waters to be licensed with an exemption for any system with a rated maximum output of no more than 20 kW [6].

There are well defined consent application processes (one for land applications and one for marine) which aims to follow best practise in the UK and includes consenting guidance documents available for applicants. It is a 4-stage process which includes a public consultation.

ACRE has split Alderneys territorial waters into identifiable blocks as shown below in Figure 2. ACRE has no statutory powers in respect of interconnector cables which currently remains with the States of Alderney.

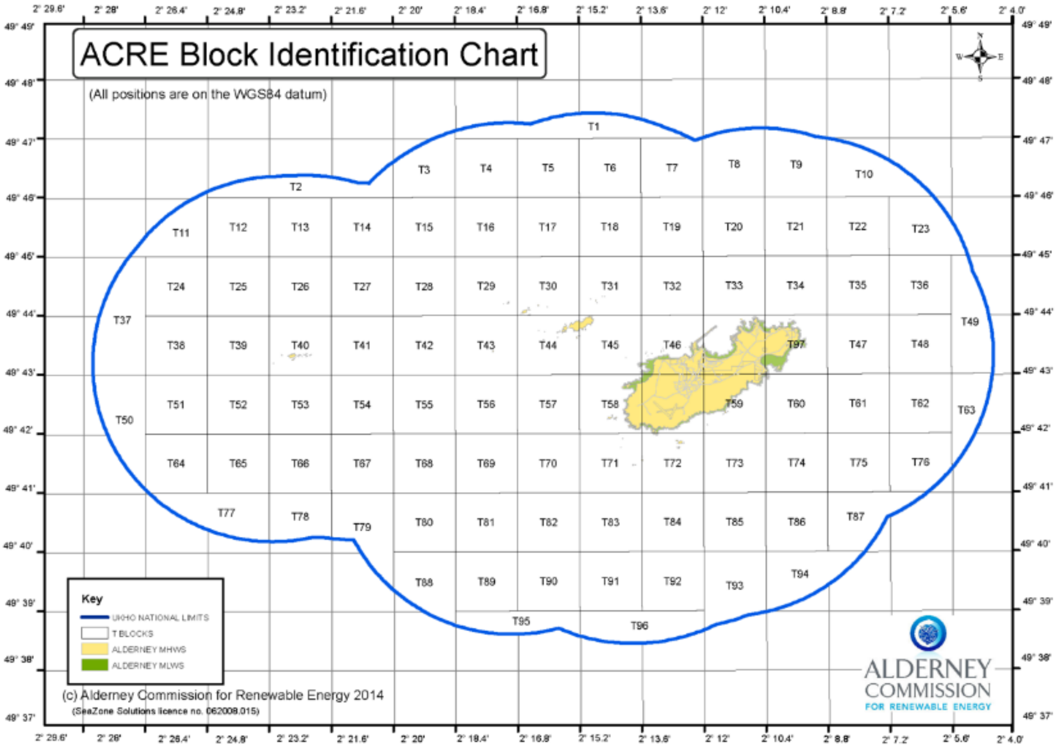


Figure 2. ACRE Block identification Chart

Alderney's Energy system

Fuel and Electricity supplies

Alderney Electricity Ltd (AEL) is the monopoly supplier and distributor of electricity on the island. The company is a wholly vertically integrated utility, responsible for everything from the import of fuel oil for generation to the billing of units consumed The company owns and operates the island power station and the distribution grid. The Company is majority owned by the States of Alderney. AEL also imports diesel and unleaded petrol for transport and kerosene for heating [7]. Diesel and kerosene are imported by bulk tankers averaging 4 shipments of approximately 1 million litres each year. Marginal fuels, currently only unleaded petrol though this also used to include aviation fuels, are brought in by 23,000 litres isotanks. Total fuel consumption in 2021 was 4.35 million litres [8] consisting of 2 million litres of kerosene for heating, 1.6 million litres of diesel for electricity generation, 400,000 litres of diesel and 350,000 litres for transport.

Liquid petroleum gas (LPG) supplies are also available on the island via separate supplier Blanchards who sold approximately 91,000kg (178,000 litres) in 2020. There are also small supplies of logs and other solid fuels brought in for heating principally by members of the public operating collectively i.e. a groups of individuals getting together to buy a container of logs..

Electricity

The power plant is located close to the Braye Harbour where the ships with the diesel and kerosene, for the heating system, arrive via Guernsey. Total billed electricity consumption during 2021 was 5.98 GWh. Total outputs to the grid were 6.43 GWh giving network losses of 7.5%. Including station consumption of 74MWh, total island generation was 6.51 GWh. Both high (HV) and low voltage (LV) cabling is predominantly buried underground, the exceptions being a single HV overhead transmission line running from Sharpe's Farm near Longis Common out to the east end of the island and a mixture of low voltage overheads and facia mounted LV supplies in the town area. There is adequate capacity on the primary HV grid across the whole island. It is estimated that the current grid capacity for small scale renewable energy is approximately 300 kW.

According to the AEL the current substations and protection systems are not designed or configured to back feed from the low voltage (LV) consumer side to the HV side placing a practical limit for distributed generation feed in on each LV branch equivalent to the minimum daytime load. This is highly location dependent; in some areas where a high proportion of properties are unoccupied for extended periods consumption the maximum feed in value might be zero would be much lower, as would be the case for much of the town of St. Annes where LV infrastructure is very limited and expensive to upgrade (large section of town are still fed from twin core and earth cabling daisy chained along facia boards). Future improvements would include upgrading the remaining antiquated sub-stations and protection systems and taking property feeds underground and increasing the capacity of those feeds and adding a system on the HV side to manage output transients 11 kV three-phase stabilised voltage-controlled output and for all cables to be laid underground, with at an estimated cost upwards of £10 million. The preferred solution to meet the current capacity for renewable generation would be to take an institutional approach feeding into the nearest grid access point at 11kV three phase via switch gear at the feed-in point. AEL have suggested the least appropriate grid connection point for renewable energy installation are at the western and eastern extremes of the island where there is a no HV infrastructure. Grid infrastructure would need upgrading at significant cost to enable such a connection.

In the last 7 years AEL have invested over £2.5 million in improvements to grid, generation, and system management infrastructure. Creating a smart platform as a foundation to introduce technology to reduce carbon footprint and meet future energy challenges is already underway. The most recent grid upgrades completed in 2020/2021 were to those sub-stations key to network switching protocols and focussing on delivering safe and compliant switching capability. According to AEL, the primary HV network should be considered adequate for the distribution of up to 5 MW. An area that will require focus from domestic scale energy generation is the grids capability to receive the energy, as AEL have mentioned, it depends on location, i.e., the side of the grid access is required geographically. The assumption by AEL is to move 5 MW around the island on the HV grid equivalent to the capacity required to meet the island's total requirement. There are other planned grid upgrades which are variable in respect to capacity and capability, with all grid upgrades estimated by AEL to cost £10m (+-25%).

The technical details of the network that are mapped in a software model produced and managed by Vector Power Solutions, used primarily for setting the Islands network projections. AEL have commissioned work that will upgrade the model allowing them to model network performance given different transient inputs from variable and distributed renewable and other generation, and for transient loads (heating, vehicle charging). Once the renewable energy resource has been identified running these scenarios will support the long-term projections to focus the planning and design in the future.

The primary generation capability currently comprises eight Perkins diesel gensets each with a maximum output of 500 kW in continuous operation   At any time between 1 and 3 engines run simultaneously following demand. The system is designed with a redundancy of 100% and each side has 30% excess output capacity to facilitate warranty and preventative maintenance schedules and adequate capacity under fault condition scenarios. The system currently delivers an operational efficiency of 40%. This is expected to rise further when fully automated.

Total fuel storage on island is 1.6 million litres with a similar amount in domestic and other customer tanks around the island at any time. Bulk fuels are shipped to the island using two ageing Oil tankers (Sarnia Cherie built 2008 and Sarnia Liberty built 2007). It is expected that these tankers will require replacement within the next decade at significant cost. The ships are owned by Guernsey, and it is currently unclear how the ships will be replaced, if at all. There are four shipments a year averaging 1 million litres of diesel in total. During 2021, AEL used 1.6 million litres of diesel for electricity generation. The price paid for fuel is based on Platt's spot price on the day of loading plus a premium to cover shipping and other transport and handling expenses. For the most recent shipment at the end of 2021 the premium paid was approximately 10p on a Platts price of 46p per litre giving a landed cost of approximately 56p per litre for both kerosene and diesel.

According to a 2015 study on the management of electricity supply on Alderney by Cranfield University [9] the electricity demand in the State of Alderney varies between 0.4 MW and 1.1 MW (current maximum is 1.3 MW) with the peak of demand during the Alderney week and summer periods, shown in Figure 3 (weeks 31 to 33), and winter periods (weeks 50 to 52 and 1 to 4). Since 2010 the electricity peak demand has been decreasing and the forecast tends to continue decreasing by the same trend over the next two years to 2024 (Figure 3) [9].

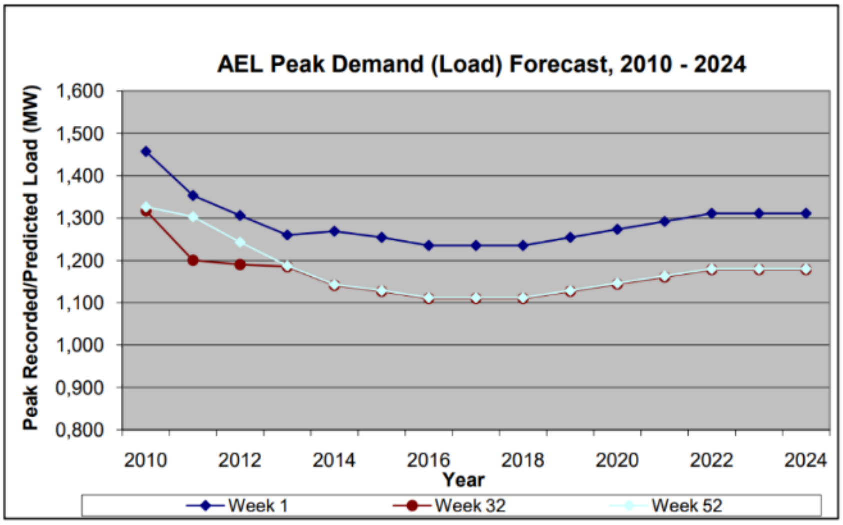


Figure 3. AEL peak power demand recorded and forecasted [9].

From historic significance, in terms of energy, there has been a substantial decrease in electricity delivered to the grid from 6,895 MWh (in 2012) to 6,017 MWh (in 2020). There was a spike in output in 2021, rising to 6,434 MWh. This can be related to changes in behaviour under COVID-19 restrictions, however early indications from late 2021 into early 2022 suggest that consumption is beginning to return towards the long-term trend as restriction ease and people come to terms with life under the pandemic. Apart from the seasonal fluctuation during summer and winter peaks, the power and energy demand shown below is stable per day, with peak demands during midday and late afternoon/evening periods, in all the weeks analysed (Figure 4 & Figure 5). The

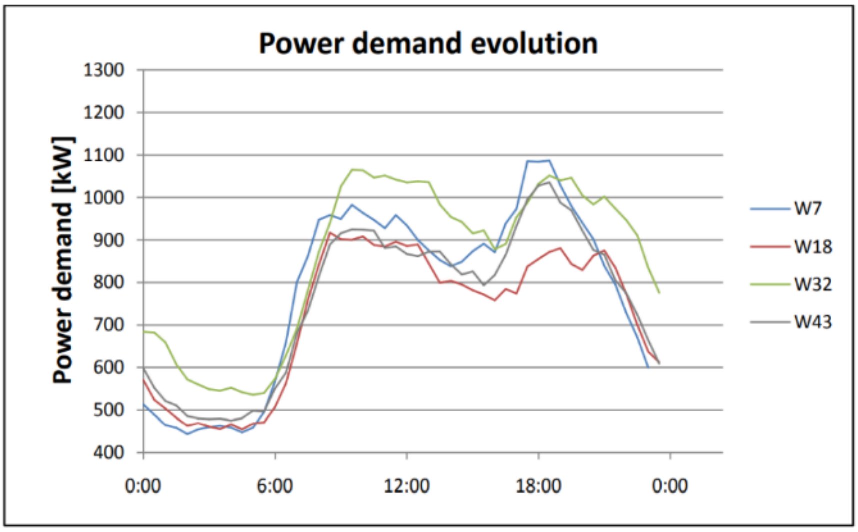


Figure 4. Power demand kW evolution during average days [9].

demand can be accredited to residential and small business property consumptions, including the hospital and the generation power plant [9].

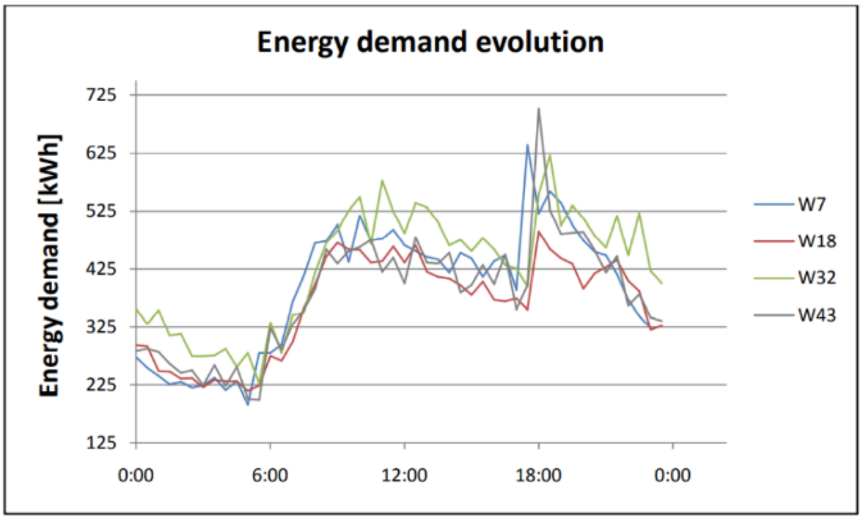


Figure 5. Energy demand kWh evolution during average days [9].

All the electricity supply is provided from the power plant, distributed through a grid distribution system of 11 kV. In Figure 6, this electricity distribution system is shown. Cables are primarily buried underground with exception for one overhead section in the northeast of the island. The reason for the majority of the gid being buried is to avoid damage from severe weather conditions Alderney experiences. According to [9], there are 20 different substations driven by (100-500 kVA) transformers, stepping-down the HVAC to 1,000 V and then on to 400/230 V ready for consumption. This LV electricity is transmitted to the different consumption points via underground cables (Figure 6).

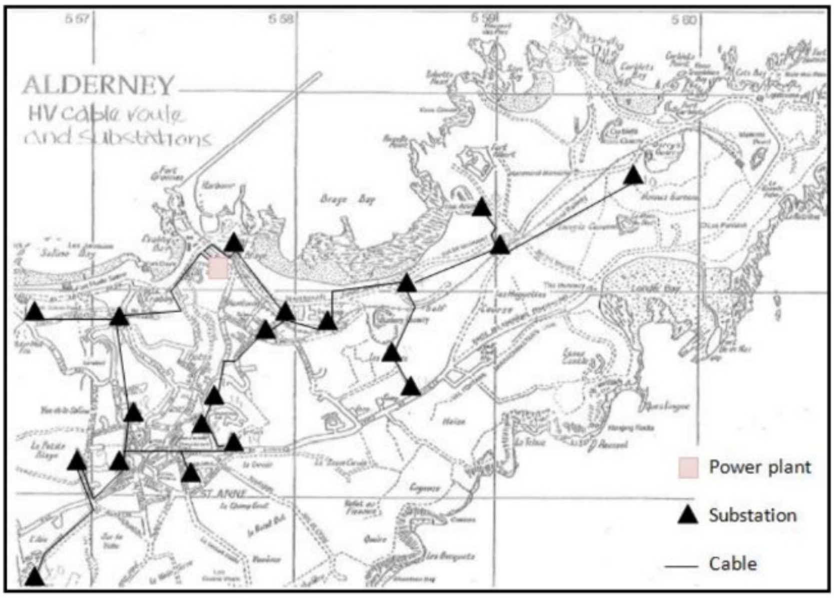


Figure 6. Alderney's electricity transmission system [9].

Current estimates for the existing grid infrastructure are that it can support loads of circa 5 MW on the primary HV. Upgrades will be required for the integration of renewable energy (RE) dependent upon which approach is taken. The required upgrades would be insignificant should, for example, solar or wind b fed in from institutional scale deployments, whereas the upgrade would be significant if the intent was to allow feed-in from distributed generation at any scale or location on the grid. Future solutions may be through microgeneration systems to the Alderney's electrical grid, to exploit diverse resource on the island in solar, wind, tidal, and air heat pumps as potential options. Leading on to electrical energy storage for surplus energy generated from RE, and to solve these challenges for optimisation by converting and storing the excess in to pumped hydrogen.

Heating

Kerosene oil is the most common heating fuel on Alderney with AEL estimating that 2 million litres of kerosene is used annually. The current price of kerosene sold by AEL is 78.73p per litre. Bottled LPG gas is also used on island predominantly for gas cookers and heaters with approximately 91,000 kg (178,000 litres) sold in 2020. Electric heating is also used on the island along with a small number of domestic solar hot water systems installed on households.

Transport

AEL have a 36,000-litre holding facility for unleaded petrol Unleaded petrol is brought in by 23,000 litre Iso tanks averaging circa 1 per month (276,000 litres per year). The States of Alderney estimate there are 2,900 total vehicles on the Island of which about 100 are light trucks, a small number of graders, loaders etc. There are a handful of electric vehicles belonging to the post office and AEL with no public electric vehicle charging points currently installed.

Fuel Supplies Channel Islands (FSCI) have a storage facility for aviation gasoline, also known as aviation spirit in the UK (AvGas) stored in Iso tanks, Jet fuel for aviation. AvGas is for private pilots. AEL estimates that Alderney uses 500,000 litres of diesel for transportation annually currently priced at 74.76p per litre [10].

Interconnectors

Interconnectors are a way of connecting electrical systems of neighbouring jurisdictions. For Alderney, an electrical interconnector would a way to both import and export electrical power. They can also be used for data transmission. Due to Alderney’s limited electrical demand on the island and the surrounding surplus of renewable resources, an interconnector would be required to be able to economically exploit the resource over and above the islands demand requirements.

For the States of Alderney an interconnector would be a solution to both import and export electrical power via high voltage direct current (HVDC) using converter and inverter technology to interchange between HVAC/DC. The interconnector could also be used for data transmission. Previous proposals like, the FAB-Link project [11] have identified Manez quarry on Alderney where the converter station could be situated. This would be an additional option to provide Alderney with a reliable, affordable, and environmentally friendly energy system.

FAB-Link Interconnector

The FAB (France-Alderney-Britain) Link project is a proposed HVDC link with a capacity of up to 1,400 MW connecting the substation of Exeter (Devon, England) to Menuel (Cotentin, France), with an option to go via Alderney to provide a route to market for marine renewable energy resources surrounding the island [12].

At the time of this literature review the FAB link project is understood to be planning to bypass Alderney rather than land on the island [13]. The SoA asked us to consider the technical feasibility of tapping into the interconnector for a feed of 5 MW 11 kV power from the DC interconnector. Our analysis was that such a connection would not be feasible without using converters and transformers for DC-AC-AC-DC conversion steps which would require a significant infrastructure footprint.

As such, the FAB link interconnector is not considered a viable option as an interconnector for Alderney without incurring significant cost and having a significant impact on the character of the island.

Normandie Hydroliennes Interconnector

Normandie Hydroliennes is a Joint Venture company set up by SIMEC Atlantis one of the UKs leading tidal turbine and project developers. Normandie Hydroliennes is a collaboration between SIMEC Atlantis, AD Normandie, the regional development agency for the Normandy region and EFINOR. In September 2019 Normandie Hydroliennes and AEL signed a head of terms with the objective of supplying Alderney with power from a 12 MW tidal stream project located on the French side of the Alderney Race [14]. The aim was to agree terms of a 25-year power purchase agreement under which AEL would purchase a minimum of 5 GWh of electricity from Normandie Hydroliennes each year. Since the signing of this agreement Normandie Hydroliennes has acquired full ownership of the rights to the 12 MW tidal project previously owned by Engie [14]. It is understood that a consent variation is being sought through the French regulators to allow Normandie Hydroliennes to install 4x 3 MW SIMEC Atlantis tidal turbines at the site.

Whilst the option of an interconnector to Alderney where electricity prices are high due to the reliance on diesel generators for electricity production may have enabled a financially viable route for both parties, it is now understood that Normandie Hydroliennes are in discussions with French authorities (ADEME) to access a feed in tariff direct from France. If successful, this option, only requiring a single export cable direct from the tidal farm to the French grid will likely be more attractive to the tidal developer in comparison to the installation of an additional interconnector from their tidal farm to Alderney. As a result it is understood discussions between AEL and Normandie Hydroliennes have since stalled.

Renewable energy technologies

This section describes the current state of the art for electricity generating technologies. This includes descriptions of what we think are the most viable technologies for Alderney, covering the following aspects:

- Operating principles, constraints and characteristics
- Current market
- Technology readiness, economic viability and levelized cost of energy (LCOE)
- Market forecast, future innovations and predicted cost trajectory
- Renewable technologies - Onshore

The island of Alderney has an area of about 7.8 km^2. While this is relatively small compared to the larger farms of renewables built in recent years[1], especially when constraints like the airport and residential areas are considered, there is still the possibility that smaller scale systems that use land more efficiently could provide meaningful contribution to the network.

Such onshore technologies are well established and have a strong and proven track record. In many countries around the world, they are cost competitive with fossil fuel alternatives, although the variable nature of their output means that backup systems and grid protection measures would be required for an island like Alderney. The costs associated with installation, operations and maintenance (O&M) and transmission are also much lower than their offshore renewable energy counterparts.

This section describes the leading onshore renewable technologies that could be viable for Alderney.

Onshore Wind

The wind turbine has been in existence for thousands of years, with early vertical axis examples found in the Middle East. In Europe, wind energy dates back to 1191AD, whereby windmills were used for pumping water and grinding grain [15]. The first wind turbine for electricity production was made by Professor James Blyth, based at Anderson's College, Glasgow, who powered his home with his turbine for 25 years [16]. The industrial revolution and subsequent rush to coal hampered progress until the 1930s and 40s, whereby small-scale turbines (<10 kW) were developed in the US and Germany for electricity generation [15].

Onshore wind as we know it today has its origins in the 1970s and 80s, with technology primarily developed in California and Denmark [16]. This was in response to an oil price shock, also amid growing environmental concerns, which led to governments exploring alternative technologies. Early support from the Danish government through schemes investment subsidies, guaranteed minimum pricing and sharing connection coasts between turbine owners and utilities has cemented their position as one of the world leaders today.

1 For context the largest wind farm (Clyde) and solar farm (Shotwick) in the UK are 75 km2 and 0.9 km2 respectively.

Onshore wind is a large and globalised industry. While the spotlight is usually on offshore wind in the UK, in Europe 80% of the capacity installed is onshore, with major markets including Germany, Norway and Spain [17]. This trend is also mirrored globally.

Operating principle

Onshore wind is an established technology. In the earlier years there were vertical axis models, for example Savonius and Darrieus turbine designs built in the 1980s, however now the industry standard is the horizontal axis wind turbine (HAWT). An annotated example is shown in Figure 7. This proved to be more reliable and have higher operating efficiency [18], becoming the dominant design. While there has been recent interest in revisiting vertical axis designs, as materials have become more advanced, it is unlikely that they would see any use beyond niche applications (for example urban environments, as previous mentioned).

Horizontal axis wind turbines are also predominantly three-bladed. This convention was established more for environmental than performance reasons, as one and two bladed turbines are noisy and have a pronounced visual "flicker". They also require more complicated engineering with a teetering hub to reduce uneven loading on the structure as the blades rotate.

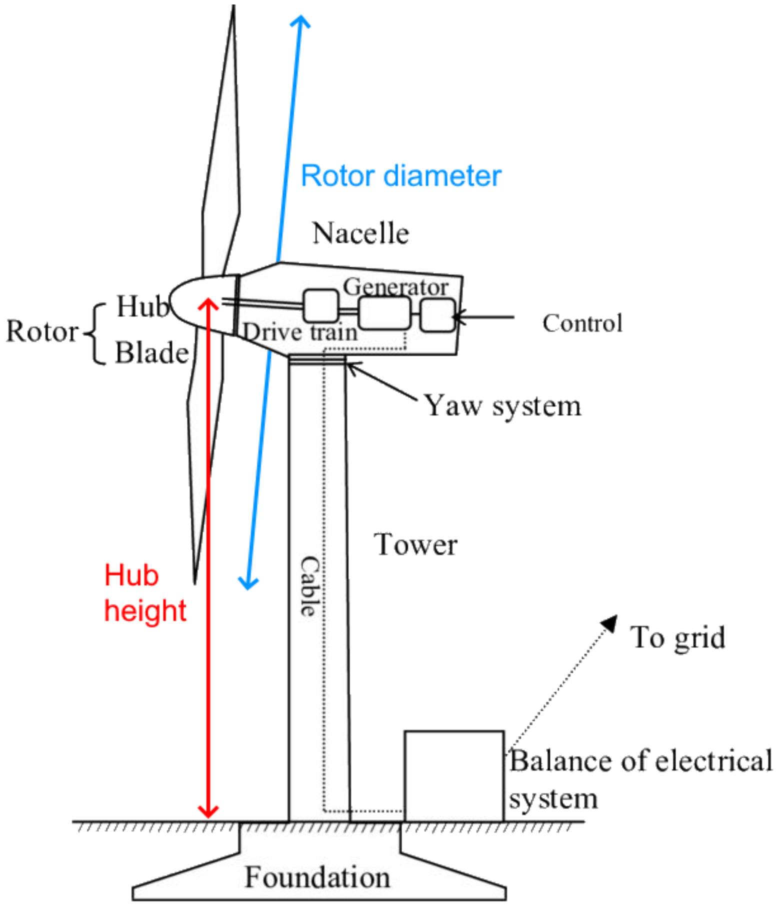


Figure 7 Typical horizontal axis wind turbine. Adapted from [186].

Wind turbine performance is defined by its power curve. This describes the power output at a given speed. An example of a typical, idealised power curve is shown in Figure 8. Due to the Betz limit, a turbine can only extract a maximum of 59.3% of the energy in the wind. Turbines will have a minimum operating wind speed (cut-in wind speed), a maximum operating wind speed (cut-out wind speed, limited to prevent damage to the turbine in case of storms) and a rated windspeed whereby the turbine will produce its rated power. Power curves are an approximation, as in reality the power output at a given wind speed will be influenced by the wind direction, turbulence and other environmental parameters (e.g. humidity and temperature). There are international standards covering how power performance of a turbine at a site should be measured, e.g. IEC 61400-12-1 *"Power performance measurements of electricity producing wind turbines"*.

Device scale

Wind turbine sizes onshore continue to grow. This is both in terms of tower height, to capture higher wind speeds at higher altitudes, and in terms of rotor diameter. This increase in swept area means that more energy can be captured, as energy can be extracted from a larger surface area. In Europe in 2020, the average onshore wind capacity factor was 25% [17]. Capacity factors are lower than offshore wind turbines as the wind resource is exposed to more friction from the land topography and manmade structures.

