In partnership with

Llywodraeth Cymru
Welsh Government

CATAPULT
Offshore Renewable Energy

Non-Technical Summary

OFFSHORE WIND AND GRID IN WALES
IN COLLABORATION WITH WELSH GOVERNMENT

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Acknowledgements

ORE Catapult wishes to acknowledge **ITPEnergised** for delivering the technical aspects of this study.

CONTENTS

LIST OF ABBREVIATIONS

Acronym	Full-Term
BEIS	Department of Business, Energy and Industrial Strategy
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
DC	Direct Current
DNO	Distribution Network Operator
ETYS	Electricity Ten Year Statement
FOW	Floating Offshore Wind
GB	Great Britain
GIS	Gas Insulated Switchgear
GSP	Grid Supply Point
HRA	Habitats Regulations Assessments
HVDC	High Voltage Direct Current
ITPE	ITPEnergised
LCOE	Levelised Cost of Energy
MER	Maximising Economic Recovery
NGESO	National Grid Electricity System Operator
NGET	National Grid Electricity Transmission
NOA	Network Options Assessment
O&G	Oil and Gas
O&M	Operations and Maintenance
ORE Catapult	Offshore Renewable Energy Catapult
OTNR	Offshore Transmission Network Review
PDZ	Pembrokeshire Demonstration Zone
SQSS	Security and Quality of Supply Standards
TCE	The Crown Estate
TEC	Transmission Entry Capacity
TNUoS	Transmission Network Use of System
TWR	Transmission Works Register
UK	United Kingdom
VSC	Voltage Source Converter
WMO	World Meteorological Organization
WPD	Western Power Distribution

FOREWORD

Physical infrastructure such as electrical grid will be a key enabler for us to achieve our net zero ambitions, not only in generating clean energy but also unlocking wider economic and societal benefits.

We also need to be aware of the impacts of decarbonising our homes, transportation, business and industry via electrification. This will place an enormous strain on our existing infrastructure. Therefore, it is vital that a holistic approach is taken to ensure that our grid infrastructure onshore and offshore is fit for purpose now and in the future.

To further our understanding of the likely demands of the offshore renewables sector, we have undertaken a comprehensive review alongside the Offshore Renewable Energy Catapult (ORE Catapult) and ITPEnergised to identify our onshore grid's current capacity and pinch points. Needless to say the findings have been illuminating.

The review found that both the North and South Wales electrical grid requires significant reinforcement to enable the connection of forecasted offshore renewable energy projects over the next several decades. The announcement of the Crown Estate's Round 4 seabed licensing in 2020 has highlighted the requirement for network reinforcement in North Wales. Also, in South Wales the emerging floating offshore wind sector is forecast to grow at a rapid pace in the Celtic Sea which will put pressure on our existing grid infrastructure.

Key recommendations from the review include the requirement of strategically planning and undertaking proactive infrastructure investment prior to use. Ultimately, this approach will reduce costs over the life of the asset and minimise disruption to local communities. Additional work has been identified to investigate offshore transmission network design and implementation to minimise onshore pinch points and to ensure that the number of onshore connection points are contained and environmental impacts are minimised. We will work with UK Government to ensure that Wales' requirements are fully understood and implemented.

The reports insights will be important evidence in our pan Wales strategic electricity and gas grid review with National Grid ESO, Western Power Distribution, Scottish Power and Wales & West Utilities to ensure that our gas and electricity system is fit for purpose to achieve net zero.

Vaughan Gethin, MS,
Minister for the Economy

1 BACKGROUND

1.1 OFFSHORE WIND IN THE UK

The UK can be considered the world leader in offshore wind, having installed more capacity than any other country. Once an expensive form of electricity generation, the costs of offshore wind have fallen by 50% since 2015 and it is now one of the cheapest forms of new power. It is expected that upcoming offshore wind projects could agree contracts that would effectively make them subsidy-free.

Current operational capacity in the UK exceeds 10GW and accounts for more than 10% of electricity needs. The UK Government has committed to achieving 40GW of operational offshore wind by 2030, while the Committee on Climate Change has advised that 75GW of offshore wind will be needed for the UK to achieve its net-zero greenhouse gas emissions target by 2050.

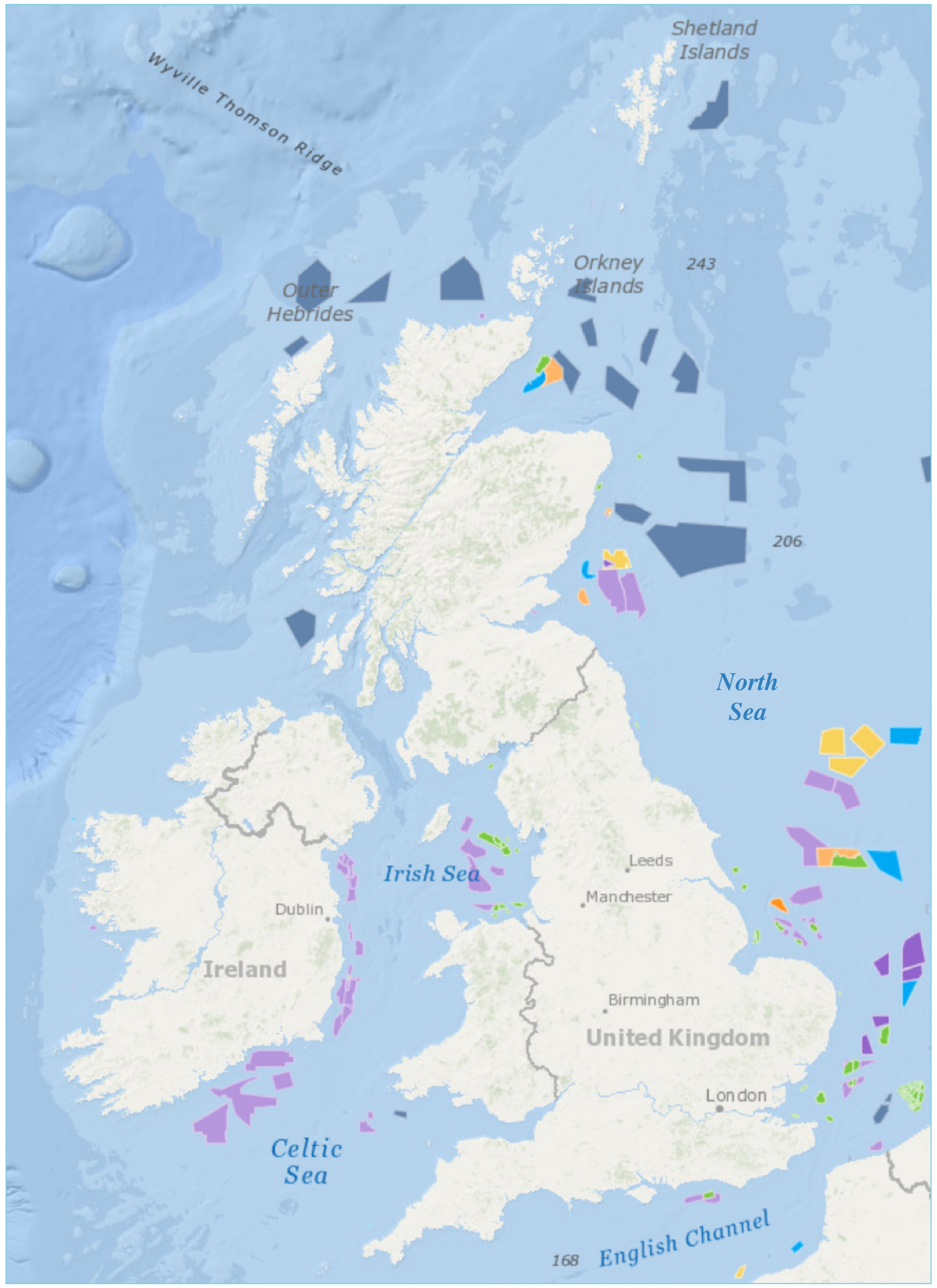
The majority of offshore wind projects to date have been developed in the North Sea, which has led to the considerable redevelopment of areas in the North East and East Anglia to support the industry. Elsewhere, projects in North Wales and the Irish Sea region currently amount to around 2.7GW, while Scotland has just under 1GW of operational capacity and a healthy project pipeline, with the Scottish Government targeting 11GW by 2030. **Figure 1** provides an overview of offshore wind activity in the UK.

1.2 OFFSHORE WIND IN WALES

Offshore wind projects in North Wales have been developed since the dawn of the industry, with North Hoyle (60MW) being the first of the UK's Round 1 offshore wind farms to become operational in 2004. This was followed by Rhyl Flats (90MW), another Round 1 project, in 2009, before Gwynt y Môr became operational in 2015 as one of the UK's Round 2 projects and is Wales' largest offshore wind farm at 576MW. These 3 projects off the North Wales coast are currently the only offshore wind projects in Welsh waters, although the Burbo Bank Extension (258MW) in Liverpool Bay also connects into the North Wales grid at Bodelwyddan, operational since 2017. In total this amounts to just under 1GW of offshore wind connecting into the Welsh grid at present.

During the offshore wind Round 3 process, 2 sites were shortlisted for development off Wales, including a first project off South Wales, but ultimately these projects were cancelled. In both cases the seabed conditions were cited as one of the key challenges that led to cancellation, while the projects were being developed at a time (cancelled in 2013/2014) when offshore wind was still in its infancy and expensive, which may have led to preference being given to other Round 3 sites.

Despite the setbacks experienced during Round 3, North Wales is set for a new pipeline of offshore wind projects over the next decade. In 2020 it was announced that RWE will be extending the Gwynt y Môr wind farm, under a development referred to as Awel y Môr that is set to at least double the existing capacity. In addition to this, The Crown Estate (TCE) announced in February 2021 the 6 successful bidders for new offshore wind projects that have progressed to the next stage of the Round 4 process, 3 of which are located in the North Wales and Irish Sea area. This includes a 1.5GW development off the North Wales coast, North East of Anglesey.



- Concept/Early Planning
- Consent Application Submitted
- Consent Authorised
- Pre-Construction
- Under Construction
- Partial Generation/Under Construction
- Fully Commissioned
- Decommissioned
- Development Zone

***Figure 1:** Offshore wind activity in the UK and Ireland [1]*

1.3 FLOATING OFFSHORE WIND

The deployment of floating offshore wind (FLOW) at scale will be necessary for the UK to hit its net-zero targets. FLOW will unlock deeper, offshore sites deemed infeasible for bottom-fixed technology. As much as 80% of the European offshore wind energy resource is found in water depths greater than 60m, the approximate limit for bottom-fixed technologies at present.

As part of its commitment to achieving 40GW of offshore wind by 2030, the UK Government included a 1GW target for FLOW and has separated FLOW from bottom-fixed offshore wind in the upcoming Round 4 Contracts for Difference (CfD) scheme, meaning that FLOW developers can bid for projects without having to compete directly with bottom-fixed projects. This should provide the FLOW sector with a suitable revenue support mechanism in which it can build pre-commercial scale projects and reduce costs through learning, following a similar trajectory to that taken by the bottom-fixed offshore wind sector over the last decade. Recent work by ORE Catapult has shown that, depending on the deployment scenario pursued by the UK, FLOW could reach subsidy-free levels as early as 2029 [2].