Typical wind turbines are rated at 2-3 MW. This is increasing on average, for instance in the US the average rating for installed turbines increased from 2.43 to 2.55 MW from 2018 to 2019 [19]. Companies are developing increasingly large onshore wind turbines to take advantage of economies of scale, for example in 2020 GE unveiled their latest 6 MW Cypress turbine, with a modular two-piece blade and 11% higher annual energy production compared to its 5.3 MW predecessor [20].

At the 2 MW scale, wind turbine products include:

- The GE 2 MW onshore platform, available with rotor diameter from 116-132 m and at hub heights from 80-150 m [21].

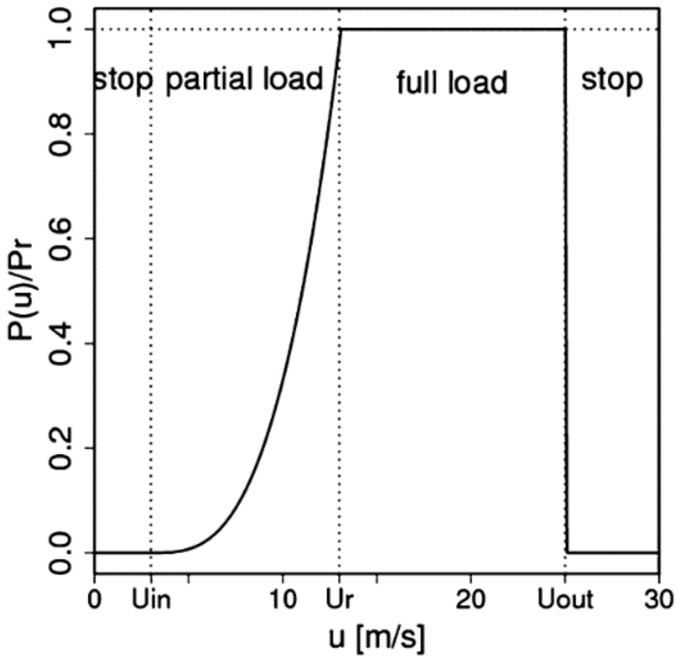


Figure 8 Typical, idealised power curve [188].

- The Vestas 2 MW platform: available from 90m rotor diameter (V90, 80 m hub height recommended) up to 120 m rotor diameter (V120, 2.2 MW) [22].

- The Enercon E-70 E4, rated at 2.3 MW with a rotor diameter of 71 m and designed for hub heights between 54 and 98 m [23]

There are also smaller below 1 MW and including small scale below 100 kW. In the US, the average installed cost of a small (<100 kW) wind turbine was about $8,300 per kW [19]. Examples of companies with products in this range include Wind Energy Solutions BV, who supply the 100 kW WES100 and 250 kW WES250 [24], and Norvento who supply the nED100 100kW turbine [25]. At these scales, rotors diameters are typically in the 20-40 m range, with tower height about 30-50 m.

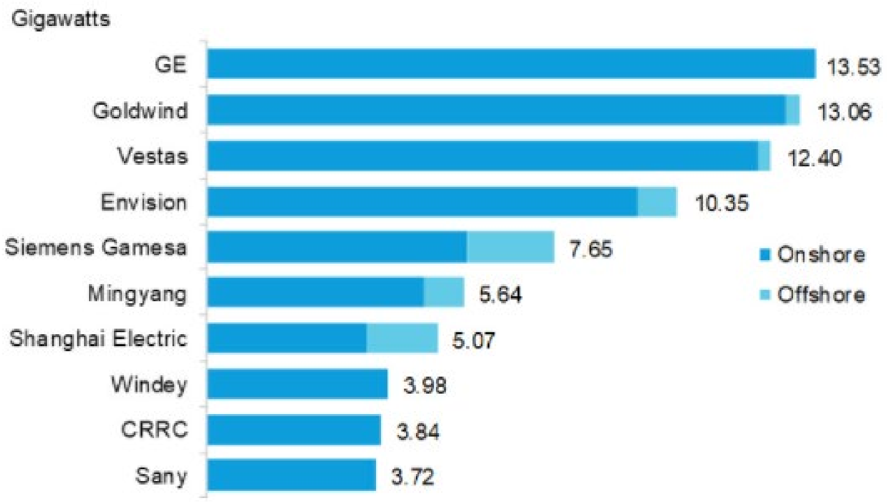
As the wind technology is mature, it is also possible to get previous smaller models from market leading companies like Vestas and GE second-hand.

Very small turbines (<10 kW) have been designed for urban areas and domestic use. Commonly these designs are vertical axis, more suitable for the more turbulent and less consistent winds as they do not need to yaw into the wind.

Companies

There are over twenty wind turbine manufacturers, however four accounted for over half of the turbines installed in 2020: GE, Vestas, Goldwind and Envision [26]. BloombergNEF (BNEF) suggest that GE and Goldwind were the two largest, focussing on their rapidly growing home markets (the USA and China respectively).

Current and Future markets



Source: BloombergNEF. Notes: Total commissioned wind capacity in 2020 was 96.3GW. MHI Vestas capacity is attributed to Vestas since Vestas' acquisition of MHI Vestas in late 2020. Top ten in 2019: 1) Vestas 2) Siemens Gamesa 3) Goldwind 4) GE 5) Envision 6) Mingyang 7) Windey 8) Nordex 9) Shanghai Electric 10) CSIC (now CSSC).

Figure 9 Ten largest wind turbine suppliers in 2020 as identified by BloombergNEF. [26].

China is a particularly fast-growing market, with BNEF identifying about 58 GW of new capacity installed in 2020 [26]. This is more than the entire world in 2019 and has largely been driven by developers rushing to complete projects before feed in tariff subsidies are phased out [27]. Outside of China, the US commissioned about 16.5 GW of capacity and Europe 12.6 GW.

Since 2000, the wind industry has increased at a CAGR of 21%. Industry projections by IRENA [28] see the industry increasing at a slower rate of 7.2% into the future, to 1,700 GW by 2030 (3x 2018 levels) and 5000 GW by 2050 (an almost 10x increase). 5000 GW could be equivalent to an area the size of Iran (about 1.6 billion km^2). Installations would be led by Asia, mainly China, with Africa another fast-growing market. A significant amount of capacity could come from repowering and upgrading older farms, for example with larger and more efficient turbines.

Figure 10 shows the main revenue support schemes that new wind installations have been given for the period 2020-25 [27]. The feed in tariff is the dominant scheme in China, which has led to a huge growth in wind capacity. The older and more mature European market is dominated by competitive auctions, while the US has preferred a corporate PPA and tax credit approach.

LCOE and cost reduction potential

Onshore wind is a mature technology and can be cheaper than fossil fuel equivalent projects in some markets. Despite this, industry bodies still see further cost reduction: mostly due to larger turbines which decreases the

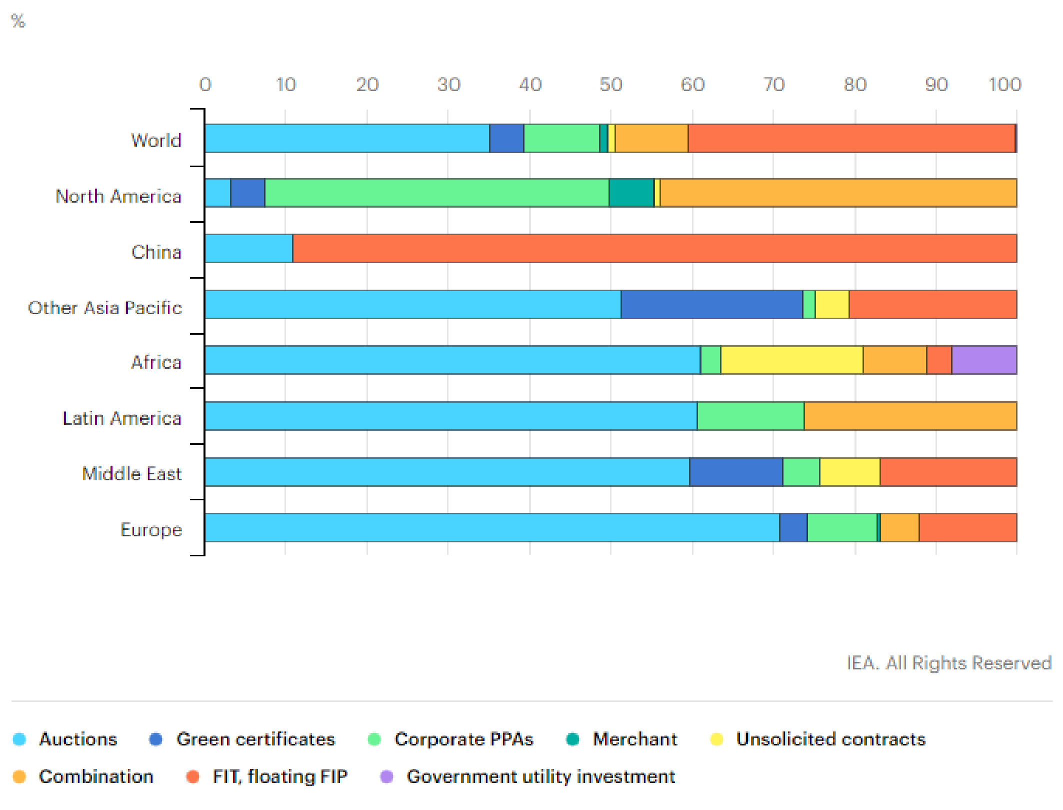


Figure 10 Wind energy support schemes by region [27].

LCOE by increasing power output per mega-watt installed. The LCOE trajectory and future estimated levels estimated by International Renewable Energy Agency (IRENA) are shown in Figure 11.

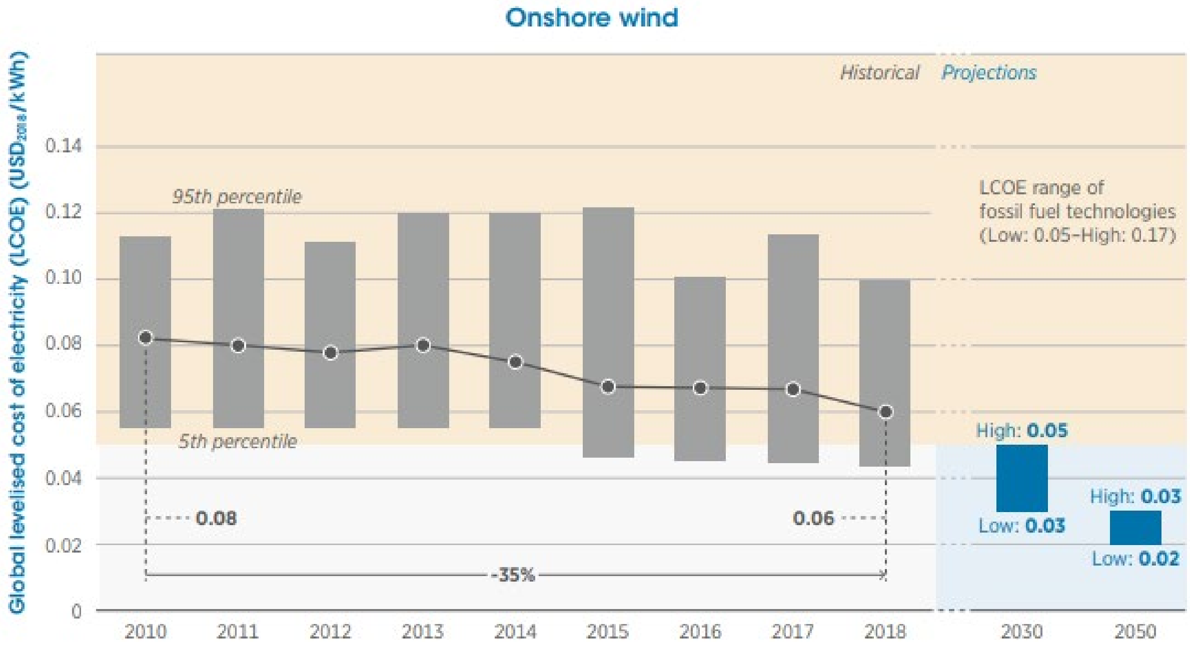


Figure 11 LCOE of onshore wind compared to LCOE range of fossil fuel technologies, as well as a future projection [28].

Some forecast LCOE reduction to decline at a slower pace as past trends. For example, the International Energy Agency (IEA) estimated only a 15% reduction between 2020 and 2025. They attribute this in part because a lot of highest wind speed sites have been built, meaning that the next generation of projects will have to settle for lower wind speed sites [27].

Solar

As for onshore wind, solar is a mature technology. It has seen large scale adoption; unlike wind a substantial amount of this is in the residential market, with solar PV panels a common sight among rooftops around the world.

In essence, every type of renewable energy can be attributed to the sun. Wind energy is a second-hand form of solar, with the differential, uneven heating of the Earth's surface causing atmospheric pressure gradients [29]. Wave energy is a third-hand form of solar, as these winds power the waves. Tidal currents are produced from the relative movement of the Earth, Sun and Moon.

The energy from the Sun that falls on the Earth is massive, and far exceeds global energy consumption (by about 7500 times by some estimates [30]). However, only a small proportion of this can be harnessed in reality, due to the conversion efficiencies of the solar technologies, other land uses and the impractical nature of deploying solar in the oceans on mass.

Solar has been used as a passive source of lighting and heating since the dawn of mankind. The photovoltaic effect was discovered in 1839 by nineteen-year-old physicist Edmund Becquerel, whereby some material could produce small electrical currents when exposed to sunlight [31]. A further innovation was the first solar powered steam engine in 1878, which led to increasing interest in solar into the 20th century. The industrial revolution and a newfound interest in coal meant that solar advancements were largely confined to geographic areas with lower coal reserves, for example California where William J Bailey invented an early solar thermal collector (the “Day and Night Solar Hot Water Heater”).

The first solar PV cell that could produce significant power was invented in 1954 by Bell Laboratory in the US, building on previous work by Russell Ohl (the discovery of the “P-N junction”). Early-stage solar cells were used in satellites, with a 14% efficient cell created in 1958 by Leslie Hoffman. By the 60s and 70s the annual market for solar cells had grown to $5-10 M. The main market was still for satellites, with NASA providing a significant part of the market. The oil crisis of the 1970s increased interest in solar, with US government investment leading to the transition of the industry from space to larger markets on earth. Early investors were oil companies, including Exxon, Mobil and Arco. Into the 90s and 2000s, awareness of climate change increased, and with it an increase of funding from governments into renewable energy applications, for example revenue support schemes like feed in tariffs and tax credits. Cost reduction was steady, for example in California between the mid-1990s and 2006 the price of solar cells was estimated to have reduced by 5% per annum on average. In the 2010s, China emerged as a dominant manufacturer of solar panels, coinciding with the growth of their domestic market [32].

Operating principle

There are several different types of solar technology, the most common being solar photovoltaics (solar PV), known as solar panels. Solar panels consist of a P-N junction, a specific combination of elements which produces flow of electrons when light is shined on it [33]. While solar panels typically have low efficiency compared to other renewable technologies, they can be easily mass manufactured, leading to low costs, and also have no

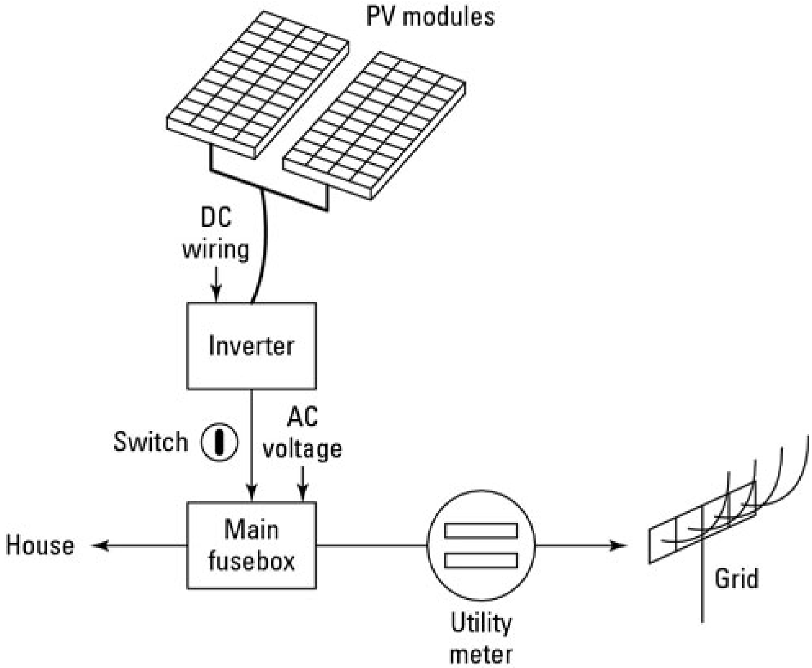


Figure 12 Typical residential solar power system [187]

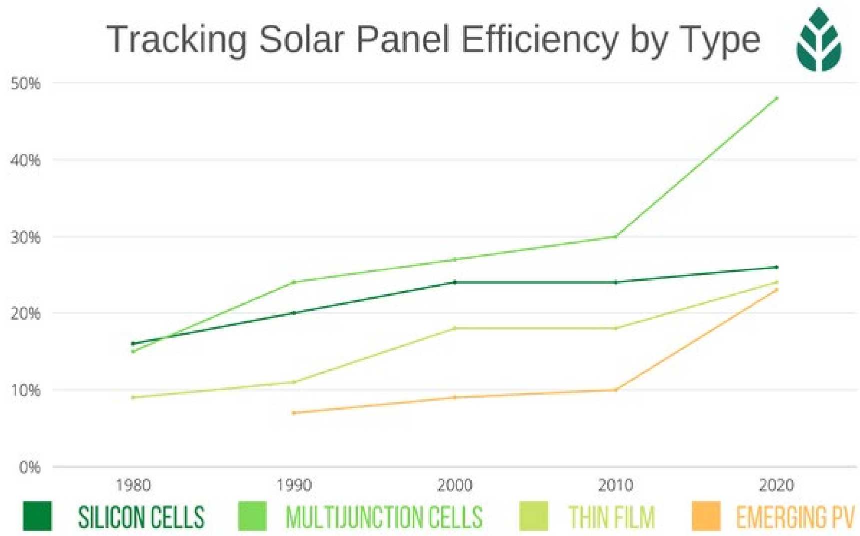


Figure 13 Solar panel efficiency by type, over time [34]

moving parts and so are easier to maintain. Figure 12 shows a typical solar panel system, as installed on a residential property. The panels generate electricity in DC, which is converted to AC via an inverter and either used for power within the home or exported to the grid.

There are several types of solar panels, with ever increasing efficiency. [34]. These trends are shown in Figure 13. Silicon cells and thin film are the most commonly used for electricity generating applications. Multijunction cells are an emerging technology whereby multiple layers of P-N junctions are contained within a single panel. These are tuned to respond to different wavelengths of light, making the panels incredibly efficient. They are currently limited to the space industry and satellites [35], as the cost is too high for large scale application. Emerging PV includes novel and innovative materials, including organic cells, dye-sensitized cells and quantum dot cells [36]. These are generally less efficient (with many concepts below 15%) and suffer from other challenges like material toxicity, higher degradation and high cost. However, some have potentially landscape altering properties, for example quantum dot technologies can be tuned to specific wavelengths giving them potential as a layer within multijunction panels.

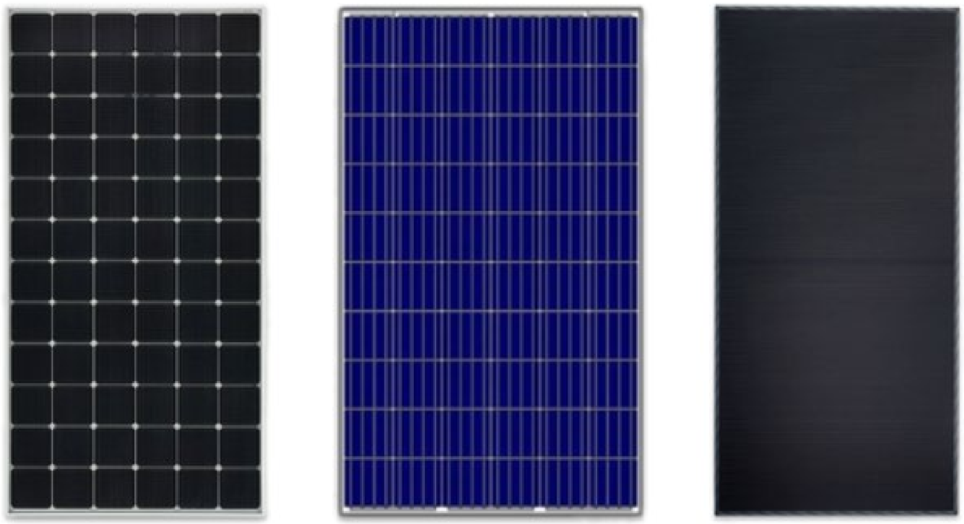


Figure 14. The three most common types of commercially available solar panels: monocystalline (left), polycystalline (middle) and thin film (right) [37].

Solar panels can be monocrystalline (made from a single solid silicon crystal) polycrystalline (made from multiple crystals) or thin film (where a thin film of photovoltaic substance is deposited onto a solid surface like glass) see Figure 14. Residential applications tend to use monocrystalline or polycrystalline [37]. While monocrystalline are more efficient, polycrystalline are cheaper and so there is a cost vs performance trade off. Thin film panels tend to be used for commercial applications, i.e. energy farms make up of arrays of panels. This is because they are much lower cost and, while they are less efficient, they can be connected and deployed over larger areas compared to e.g. a household which is limited by its roof area.

Generally, for commercially available panels, monocrystalline efficiency is of the order of 17-22%; polycrystalline 15-17% and thin film 10-13% [37], although this depends on operating conditions and specific models. Monocrystalline are regarded as the most suitable for residential rooftop applications, with thin film best for commercial farms and polycrystalline an option if cost is a significant factor.

As well as solar PV, solar power is also a popular choice for providing hot water. This is known as solar thermal. A diagram explaining the solar thermal principle is shown in Figure 15 [38]. In this example, and generally, the solar thermal system is paired with a conventional condensing boiler to supply hot water, reducing the gas usage of the overall system.

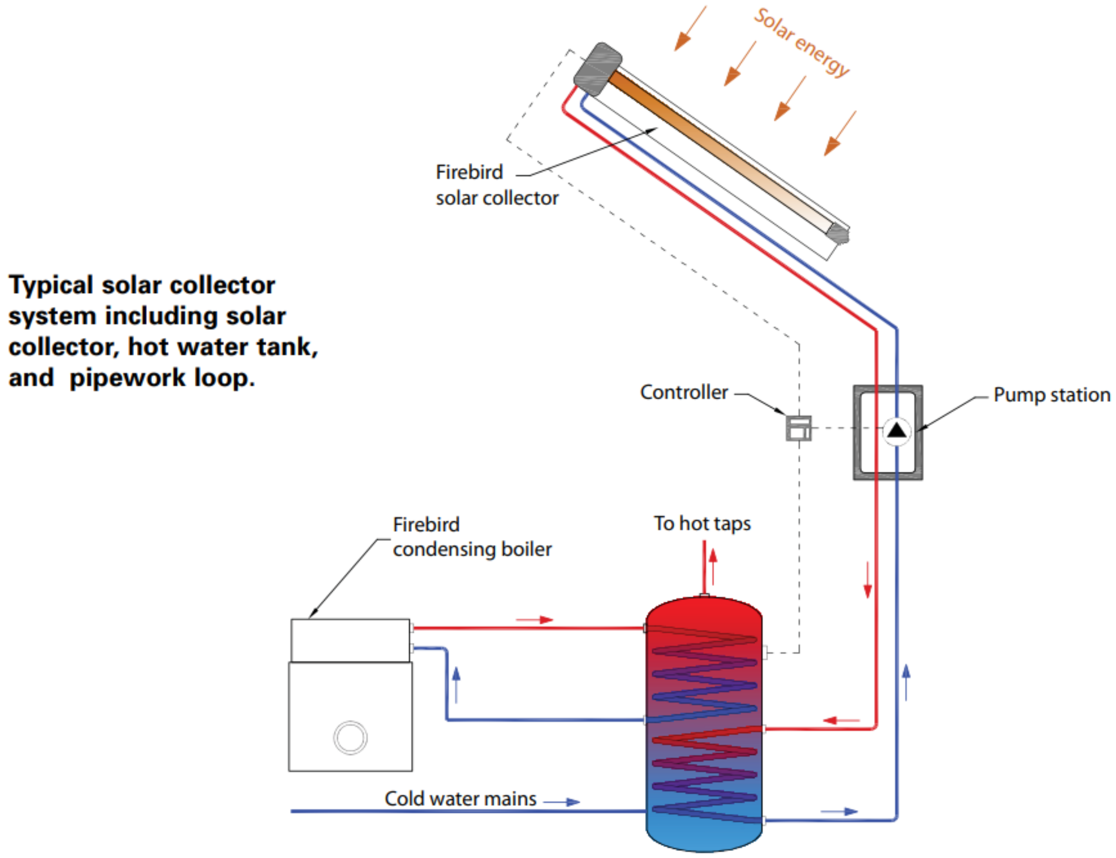


Figure 15 Typical solar thermal system [38]. Note that Firebird is the brand of solar thermal system, and many suppliers exist.

Solar thermal systems do work in winter, however there will be more reliance on the conventional boiler. Solar thermal is generally more efficient than solar PV, typically above 50%, and also more space efficient, with systems taking up less space. The main disadvantage is that the production is lower grade heat, compared to electricity which has more numerous applications. For example, solar thermal is more productive in the summer months (northern hemisphere), when temperatures are warmer and hence heating less required. For this reason, solar PV is typically more common.

A growing trend is for combined solar PV and thermal systems, known as solar PVT. These are collectors that can produce both electricity and heat, effectively combining the advantages of both systems. They were first researched in the 1970s, and have increased in popularity, with commercial adoption in the 2000s as a way to save space on rooftops. PVT panels are less efficient than the equivalent PV and thermal panels, and are also more expensive, and as such are considered a niche product where efficient use of space is the primary concern.