Within the UK there are 3 primary areas where FLOW is expected to develop at scale: Scotland, the North East of England and the Celtic Sea. The latter covers an area off the coastlines of South Wales, Cornwall and the South coast of Ireland. Prior work by ORE Catapult identified that between 50 – 120GW of realisable FLOW potential exists in areas of least constraint in UK Celtic Sea waters [3], which would represent a significant contribution to UK net-zero targets from a currently untapped offshore wind region. At present, 2 FLOW projects are in development in Welsh Celtic Sea waters: Erebus a 96MW demonstration project; and Valorous a 300MW pre-commercial project. In addition to this, TCE in March 2021 announced the commencement of work to design and deliver new leasing opportunities for early commercial-scale (~300MW) floating wind projects in the Celtic Sea [4].

Outside of the Celtic Sea, there are other areas along the Welsh coastline that have suitable characteristics for FLOW, particularly to the West of the Llŷn peninsula and Anglesey. ORE Catapult is aware of some developer interest in the latter for stepping stone FLOW projects in North Wales.

1.4 GRID CAPACITY IN WALES

To realise the significant potential for new offshore wind in North and South Wales, the onshore grid will need to be upgraded to accommodate the volume of power coming to shore. The motivation for this study is to identify where the existing transmission network in Wales will become constrained in various future offshore wind deployment scenarios, while highlighting the potential solutions to these constraints that will ensure that grid capacity is not a show stopper for new offshore wind projects.

Related to this is the ongoing Offshore Transmission Network Review (OTNR) [5], being led by the Department of Business, Energy and Industrial Strategy (BEIS). This review aims to develop a strategy to coordinate interconnectors and offshore networks for wind farms and their connections to the onshore network, rather than the current approach of building point-to-point connections for each project, which can be a barrier to delivery due the considerable environmental and local impacts. The work to date does not consider the significant potential for FLOW in the Celtic Sea. This study, therefore, aims to initiate a dialogue for a coordinated transmission network for the Celtic Sea.

2 INTRODUCTION

2.1 WALES' TRANSMISSION NETWORK

The transmission network (275kV and above) in Wales spans along its North and South coastlines (Figure 2) [6]. Historically the North Wales circuit was built to accommodate various hydroelectric schemes and the Wylfa nuclear power station on Anglesey, whereas in South Wales the transmission network hosts several thermal power stations. Given that there are substantial offshore renewable energy resources off the North and South Wales coastlines, the existing transmission network offers an attractive connection opportunity for such projects. This is not always the case for energetic offshore sites. For example, the far North and North West of Scotland are blessed with considerable offshore wind, wave and tidal energy resources, but several potential projects have hit barriers due to the availability of grid connection. This is also true for onshore wind projects that have been proposed for Mid-Wales, which currently operates only on the distribution network.

Generators in Wales pay low Transmission Network Use of System (TNUoS) tariffs, which are charges to recover the cost of installing and maintaining the transmission system set and billed by National Grid Electricity System Operator (NGESO). This is mainly due to the fact that the charging structure favours generators that are nearer to areas of demand, and charges more to those that need to send power over long distances on the transmission network. These costs can be substantial and need to be considered by developers when they evaluate the economics for prospective offshore renewable energy projects. In a recent study by ORE Catapult that investigated the cost reduction pathways for various potential FLOW project zones around the UK [2], projects off Wales in the Celtic Sea were projected to have some of the lowest levelised costs of energy (LCOE), which was in part attributed to lower TNUoS tariffs. These tariffs in Wales are also expected to remain almost constant over the next 5 years [7], whilst they are forecast to increase in parts of Scotland over the same period, which ORE Catapult estimates could increase the LCOE of FLOW projects there by up to 6.8%.

2.2 FUTURE OFFSHORE WIND SCENARIOS

The transmission network in North and South Wales can be considered as separate circuits that operate behind different network boundaries, which are used when assessing power flows across the UK network. For this reason, future offshore wind scenarios have been developed for both North and South Wales in this study. These represent low, medium and high offshore wind rollout scenarios, chosen such that the level of required grid reinforcements differs in each case.

2.2.1 North Wales

Table 1 shows the future offshore wind scenarios for North Wales used in this study. At the time of preparing these scenarios, only the Awel y Môr project was known with any certainty, which appears in all scenarios. The outcome of the Round 4 tender process was announced after the modelling work finished, and as a result 3 differing levels of new deployment from Round 4 were predicted for the low, medium and high cases. In the low case scenario, 800MW was modelled for Round 4, which is 700MW short of what is currently being proposed. This could be considered a pessimistic outcome from the Round 4 process or reflect a staggered deployment where just 800MW is installed by 2032.

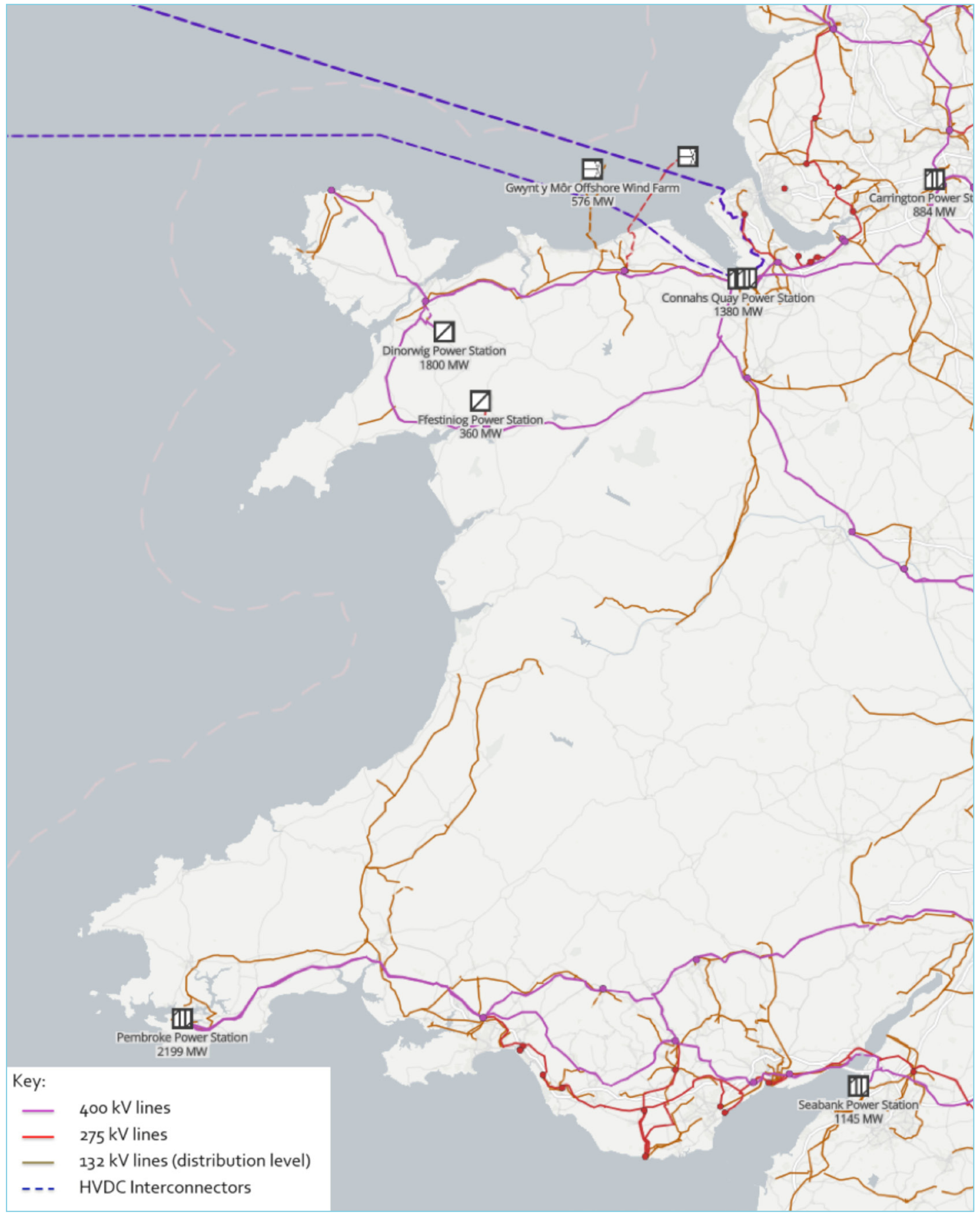


Figure 2: Transmission network in Wales [6]

In the medium case scenario, 1800MW was modelled from Round 4 projects, which is close to what is currently proposed. In addition to this, a FLOW steppingstone project off Anglesey was modelled to come online by 2030, while by 2040 an additional 1,000MW of FLOW was included from a future leasing round as FLOW begins to unlock new sites at scale.

The projects in the high case scenario are the same as those in the medium case, only the installed capacities have increased. 2,500MW of bottom-fixed wind from Round 4 projects was modelled, which could comprise other projects in the Irish Sea making landfall in Wales, similar to the Burbo Bank Extension. Additionally, 3,500MW of FLOW was included from a future leasing round expected to bring projects online by 2040.

It is worth noting that given that bottom-fixed and FLOW will be expected to use many of the same substations in North Wales, the type of the listed projects is not particularly important to the relevance of the grid analysis. For example, some or all of the 3,500MW of FLOW by 2040 could consist of additional bottom-fixed wind, e.g. from a future leasing round in North Wales.

To summarise the North Wales scenarios, the study considers adding new offshore wind at capacities of 1.4, 3.7 and 6.9GW in the low, medium and high case scenarios respectively.

2.2.2 South Wales

Table 2 shows the future offshore wind scenarios used in this study for South Wales. Both Erebus and Valorous have grid connection agreements and as a result were used as assumptions for all scenarios. These projects are expected to come online by 2030. The low case scenario adds 1,000MW of further FLOW capacity to Pembroke by 2035, which assumes that further FLOW projects in the Celtic Sea are developed in upcoming TCE leasing rounds.

The projects in the medium case scenario are the same as those in the low case, only the installed capacity from upcoming leasing rounds in the Celtic Sea increases to 3,500MW.

An additional future leasing round for the Celtic Sea is assumed in the high case scenario, where a further 5,000MW is developed by 2040. In addition to this, the installed capacity from the preceding round is also increased to 5,000MW.

All projects are modelled as connecting to Pembroke due to the fact that this represents the nearest onshore connection point for Celtic Sea projects in Welsh waters. This might lead to the requirement for an additional substation to be built in the area, which is discussed later in Section 4.2.

The study considers new offshore wind in South Wales at capacities of 1.4, 3.9 and 10.4GW in the low, medium and high case scenarios respectively.