Device scale

Solar panels are modular units and are connected together into arrays. The largest solar farm in the UK is Shotwick Solar Park in Wales, a 72.2 MW farm covering about 1 square km [39]. Domestic solar panel systems are typically between 1-4 kW in the UK, producing about 250-400 Watts per hour depending on weather

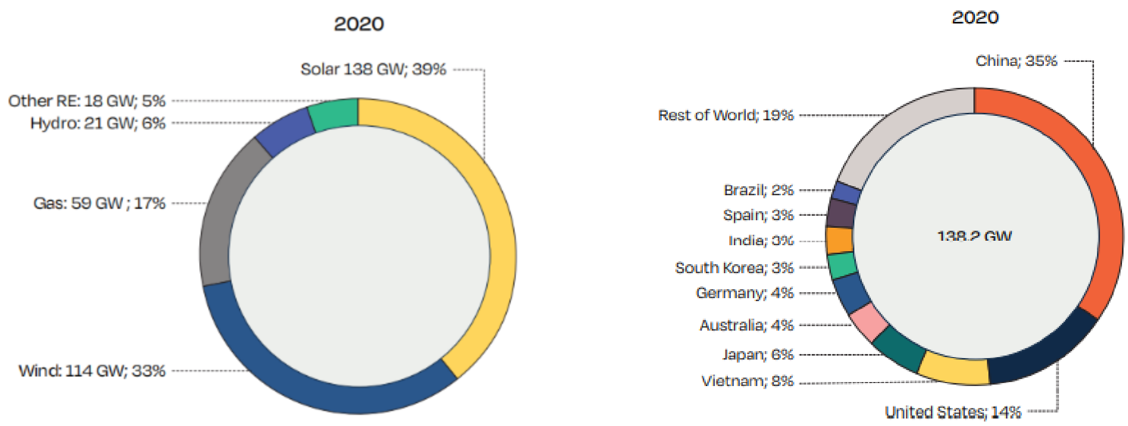


Figure 16 Net power generating capacity added globally in 2020 (left). Solar capacity installed by country (right). [42]

conditions [40]. This depends on the size of the solar panel, with a rule of thumb that solar panels at rated at about 1kW per metre square [41], with a typical individual panels rated at 250W.

Even commercial solar farms tend to be small enough that they would be connected into the distribution rather than transmission system. Typical power density of a solar farm is 10 W/m^2 in sunny conditions, however it depends heavily on the location and time of year [31].

Current and Future markets

Germany was one of the earliest adopters of mass solar, in 2012 they had more solar capacity than the rest of the world combined [31]. The landscape has since shifted, with China now the dominant force, both in terms of manufacturing capacity and installations.

In 2020, a net 138 GW of solar was installed, exceeding all other forms of energy. This is shown in Figure 16 [40]. Solar now makes up 3.1% of the global power that is generated. China grew their grid connected solar by 60%, to 48 GW, exceeding the USA in second place by 2.5 times [42]. Into the future these markets are expected to grow further, especially developing markets where solar can provide green energy at lower cost than fossil fuel alternatives.

The Sahara Desert is frequently touted as an area with high potential for solar. It is one of the sunniest locations on the planet, rich in silicon which is used to make the semi-conductors needed for solar panels. Studies have estimated that the Sahara Desert could supply all of the world's electricity needs if 4% of the land was covered by solar panels [43]. This area is illustrated in Figure 17. While the cost of the transmission system to get this to the rest of the world would likely be prohibitive, it illustrates the size of the global resource. There would also be environmental implications. For example the black solar panels would reflect a lot of heat back into the atmosphere and into the local environment [44], and some studies suggest that a large area of solar panels could increase rainfall and lead to an increase in local vegetation (through a "positive albedo-precipitation-vegetation feedback" loop [45]).

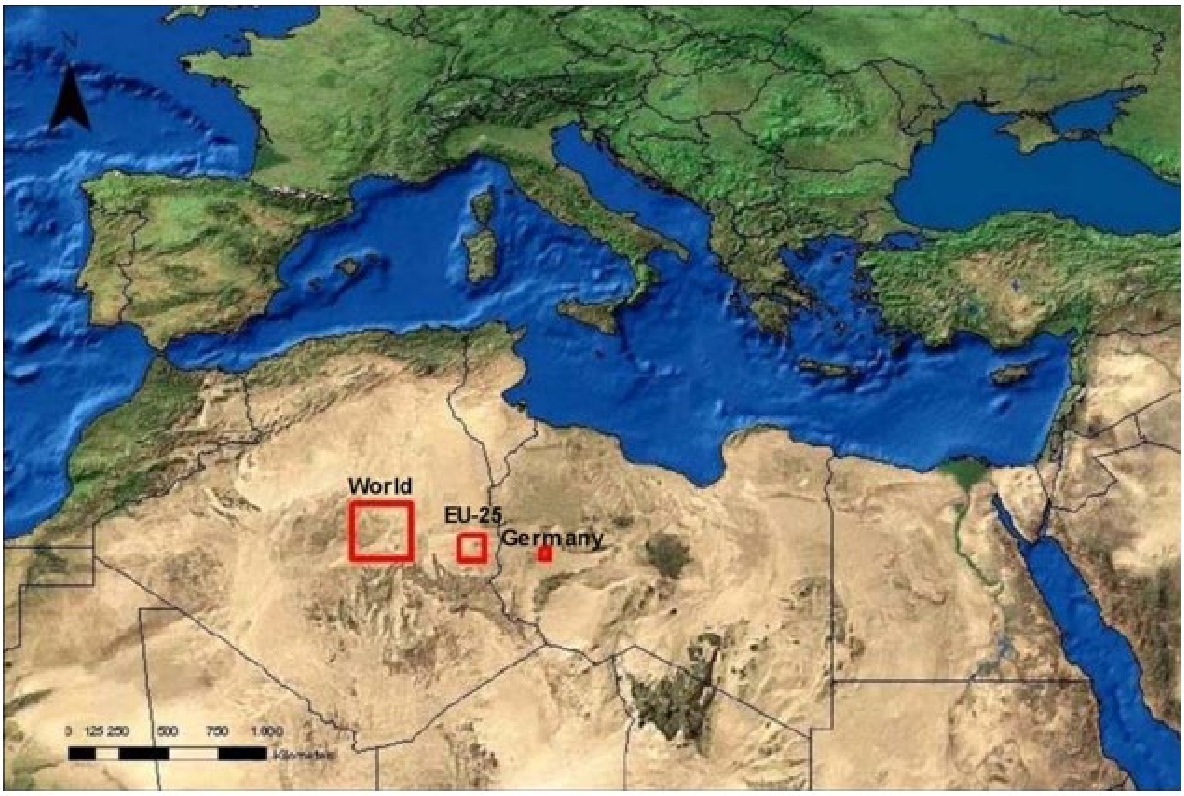


Figure 17 The area of the Sahara Desert that would be needed to supply the World with electricity [43].

LCOE and cost reduction potential

The LCOE of solar has declined rapidly in the last ten years, as illustrated in Figure 18. This has largely occurred due to a huge reduction in solar module prices (a 93% reduction of crystalline solar PV modules in Europe between 2010 and 2020 [46]) due to ramping up of manufacturing capability in China, bolstered by favourable government policy and a political desire to grow their domestic market. While growth is expected to slow into the future, there are still technological innovations that are expected to reduce costs and improve efficiency. These include new types of solar panels coming to market (for example multijunction and quantum dot panels), advanced monitoring and inspection of panels by drones [47], and integrating energy storage within farms to mitigate the diurnal production cycle.

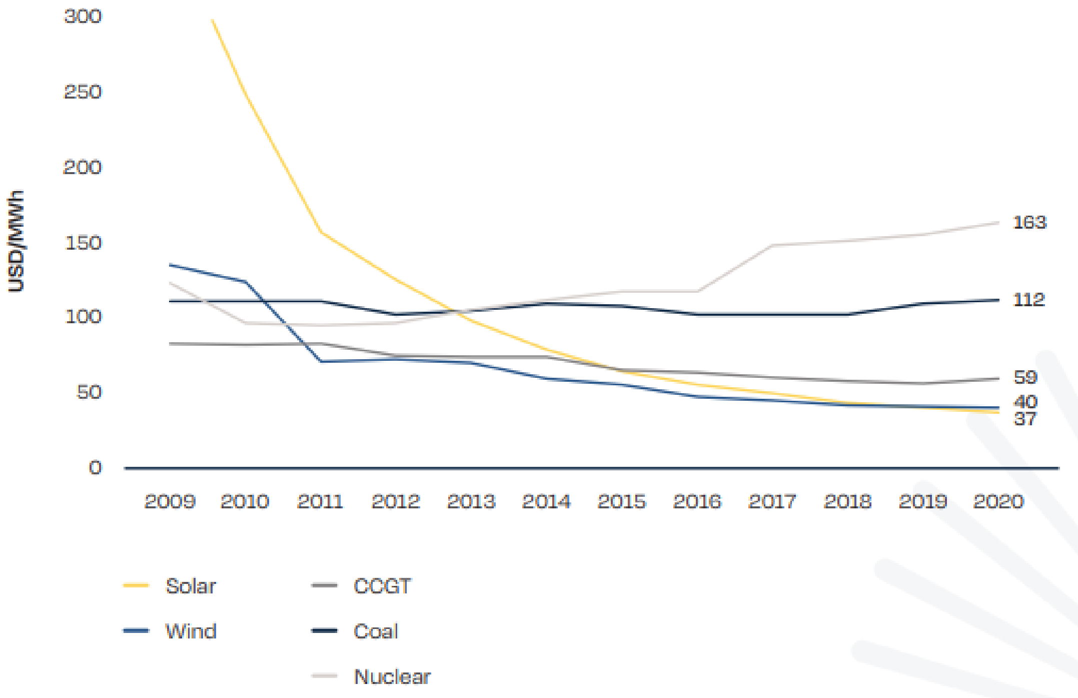


Figure 18 LCOE reduction of solar compared to other technologies [42].

Waste recovery

There are several technologies that can create heat, electricity or biogas from landfill waste. As environmental concerns have increased, these are seen as a sustainable alternative to just leaving the waste to build up over time. These technologies are at various stages of technology readiness, and can be summarised as follows:

- **Combined Heat and Power (CHP) energy from waste:** The operating principle is defined as the simultaneous generation of heat and power within a single process. This has efficiency savings, as both the heat and electricity are used, unlike traditional processes which tend to use one or the other. This is illustrated in Figure 19 [48].

  For CHP from waste, power is generated by burning landfill waste within a furnace. The waste heat that is produced can either be used directly or converted to electricity via a heat engine and generator. CHP generators can be used in several different sectors, as shown in Figure 20.

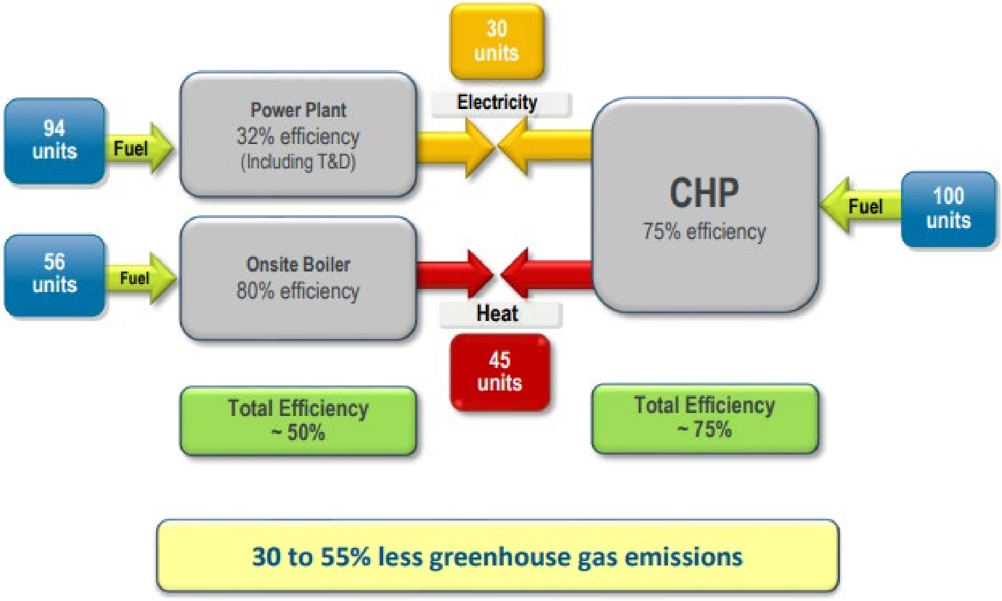


Figure 20 Example of CHP efficiency savings, compared to a dedicated power plant and boiler [48]

CHP User Sector	**No. of CHPQA plant installed in 2018**
Industrial (non-oil refineries)	167
Oil refineries	6
Large hospitals	22
Other health facilities	121
Universities & colleges	43
Other education facilities	19
Museums & libraries	8
Leisure centres	311
Retail	156
Hotel/Hospitality	118
District heating	72
Sewage treatment	49
Horticulture	50
Other	84
Total	**1,226**

Figure 19 CHP plants by sector, operational in the UK in 2018 [183].

- **Anaerobic Digestion (AD):** This is process whereby microorganisms break down organic waste materials into gas, which can then be burnt for electricity. Examples include inedible food waste, livestock manure, wastewater, and agricultural waste. The decomposition of these types of waste produces methane gas, which can be used to create "biogas". Methane absorbs 86 times more heat than carbon dioxide, hence this technology can be "carbon negative" [49].

The AD process is shown in Figure 21. Biogas can be burnt, for heat or electricity (for example in a CP plant as previously mentioned) or converted into biomethane (also known as renewable natural gas) which can be injected into gas grid or used in vehicles.

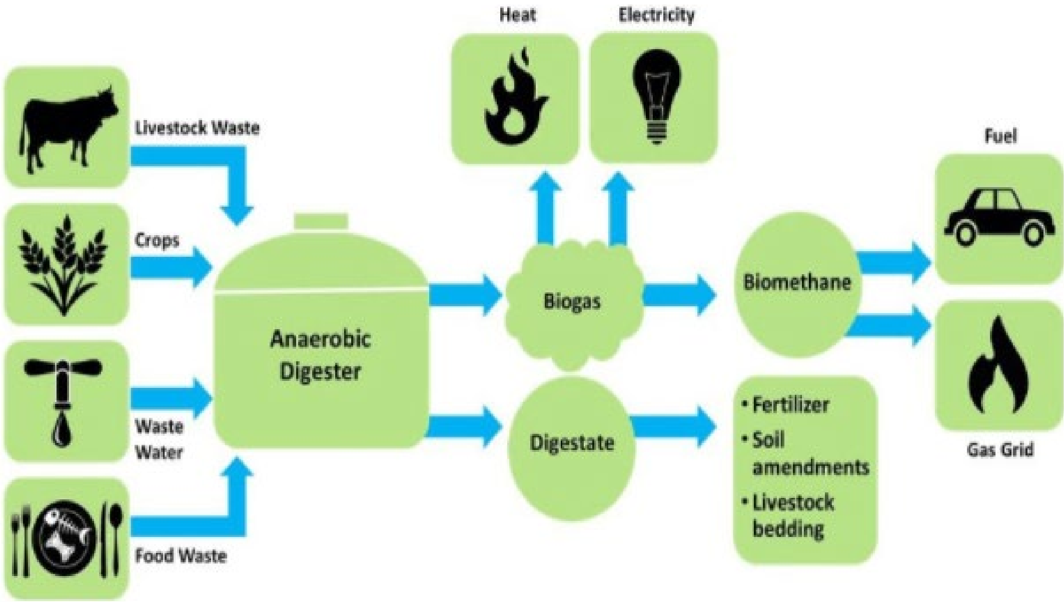


Figure 21 The anaerobic digestion process.

Generally, digesting a tonne or food waste can generate about 300 kWh of energy, and in the UK, there are approximately 650 AD operational facilities [50]. In 2016 the largest AD plant in Wales was built in Bridgend. The £14 M plant processes about 48,000 tonnes of organic waste per year and generates 3 MW of electricity [51]. In 2018 a similar plant in East Yorkshire was scrapped, following protests and complaints by local residents [52]. The main concerns were the large scale of the facility, in an area "heavily promoted for tourism" and the perceived impact on local traffic.

- **Advanced conversion technologies (ACT):** These are technologies that use gasification and pyrolysis processes to generate energy from waste.

  Advanced thermal treatment (ATT) is one example, designed to convert solid waste that is non-recyclable or biodegradable into a gas (known as syngas), which is then combusted to produce steam. The conversion process is known as pyrolysation. Materials can also be recovered from the process, from the front-end preparation or "out the back end of the process out of the ash" [53]. Some plants have been developed in countries like Japan, Germany, Norway and the USA by companies like Erergos, Mitsui Babcock and Thermoselect [53], however the technology is immature and yet to be demonstrated on a large scale [54].

Renewable technologies - Offshore

The States of Alderney have jurisdiction over their territorial waters, an area extending up to 3 nautical miles from the shoreline. Beyond this, the area out to 12 nautical miles is controlled by the Bailiwick of Guernsey. Historically, such distances out to see have seen a multitude of offshore renewable energy projects deployed all over the world: primarily offshore wind but also floating solar, tidal stream and wave energy devices.

These technologies are in various stages of deployment, but all have their advantages and it can be argued that they all have a part to play in getting the world onto a low carbon, net zero trajectory. Putting these renewables offshore avoids many of the conventional problems associated with renewables, including land use conflicts, visual impact and general opposition due to Nimbyism. It does introduce other considerations though, for example the added complexities of marine operations, the need to wait for suitable weather windows, availability of vessels and potential impacts on marine life.

This section describes the leading offshore renewable technologies that could be viable for Alderney.

Offshore wind

The offshore wind industry has been one of the renewable sector's biggest success stories over the last ten years, and it is now a truly a global industry. The offshore wind industry has been one of the renewable sector's biggest success stories over the last ten years. From 3.1 GW in 2010, over 35 GW has, and it has now been installed [46], a compound annual growth rate (CAGR) of about 27%. It is truly a global industry. While the heart of the industry is still in Europe, with about 25 GW installed, there is increasing attention on the USA and Asian countries like South Korea, Vietnam, Japan and most significantly China.

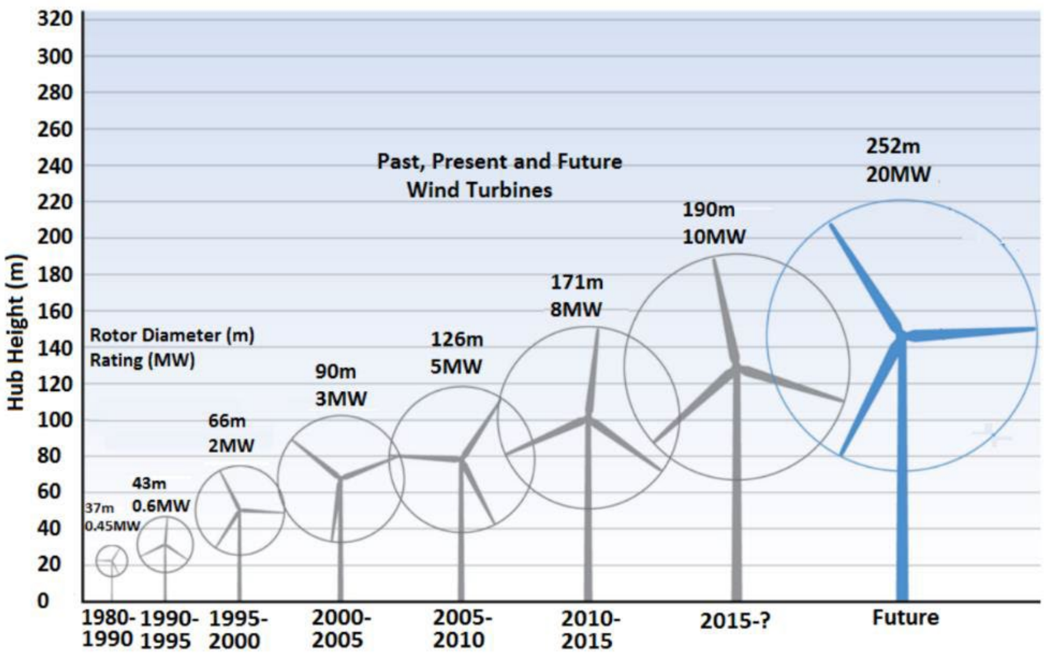


Figure 22 Evolution of wind turbine rated power and rotor diameter. Taken from [182].

A main reason for this success has been the ever-increasing size of turbines. This is illustrated in Figure 22. Larger turbines mean a larger rotor swept area, so more energy can be extracted. The turbine towers are also increasing in size, exposing the turbines to greater wind speeds with less wind shear. Turbines are also rated at a higher capacity, with 15 MW turbines currently in development compared to 3-5 MW a decade ago. This means that, for a given farm size less foundations and turbines need to be installed and maintained, dramatically lowering installation and O&M cost. Vessels are ever increasing in size to keep up with the growing turbine sizes, which could reach 20 MW+ by 2030 [55].

Devices

Operating principle

The three-bladed horizontal axis wind turbine has been the industry standard for a number of years, which is unlikely to change. While there are some novel turbine and technology types, for example vertical axis and airborne wind energy, these are generally at lower technology readiness levels (TRL) (typically 5-8). The offshore wind turbine supply chains are incredibly developed and globalised which drives down costs, and so it is unlikely that any other design could compete on cost outside of niche cases and applications (for example small off-grid systems). We would recommend focussing attention on established companies and turbines to provide lowest cost of energy and eliminate potential risk.

Device scale

Turbine sizes are getting increasingly larger. However, these larger turbines may not be suitable for all locations, for example nearshore locations with visual amenity would be a problem, and so there will always be a range of turbine sizes available. The largest turbines offer the lowest LCOE due to the large economies of scale and energy that can be extracted, although vessel availability is becoming more of an issue as fewer vessels are capable of installing the latest device generations.

There are some companies who are exploring the possibility of using large onshore turbines (4-5 MW) in the nearshore marine environment, which could benefit from easier installation (no need for large vessels). An example of a nearshore project in development is Vatenfall's Vesterhav Syd and Nord wind farms, which would use 8.4 MW Siemens Gamesa turbines 9 km from the shore [56]. This was consented and reached financial investment decision in December 2021 [57].

Foundations

Monopiles have been the dominant foundation of choice, suitable for water depths up to about 40m. In deeper waters the foundations become less economic, mainly due to high installation costs and the large piling equipment that is needed, however there is much focus on the next generation of "XXL" monopiles for the large turbines of the future, which could potentially be viable in 50 or even 60 m depths. Jacket foundations are the foundation choice for deeper projects, up to about 60 m. These lighter structures are more complex but are held in place via smaller pin piles and thus are easier and cheaper to install in deeper waters.

Some early-stage projects used gravity base foundations, especially popular in Sweden [58]. However, these are inefficient from a material and size perspective, taking up a lot of room on the quayside, and are generally too big and heavy for use with larger turbines (although there are companies re-examining gravity designs and innovations, for example OWLC[2].

Arguably the most rapidly developing and exciting trend in offshore wind is towards floating foundations. These are designed for water depths beyond 50 m and utilise learning from offshore structures used in other industries (mainly oil and gas). There are several categories of foundation:

- Semi-submersible: This is the leading design concept, with the most companies working on these designs. These consist of relatively low draft designs, which are partially submerged and moored to the seabed via catenary mooring lines. Examples of suppliers include Principle Power (WindFloat), Ideol (Damping Pool), Saitec (SATH) and Hyundai Heavy Industries.

- Spar: These are long cylindrical floaters, the length keeping the platform stable in the water. Because of the larger draft, these require deepwater ports for construction (for example within Nordic Fyords) and thus are expected to command less market share in the future. The main supplier is Equinor, who have deployed their spar design at early-stage demonstrator project Hywind Scotland.

- Tension leg platform (TLP): these foundations are moored to the seabed using taut moorings and suction anchors (sediment/clay covered areas) and can be partially submerged like semi-sub designs. An example of a TLP foundation is the Tetraspar, a design being developed by Stiesdal (a company led by Henrik Stiesdal, Danish inventor who designed one of the first wind turbine designs and was CTO at Siemens Wind Power for many years).

There have been a handful of floating wind demonstrator and early commercial projects including Hywind Scotland (30 MW, commissioned in 2017), WindFloat Atlantic (25 MW, commissioned in 2020) and Kincardine (50 MW, commissioned in 2021). The latter uses Principle Power's Windfloat design, whereas Hywind Scotland uses Equinor's spar.

By 2030 the UK government aims to have 1 GW of floating wind operational [59], with Scotland and the Celtic Sea regions of particular interest. For Europe, WindEurope have estimated that there could be 7 GW installed [60], with GWEC predicting "Floating offshore wind will reach full commercialisation by 2030 with at least 6 GW installed globally" [61]. ORE Catapult have predicted that floating wind could be subsidy free by 2030 [62].

Companies

The three main wind turbines suppliers are Siemens Gamesa, Vestas and GE. All of these companies are developing turbines in the 15 MW range. There are also Chinese suppliers, for example Goldwind and MingYang,

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2 https://www.owlc.co.uk/gravity-tripod.html

however these companies are yet to break into the European or North American market in a big way. Currently Siemens Gamesa is the largest offshore wind supplier worldwide, with about 70% of European market share [63].

There are a large number of project developers. These include large utilities (e.g. EDF, RWE, SSE), dedicated offshore wind developers (Ørsted) and increasingly oil and gas majors (BP, Equinor, TotalEnergies). It is common for companies to partner up and enter in JVs to deliver projects. Recent examples include SSE, Equinor and Eni who are developing the Dogger Bank wind farms, and BP and EnBW who are preferred bidder for two 1.5 GW Round 4 sites [64].

There is a clear trend towards the oil and gas companies taking project ownership as the industry has matured. These companies have large financial resources, and ample experience of working on the marine environment,

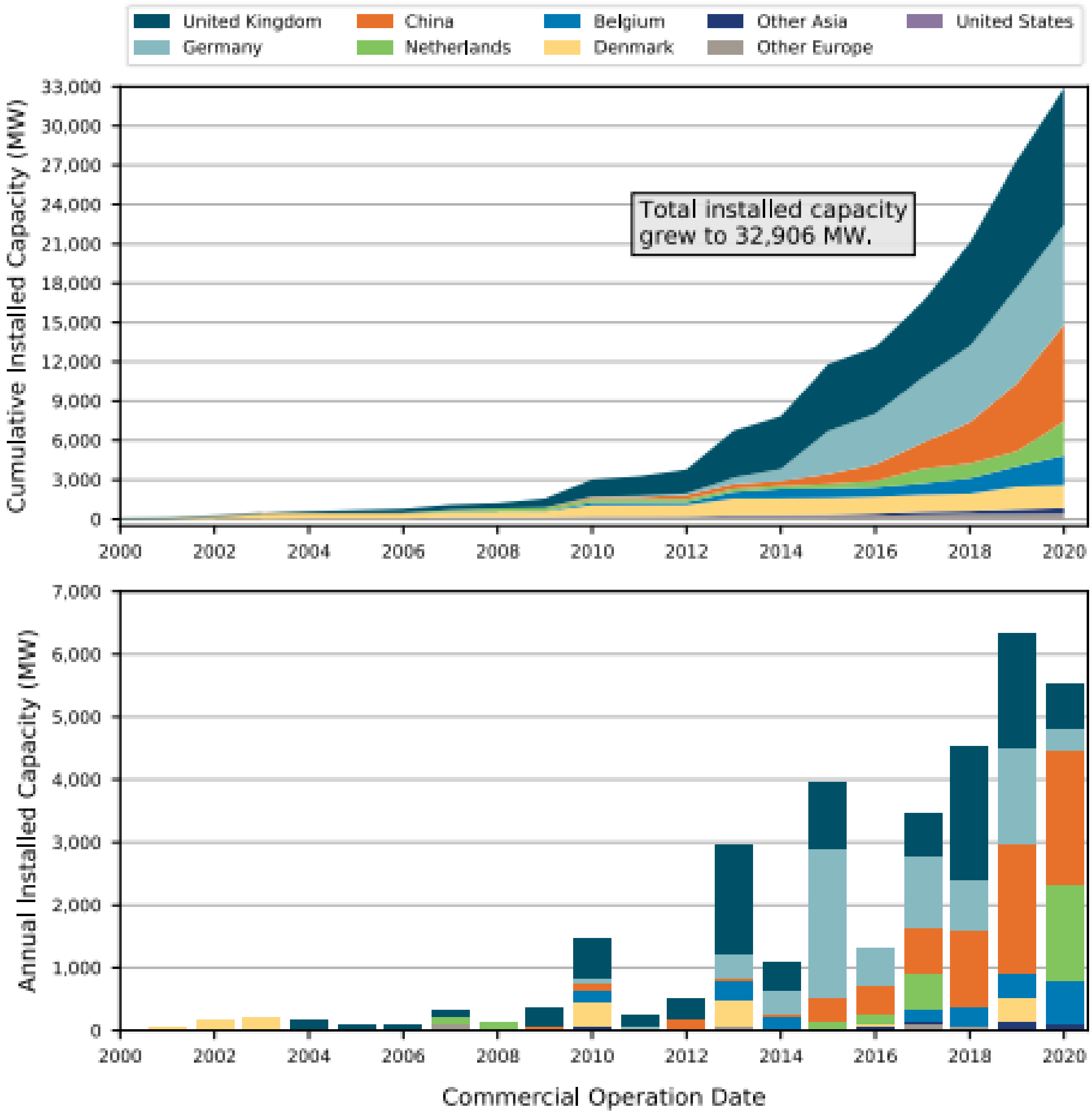


Figure 23 Global offshore wind markets: cumulatively installed (top) and annual capacity additions (bottom). [66].

and the offshore wind space gives them both commercial opportunity and the opportunity to offset the carbon emissions from their main business segments.