Table 1: North Wales future offshore wind scenarios used in this study

North Wales					
Case	Project	Size (MW)	Substation Location	Year	Total (MW)
Low Case	Awel y Môr	576	Bodelwyddan	2030	1,376
	New bottom-fixed project(s) from Round 4	800	Wylfa	2032	
Medium Case	Awel y Môr	576	Bodelwyddan	2030	3,676
	FLOW stepping stone project off Anglesey	300	Pentir or Wylfa	2030	
	New bottom-fixed project(s) from Round 4	1,800	Pentir or Wylfa	2032	
	Further FLOW projects from future leasing rounds	1,000	Pentir or Wylfa	2040	
High Case	Awel y Môr	576	Bodelwyddan	2030	6,876
	FLOW stepping stone project off Anglesey	300	Pentir or Wylfa	2030	
	New bottom-fixed project(s) from Round 4	2,500	Pentir or Wylfa	2032	
	Further FLOW projects from future leasing rounds	3,500	Pentir or Wylfa	2040	

Table 2: South Wales future offshore wind scenarios used in this study

South Wales					
Case	Project	Size (MW)	Substation Location	Year	Total (MW)
Low Case	Erebus	96	Pembroke	2027	1,396
	Valorous	300	Pembroke	2030	
	FLOW projects from future leasing rounds	1,000	Pembroke	2035	
Medium Case	Erebus	96	Pembroke	2027	3,896
	Valorous	300	Pembroke	2030	
	FLOW projects from future leasing rounds	3,500	Pembroke	2035	
High Case	Erebus	96	Pembroke	2027	10,396
	Valorous	300	Pembroke	2030	
	FLOW projects from future leasing rounds	5,000	Pembroke	2035	
	Further FLOW projects from future leasing rounds	5,000	Pembroke	2040	

3 METHODOLOGY

3.1 GRID CAPACITY ASSESSMENT

ITPE's method to provide an initial review of likely onshore grid capacity and programme implications to the future offshore wind scenarios in Wales is as follows:

1. Review the onshore grid and identify the most relevant onshore connection point(s) based on the identified areas of interest, prospective MW capacity of the offshore project, distance, voltage and overall grid configuration in the future.
2. Create a power flow model of the local transmission system incorporating the following:
   a. Post-fault line and cable ratings (summer).
   b. Planned and prospective reinforcements.
   c. Generation connected and contracted to connect.
   d. Interconnectors connected and contracted to connect.
   e. Demand supplied (2030 summer minimum).
3. Assess the thermal capability of the local transmission system (available MW capacity) using Security and Quality of Supply Standards (SQSS) [8] Chapter 2 and Chapter 4 style analysis.
4. In some cases where it is difficult to section and analyse the regional grid, the power flows on the grid model are determined using the future predicted power flows by NGESO [9].
5. Building on the above, ITPE separately incorporated the low, medium and high future wind scenarios. Where the thermal capability of key network boundaries is exceeded, ITPE will suggest potential additional reinforcements, as set out in Section 3.2, to alleviate the network constraints. These reinforcements will provide a thermally SQSS compliant network.

Key data sources used to inform this analysis are the Electricity Ten Year Statement (ETYS) [9], Network Options Assessment (NOA) [10], Transmission Entry Capacity (TEC) register [11], interconnector register [12], Distribution Network Operator's Long Term Development Statements and heat maps, and the National Electricity Transmission System Security and Quality of Supply Standards (National Electricity Transmission System SQSS) [8]. These data sources are supplemented by others, such as generation and interconnector project website data and planning related data.

3.2 CONVENTIONAL TECHNIQUES USED TO INCREASE GRID CAPACITY

The following is a high-level overview of the techniques commonly used to increase grid capacity:

- **Reconductoring**
  Reconductoring is a method of upgrading existing transmission lines by replacing the cabling on them with a higher rated substitute. This process increases the power which can be transmitted by the network. It has less technical and consenting risk than the construction of new lines as the existing routes and towers are reused, limiting any potential impact.

- **Additional Onshore Circuits**
  One way to reduce the loading of existing grid infrastructure is to add new onshore overhead lines and cables. These lines and cables can be added alongside existing ones, or follow a new route, connecting previously unconnected substations. Adding additional lines comes with significant technical and consenting risk, as engineering work will be required to design and build the new towers, or underground the cables, and the new infrastructure will have to undergo environmental impact assessment.

- **Interconnectors**
  Interconnectors are high voltage cables which link the grid of two different countries, allowing excess generation in one country to be exported to another. This ensures less renewable energy generation is wasted as excess can be shared. The UK currently has interconnectors to France, Ireland, the Netherlands and Belgium, while four more are under construction to Norway, Ireland, Denmark and France. Although these can help reduce network constraints, they are generally bi-directional and can increase GB network constraints whilst importing.

- **Bootstraps**
  Bootstraps are high voltage connectors within a country, typically of High Voltage Direct Current (HVDC) technology type for long distance power transfer. They work in much the same way as interconnectors, passing excess power generated by one region to another. These are typically routed offshore and cover multiple network boundaries and, although a Marine Licence is required, they typically pose a lower consenting risk than additional onshore circuits. At the interface with the onshore grid which utilises alternating current, converter stations are required. These pose significant cost which is not correlated to distance of the link. Therefore, bootstraps are typically only cost effective over long distances.

3.3 SUBSTATION CAPACITY

Substation capacity is the amount of generation which can connect to a substation. There are two limiting factors to this:

- Firstly, the rating of the substation transformers. Transformers are required to interface between assets of varying voltage, such as between the 400kV and 275kV levels of the transmission system. The export voltage of a project is site specific and if the transmission system interface point is of a different voltage, additional voltage transformers will be required. The rating of the transformer is given as a mega-volt-ampere (MVA) value that cannot be exceeded without damaging the equipment.

- Busbar capacity. This is the number of individual lines and connection bays that can be connected into a substation's busbar. It is limed by the space on the busbar. It is possible that a substation can be upgraded to include more busbar capacity, however this often involves expanding the footprint of the substation to allow for space for the busbars.

4 GRID CAPACITY ASSESSMENT

4.1 NORTH WALES

4.1.1 Grid Connection Overview

The transmission system in North Wales (**Figure 3**) consists of a double 400kV circuit from Connah's Quay out to Pentir, and then onto Wylfa on Anglesey. A second 400kV double circuit also extends across North Wales from Connah's Quay to Trawsfynydd, which is interconnected to Pentir to form a ring around North Wales, but this part is only by way of a single circuit and constitutes a key bottleneck.

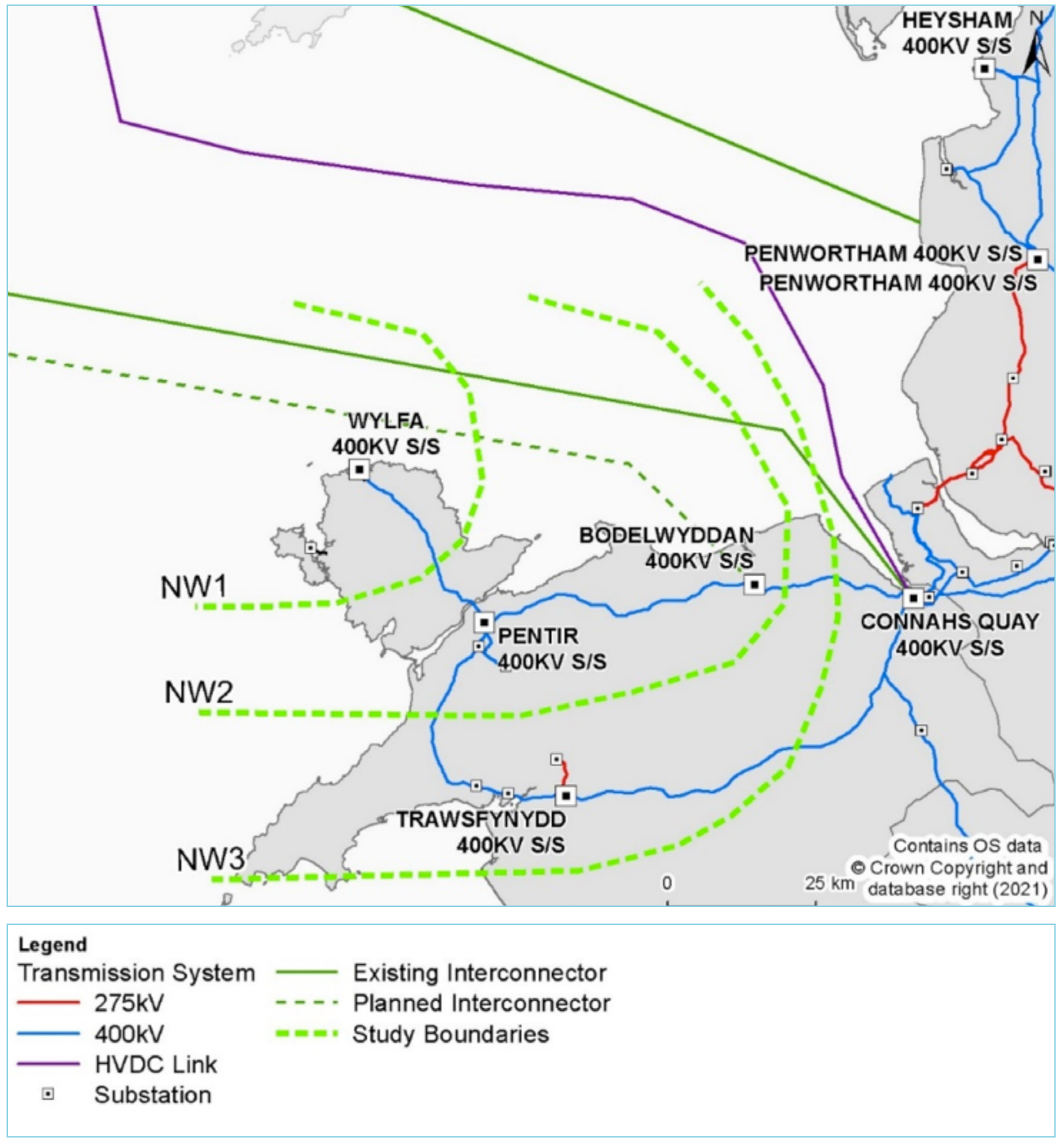


Figure 3: North Wales grid overview

There are three main network boundaries used to assess the North Wales grid, these are: NW1 which separates Anglesey; NW2 which includes NW1 and Caernarvonshire; and NW3 which includes NW2 and Merionethshire. These boundaries are utilised to assess connection capacity and propose grid reinforcements.

Connah's Quay is outside the North Wales ring and is well interconnected to Capenhurst and Daines to the North-East. Furthermore, it is connected to Flintshire Bridge and in turn Hunterston in Scotland via the Western Link HVDC bootstrap. Connah's Quay gas power plant also connects here.

4.1.2 Background Generation, Interconnectors and Demand

Currently, the North Wales grid is mainly characterised by 2000MW of pumped hydro at Dinorwig and Ffestiniog, along with almost 1000MW of offshore wind (Gwynt y Môr, Rhyl Flats, North Hoyle and Burbo Bank Extension) connected via Bodelwyddan. The former Wylfa nuclear power station was decommissioned in 2015. There is also approximately 500MW of distribution connected generation, meaning that in total approximately 3500MW of generation is currently connected within North Wales.

In the coming ten years, numerous projects are contracted to connect in the North Wales, including hybrid PV and battery storage projects at Wylfa (120MW) and Bodelwyddan (53MW), the Awel y Môr offshore wind project at Bodelwyddan (576MW), the Morlais tidal energy project at Penrhos (180MW), plus a 750MW GB to Ireland interconnector. There is also approximately 435MW of distribution generation contracted to connect in North Wales.

There is estimated to be around 40MW of minimum demand (minimum load at which the lowest available headroom for new generation connections is available) within the North Wales region.