Current and Future markets

Figure 23 shows how global offshore wind capacity has evolved from the year 2000 to 2020. From 2010 to 2020 the installed capacity compound annual growth rate (CAGR) has been estimated at 27% [65]. As previously mentioned, Europe is still the largest market for offshore wind projects, with about 25 GW of capacity. Asia is also relatively established market and growing rapidly, particularly China, the Republic of Korea, Vietnam and Japan. GWEC predict that over 234 GW will be installed worldwide by 2030, from about 30 GW at the end of 2019, with China the largest offshore wind market at 58.8GW, followed by the UK at 40.3 GW and the US at 22.6 GW [61]. In the US, while there is only 42 MW installed today, there are about 30 projects in development along the East Coast with the majority off the New York coast (14 GW in planning and permitted) [66]. The UK has a pipeline of over 40 GW and has an ambitious government target of 40 GW of capacity installed by 2030.

Near the Channel Islands there are several offshore wind projects in development. In 2021, France announced six finalists for a Normandy tender [67]. These included Iberdrola Renovables France, Shell, Oceans Winds and several consortiums including EDF, Vattenfall, RWE, Total and Enbridge. This will see a farm of 900-1050 MW capacity installed about 32 km off the coast of Normandy. In Brittany, the Saint Bruiec wind farm is being developed by Iberdrola. This will start operation in 2023, with a capacity of 496 MW, and is 16 km off the coast of Brittany [68]. It is currently under construction and uses 62 Siemens Gamesa 8 MW turbines (model SG 8.0-167 DD).

LCOE and cost reduction potential

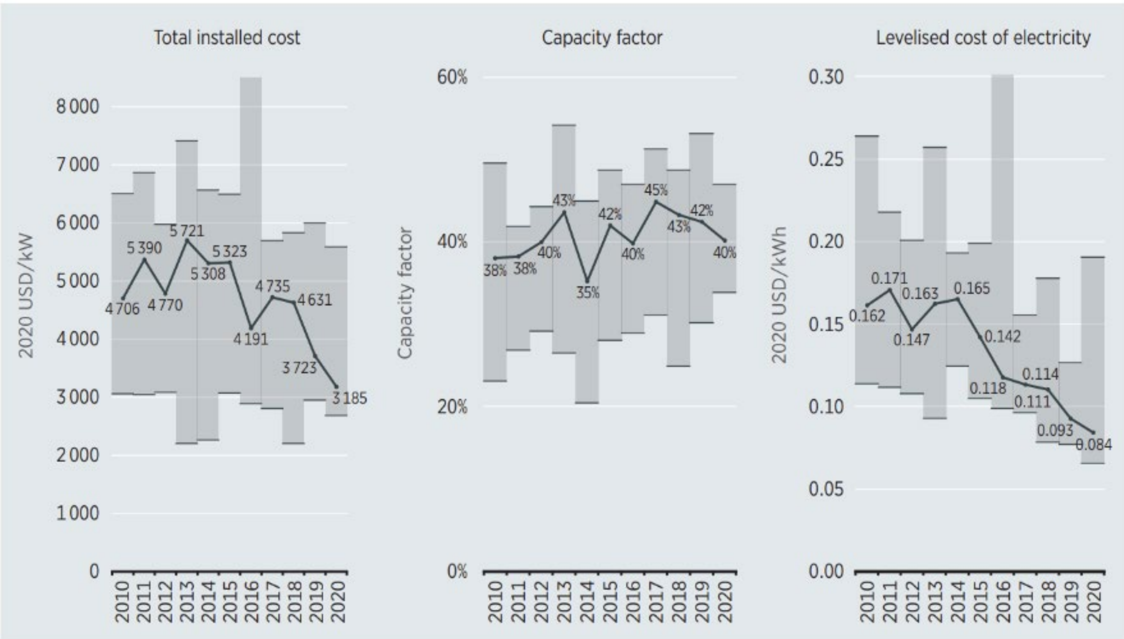


Figure 24 Trends (global weighted average) in offshore wind installed coat, capacity factor and LCOE [69].

The offshore wind industry has progressed far quicker than most expected, with exceptional cost reduction demonstrated over the last five or so years. In 2020, IRENA reported that LCOE reduced by a further 9%, year on year [69]. Trends in offshore wind costs, capacity factor and LCOE can be seen in Figure 24. Figure 25 shows global weighted LCOE (black line) and auction/PPA prices out to 2025. While there is a large spread in the subsidies secured, from about 2014 the trend has been declining, which can be attributed to larger turbines, larger project scales and a more competitive auction environment which has seen developers squeezing margins lower and lower to secure project capacity.

Into the future, most expect these LCOE reductions to continue, albeit at a slower pace. Figure 26 shows the cost reduction for fixed and floating wind that ORE Catapult anticipates for fixed and floating wind in the UK [65]. From about 2024, fixed offshore wind tails off as it becomes economically viable to develop projects without CfD.

Governments and project developers are increasingly looking at zero subsidy farms, where there is no revenue support and instead electricity is sold at wholesale market prices. Another area of increasing focus is corporate PPAs, whereby farm owners will sell the electricity directly to companies. This is particularly interesting for companies who want to demonstrate their green credentials and achieve net zero CO2 operations. A recent example was a 10-year agreement signed by Amazon and Ørsted, whereby Ørsted will supply Amazon with electricity from their planned 900 MW Borkum Riffgrund 3 wind farm in Germany [70].

Figure 25 Global weighted-average LCOE (black line) and subsidies secured (CfD/PPA) for offshore wind projects.

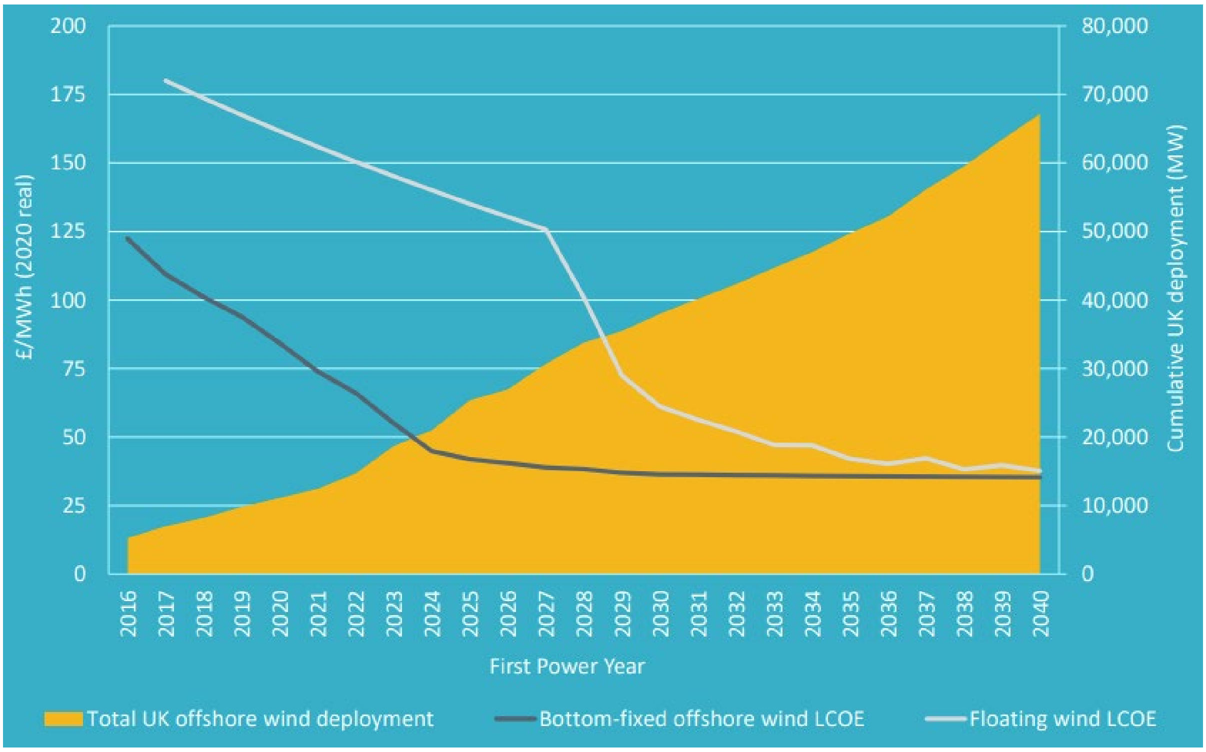


Figure 26 LCOE reduction predicted for the UK offshore wind industry [65].

Offshore wind is a mature, established technology, with a proven track record. While the industry is ever pushing towards larger turbines and bigger farms, the technology is still very economical for small numbers of turbines at lower ratings, and there is increasing interest in nearshore locations to facilitate easier installation and O&M.

We think that offshore wind could be a promising technology for Alderney, given its jurisdiction over its own territorial waters (out to 3 NM). At these distances, it is likely that smaller turbines would be better suited (possibly in the range 3-5 MW, depending on desire to export electricity), as these would be less noticeable from the shore. While offshore wind farms can be large infrastructure projects, this could be financed from an established project developer, although a subsidy could help to secure interest. As the electricity cost on Alderney is high, offshore wind could provide a favourable, lower cost and clean renewable energy resource. There could also be an opportunity for local employment for O&M activities, as these jobs tend to be primarily local content.

Tidal stream

Tidal stream energy is the concept of extracting energy from tidal flows. To date, interest has predominantly been focussed on localised shallow water tides, which tend to focus between islets and around headlands. Some companies are examining the possibility of extracting energy from deep ocean currents, which are more consistent, however this is at an early stage of development and targets deeper waters than the territorial waters around Alderney (which reach a maximum depth in the 80-100 m range).

The tides are driven by the relative movement of the Earth, Moon and Sun. Because of this, they are highly predictable and can be forecasted hundreds of years into the future. This gives tidal stream the potential to be a very predictable and dependable renewable energy source, with clear associated benefits to the wider electrical system. For example, the wind resource can be forecast about a day in advance, but to a much lower degree of accuracy. This means that greater close to real-time costs are incurred in the energy system, from having to curtail excess wind energy and from having to pay other generators to switch on during shortfall.

The nature of the tidal resource also means that it is completely uncorrelated with other forms of renewables. For example, winds drive waves, with both resources typically larger in stormier winter months, and solar has an obvious diurnal cycle. This makes tidal a potentially complementary part of the energy mix, helping to spread out energy generation on electrical networks.

Tidal sites tend to be close to the shore (most UK sites are within 5 km), meaning that the power can be exported at a relatively low cost through short export cables. While the high tidal flows can make O&M difficult, slack tides (periods of near zero tidal flow) give a window of opportunity, and vessels with dynamic positioning can be used at other times.

Devices

Operating principle

The most common types of devices are horizontal axis, resembling the standard horizontal axis wind turbines which are seen throughout the world. The powertrain layout and components are extremely similar, meaning that suppliers, engineering and general learning from the offshore wind industry can be applied. There tends to be divergence on the number of blades for devices with some developers currently mirroring the three bladed wind approach (e.g. SIMEC Atlantis, Magallanes), some two bladed (Orbital Marine Power, Nova Innovation) and some greater numbers of blades (for example some Sabella concepts have used six blades, although the company are moving to three blades now).

A disadvantage of the horizontal axis is that, in order to increase energy from the flow from both directions, the blades need to be able to pitch. Adding such a pitching system adds cost and complexity to the design, adding more points of failure. Some designs consider active, variable pitching systems. For example SIMEC Atlantis have been working with Spanish manufacturer Asturfeito on a new variable pitch control system [71], so that the blade angle can be optimised for given flow conditions to improve energy yield. Some designs have not used pitch control systems, for example Nova Innovation’s M100 has a variable speed rotor design said to improve the conversion efficiency in both flow directions without the need for pitch control. Nova are planning a 200 kW design, which will have pitch control [72], and so there is clearly a commercial case for implementing this design feature.

There are some examples of devices with vertically orientated (vertical axis) rotors. These include GKinetic’s latest designs and French technology developer Hydroquest. The orientation means that the device can capture the flows for any direction, meaning that no pitch control system is required. The disadvantages of the design are lower efficiency and poorer self-starting performance, with some system needed to start the turbines in low flows [73]. For these reasons, few devices of this type are being developed.

Lastly, there are some more novel device designs. These include design principles like oscillating hydrofoils, venturi turbines and Archimedes screw. Which such designs do have viable use cases, the large difference compared to established power generation technologies like offshore wind means that they are largely confined to research activity, the system being very bespoke and less able to take advantage of established suppliers and off the shelf components.

One novel design that has more merit is the kite design, as popularised by Swedish company Minesto. The device resembles an underwater kite, equipped with a small rotor, which generates energy as it "flies" through the water column. The operating principle is similar to airborne wind technology, also in its early stages, for example the previous market leader Makani (formerly funded by Google's Moonshot funding programme, liquidated in 2020 [74]). The buoyancy and much higher density of seawater compared to air means that the device is easier to suspend in the water column, also control systems are required to keep the device suspended and keep it generating.

The main advantage of this technology is in low flow areas, as the relative speed of the device moving through the water column can have an additive effect to the incident flows speed to effectively increase the flow speed going into the rotor. However, the device is more complex in nature, especially the control systems required to keep the kite suspended and the "launch mechanism" to start the energy production.

Minesto have deployed prototypes of their DeepGreen device class off the coast of Holyhead, Wales, and in the Faroe Islands. They are also deploying a microscale device at the French Paimpol Brehat test site as part of the Interreg funded TIGER project. They recently announced their new device concept the "Dragon class" [75], with an optimised shape made from a lower number of sub-components to reduce costs and improve manufacturability.

Device scale

There are many different types and sizes of tidal devices, from very small devices rated at tens of kilowatts to multi-megawatt machines targeting utility scale applications.

- **"Microscale" (<100 kW):** These devices are generally designed for very shallow and run-of-river applications or offshore locations with less extreme tidal flows (i.e. <1.5 m/s). They also have applications for remote communities and off-grid applications, for example to serve as a source of power for small villages. Due to the small scale, these devices can be tested quickly locally, offering the potential for many iterations of design improvements at low cost. Examples of companies with technology at this scale include:
    - GKinetic, who have been testing their 12 kW, vertical axis device at Strangford Lough in 2021.
    - Guinard Energies Nouvelles, who have device classes at 3.5 kW and 20 kW and have been demonstrating their technology at projects in France [76] and Togo [77].
- **"Small to mid scale" (100 kW-1 MW):** These devices are sized to capture both smaller off grid markets and utility scale farms at volume. Some companies see this as a sweet spot in capacity, as it allows larger yields

to be gained by increasing device swept area while also allowing multiple, device generations to be deployed quickly to reduce costs through learning.

These devices also target shallower sites in the 20-30 m range, which can benefit from higher tidal flow speeds from small channel cross sectional areas. Examples of companies with technology at this scale include:

- Nova Innovation operate the Shetland array and have deployed five of their 100 kW M100 turbines. These devices are horizontal axis turbines with 9 m rotor devices. Nova have recently announced partnerships with French supplier Sabella and UK based SIMEC Atlantis and have demonstrated battery storage and electric vehicle charging at their site.

- Swedish technology developer Minesto has installed and grid connected 2x 100 kW tidal kites in Faroe Islands. They also have plans to demonstrate their next generation (Dragon class) 100 kW kite design at EDF's Paimpol Brehat tidal test site in France in 2022. They are also developing a Dragon 12 application with a power rating of 50 kW-1.2 MW.

- Tocardo have developed three classes of turbines at this scale. Their initial application was run of river, but the company was recently acquired by QED Naval and Hydrowing and have increasing interest on ocean applications. Tocardo are supplying turbines for QED Naval, to be deployed and tested as part of the TIGER project.

- Sabella are a French technology developer who also are developing several different classes of devices at scales in the 250-1000 kW range. They have deployed their 1 MW D10 device at Ushant Island for testing several times, most recently recovered in January 2021, and are planning to deploy two turbines in the Morbihan Gulf as being funded by the TIGER project.

- **"Large scale" (1-3+ MW):** Lastly, a large part of the market is targeting larger, commercial scale devices. These can benefit from larger economies of scale and material efficiencies, allowing material costs to reduce. Larger rotors and swept areas also mean that more energy can be captured, and higher rated turbines mean that fewer turbines and foundations are required to scale up farm capacity. This can result in lower O&M and installation costs, following the trends being seen in offshore wind.

Because of the lager rotors, these turbines need to be deployed in deeper water to allow sufficient clearance above the rotor for marine traffic. While cheaper in terms of LCOE, the larger devices are also more expensive on a per unit basis due to the higher CAPEX costs and so earlier prototypes will require more upfront investment.

Examples of companies with technology at this scale include:

- SIMEC Atlantis operate the Meygen project in the Pentland Firth. The project consists of four 1.5 MW turbines (3x AHH turbines and 1x AR1500). The company are currently developing a larger 3 MW turbine (AR3000) to be deployed in the La Raz Blanchard, subject to achieving consent variation for the site. The AR3000 turbines will likely have a 24 m rotor diameter and be on a fixed foundation (monopile or gravity base).

- Orbital Marine Power (OMP) have developed the O2: a 2 MW floating device, consisting of two 1 MW rotors. OMP deployed this device at EMEC in June 2021 and have a track record in pioneering floating tidal technology.
- Hydroquest are a French developer who have a vertical axis technology. They have deployed several generations of the device for testing, most recently at the Paimpol Brehat test site in Brittany which is operated by EDF and SEENEOH. They are targeting 2.5 MW for their next generation of device in a neighbouring tidal site to SIMEC in the Raz Blanchard.
- Magallanes are a Spanish tidal energy developer who have developed the 2 MW ATIR device, also a dual rotor floating device. Magallanes deployed their device for testing at EMEC in 2021.

Table 1 Well known tidal stream devices, arranged by device scale and foundation type/operating principle. Black entries are devices that have seen real world deployment. Blue entries are devices in planning. Grey entries are companies who faced financial problems and were liquidated.

	Microscale (<100 kW)	Small-mid scale (100-1000 kW)	Large scale (1000 kW+)
Fixed foundation Horizontal axis		Nova Innovation (GB) M100 Sabella (FR) D8, D10 SIMEC Atlantis (GB) AR500 Verdant Power (US) Gen4, Gen5 QED Naval (GB) Community Scale Subhub	SIMEC Atlantis (GB) AR1500, AR2000, AR3000 OpenHydro (IE) TEL (GB) Deltastream MCT (GB) Seagen
Fixed foundation Vertical axis			Hydroquest (FR) Oceanquest 1, Oceanquest 2
Fixed foundation Other	Minesto Dragon (SE) 4	Minesto (SE) DG100, DG500	Minesto Dragon (SE) 12
Floating foundation Horizontal axis		Sustainable Marine Energy (GB) PLAT-I	Orbital Marine Power (GB) O2 Magallanes (ES) ATIR
Floating foundation Vertical axis	GKinetic (IE) hydrokinetic turbine		

Foundations

In terms of foundations, tidal devices fall into one of two categories:

- Fixed bottom devices: As for offshore wind, tidal devices can be secured to the seabed via gravity base or piled foundations. Historically gravity bases have been more common, as these are relatively simple to design and deploy for the smaller devices that have been seen. However, as the industry develops and devices get bigger it is expected that there will be a significant transition towards monopiles. Highly tidal locations tend to be rocky, so drilling would be required which impacts the installation cost of these foundations and may make them prohibitive for smaller devices/arrays. However, monopiles are smaller and easier to transport and install than gravity base foundations, and the industry can tap into the mature offshore wind supply chain, where monopiles are the dominant foundation type.

  Fixed foundations benefit from relative simplicity. They also mean that devices are fully submerged, mitigating the navigational hazard, reducing visual dis-amenity and reducing the impacts of wave loading on the device.

  Examples of companies who use these foundations include Simec Atlantis, Sabella, Nova Innovation and Verdant Power.

- Floating devices: These devices somewhat resemble conventional vessels, floating on the water surface and are moored to the seabed. Commonly mooring systems consist of catenary lines which are fixed to the seabed using gravity or drag embedment anchors.

  The main advantages of these foundations are that the devices are easier to install, as can typically be towed to site without needing a heavy lift vessel, and also maintain as the main device structure is accessible via a service vessel like a CTV. Because the device rotors are higher in the water column, the flow speeds are also greater, so higher energy extraction is theoretically possible.

  The mooring systems used for these devices tend to be more complex to design than fixed foundations. The devices are also more susceptible to wave loading and associated snatch loading and fatigue, which means that regular inspection of the mooring systems components is critically important. Because of this, there tends to be a large amount of CAPEX in the device hull to ensure survivability. Lastly, these devices can be navigational hazards so will be less viable for busy stretches of water.

  Developers using these types of foundations include

  - Orbital Marine Power
  - Magallenes, a Spanish developer who also are also testing their latest ATIR 2 MW device at EMEC
  - Sustainable Marine Energy, who have designed the PLAT-I floating platform. This is sub 1 MW and is fitted with six 70 kW Schottel Hydro turbines, with the company targeting Canada as their primary market focus.

As for offshore wind, it is likely that fixed and floating devices can co-exist together, as both designs have merits that make them suitable for different site characteristics. It is even possible that both types of device could be deployed within a single farm, to capture more of the energy throughout the water column.

Current and Future markets

To date, the majority of industry activity has been in the UK, France and Canada.

- In 2021, the UK government announced a long-term commitment to the sector in CfD Allocation Round 4 (AR4), a ringfenced amount of up to £20 M per year (at an administrative strike price of £211/MWh) [78]. This significant announcement could see 30-40 MW of new commercial tidal capacity deployed in the UK compared to the circa 10 MW installed at the current time (and of this only the 6 MW Meygen project has any revenue support).

  It is likely that bid will come in from across the UK. These could include an expansion of the Meygen Project, an array at the Perpetuus Tidal Energy Centre (PTEC) site off the coast of the Isle of Wight and an array at Morlais in North Wales.

  The overall UK market has been estimated at 10-12 GW and could be even higher if low flow sites can be exploited. While the Pentland Firth is the most renowned area, with a potential that could be as high as 4-5 GW, the resource is reasonably spread across Scotland, Wales and the south coast of England.

- France has a notable track record in tidal, including Sabella's activity at Ushant Island and Hydroquest's testing at Paimpol Brehat. Hydroquest and Normandie Hydroliennes (a JV including Simec Atlantis) are both developing projects in the La Raz Blanchard. These have some consents, acquired from previous now defunct projects, and are working on variations to upscale the turbine sizes and project capacity that will be deployed (each site will be around 15 MW if granted). Decisions are expected in 2022. There are also negotiations going on with ADEME, the French Agency for Ecological Transition, to secure revenue support for the projects. This could be in the form of a feed in tariff.

  The resource in the La Raz Blanchard region has been estimated at 2-3 GW with about 8 GW estimated for the country as a whole.

- Canada has long lasting and notable support for the tidal industry. The Bay of Fundy in Novia Scotia has the highest tidal range in the world, at about 12 m [79] (although some sources state as high as 20m). It is home to the Fundy Ocean Research Centre for Energy (FORCE), and has seen several leading technologies deployed at the bay in recent years including both European companies (e.g., Sustainable Marine Energy, OpenHydro) and North American (e.g. BigMoon Power and Jupiter Hydro). Several projects have secured approvals for feed in tariffs including:

  - DP Energy's Uisce Tapa Project plans to deploy 9 MW of 1.5 MW Andritz Hammerfest turbines [80]. The first three turbines are to start operation in 2023 [81].

- Spicer Marine Energy’s Pempa’q In-stream Tidal Energy Project. This will see three of Sustainable Marine Energy’s 420 kW PLAT-I platforms deployed, with up to 9MW envisioned. Spicer Marine Energy is a JV between Sustainable Marine Energy and Minas Tidal LP.

This feed in tariff is 53 CAD cents per kWh, equivalent to £310/MWh. Note that, as well the amount being higher than the £211/MWh UK AR4 administrative strike price, the feed in tariff mechanism is also good for developers as the full amount up to the strike price is paid, rather than just the top up from the wholesale market price. This generous subsidy has been a big part in attracting European companies. Nova Innovation are also very interested in the area, and received a grant of $4M CAD from Natural Resources Canada’s (NRCan) Energy Innovation Program to deploy five turbines in the region [82].

LCOE and cost reduction potential

The current LCOE of tidal stream is in the £200-350/MWh range. The UK’s AR4 tidal ringfence at a £211/MWh administrative strike price is seeing significant praise and interest, with developers confident that they can deploy competitive multi-megawatt scale projects at this level of revenue support. Tidal stream proof of concept has been demonstrated by projects like SIMEC Atlantis at Meygen Phase 1A, which has shown a 34% capacity factor and 95% availability [83], and the Orbital SR2000 device (previous generation) which generated continuously for 12 months and exported 3 Gwh into the Orkney electricity grid [84].

In 2018, the Offshore Renewable Energy Catapult derived an LCOE trajectory for tidal stream technology [85], shown in Figure 27. While this is a couple of years out of date, the industry has not progressed at the rate anticipated and so the trajectory is deemed appropriate for the current state of the industry. The study predicts an LCOE of £90/MWh by 1 GW of capacity installed. This could be possible into the early to mid-2030s, the opinion of industry bodies like Ocean Energy Europe and the Marine Energy Council, if the government continue to back the sector with revenue support.