Outside the North Wales loop, there is a 1380MW gas power plant and a 505MW interconnector to Ireland connected at Connah's Quay.

4.1.3 Grid Constraints Analysis

In addition to the contracted background generation (including Awel y Môr), the low case scenario adds a further 800MW of new offshore wind (1.4GW total) to North Wales (**Table 1**) at Wylfa. This has been assumed as the preferred connection point for initial future projects due to the proximity to TCE Round 4 leasing zone, which will offer the most economic and efficient solution.

The contracted generation alone is enough to exceed the NW2 boundary capacity. Adding a second 400kV circuit between Pentir and Trawsfynydd would enable at least an additional 1GW of capacity to this section of the network and would be enough to accommodate the contracted generation, including the Awel y Môr project. This work is currently under consideration by NGESO **[13]**. The exiting steel lattice towers for the first circuit should be able to accommodate the second, reducing engineering and consenting risks. However, the local DNO is currently using sections of these towers for a 132kV circuit from Trawsfynydd to Four Crosses. Therefore, a new Grid Supply Point (GSP) will have to be built around Bryncir to provide for the load at Four Crosses if the 132kV circuit is replaced with 400kV.

The remaining 800MW in the low case scenario can be accommodated by reconductoring the existing Pentir-Bodelwyddan-Connah's Quay and Pentir-Trawsfynydd circuits to higher thermal ratings. No work would be required on the Wylfa to Pentir circuits.

The medium case scenario adds a further 2.3GW of new offshore wind (3.7GW total) to North Wales (**Table 1**). These additional projects connect at both Pentir and Wylfa, the latter of which can accommodate 1.4GW of offshore wind before additional grid reinforcements across Anglesey will be required. The grid works in this scenario are largely the same as those in the low case, with the only difference being a greater amount of reconductoring, i.e. to even higher thermal ratings, to the Pentir-Bodelwyddan-Connah's Quay and Pentir-Trawsfynydd circuits. Some tower rebuilds might also be required in this scenario, but this is unlikely to present a major consenting risk. The grid works for this scenario are illustrated in **Figure 4**. Note that the upgrades are performed in phases (as denoted by the colour scheme) corresponding to the timeline in **Table 1**. With the benefit of foresight, the upgrades could be carried out more efficiently in fewer stages, since the limitations are found in the same circuits.

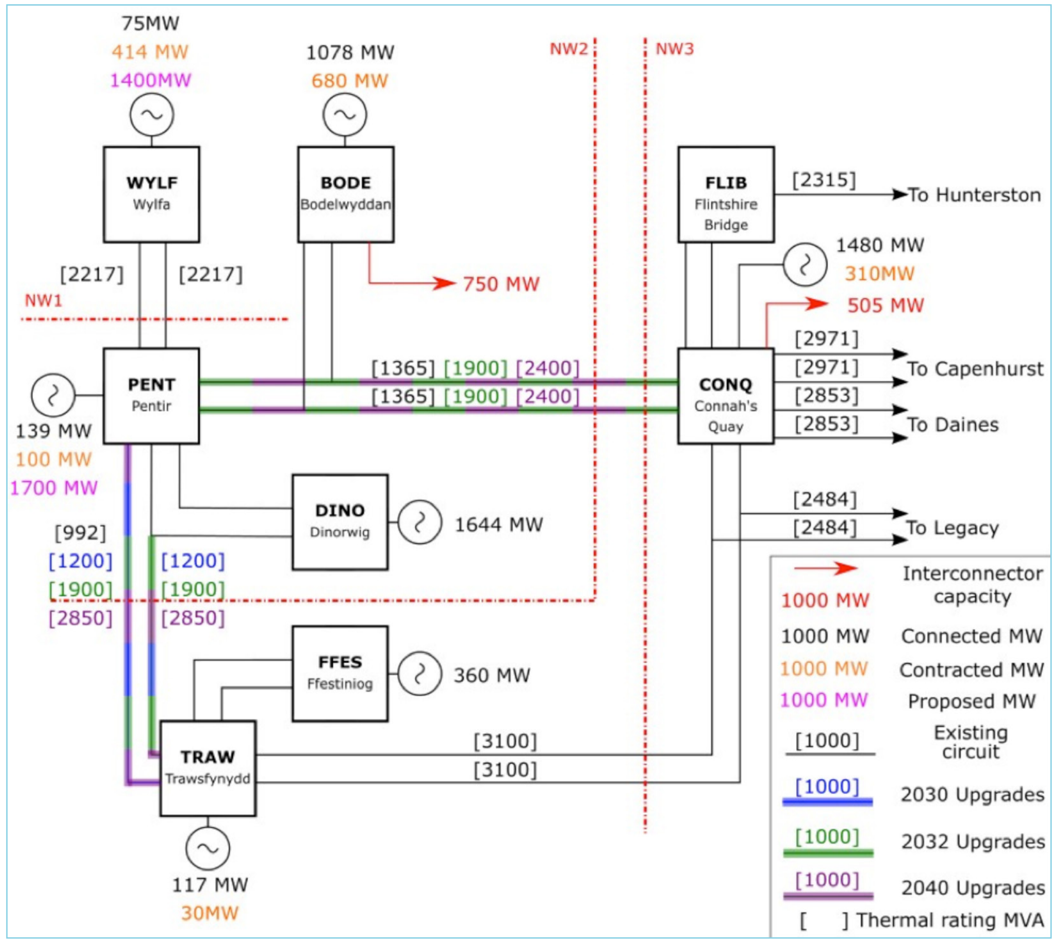


Figure 4: North Wales grid reinforcements to accommodate the medium new offshore wind scenario

For the high case scenario (6.9GW total), 3.4GW of offshore wind connects at Wylfa and 2.9GW connects at Pentir. The remaining 0.6GW (Awel y Môr) is connected at Bodelwyddan. In addition to a comparable amount of grid work to the medium case scenario (**Figure 4**), this scenario would require at least a new single 400kV circuit to be built between Wylfa and Pentir, as well as new double 400kV circuits between Pentir and Connah's Quay. There would be significant engineering and consenting risks associated with these works.