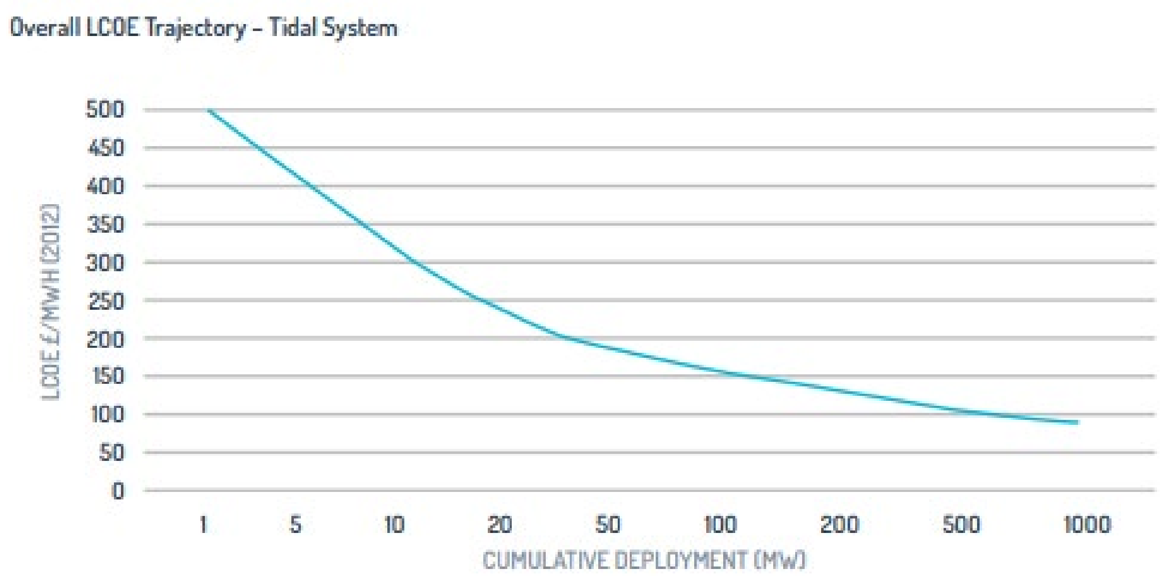


Figure 27 Tidal stream levelized cost of energy (LCOE) trajectory [85].

This cost reduction will be made possible through innovations and industry drivers such as:

- Larger rotor devices, with higher rated powers to take advantage of economies of scale and improve energy yield for only modest device size increases
- Improved foundations and mooring systems (for example monopiles for fixed devices and taut moorings and innovations like rock bolt anchors for floating devices)
- Improvements in materials, for example blade materials like thermoplastics, which can reduce O&M costs due to blade maintenance and repair.
- A competitive and diverse supply chain, enhanced through a firm project pipeline and government commitment to the sector. This will reduce component costs through, for example, by purchasing components in bulk through more competitive tendering processes.
- Improving the financing arrangements on projects, for example reducing WACC by introducing more commercial debt on projects available at lower interest rates
- Improvements in offshore operations, including things like innovations in "plug and play" systems to allow quick installation and recovery, wet mate connectors and potentially purpose-built vessels for the sector to reduce reliance on expensive vessels from other industries (oil and gas, offshore wind).

While the costs of tidal stream technology are coming down rapidly, it is still about 5-10 times more expensive than offshore wind.

Wave

Wave energy has its origins in the 1970's, when the UK Government funded alternative energy technologies as a response to high oil prices at the time. There were a variety of early-stage devices, including the well renowned "Salter's Duck", however government funding was cut in the early 1980s as the oil price declined, leaving the industry in hiatus.

In the early 2010s there was a resurgence of wave energy in the UK. The University of Edinburgh again provided a hub for this activity, led by devices such as Pelamis and Aquamarine, as well as international developers like Wavestar, Carnegie and AW Energy. Unfortunately, this again proved to be a false dawn, with many of these developers forced to face bankruptcy as offshore wind costs fell and funding and revenue support became less available. When they went bankrupt in 2014 Pelamis had 56 staff, in excess of many wave and tidal stream developers today, showing the scale of the world leading company and technology in general.

Currently wave is seeing renewed interest, especially small and mid-scale devices (<1 MW) for niche and off-grid applications.

Technologies and companies

Wave energy technology has seen much less convergence than wind or tidal stream, with many different device concepts and operating principles deployed to date. Much of this is because the power in waves is multi-variate, depending on the wave frequency as well as wave height. This means that it is difficult to have a "one size fits all" solution, as different device scales will respond differently depending on the properties of the wave climate.

The early devices to market will likely influence the proceeding designs that are seen. Currently there have been no commercial wave energy projects. The main device concepts can be classified as follows:

- Point absorber – This is the most common device type, consisting of a single bodied device. The device body floats on or near the water surface and moves up and down with the waves, typically producing electricity via a linear generator or hydraulic system for any wave direction. Examples of this device concept include CorPower Oceans C4 and the Carnegie CETO device.

- Attenuator – This device also floats on the water surface but operates parallel to the waves and produces electricity from the relative movement between different parts of the device. Examples include Mocean and Pelamis (now defunct).

- Oscillating surge – This device resembles a paddle, usually fixed to the seabed and generating electricity when it is pushed by surge waves. Examples include AW Energy and Aquamarine (now defunct)

- Submerged pressure differential: As the waves rise and fall, they introduce a pressure differential in the device, which can be used to drive a generator via the movement a device body or a circuit of air or hydraulic fluid. Examples of this device include Bombora and AWS.

- Oscillating water column: This device contains a hollow body. When waves go into the device they force air through a Wells turbine, which spins the same direction regardless of the direction of air flow. The devices tend to be constructed onshore, but some floating device concepts do exist. Examples include the Islay Limpet and Mutriku Breakwater Wave Plant in Spain. OceanEnergy have a floating concept.

- Rotating mass: These devices resemble conventional ships. They are moored and float on the water surface, the waves rocking the devices and turning a rotating gyroscope to produce power. The best known of these devices is the Wello Oy Penguin.

The point absorber is generally regarded as the most common device class, due to its relative simplicity. Different device classes could have applications at different metocean sites:

  - Point absorbers tend to be fixed to the seabed via a gravity anchor or piles and are usually scaled to respond best to shorter, wind driven waves. This makes them more suitable for shallower, relatively nearshore sites.

  - Attenuators are akin to floating wind/tidal devices, fixed to the seabed via a mooring system, and so are more suitable for deeper waters.

- Oscillating surge devices are designed for the nearshore environment. Here, breaking waves can introduce uneven, large loading on the device, and so they have to be designed to withstand these breaking wave impacts.
- Submerged pressure differentials offer a particularly interesting application, possibly for more remote and extreme wave climates. For example, the Bombora device sits on the seabed and is relatively benign, with few moving parts. It could be deployed far out at sea, for example on floating wind platforms or on the seabed to power oil and gas assets.
- Oscillating water columns could have applications nearshore, for example the Mutriku Wave Plant is built into a breakwater.
- Rotating mass devices are typically moored so, like the attenuator, could be more suited for deeper waters.

As for the wind and tidal offshore devices, wave devices tend to be fixed to the seabed via fixed foundations (gravity base or piles) or mooring systems and anchors.

Companies

There are many companies developing wave energy devices. The EMEC website includes a table of 256 known companies from across the world, but with a majority operating in the UK, USA, Norway, Sweden, Ireland and Denmark. These organisations tend to be very small (<20 employees), with funding coming from equity (for example angel investors) and research grants.

From our knowledge of the sector, we consider the following companies market leaders and ones to watch to monitor the overall health of the industry:

- **CorPower Ocean** are a Swedish developer. They are developing a point absorber technology, made from composite materials, with their C4 device rated at 300 kW. Their key selling point is in their novel Wavespring system, which relies on advanced control systems and provides damping to the wave converter to allow its response to be tuned to the specific sea conditions, resonating according to the incident waves.

  Corpower are involved in several projects. Their flagship project is the HiWave-5 project being developed at Agucadoura in north Portugal, which will eventually see four devices deployed at the site. This would be the first wave energy array deployed at reasonable scale (>1 MW) since Pelamis's array installed at the site in 2008 (which was only in operation for four months due to technical problems [86]. The HiWave-5 project has received over €20 M in equity funding from various private investors [87], and is a project to watch to gauge the health and future of the industry.

- **AWS Ocean** are one of the oldest companies still active. Founded in the early 2000s, their device is the Archimedes Waveswing. This is a submerged buoy, which generated electricity through movement caused by the pressure differential caused by the waves overhead.

AWS have developed various iterations and scales of the device over the years, with the current product a 25 kW unit for niche applications. While AWS state that the product is "available to order" on their website, it is still undergoing testing, with a deployment at EMEC for testing planned for early 2022.

- **AW Energy** are a Finnish company who are developing the Waveroller device. As previously mentioned, this is an oscillating surge device which captures nearshore waves (about 0.3-2km from the shoreline) in water depths between 8-20 m [88]. Energy is generated onboard the device via a hydraulic system and exported to shore through subsea cables.

  The company are exploring opportunities to install wave farms in Ireland, Indonesia and Sri Lanka, and also hydrogen production and water desalination applications. In 2021 they recorded a 350 kW device prototype off the coast of Portugal, which had been undergoing two years of testing in the mafrine environment [89].

- **Wello** are also Finnish. They are one of the older developers, working on their novel Penguin rotating mass device. This device has a lot of merits due to the synergies with conventional ships. The hull shape has been designed to maximise the movement in the water.

  Wello deployed their first full scale Penguin in 2010. In 2019 they constructed the latest 44m device, the WEC-2. This has a rated power of 500-1000 kW. Wello have a partnership with offshore engineering company Saipem and used their vessel to deploy the 600 kW Penguin WEC-2 off the coast off Bilbao, Spain in July 2021 [90]. This device, located at the BiMEP test site, has exported power to the local grid, and will be deployed for 2 years for testing and validation.

- **Mocean** are a Scottish developer and new to the industry. Founded in 2015, the company is developing the Blue Star and Blue Horizon devices to target niche subsea applications and utility scale markets respectively. The workforce combines expertise from several previous wave energy developers (including Pelamis and Albatern), as well as the University of Edinburgh. In 2010 they deployed a device prototype, the BLue X, at EMEC. Their device concepts are all floating, hinged rafts, with electricity generated via the relative movements of two platforms.

  Mocean have received a notable amount of funding and publicity in recent years, for example receiving £3.3 M in funding from Wave Energy Scotland in 2019 [91].

- **OceanEnergy** are an Irish company. They are developing the OE buoy, a floating oscillating water column. The company has a highly experience team including Professor Tony Lewis, who has been a leading academic in the marine energy field for over 40 years and is world renowned expert on the technology. In 2011 the company completed three years of sea trials and are increasingly looking at commercialisation opportunities. In 2020 they deployed their 500 kW, 826 tonne OE Buoy in Hawaii for further testing [92]. This $12 M project was joint funded by the US Department of Energy's Office. In July 2021, the company partnered with Dublin based Mindseed, a space technology consultancy, and were awarded funding from the European Space Agency to investigate potential uses of satellite data to support marine operations [93].

- **Eco Wave Power** are an Israeli company with a land-based device concept. Their device resembles a point absorber, but with the PTO located onshore. The movement of a surface tracking floating moves a piston, located onshore, which pumps hydraulic fluid into a hydraulic motor/generator to produce electricity. Eco Wave Power recently floated on the US Nasdaq in July 2021. They are eyeing projects in Israel, Gibraltar, Portugal and Morocco, among other countries. In August 2021 they secured permits for a 1 MW farm in Portugal.

  By the time waves get to shore a lot of the energy has been dissipated. While the design has advantages, for example ease of access for O&M, the individual devices are very small and thus economies of scale will be very hard to achieve.

- **Bombora Wave Power** are based in Pembroke Dock in Wales. An Australian company, Bombora have a pressure differential design which sites of the seabed and generated electricity via the expansion and contractions of modular mWave units. These consist of a rubber membrane which pumps air through the system. Multiple units can be joined together into arrays, interconnected onto a single foundation to improve the flow pressure and this energy that can be produced.

  Bombora envision multi megawatt arrays of mWave units. They are currently developing a 1.5 MW project in Pembrokeshire. The £17 M project includes £10.3 M of funding from the Welsh European Funding Office and will be a 6–12-month commercial scale demonstrator. Other projects include the INSPRIE project, a partnership with TechnipFMC to deploy units on a floating wind platform, and early-stage projects in Japan and Spain.

Current and Future markets

The UK has an estimated 35% of Europe’s wave energy resource and could contribute up to 15% of the UK’s energy demand [94]. Both the UK and Ireland have significant west coast potential, due to the large fetch from the Americas which allows large energy to build up in the waves as they propagate across. Both of these countries have a long-lasting history of wave energy research, including institutions like:

- UK: EMEC, Wave Energy Scotland, the University of Edinburgh, University of Strathclyde, Highlands and Islands Enterprise, Marine Energy Wales
- Ireland: Sustainable Energy Authority of Ireland (Atlantic Marine Energy Test Site), University of Maynooth, MaREI, University College Cork

There is also significant research activity in Portugal which has seen some notable projects over the years (including Pelamis’s Aguçadoura Wave Farm and the BIMEP test site).

Other markets of interest include the USA, Chile, Norway, Australia and China. As previously mentioned, there has been a trend towards niche, off-grid system applications. These include aquaculture, defence, scientific monitoring, powering subsea equipment (e.g., oil and gas platforms) and supplying remote islands with electricity as part of hybrid systems.

LCOE and cost reduction potential

Over the years there have been many cost reduction and LCOE predictions, however the industry has yet to meet these expectations. Currently the LCOE is thought to be in the £300-500/MWh range, but this is difficult to estimate as there have been no commercial arrays deployed.

Ocean Energy Europe forecast 494 MW of wave energy installed globally by 2030 in their “high growth” scenario and 178 MW in their “low growth” scenario, as published in 2020 [95]. The former scenario would see “larger wave farms at utility scale along the Atlantis coastline”, with some co-location with floating wind and global exports to the USA, Chile and India. The low growth scenario assumes the majority of this capacity comes from niche applications, as previously introduced.

Unlike tidal stream, there is currently no route to market for wave energy. The AR4 ringfence in the UK only applies to tidal stream technology, and it would be unlikely that wave could compete anyway given its higher costs and the fact that it has not demonstrated sustained generation and proof of concept at array scale.

The market readiness of the industry could be monitored by tracking companies like CorPower Ocean, Wello, OceanEnergy and Eco Wave Power to see when the first arrays are deployed in the water and can demonstrate consistent generation. This could be expected in 2023/24 if planned projects by CorPower Ocean and Eco Wave Power are delivered as promised. This could be followed by e.g., some form of revenue support by the UK or another country, which could signal the start of a commercial age for the technology

In general, the wave energy sector is a fascinating prospect and very interesting industry, however we believe that it lacks commercial readiness and is unsuitable to form a part of Alderney’s energy strategy in the near or mid-term.

Tidal range

Tidal range is a large-scale renewable technology. It consists of walling in large bays or across rivers. Turbines are built into the wall, and electricity is generated when water flows through the wall. Some designs allow the water to be stored in the bay on short timescales (typically a few hours), so that the water can be released at the optimal time (for example to make up for some other shortfall on the grid). In this regard, these types of tidal barrages can also be considered a short-term energy storage option.

There are two common tidal range concepts: tidal barrage and tidal lagoon. These are essentially the same, with the minor difference that barrages enclose a whole river estuary, enclosing a natural feature, whereas lagoons will enclose an “artificial area”, for example a nearshore area of sea which has been enclosed by a wall [96]. Because the locations of tidal lagoons can be decided more arbitrarily, they are considered to be more environmentally friendly (for example not disturbing existing marine habitats).

Tidal range projects tend to be large infrastructure projects, to take advantage of the economies of scale from large material volumes. The sea walls will typically be constructed from concrete caissons or blocks, with turbines and sluice gates (to regulate the water flow) constructed at regular intervals.

The best locations for tidal range projects will be where the tidal range is large. The differential height of the head, the difference between the water levels either side of the dam, is critically important as is used to drive the water flow in and out of the barrage. Barrages also seek to maximise the area enclosed (known as the basin area), as this is proportional to the potential energy of the water stored in the barrage. This energy (*E*) is a function of the basin area (*A*) and the head differential (*R*) [97]:

$$E = A\rho g \frac{R^2}{2}$$

Where ρ is the density of seawater and g is gravitational acceleration constant.

The turbines used for these projects are much like the rotors seen in tidal stream devices and could be a market of interest for these companies if any large-scale projects were given the go ahead. Some of these companies have been involved before, for example Andritz were supplier of choice for the Swansea Bay lagoon project [98]. Bulb turbines are the most common turbine of choice, as they are especially efficient when the head of low and are reversible so can generate electricity in both directions [99].

Notable projects

Around the world there is about 500 MW of tidal range deployed. The majority of this is in two projects: the La Rance (240 MW) Project in France and the Sihwa Lake Tidal Power Station (254 MW) in South Korea.

- La Rance is a 240 MW tidal barrage which has been operating since 1966, the oldest tidal barrage in the world. It is a 145 m barrage with size gates, enclosing a basin area of 22 km^2. [100]. The location was chosen as this corresponds to the highest tidal range in France, at 8.2 m. It has operated with an average capacity factor of 26%. The barrage took five years to construct at a cost of about $100 M (equivalent to about £3.3 Bn today), with a payback period of about 20 years [101].

- The Sihwa Lake Tidal Power Station was constructed in 2011. It is the world's largest tidal barrage, rated at 254 MW. It uses ten bulb turbines, each rated at 25.4 MW and built into an existing sea wall. It has a capacity factor of about 25% [100]. Sihwa Lake is an artificial lake, covering an area of about 44 km^2. The lake was constructed in 1994 to aid with flood mitigation and secure freshwater for irrigation, however by 1997 the water had become so contaminated that it could no longer be used [102]. The power station cost about $355.1 M and took about seven years to build [103].

There have been a small number of small-scale tidal schemes, perhaps with more relevance given the size of Alderney.

- The Annapolis Tidal Generating Station (Figure 28) was a 20 MW facility built in Nova Scotia, Canada by Nova Scotia Power Inc in 1984. Construction took four years, and the facility was built on a small island at the mouth of the Annapolis River near the Bay of Fundy [104]. The sluice gates control the flow of water through the facility, with the gates closed until the heads differential is large, upon which the gates open and water is driven through the turbine.

- Jiangxia power plant in China is a 3.9 MW tidal barrage. The mean tidal range is about 5m, and it was first commissioned in 2008, with an additional turbine added in 2007. Sources note that the plant is "still not economical from the point of view of energy generation", however it is noted that's there have been wider economic benefits from the reservoir itself including aquaculture and shellfish farming [105]. In China there are potentially 400+ locations suitable for tidal range projects of the 200-1000 kW scale, with some feasibility studies ongoing.

In the UK there have been some notable tidal barrage/lagoon projects which have not progressed. These include:

- The Severn Barrage, with a 14 m tidal range giving the potential for a 13.5 GW project [106]. This was shelved in 2010 over environmental concerns, its high capital cost (estimated at £23.6 Bn [107] and strong public opposition. Recently there have been talks of re-examining the project, with a new commission set up by Western Gateway, a regional group of local authorities in the Severn area [108]. It is believed that new technology could reduce the environmental impacts, compared to the project design from ten years ago.

- Swansea Bay Lagoon is a tidal lagoon project being developed by Tidal Lagoon Power. The plan was to construct a circular wall close to Swansea, containing 16 turbines with a capacity of 320 MW. The wall would be 9.5 km, enclosing an area of about 11.5 km^2 [109]. Tidal Lagoon Power state that £35 M has been spent on development, with the majority of this from the private sector.

  The project attempted to secure a CfD at a price of £92.5/MWh, matching the support for Hinkley Point C nuclear power station. The government commissioned a study to examine the project (The Hendry review) which recommended backing the project [110], however this was ultimately rejected over the high cost (the CfD ask covering a 60-year project lifetime).

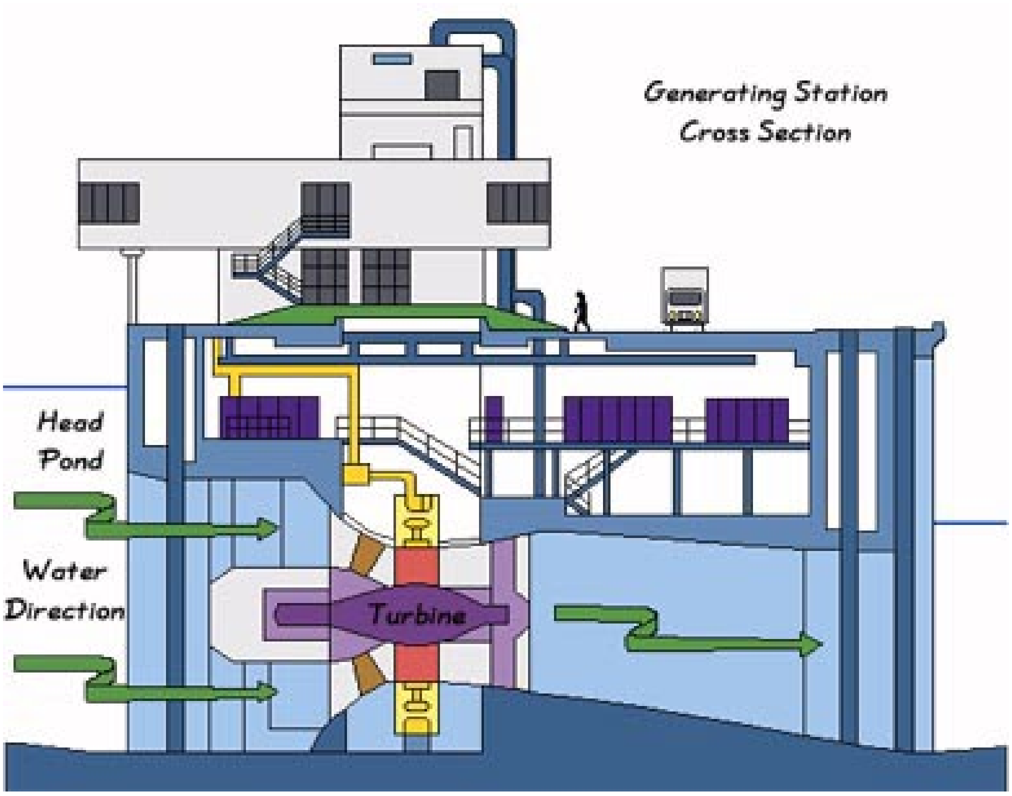


Figure 28 The Annapolis Tidal Generating Station [104].

The company were in court, trying to argue against the lapse of their five-year development consent order (which gave the project consent in 2015 for a five-year period) [111]. This was unsuccessful. In the meantime, other organisations have examined the possibility for a lagoon, with competing projects being explored, for example the £1.7 Bn Blue Eden Project. This would include a manufacturing battery plant, floating solar array, 150 floating homes within the lagoon basin, as well as an almost identical lagoon to the Tidal Lagoon Power project [112].

LCOE and cost reduction potential

The larger economies of scale mean that tidal barrage and lagoon projects can create energy at a lower LCOE than wave and tidal stream. For example, the aforementioned Swansea Bay Lagoon was seeking a CfD at £92.5 in 2018, compared to the £211/MWh administrative strike price set for tidal stream in AR4, announced in 2021.

While there could be cost reduction improvements in the turbines, for example using larger or more efficient turbines, the majority of the project cost is in the concrete for the sea wall. This uses conventional and established manufacturing techniques and materials, and so it is unlikely that the technology can obtain the same level of cost reduction as other renewables. There are also the added environmental impacts, which have been a barrier for the industry to date (especially in the case of the Seven Barrage, which could have provided up to 5% of the UK's electricity (DECC, 2010).

The viability of a tidal range project depends on the local geography and environment, especially the tidal range. Generally, locations need a range of at least 3 m to be economically viable [113]. While to date most interest has been in larger scale projects of 200 MW+, barrages have been demonstrated on smaller scales (<20 MW) and so it could be a viable option for Alderney if the resource is sufficient.

Storage technologies

Hydrogen

In the pathway for decarbonisation there is an evolving industry that is gaining traction, namely hydrogen storage, in particular green hydrogen that is been produced exclusively from renewable energy. The advantage of green hydrogen is that it's a clean burning molecule meaning that it can help us to decarbonize a range of sectors that have proved hard to clean up in the past. This includes the chemical iron and steel industries as well as transportation especially long haul. Hydrogen can also be used to heat our homes and store renewable electricity. Hydrogen is very reactive and not found freely in nature as it only exists combined with other elements, for example, water is a combination of two hydrogen atoms and one oxygen atom. To produce hydrogen we must extract it from naturally occurring compounds, like water. The process is energy-intensive and although hydrogen itself is a clean molecule most of the hydrogen produced at present is extracted from fossil fuels (the reason why green hydrogen is so appealing). However, producing green hydrogen is still very expensive and although costs are reducing, a number of other challenges remain. Hydrogen can be produced in a number of different ways and experts categorize the sources and processes by which hydrogen is derived, using colours. Brown hydrogen is made from coal in a process known as gasification; grey hydrogen accounts for three quarters of all hydrogen production in the world - extracted from natural gas through a method known as, steam methane reforming (Figure 29).

The downside to both brown and grey hydrogen is that they emit large amounts of CO_2 in their process (Figure

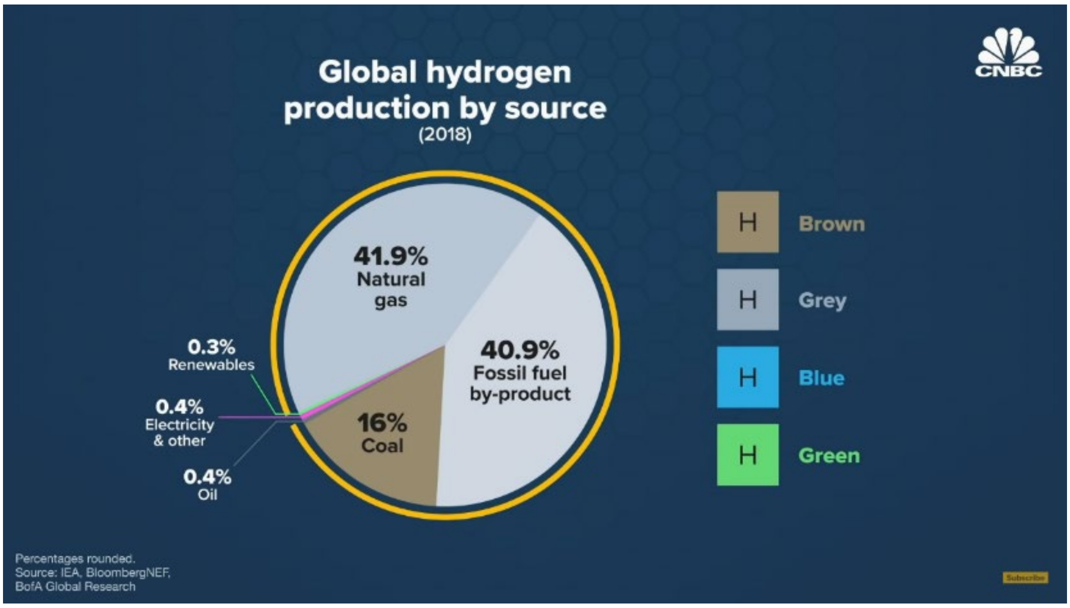


Figure 29 Global hydrogen production by source; natural gas, fossil-fuel by-product, goal, and renewable energy. [189]

30). Blue hydrogen is also made from fossil fuels and must be classified in the same category as brown and grey

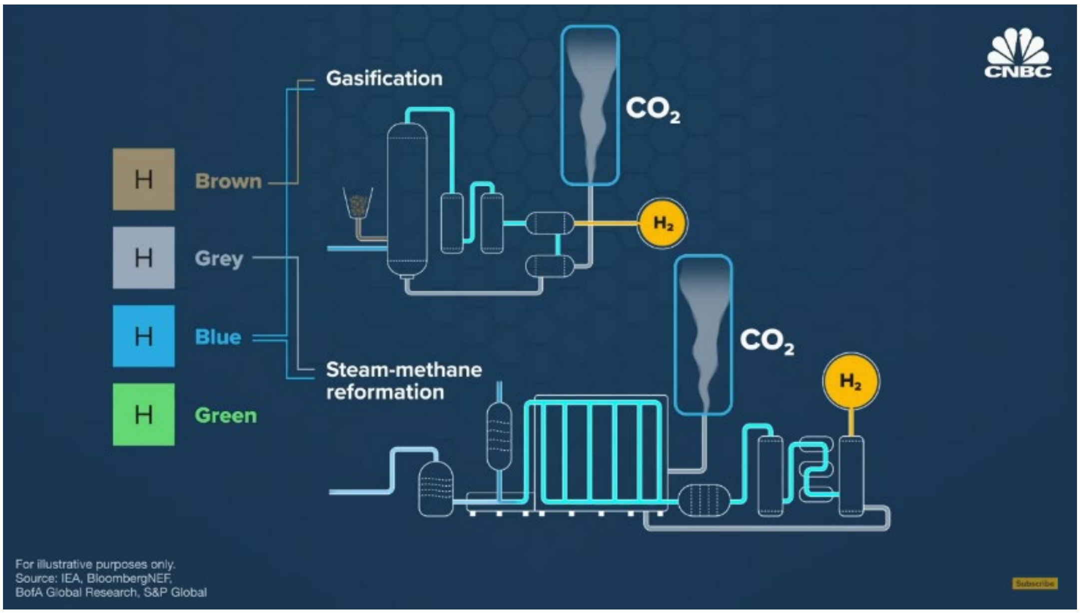


Figure 30 Brown, grey, and blue hydrogen that emit large amounts of CO2 in their process (in gasification and steam-methane reformation) [189]

hydrogen but incorporates carbon capture and storage (CCS) technology. Another way to produce hydrogen is through a method known as electrolysis, here a device known as an electrolyser splits a compound into their constituent elements using an electric current. Using this method the compound is fresh water (H_2O) which is split into 2 parts hydrogen and 1 part oxygen if the electricity comes from renewable sources; like wind and solar the subsequent hydrogen is known as green (Figure 31).

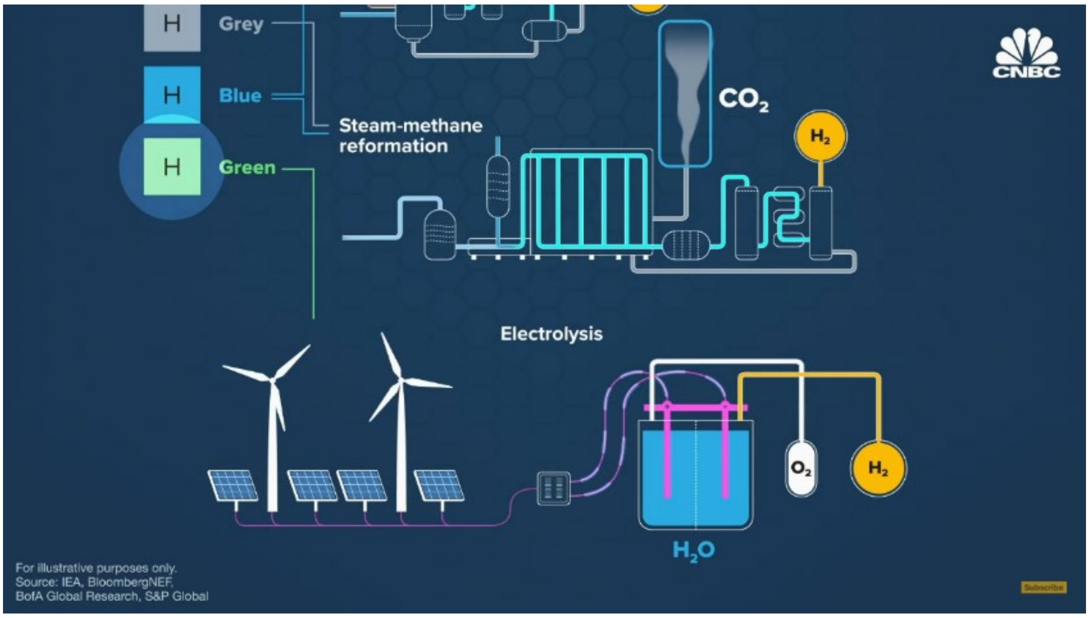


Figure 31 Green hydrogen using electrolysis from renewable energy resources [189]

Recent advancements in green hydrogen production and storage combined with a global push towards sustainability; means that green hydrogen is becoming attractive for industry, and nations are seeing this potential. The first industry hydrogen has the potential of transforming is transportation, where hydrogen can act as a direct replacement of gas and diesel; and holds some advantages over electric vehicles (EV). The difference between a battery electric vehicle and a hydrogen fuel cell vehicle is faster refuelling times, on average five minutes for the hydrogen fuel cell vehicle in comparison to 45 minutes for the equivalent battery vehicle. Therefore, the hydrogen fuel cell vehicle is 5x better for energy storage per unit volume and weight. Making hydrogen transportation especially effective when it comes to long-haulage (trucking and other hard to electrify sectors), such as freight shipping and long-haul air travel. The adoption of hydrogen fuel cell vehicles has been slow globally, in 2019 circa 18,000 hydrogen fuel cell vehicles were on the road, by comparison to 7.2 million electric cars. Europe's oil and gas giant Total recently invested in hydrogen fuel cell truck and bus start-up's, namely Hyzen and Nikola motors. The barrier to the adoption of hydrogen fuel cell vehicles has been a lack of re-fuelling station infrastructure. Aside from the infrastructure one point that is frequently brought up with hydrogen fuel is its inefficiency. Because by the time hydrogen fuel is manufactured, transported, distributed and transformed to electricity in the fuel cell, 70% of its efficiency is lost as seen in Figure 32. This challenge is mitigated somewhat by the fact that hydrogen is very energy dense; that means hydrogen can hold more energy in a small volume. In comparison, buying a kilogram of hydrogen equates to a gallon of fuel, and hydrogen has to be kept under a high pressure. Hydrogen applications are relevant to be used for storing renewable energy that would otherwise be wasted. This has enabled hydrogen to come to the forefront due to the simple fact that we have so much renewable energy on the grid ready, for storage for extended periods.

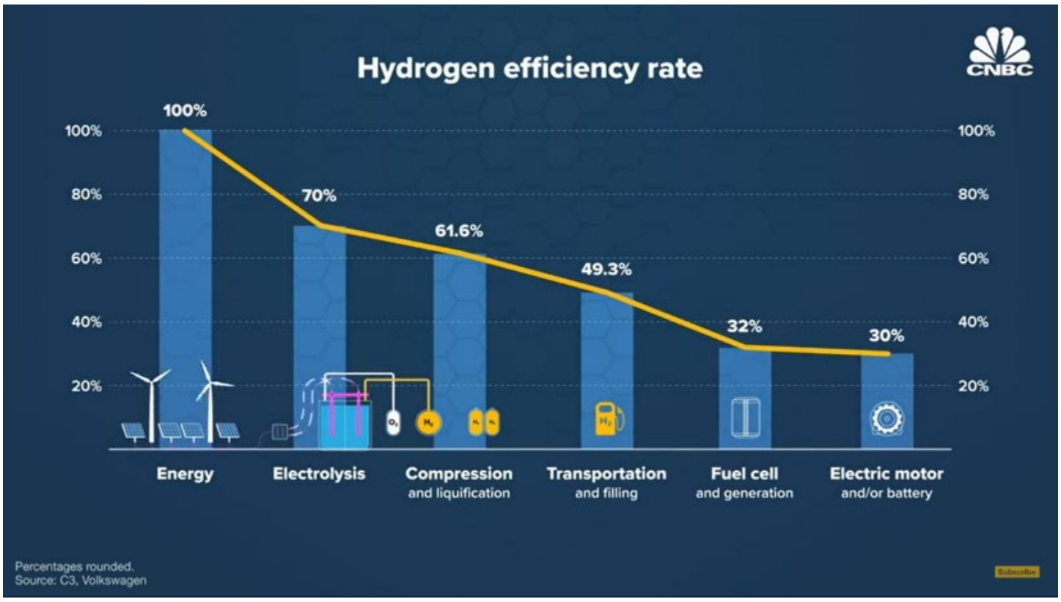


Figure 32 Hydrogen efficiency rate at 70% losses from manufacture to transformation to electricity [189]

Battery Storage

Battery storage, as for hydrogen, is of rapidly growing interest as a technology to help balance the grid and smooth out the intermittency of renewable energy sources. Units of batteries can be arranged in banks, connected in series and parallel, meaning that it is easy to size a battery system for the intended application.

Renewable energy is inherently non-dispatchable, meaning that the timing of the energy production cannot be controlled. This means that prolonged periods of little to no generation can occur, increasing CO_2 emissions through reliance on dispatchable power sources like diesel generators or gas plants, which can be ramped up very quickly. Alternatively, sometimes there can be periods where there is an excess of renewable energy, typically when there are macroscopic weather events that maximise production at a number of geographically spread farms. Without storage this excess energy must be curtailed by shutting down farms, both costing money (as generators typically will be compensated for this) and leading to wasted energy. Having battery storage could offer a way to harness this otherwise wasted energy, and also supply power when generation from renewables is otherwise low.

Battery technology for these grid balancing applications has had limited deployment so far, with 1.3 GW of operational capacity in the UK [114]. This has increased rapidly in recent years, for example the capacity was only 20 MW in 2012 [115], and the pipeline currently stands at about 16.5 GW. Of this 16.5 GW the majority of projects above 5 MW in size (16.2 GW, 546 sites) and about 3 GW have full consent and could be deployed in 2021 or 2022 [114]. This large pipeline has been made possible by favourable government policy, for example in 2020 the government eased planning rules for deploying larger battery arrays (>50 MW in England) [116]. These trends are being seen worldwide, for example the US doubled their grid-level battery storage capacity by adding about 1.7 GW [117].

The fast adoption of batteries has been partly due to the falling price of batteries. S&P Global Platts noted in 2021 that:

> "According to a recent analysis of global battery-storage projects by Bloomberg NEF, lithium-ion batteries are now undercutting gas peaking plants in much of the world. At an all-in cost of $132/MWh, a four-hour utility scale battery is now priced below the global gas-peaker plant average at $173/MWh.
>
> *Even within the US, where gas prices are significantly lower than elsewhere, batteries are now cost competitive with gas-fired generation – thanks in part to state-level clean energy policies and federal tax credits. Both have boosted the competitiveness of renewables in recent years and now threaten to undermine the economic viability of new gas-fired power investments, says Morris Greenberg, S&P Global Platts Analytics senior manager for North American Power." [117]*

One example of where replacement of gas peaking plants is being seen in California. in 2019 an agreement was signed to replace a decades old jet fuel burning peaker plant with a 20 MW, four-hour duration lithium-ion battery plant, this one of many such projects [118].

There are several types of batteries suited for grid balancing applications. These include:

- **Lithium ion batteries:** These are the most widely used batteries for grid applications [119], and are well known as they are used in consumer products like mobile phones. They were developed in 1990 by Sony [120]. While the batteries are typically expensive, they make up for this with a high efficiency, high energy density, long cycle life, low discharge rate (2-8% per month) and rapid charge capability [120].

Prices are coming down rapidly, due to their widespread adoption in other applications. These batteries are best suited for storage durations of 30 minutes to 3 hours [119].

- **Lead acid batteries:** These batteries are an older technology, with its origins in the 1860s [121]. Applications include automotive starting motors, emergency lighting, golf carts and marine. These batteries are very cheap but have a short cycle lifetime (especially when deeply discharged regularly) and also a poor energy density (and high relative mass) due to the high density of lead. They have been used for island energy systems and small off-grid applications, for example an 1000 Ah battery bank (made up of 264 cells) is used on Shetland, UK [122].

- **Flow batteries:** Flow batteries are an emerging technology. Also known as "redox-flow" batteries, they consistent of a large tank filled with two chemical components separated by a membrane. They have been in development since the 1970s and working examples can be found at Minamihayakita Transformer Station in Abira-Chou, Hokkaido (15 MW, can provide 4 hours of power). There are several different types of flow batteries, with specific advantages and disadvantages. Vanadium flow batteries are arguably the best suited for grid applications, with very long cycle lifetimes (12,000-15,000 up to unlimited cycles compared to typically <7,000 for lithium-ion [120] [123]). While the energy density is low, and hence space requirements large, the efficiency can be high (75-85% for vanadium concepts). The poor energy density and high costs have limited adoption of the technology, and there have been notable failure to deploy the technology in the past (for example the Regenesys energy storage system in the UK in the early 2000s [124]).

Table 2 Advantages and disadvantages of main battery types for grid applications [116].

Battery type	Advantages	Disadvantages
Lead–acid	Low cost Availability of large quantities with various sizes and designs High battery voltage Good high-rate performance Good charge retention for intermittent charge applications Availability in maintenance-free designs High recyclability of battery components	Limited energy density Relatively short cycle life Irreversible polarization of electrodes (sulfation generation after long-term storage in a discharged condition) Potential hydrogen evolution
Ni–Cd	Long cycle life Ability to withstand electrical and physical abuse Excellent long-term storage Low maintenance	Limited energy density Relatively high cost (compared with lead–acid batteries) Memory effect Containing toxic element cadmium Containing caustic alkaline electrolyte
Ni–MH	Relatively high energy density Good high-temperature capability Good high-rate capability Long cycle life Long shelf life Good charge retention Rapid recharge capability Sealed maintenance-free design High safety which can be operated at high voltage Safety in charge and discharge, including tolerance to abusive overcharge and overdischarge Environmentally acceptable and recyclable materials	Relatively high cost (compared with lead–acid batteries) Decreased performance at low temperature
Na–S	Relatively high energy density Relatively long cycle life Pulse power capability High self-discharge resistance	High working temperature High cost
Li-ion	Relatively high energy density Low maintenance fee Broad operation temperature range Long cycle life Long shelf life Rapid charge capability No memory effects Many possible chemistries offer design flexibility	Relatively high cost Poor high-temperature performance Requirement of protective circuitry
Zinc–bromine	Relatively high energy density High design flexibility Relatively low cost Capability of rapid charge. Capability of 100% depth of discharge	Potential zinc dendrite formation Poor cycle life
Vanadium redox	Long cycle life High safety Low operation cost and maintenance Capability of deep discharge	Requirement of large space Relatively low energy density
Polysulfide bromide	Fast response time	Limited energy density Relatively low efficiency Cross-contamination during the long-term battery operation

Table 2 shows the main advantages and disadvantages of these three types, as well as other commonly considered batteries [120].

Pumped Storage

Pumped storage is one of the most mature energy storage solutions. It relies on a height differential between two bodies of water, as shown in Figure 33. When there is excess electricity, it is used to pump water to a top reservoir. When electricity is need, the water is let through an intake, flowing to the bottom reservoir via one of more turbines, which generate electricity from the flow of the water. The storage capacity E, in kWh, can be estimated using the equation [125]:

$$E = \rho g V h \eta,$$

Where ρ is the density of water, g the gravitational acceleration (9.81 m/s), V the volume of the top reservoir, h the height difference between the top and bottom reservoir and η the turbine conversion efficiency.

Typical conversion efficiency of pumped hydro is 70-85%. As the energy stored is the potential energy of the water in the top reservoir, the height differential is crucial to the viability of the storage scheme. Projects can be open loop (whereby the flow discharge is connected to a naturally flowing water feature like a river) or closed loop (where the water is discharged into a static lake or reservoir). Installed cost can vary greatly depending on the topography and civil works required, with the CAPEX cost range for US projects cited as $1,700-$5,100/kW [126].

There are pumped hydro schemes all over the world. One of the largest is in Bath County, Virginia (US) which supplies power to about 6750,000 homes with a generation capacity of 3 GW and storage capacity of 24 GWh [127]. In the UK there is about 2.8 GW of pumped storage. This is mainly made up of four projects, the largest being Dinorwig in north Wales with a 1.7 GW capacity [128]. In the UK no pumped storage project has been developed for 30 years, but it is increasingly of interest to counteract the intermittency of renewables. For example, SSE received consent for a 1.5 GW pumped storage scheme in the Scottish Highlands, the Coire Glas project [129]. This project could power around 3 million homes for 24 hours non-stop and is currently in the tendering stage [130].

Pumped storage projects are typically large-scale infrastructure projects, with similarities to the aforementioned tidal barrage. Because of this, permitting and construction can take 3-5 years [131]. In the US, pumped storage accounts for about 95% of all utility scale energy storage [126] and 99% of global storage energy volume [132].

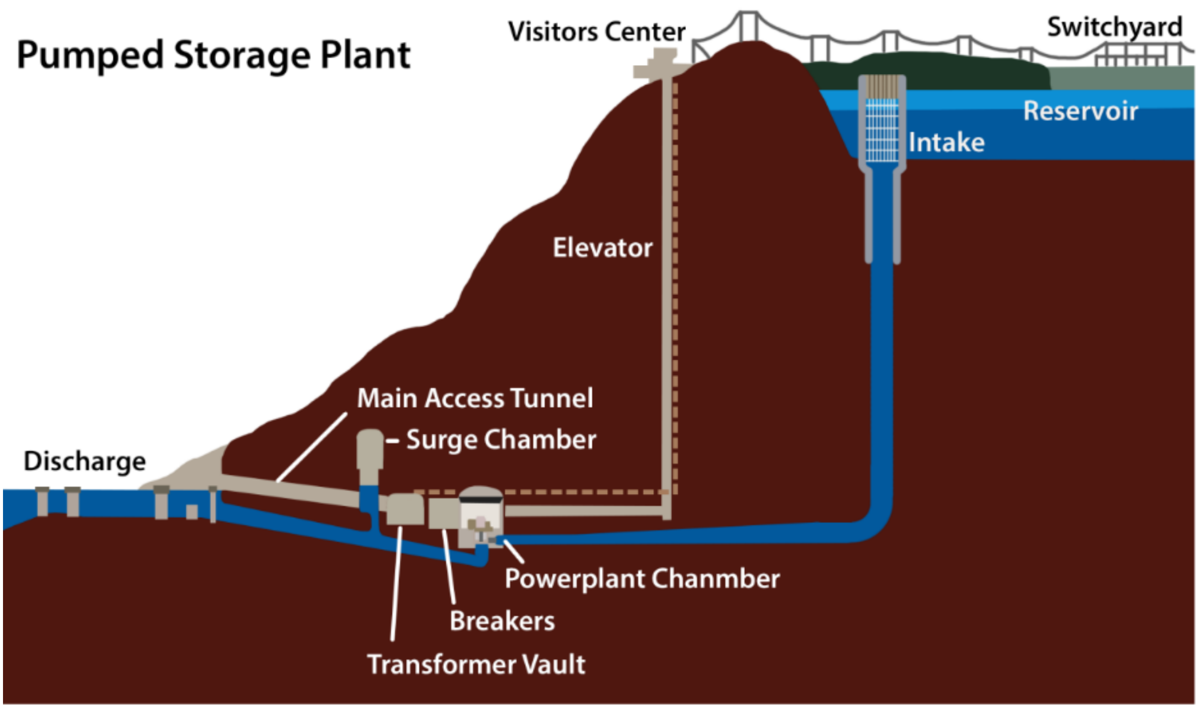


Figure 33 Main components of a pumped storage system [185]

There is increasing interest in smaller pumped storage schemes, for example kW scale systems have been tested on buildings (for example the 3.5 kWh Goudemand apartment building in France has a small pumped hydro system, with water tanks on the top floor and in the basement [127]). Due to the inefficiencies of small turbines and lack of costs savings through large economies of scale, these scales of projects are generally not economically viable compared to alternatives like lithium-ion batteries [133].

At the megawatt range, an example of a product that was examined was the Shell Energy North America (SENA) Hydro Battery [134]. The concept, as shown in Figure 34, consists of a large pool of water which is located at the top of a hill, pumping water from a body of water below. SENA had planned to test a prototype at the Columbia River in 2018/19, which would have been a 5 MW generating capacity plant (30 MWh stored energy) [135]. However further information about the project and product is not available, with the project believed to be in hiatus. A lack of activity is likely to due to the large decrease in lithium-ion battery cost in the last few years, which makes pumped hydro projects in this range uneconomical.

One UK start-up, RheEnergise, is investigating using high density fluids within a closed loop pumped storage

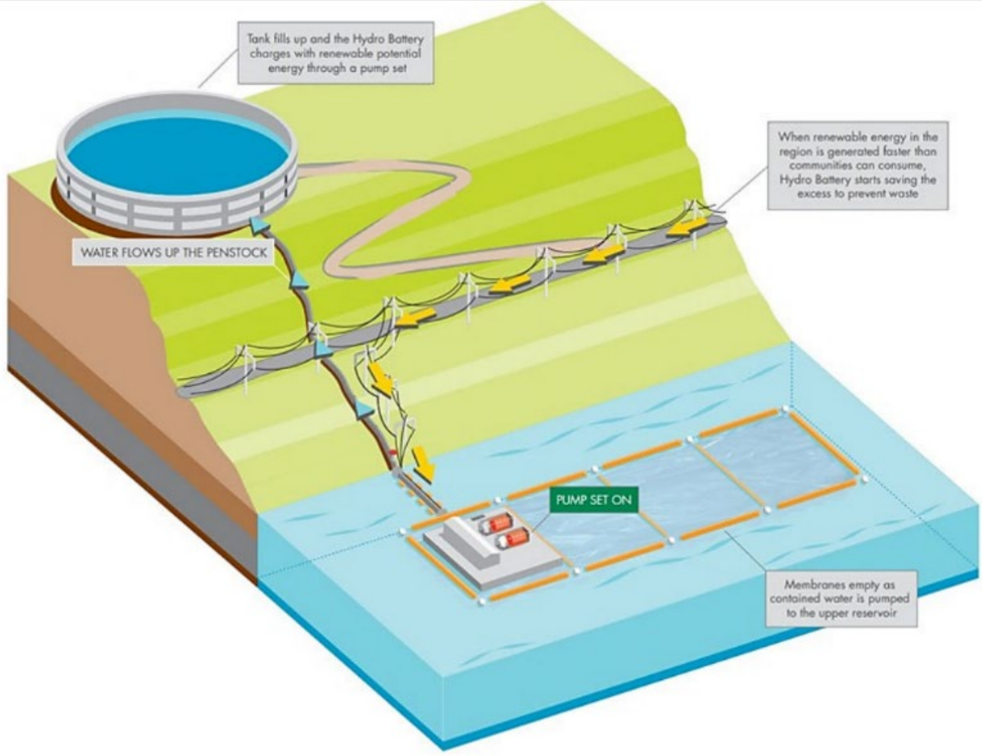


Figure 34 SENA "Hydro Battery" concept [134].

system [136]. Because the potential energy stored in the system is proportional to the density of fluid, increasing the storage capacity of the scheme. This also makes pumped hydro schemes more viable on smaller hills, as the increased density makes up for the smaller height difference between the reservoirs (see the previous equation). The company plan to install their first commercial system in 2024 and reach 100 commercial scale systems in the next decade, with a focus on smaller scale systems (10-50 MW) [137].

RENEWABLE ENERGY RESOURCES IN ALDERNEY

Offshore and onshore Wind

Alderney has a good wind resource both onshore and offshore, which can help the island to meet some of its energy demand and reduce its dependency on imported fossil fuel energy sources. Alderney's potential wind resource data has been obtained from the global wind atlas [138]. Figure 35 shows that apart for some exceptional years, there is low annual variation in the Alderney's wind resource. Seasonal (monthly) variation is more noticeable however, Jaguaribe [139] has indicated that the winter months are 45% windier than the summer months. On the daily wind variation, both the Jaguaribe study and the global wind atlas show some minor variation in the wind speed.

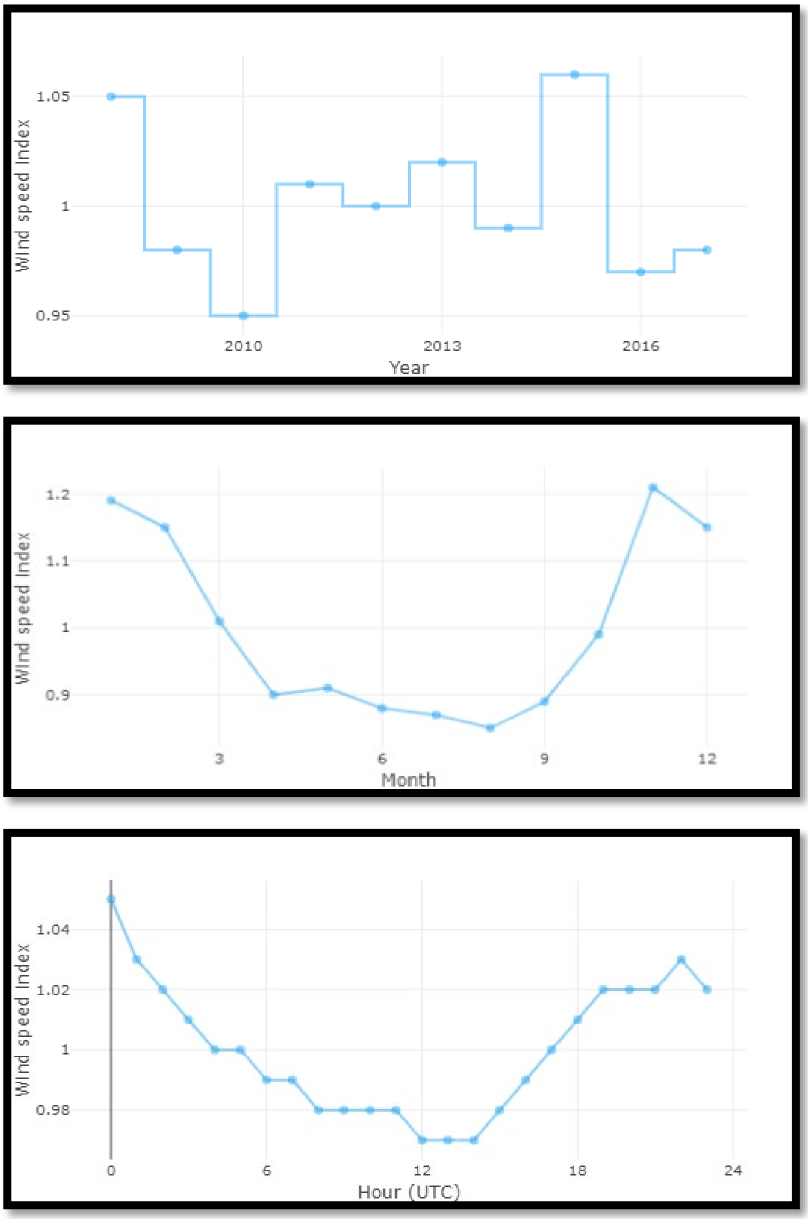
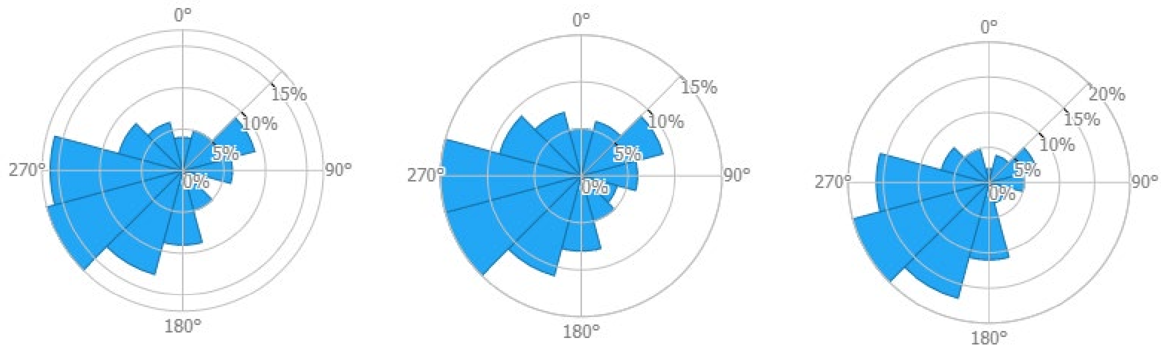


Figure 35 Wind Speed Variability

On an annual average, the dominant strong wind direction is from the West and South-West. Then, it is followed by an equal and much smaller occurrence across the other directions, as it can be seen in Figure 36, which represents the wind roses for the Alderney.



Wind Speed Rose | Wind Frequency Rose | Wind Power Rose

Figure 36 – Wind Roses

To better understand the Alderney's wind energy potential, the available wind resource has been divided into 3 areas: onshore South-West, onshore North-East, and offshore. The average onshore wind speed can reach approx. 9.43 m/s for the 12% windiest areas in Alderney (Figure 37 - a), which can provide power density up to 906 W/m^2. On the South-West area of Alderney, the wind gets stronger, with approx. 9.91 m/s for the 10% windiest areas (Figure 37 - b), which can provide a higher power density of 1042 W/m^2. The North-East area has lower power density, with approx. 9.68 m/s for the 10% windiest areas (Figure 37 - c), which can provide a higher power density of 964 W/m^2. It worth to note that all the measurements are recorded at 100m above sea level. The following formula can be used to estimate the wind speed at different hights:

$$U_x = U_{100}\left(\frac{Z_x}{Z_{100}}\right)^a$$

Where U_x is the wind speed at hight x, U_{100} is the wind speed at 100 m, Z_x is the new hight, Z_{100} = 100 m, and a is the correction factor based on the surface roughness.

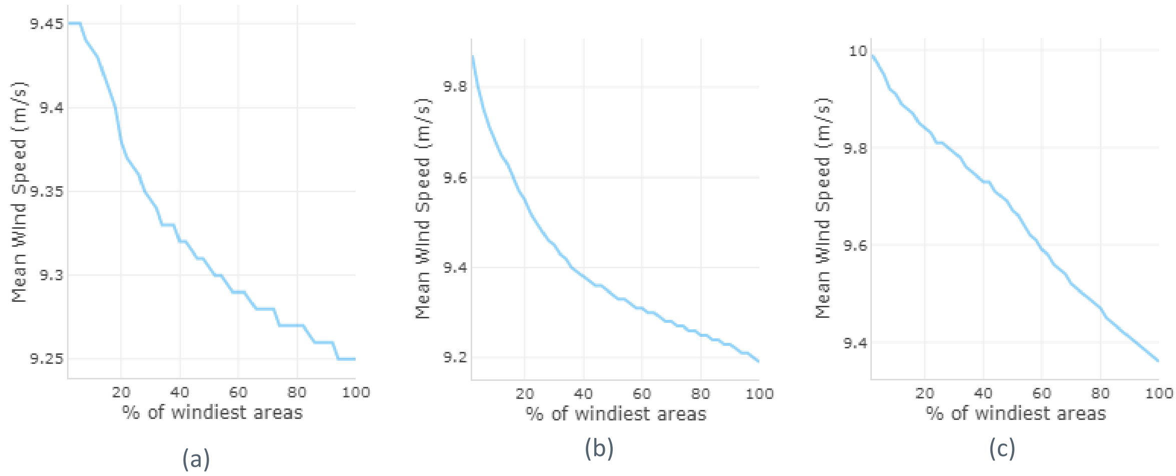


Figure 37 - Mean Onshore Wind Speed @Height 100m

Compared to the onshore wind potentials, Alderney has slightly lower offshore wind energy density. The mean offshore wind speed at 100 m above sea level is approx. 9.30 m/s (Figure 38), which provides 870 W/m^2.

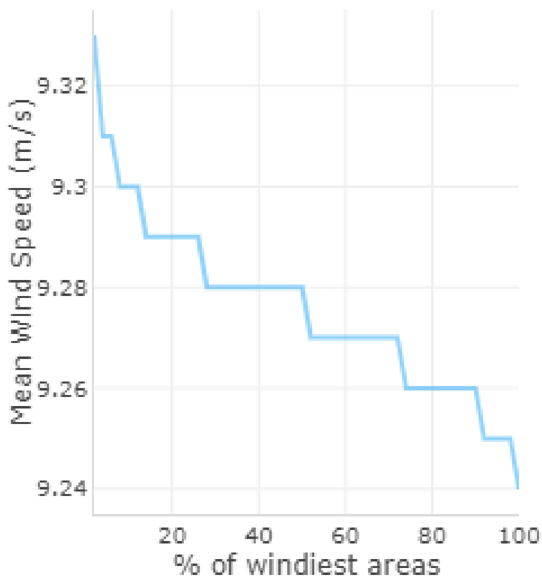


Figure 38 – Mean Offshore Wind Speed @Height 100 m

Solar

As Alderney is around 9 miles from the French coast (compared to 84 miles from the nearest points of UK coast), Alderney's solar irradiation data was extrapolated from the Pte De La Hague climate data in France using

RETScreen Expert software. Figure 39 provides a summary of the potential solar energy resource in Alderney and its seasonal variation. It shows a high variation in the daily solar radiation between the summer and the winter months, which can reach a ratio 5:1 [139]. Based on the average annual solar radiation, the expected energy density can be estimated as 1.20 MWh/m^2 using horizontal PV panels and 1.34 MWh/m^2 using tilted PV panels with fixed slope at 50 °. This can be slightly improved with adding solar tracking system.

	Unit	Climate data location	Facility location	Source
Latitude		49.7	49.7	
Longitude		-1.9	-2.2	
Climate zone		4A - Mixed - Humid		Ground+NASA
Elevation	m	12	0	Ground – Map
Heating design temperature	°C	2.4		Ground
Cooling design temperature	°C	20.9		Ground
Earth temperature amplitude	°C	8.6		NASA

Month	Air temperature	Relative humidity	Precipitation	Daily solar radiation - horizontal	Atmospheric pressure	Wind speed	Earth temperature	Heating degree-days 18 °C	Cooling degree-days 10 °C
	°C	%	mm	kWh/m²/d	kPa	m/s	°C	°C-d	°C-d
January	7.7	83.7%	93.62	0.92	101.6	9.6	8.8	319	0
February	7.8	82.2%	68.32	1.63	101.6	9.3	8.1	286	0
March	8.4	83.0%	62.00	2.78	101.5	7.9	8.5	298	0
April	9.8	82.2%	58.20	4.36	101.3	7.5	9.6	246	0
May	12.2	84.3%	49.91	5.59	101.5	7.0	11.7	180	68
June	14.8	84.7%	46.50	5.99	101.6	5.7	14.0	96	144
July	16.7	86.0%	45.26	5.80	101.6	5.7	16.1	40	208
August	17.7	85.1%	48.98	5.05	101.5	6.0	17.3	9	239
September	16.7	81.3%	66.60	3.49	101.5	7.1	16.8	39	201
October	14.5	81.2%	96.41	1.96	101.3	8.8	15.1	109	140
November	11.1	80.4%	104.40	1.09	101.3	9.2	12.6	207	33
December	8.7	82.9%	111.29	0.71	101.5	9.5	10.3	288	0
Annual	**12.2**	**83.1%**	**851.49**	**3.29**	**101.5**	**7.8**	**12.4**	**2,117**	**1,032**
Source	Ground	Ground	NASA	NASA	NASA	Ground	NASA	Ground	Ground
Measured at					m	10	0		

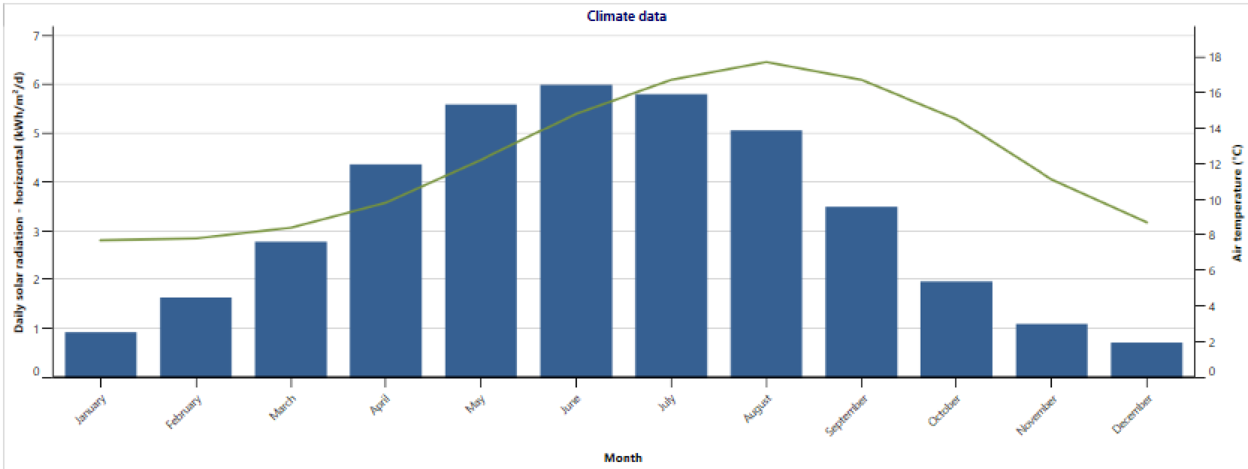


Figure 39 - Solar resource in Alderney

Tidal stream

Due to its location and morphology, Alderney is surrounded by a remarkable tidal stream resource in the Swinge and the Race of Alderney. Both locations are well known for strong tidal flow. However, the seabed conditions on the west of the island were found to be less suitable. Therefore, the

Alderney Race is considered as a more favourable location for any tidal stream energy development [5]. On the other hand, the Admiralty Tidal Stream Atlas (Figure 40), indicates that the flow velocity is higher towards the east of the race than to the west, which means a significant proportion of the resource will fall within the French territories. It is worth to note that tidal current data in Admiralty charts are designed to help mariners predict when and where dangerous currents might arise and are not accurate enough to predict the potential energy from tidal stream energy developments. Therefore, to accurately assess the potential tidal stream resource in the Rase od Alderney, in-situ measurement and hydrodynamic modelling would be required.

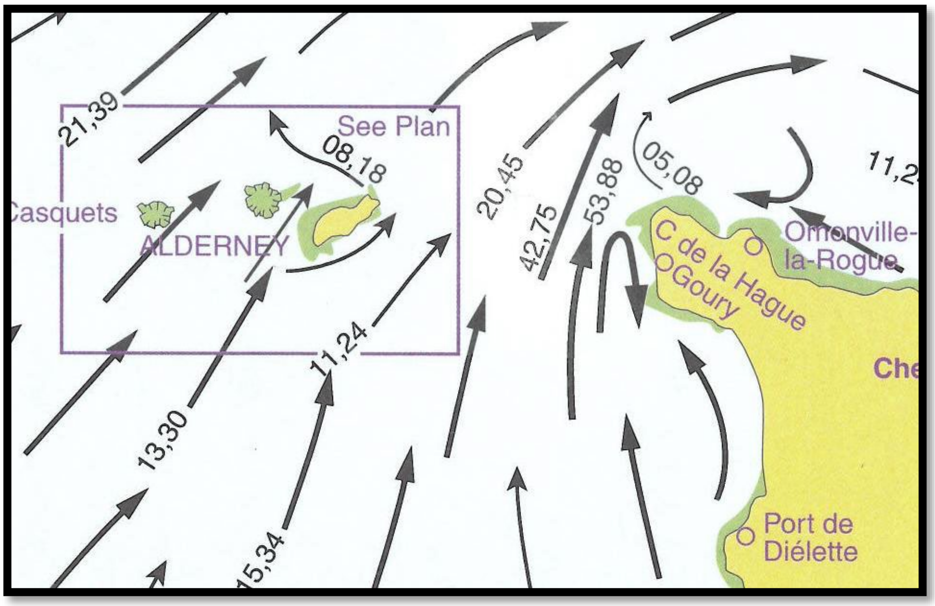


Figure 40 Admiralty Tidal Stream Atlas - NP 264 for 3 hours before High Water at Dover - 1h 50 m after HW at St Helier [5]

Several studies have investigated the tidal steam potentials in the Race of Alderney, using real measurements and modelling tools to estimate the available resource in the area [140] [141] [142] [143] [144] [145]. In their study, Bahaj and Myers (2004) [143] have suggested that the strongest flows are found on the east side. Nevertheless, their study shows that the west side of the Race can still experience decent flow, as shown in Figure 41.

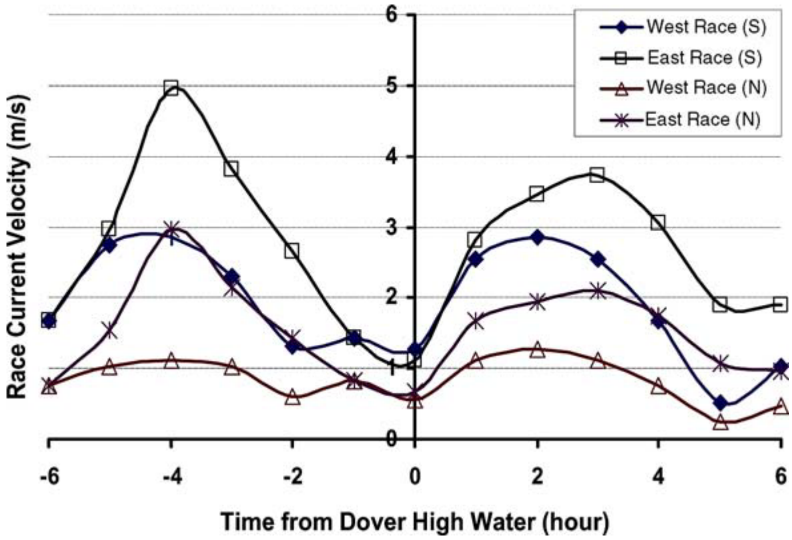


Figure 41 The 12-h variation of marine current velocity in the Alderney Race relative to Dover High Water [133]

As study by the Alderney Renewable Energy (ARE) [5] has suggested that a 3 GW tidal stream energy can be developed in the Race within Alderney's 3 nautical mile territorial limit (Figure 42), which would require 24 km^2. However, this type of studies has used the farm method to estimate the array capacity and relied on low spatial and temporal resolution flow data. The farm method does not consider any change to the ambient flow field with the inclusion of turbines due to the blockage effects, which cast some doubts about the validity of the results.

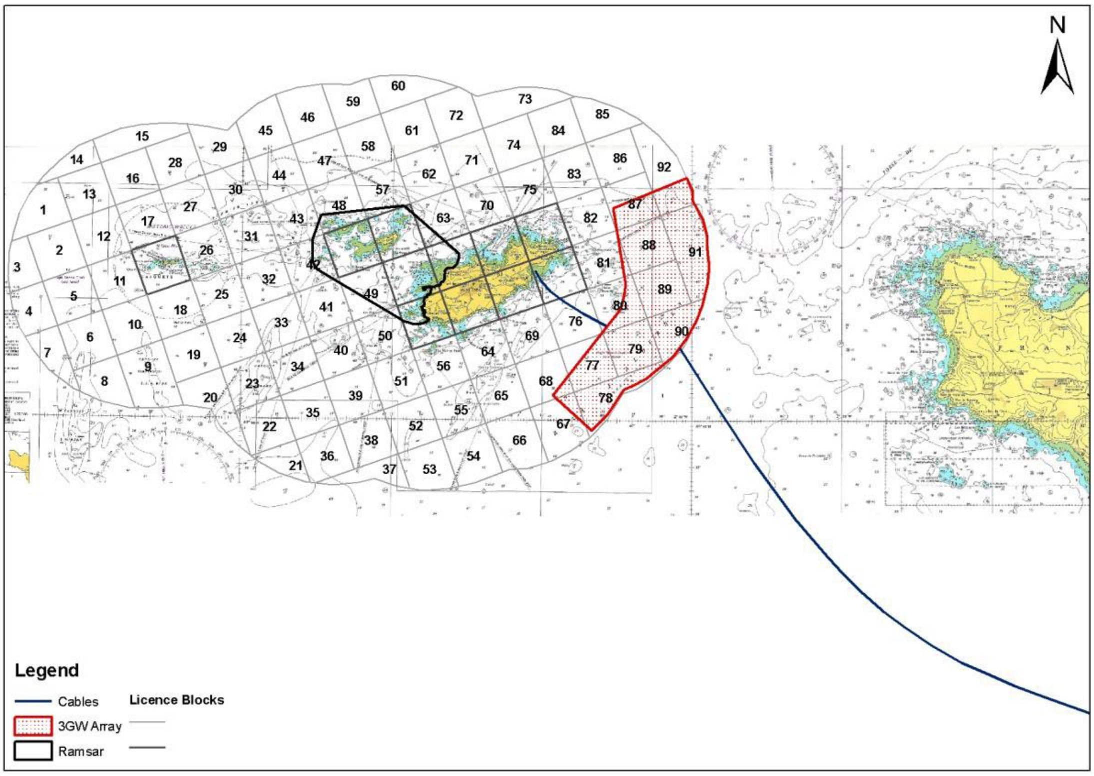


Figure 42 Potential area for the 3 GW tidal array development [5]

Coles et al. [145] have conducted a study adopting more accurate methods to estimate the maximum average power potential by implementing drag in the hydrodynamic model to emulate the turbines effects. The study indicates that on the east side of Alderney, in the Casquets area, the economically viable tidal development area (mean power densities greater than 2.5 kW/m^2 and depth between 15-50 m) is about 7 km^2, which is relatively small compared to the Race area. The study estimated the maximum extracted power from the Casquets is about 0.47 GW, while the Race can provide around 5.10 GW. However, majority of the Race potential resources fall within the French territories as it can be seen in Figure 43. The study has also estimated the cumulative impact of developing more than one area, which can reduce the Alderney Race potentials to 3.86 GW. Further dedicated analysis for the Alderney Race tidal resource within the territories of the Alderney is required to accurately estimate the available tidal energy potentials.

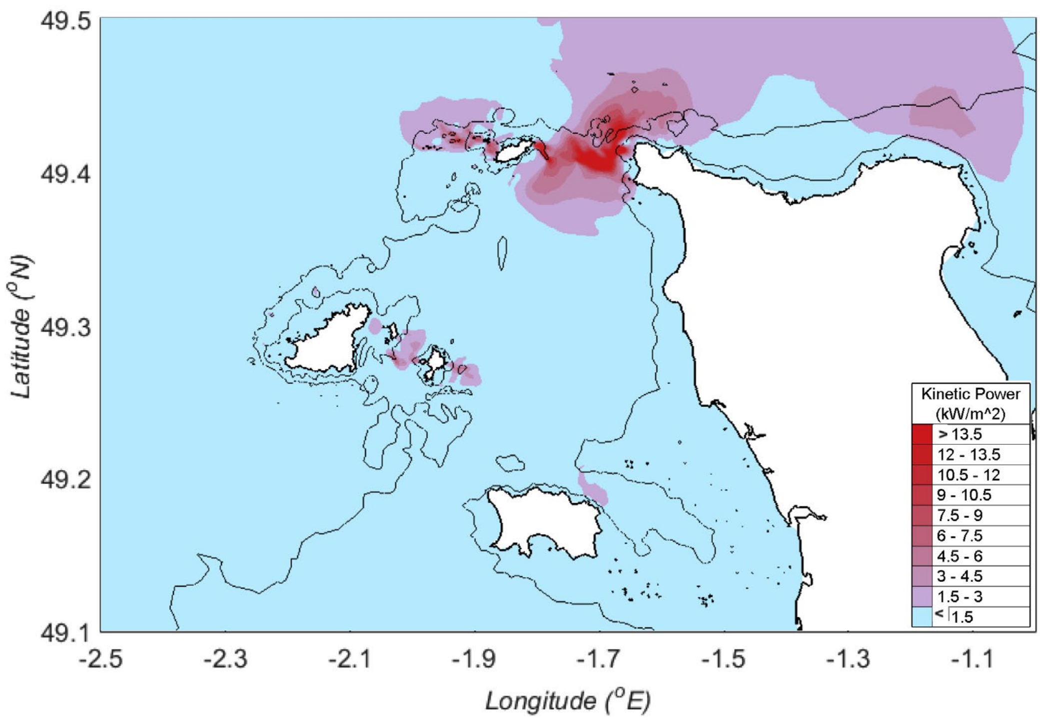


Figure 43 Mean kinetic power density distribution around the Channel Islands, with 50 m and 15 m depth contours also shown [135]

Wave

A study commissioned by the ACRE estimated the potential annual average wave power density around Alderney in the range 10 - 15 kW/m (Figure 44), with no details about the direction of the waves (likely from the west) [5].

The maximum length of a wave energy array across the north-south side of Alderney to face into waves coming from the west would be approx. 10 km, which might be able to generate between 438 and 657 GWh/year.

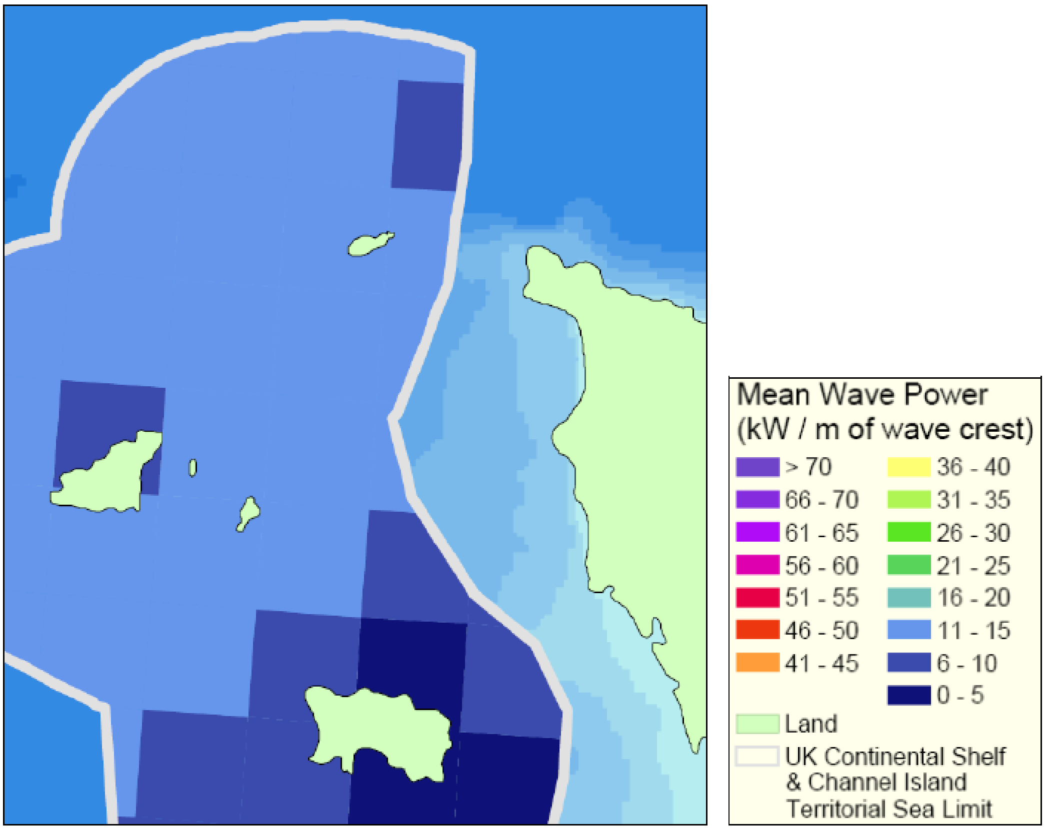


Figure 44 - Annual average wave power density (kW/m) around the Channel Islands, from the BERR Atlas of Offshore Renewables [5]

Ground source heat pumps

A study conducted by Jaguaribe [139] investigated the ground source heat pumps potential as a source of energy in Alderney. Due to the type of Alderney's soil, the study concluded that heat pumps are only suitable for houses with good insulation to provide space heating in the winter only.

Anaerobic Digestors

Alderney has several sources that could be used as feedstock to generate electricity or heat from waste, including:

- Animal and process waste from farming
- Animal waste from pig farms (with a total of around 250 animals)
- Garden and kitchen waste from the island's residents.

A detailed assessment of the waste quantities generated each of these sources is required to determine the appropriate scale of digestion for Alderney [146].

ISLAND ENERGY SYSTEM CASE STUDIES

This section provides case studies of other island energy systems which have transitioned or are set to transition to an energy mix powered predominantly by renewables. The island energy systems to be discussed are located on Eigg, The Shetland Islands, The Faroe Islands, the Isles of Scilly, and Ushant. Details of each islands' current energy mix will be presented before discussing the approaches taken by each in order to transition to a less carbon intensive energy system. At the end of each case study, lessons that can that Alderney can draw from are also provided.

Eigg

The Isle of Eigg is one of the Small Isles located in the Scottish Inner Hebrides with a population of just under 100. Since 2008 the island has benefited from a microgrid predominantly powered by hydro, wind and solar. Up until 1997 the island was privately owned by various lairds until it was eventually brought into community hands via the Isle of Eigg Heritage Trust (IEHT). After purchase of the island by IEHT, one of the most pressing issues was developing a means of mains electricity supply. This need to produce an adequate energy system for the islands residents led to the formation of Eigg Electric (EE), a subsidiary of IEHT, which is responsible for providing residents with a reliable electrical supply [147].

Before the creation of the island's microgrid, many residents relied on their own diesel generators as a means of electrical supply, but with a desire to reduce noise and improve sustainability on the island, alternative approaches were taken. Through a funding package set up by IEHT, alongside the National Lottery Community Fund, European Regional Development Fund, Highland Council and others; the total cost to construct the microgrid was estimated at £1.6 m.

At present, the island's microgrid is served by a 100 kW hydroelectric generator on the west of the Island, as well as two smaller 6 kW hydro facilities on the island's east. Wind generation is provided by four 6 kW turbines, while solar is provided by 50 kW of photovoltaic (PV) panels [148], (10 kW of PV was initially installed but this was eventually increased to 50 kW in 20 kW increments). Distribution of electricity is achieved using 11 km of high voltage cable which stretches across the island. The renewable generation sources on the microgrid have provided around 95% of the island's electricity supply since it was installed, with the remaining 5% mostly provided by two diesel generators when renewable output is low, or maintenance is being carried out on the system. In addition to the diesel generators, the island also has a battery bank fitted with inverters as form of back-up power and means of grid balancing. The battery bank's state of charge is monitored by the inverters which signal when the diesel generators should take over as the main source of back-up generation (at 50% charge), and when the diesel generators should switch off (at 90% charge), with the batteries being recharged either by renewable or diesel generation. All aspects of grid balancing are managed within a central control building on the island [148]. In Figure 45, a schematic of the Eigg microgrid is displayed [149].

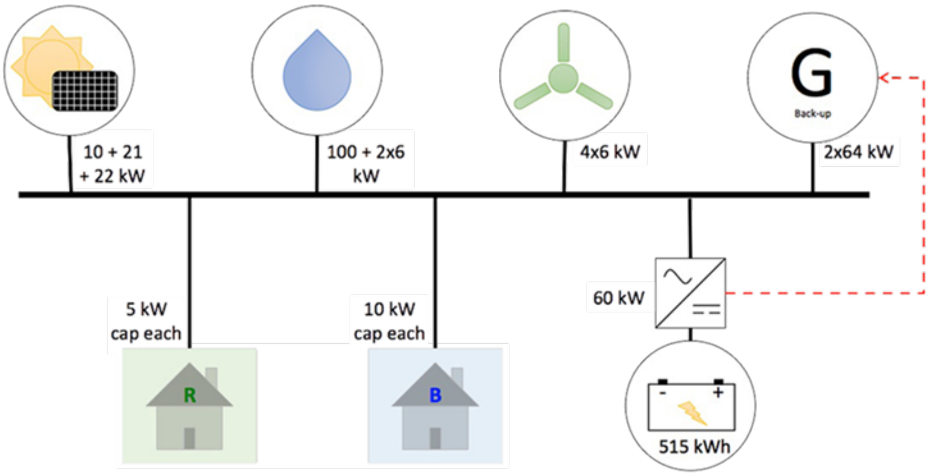


Figure 45. Isle of Eigg Microgrid [149].

To protect the system during times of overgeneration and subsequent frequency rises, the battery bank will initially be charged to 90%. However, once the batteries reach 90% charge, the system frequency will continue to rise above acceptable levels. To counter this, 3 kW space heaters are activated at the island's community centres, with there being four space heaters in total (located across the island's two churches and community hall). While this could be seen as wasteful by some, the free energy provided by the space heaters results in cost reductions associated with the central heating in the community hall, thus reducing the amount of kerosene that must be consumed in the winter months.

Renewables Obligation Certificates (ROC) and Feed-in Tariffs (FiT) have served as the main funding mechanisms for the Isle of Eigg's microgrid which has allowed affordable tariffs to be set for consumers while also allowing enough to be left for maintenance and replacement of system apparatus.

Despite being a highly robust island energy system, the Eigg microgrid does have built-in limitations to ensure its stability. Domestic consumers are limited to 5 kW consumption at any time, while commercial consumers can consume 10 kW [148].

Lessons for Alderney

The main learning points that the States of Alderney can take from the system on Eigg is the fact that its residents managed to install a highly reliable microgrid run predominantly by renewables on a budget. However, it is acknowledged that Eigg had far more access to a wider range of external funds through bodies such as the European Regional Development Fund (ERDF), to which Alderney does not. Regardless, the Eigg microgrid is one which demonstrates a strong degree of stability and redundancy, and one which combats over/undersupply issues effectively within its current operating limitations. Furthermore, with the microgrid having no external input from a mainland utility, it is operated and maintained by a its a trained team of island residents, thus showing the success that can be achieved by maximising community involvement to ensure the smooth operation of an island energy system.

Shetland Islands

The Shetland Islands are an archipelago of the UK located in the Northern Atlantic which has a population of approximately 23,000. They are the northernmost part of the United Kingdom. The Shetland Islands are currently not connected to the rest of the Great Britain (GB) transmission system, leaving them dependent on local electricity production. The distribution network on the islands operate at 11 kV and 33 kV and is formed of over 1,600 km of underground cables and overhead lines. To connect the smaller islands to the main island, thirteen subsea cables are also in operation. As the Shetland Islands fall within the north of Scotland distribution network operator (DNO) catchment area, operation of the network is overseen by entirely by Scottish and Southern Electricity Networks (SSEN) [150].

In terms of the energy mix on Shetland, two power stations provide the majority of electricity demand while the remained is mostly fulfilled from a mix of wind and tidal generation. Details of the two power stations and the renewables mix are described in greater detail below:

- Lerwick Power Station – A diesel-fired power station with a maximum capacity of 72 MW. Around 50% of Shetland's electricity demand is provided from the station. An 8 MW battery bank was installed within the station to increase the amount of renewable generation that can be installed on the wider grid network [150].
- Sullom Voe Terminal Power Station – An independently gas-fired power station which provides around 30% of Shetland's electricity demand [150]. The station's main function is to provide electricity to the Sullom Voe terminal which handles production from 38 oilfields in the East Shetland basin [151], but it also provides power to the Shetland system through a contractual arrangement. The total capacity of the power station is 100 MW, with a maximum of 22 MW being exported to the Shetland system [152].
- Renewables mix – approximately 20% of the demand on Shetland is met from renewables, primarily in the form of onshore wind and tidal stream [150]. Onshore wind projects include the Burradale Wind Farm which is owned by Shetland Aerogenerators and has been operational since 2000 [153], while the tidal array on Shetland is managed by Nova Innovation at Bluemull Sound. To provide more detail on Shetland's tidal array; the first turbine of 30 kW was installed in 2014 before being decommissioned in 2016 when it was replaced with three M100 (100 kW) turbines to form the world's largest offshore tidal array. Licenses were granted in 2018 to expand the array to six turbines (600 kW), and in 2020, a fourth turbine was added which marked the first deployment of Nova's M100-D direct drive turbine [154], with the other two turbines set to be installed in 2022. Beyond Burradale and the tidal array at Bluemull Sound, there are also several small-scale community-based wind generators [152].

The state of Shetland's energy mix is set to experience a significant shift in the coming years. The main driver of this is SSEN's development of a 320 kV 600 MW HVDC interconnector between Shetland and the mainland of GB which is scheduled to be operational by late 2024. With this interconnector comes a vast reduction in dependency on Lerwick Power Station which is close to the end of its full-duty operational life. However, there are plans to keep the station in use as a back-up source of power during interconnector outages due to faults or annual maintenance. It is expected that the interconnector will result in a 97% emissions reduction from Lerwick Power Station [155], with the total project cost being budgeted by Ofgem at £641.8 m [156]. Below in Figure 46Figure 46, a map of the interconnector route is illustrated [157].

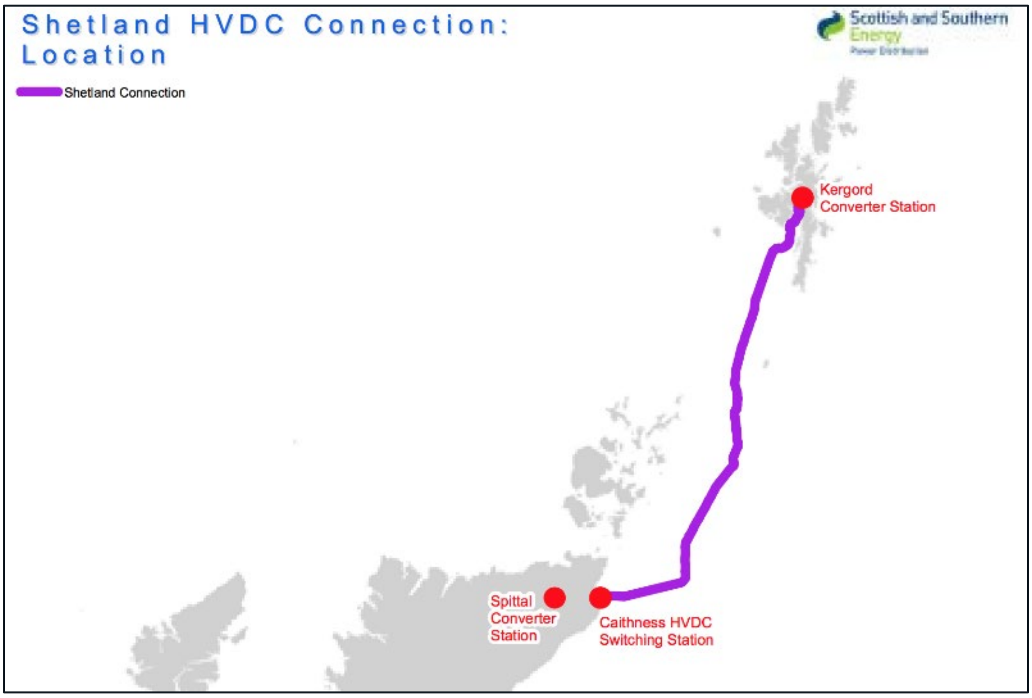


Figure 46. Shetland HVDC Connection [22]

In addition to the HVDC interconnector, SSEN are also constructing a 132 kV transmission network which will connect future onshore wind projects on Shetland to the GB grid. Of these are the Viking Wind Farm, as well as the Energy Isles, Beaw Field and Mossy Hill windfarms [155], [158].

One of the distinguishing features of Shetland's onshore wind development is the emphasis on maximising community benefit. This has been a long-standing theme on the Shetland with the director of the Burradale stating back in 2003 that future scaled-up developments should have a strong degree of community ownership [159]. Examples of community benefit in action can be seen with the Viking Wind Farm which is to set up a community fund from 2024 which should contribute £72 m over the lifetime of the project [158]. The desire for maximum community benefit can also be seen with the Energy Isles Wind Farm which is being developed via a partnership between Energy Isle Ltd and Statkraft. Energy Isles Ltd is a consortium of over fifty companies, mostly based in Shetland, which wishes to retain as much benefit within the isles as possible when utilising its vast renewable energy resource [160].

The development of offshore wind is also a long-term priority on Shetland. The most ambitious project proposal to date is a 10 GW floating wind farm 136 km to the north of Shetland which was announced by Aker Horizons at COP26. The project intends to use next generation 20 MW turbines and plans to use part of the wind farm's generation capacity to produce significant quantities of green hydrogen via offshore hydrogen production infrastructure. Aker Horizons intends for their plans to tie into the goals of the Orion project which seeks to turn Shetland into a "green energy island" and exporter of export electricity, hydrogen, ammonia and a range of other synthetic low-carbon fuels [161]. As far as the Orion project is concerned, has proposed that the Sullom Voe Terminal and the Shetland Gas Plant could be repurposed towards hydrogen refinery operations [162]. In Figure 47, a schematic of potential future installations as part of the Orion project is displayed [161].

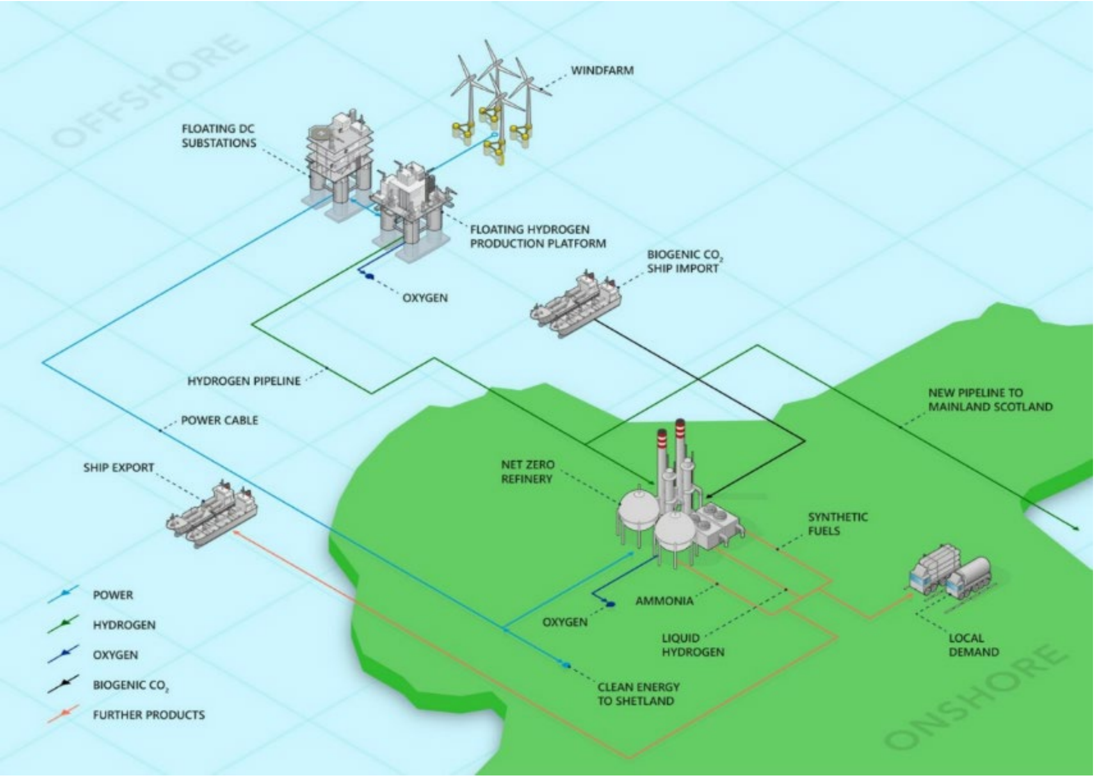


Figure 47. Shetland Future Installations Schematic [26]

Beyond the Northern Horizons project, proposals have also been made for a 3 GW project off the west coast of Shetland. However, such projects are currently experiencing resistance from the Shetland Fishermen's Association who feel that the plans for offshore wind projects in rich fishing waters are being rushed through without adequate consultation whilst failing to consider the impact that these projects have on their industry [163].

Lessons for Alderney

Despite Shetland having a far larger population than Alderney, the main lessons that can be taken from Shetland is the long-term gains that can be achieved through exploiting the full range of clean energy resources that an island has available and maximising economic gains through exporting electricity generated via said resources. However, Shetland possesses a huge advantage over Alderney in terms of its access to funding and approval for new energy infrastructure projects by virtue of being part of GB, and part of SSEN's DNO catchment area for the North of Scotland, thus making them far less susceptible to their energy strategy being slowed by external political disputes elsewhere (e.g. FAB link being taken off the agenda due to issues between the UK and France). With the development of an interconnector serving as a means for Shetland to reduce its greenhouse gas emissions, while providing an opportunity for the islands to become a net exporter of electricity and hydrogen in the long-term, it shows that gaining access to larger energy markets via interconnectors is paramount to maximising the long-term success and redundancy of island energy systems which possess high renewable resource.

Faroe Islands

The Faroe Islands are an archipelago of around 50,000 people located in the North Atlantic approximately halfway between Iceland and the UK mainland. It is part of the Kingdom of Denmark but has been self-governing since 1948 with autonomy in most areas of government apart from key areas such as defence, justice, currency, and foreign affairs.

Regarding the energy system on the Faroe Islands, SEV is responsible for power production and distribution. At present they oversee the operation of six hydroelectric plants, three thermal power plants, three wind farms and one solar power plant. Outside of the mentioned generation assets overseen by SEV an additional wind farm and a biomass plant are operated by external suppliers [164]. In addition to these generation assets there is also a 200 kW tidal site located at Vestmannasund. The turbines in operation at Vestmannasund are Minesto's DG100 turbines. An initial agreement was made between SEV and Minesto in November 2018 for the installation, commissioning and operation of two DG100's (rated at 100 kW each), before electricity was eventually delivered to the Faroese grid in December 2020, marking the first time that a tidal turbine of kite design had been used to deliver grid electricity [165], [166]. In Figure 48, a diagram of the Minesto DG100 is shown [167].

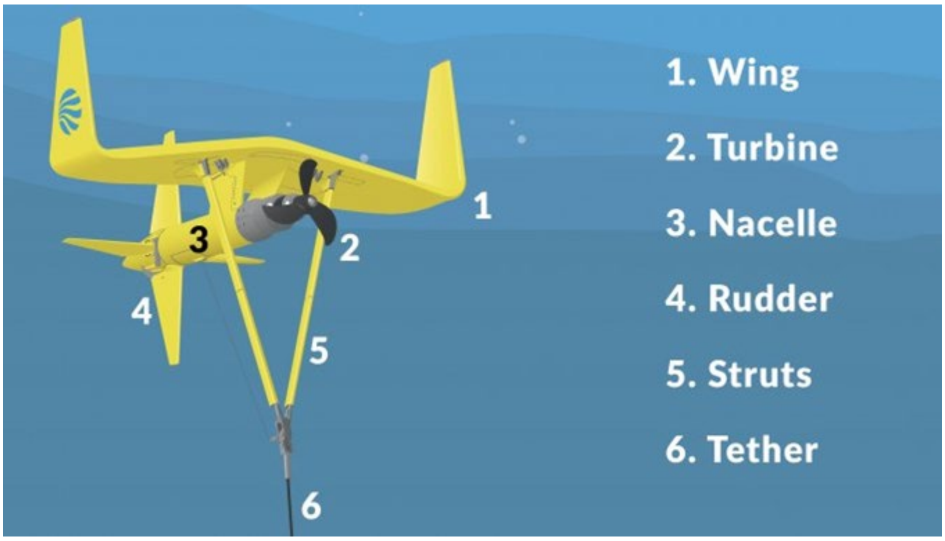


Figure 48. Minesto DG100 [32]

As of September 2021, SEV and Minesto signed an extension to their power purchase agreement (originally signed in February 2020) which contains plans for up to 2.2 MW of Minesto's technology being installed in the Faroe Islands. Beyond this extension to the power purchase agreement, site analysis at Vestmannasund has also concluded that the current 200 kW of capacity could be expanded to 4 MW, thus having to potential to make tidal stream a significant part of the Faroese energy mix [168].

Despite thermal power plants taking up a large portion of the current energy mix on the Faroe Islands, there is a big push to get the islands to 100% renewables by the year 2030. In the long-term Minesto a looking to continuously expand their tidal technology across the Faroe Islands, however, other technologies such as wind and solar will need to be considered alongside storage options such as batteries and pumped hydro. Before reaching 100% renewables by 2030, the Faroe Islands also plan to half their oil consumption for heating by 2025, with heat pumps having been proposed to play a role in reducing dependence on oil [169]. However, with the use of heat pumps alongside a transition to electric vehicles, energy storage becomes essential to accommodate not only the overall increase in electrical demand but the inflexibility of new electrical heating loads that are to be satisfied largely by intermittent generation sources [169].

One development on the Faroe Islands that will lessen strain on the grid when it comes to inflexible heating loads is the expansion of the Sund power plant near the capital of Torshavn, with new high efficiency diesel powered MAN 9L51/60 engines having been installed largely for the purpose of providing district heating as well as having spare electrical capacity to serve as a variable reserve [170].

Lessons for Alderney

With the Faroe Islands being far more isolated than any other island/islands being discussed in this section, the development of their energy strategy is one which Alderney can draw knowledge from in the case that Alderney sees no long-term development of an interconnector. With Alderney being in possession of world-class high flow tidal stream resource there are plenty of opportunities for a range of developers to exploit this. For lower flow tidal stream locations, there is also an opportunity for turbine designs such as Minesto's to contribute towards Alderney's energy mix. However, investigations will need to be carried out to confirm if lower flow sites around Alderney exist that are worth utilising. Regarding the problems that inflexible load patterns that are presented when heat pump use becomes widespread, efforts should be focused on alternative forms of low-carbon heating, with district heating being a possible approach as has been done on the Faroe Islands as well as Shetland. Of course, the approval and subsequent installation of such a scheme will be largely dependent on its long-term cost and benefit in comparison to alternative methods of heating.

Isles of Scilly

The Isles of Scilly is an archipelago off the southwestern coast of Cornwall. The isles have a population of around 2,200. Of the 145 islands that make up the archipelago, five are populated which are St Mary's, Tresco, St Martin's, Bryher and St Agnes, with St Mary's being the largest and most populous with a population of 1,800 [171].

With the Isles of Scilly ranking far above the English average in terms of fuel poverty due to a heavy reliance on expensive electricity and imported oil for heating purposes, the islands decided to improve their energy system through the Smart Islands Programme in collaboration with Hitachi, who took on this project building on the findings of their original demonstration project on the Island of Maui in Hawaii. As of 2018, the Smart Islands Programme was estimated to cost £10.8 m [172].

As of 2015, the Isles of Scilly set goals which aim to reduce electricity bills by 40%, meet 40% of their energy demand through renewables and switch to 40% low carbon or electric vehicles by 2025. To achieve this the islands have implemented Hitachi's internet of things platform alongside artificial intelligence which will help manage the performance of the islands' PV panels, heat pumps and storage batteries while learning the general consumption patterns of residents.

Looking ahead, the Island plan on transitioning to electric vehicles and integrating them with the island grid by using them as a means of storage during times of high demand/low renewable output and charging them during times of low demand/high renewable output, thus enhancing system balancing and providing an additional means of supply during times of high demand [173].

Lessons for Alderney

Regardless of how the future energy mix of Alderney forms itself in the coming years, the use of smart grid technology to optimise energy system efficiency on Alderney should always be considered. Whatever generation and heating sources are selected going forward on Alderney, the use of data driven solutions i.e. internet of things should play a role in striking an optimal balance which largely reduces both emissions and costs for consumers, all while maintaining security of supply.

Ushant

Ushant is a French island located in the southwestern edge of the English Channel with a population of around 850 people and a land area of 15km². However, the population rises significantly during the summer months (up to as much as 3,000 during the peak of the tourist season) [174]. Similar to Alderney, Ushant has a wealth of tidal resource and has been the site of extensive work with tidal stream developer Sabella. In 2015, Sabella located their first full scale demonstrator turbine in the Fromveur Passage. The 1 MW D10-1000 turbine was connected to Ushant, supplying electricity to island residents. Furthermore, the demonstrator project also validated the electrical and mechanical performance characteristics of the D10-1000 [175].

In terms of reducing the island's carbon footprint and reliance on imported fossil fuels, Ushant was a central focus of the Intelligent Community Energy (ICE) project funded by Interreg. The project ran from September 2016 to August 2021 [176], with the project's objectives aligning with Ushant's desire for 100% of electricity on the island to be generated by renewable sources by 2030. The aim of the ICE project was to form a means of optimising energy production from the D10-1000 turbine and future renewable installations on the island. In order to do this, the use of the following three solutions were considered:

- Sensors to control energy production, storage and consumption,
- A power battery solution dedicated to the tidal turbine,
- An IT solution for the regulation of the energy system.

[174]

Regarding future renewable installations on Ushant, Sabella are to trial a two-turbine tidal array in the Fromveur Passage as part of the Phares project which is effectively the continuation of the initial D10-1000 demonstrator. The tidal turbines in discussion are both rated at 500 kW and are expected to be commissioned for early 2023. Additionally, these two tidal turbines are scheduled to operate alongside energy storage, 500 kW of Solar PV and a 900 kW onshore wind turbine which is expected to reduce diesel consumption on Ushant by 80-85% [175], [177].

Lessons for Alderney

Similar to the Isles of Scilly, the use of smart grid technology to maximise utilisation of renewables while minimising emissions is an approach that has the potential to significantly improve any island energy system by storing excess production for times of low renewable output. As a result, imported fossil fuels are only consumed as a last resort. Also, with Ushant having allowed Sabella to trial their turbines in the Fromveur Passage, Alderney can learn from this by having future turbines tested in their waters through appropriate engagement with developers, thus creating a pathway for Alderney to obtain some form of predictable renewable generation as part of their energy mix, with or without an interconnector.

Conclusions

In this literature review the range of issues facing the Island of Alderney are presented with regards to its energy arrangements. Currently the island's residents face high energy costs which are subject to the volatility of global oil markets. This dependence on diesel (1.5 million litres/annum for electricity generation and 500 thousand litres/annum for transport) and kerosene (2 million litres/annum) combined with an ageing shipping fleet has left Alderney in a position where drastic changes are required to ensure the long-term security, affordability, and sustainability of its energy system. At present there is a very strong appetite for a transition to an energy system powered predominantly by renewables, with 90% of respondents saying renewable energy is a top priority for Alderney as part of a public consolation in October 2021.

The introduction of this literature review presented the timescale scenarios in which Alderney are looking to transition to a more sustainable energy system, with these scenarios being short-term (5-10 years), medium-term (10-20 years), and long-term (20+ years). These scenarios will be presented in greater detail during the scoping study phase of this project. It must be noted that before any future renewable technologies are installed, the island already faces significant challenges in upgrading its grid infrastructure, with around £2.5 m already spent since 2014. In addition to this there is a further £2.5 m (approx.) to be spent on further repairs and £10 m of repairs beyond that which have been identified, thus highlighting the cost constraints that Alderney faces when seeking to decarbonise and future-proof its energy system.

Due to the abundance of renewable energy resource in Alderney's territorial waters (most notably in the form of tidal stream), it would be economically desirable for the Island to be capable of exporting surplus generation to external electricity markets in the UK and France via the use of interconnectors. To date there has been two proposals for interconnectors, with these being the FAB-link and Normandie Hydroliennes projects. Unfortunately, both projects have seen proposals for their development stall for various reasons. With regards to the Fab-link which was proposed to serve as an interconnector between the UK and France via Alderney, political tensions between the UK and France have halted progress on its approval. Beyond politics, FAB-link has also been considered to be unviable at this stage by the SoA due to the costs associated with its installation as well as the infrastructure footprint which has the potential to impact the character of the island. Similarly for Normandie Hydroliennes project, the costs associated with an additional connection to Alderney, rather than just a single connection between the proposed tidal array in French waters and mainland France, adds complexity to projects design which reduces appeal for developers looking to install such an interconnector. For these reasons, proposals such as interconnectors are one that can be negated from any short-term energy scenarios.

In the next section of the literature review a range of renewable energy technologies were presented. This section covered each mentioned technology's operating principle, current and future market forecast, and LCOE & cost reduction potential. This was done to provide greater context to the range of technologies that have a strong degree of viability on Alderney, with offshore & onshore wind, solar, tidal stream, and to lesser extent wave energy all being solutions that should be considered in either of the three timescale scenarios being covered in the scoping study section of this project.

After solutions which show signs of commercial viability in the short, medium or long-term were presented, a range of energy system case studies from other islands were presented to provide insight into their choice of technologies as well as the approaches taken by each island to achieve greater decarbonisation, with the islands in discussion being Eigg, The Shetland Islands, The Faroe Islands, the Isles of Scilly, and Ushant. After each energy system was presented, lessons in which Alderney can learn from each of these islands' approach were put forward to provide insight into the range of options that Alderney can pursue along its own decarbonisation pathway.

In the scoping study which comprises the next part of this project, details of Alderney's potential options in terms of technology choice within short (5-10 years), medium (10-20 years) and long (20+ years) time scales are presented. For each solution mentioned within a given timescale, analysis will be provided into suitable installation capacity, purchase and installation costs, maintenance costs, expected lifetime and the benefits that each solution has in achieving the project objectives of reduced energy costs, supply risks and emissions through minimising the use of imported fossil fuels on the island.

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