An alternative solution to accommodate the high case scenario would involve establishing a subsea HVDC link between Wylfa and Flintshire Bridge. This would mitigate the need for additional Wylfa-Pentir and Pentir-Connah's Quay onshore circuits, with the required onshore works instead being comparable to the medium case (**Figure 4**). National Grid previously tabled a number of offshore options similar to this when the Wylfa Newydd nuclear power station was being considered **[14]**.

4.2 SOUTH WALES

4.2.1 Grid Connection Overview

The grid in South Wales (**Figure 5**) consists of a 400kV ring from Walham to Pembroke, and from there to Melksham. There is a meshed 275kV network that connects to this 400kV ring at Swansea North, Cilfynydd and Melksham.

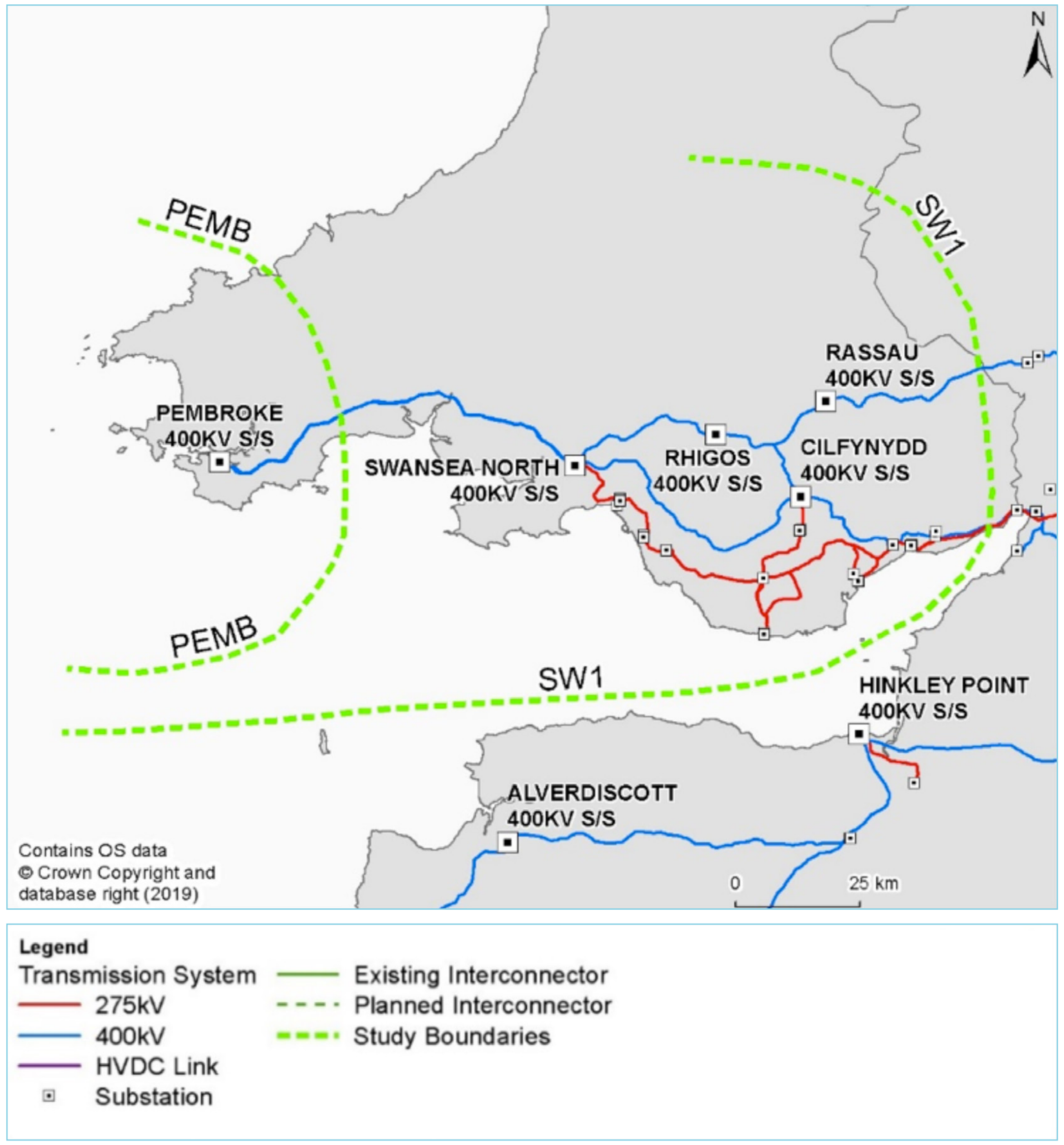


Figure 5: South Wales grid overview

Pembroke substation is ideally located close to the Celtic Sea and offers a distinct opportunity for future FLOW connections to South Wales. The four 400kV circuits that link Pembroke to the rest of the GB grid are very long, with the Pembroke to Walham line being the longest NGET circuit at over 200km. This is understood to give rise to stability issues potentially limiting connection capacity.

Pembroke substation is physically constrained by the adjacent power station and expansion for large volumes of future generations may not be feasible. NGET may be required to establish new nearby connection points in the future and has tabled using near-shore loops to reduce onshore disruption **[15]**.

There is one main network boundary, SW1, which separates South Wales from the rest of the transmission network. It bisects the 400kV double circuit entering Walham from Pembroke and Rassau, the 400kV double circuit entering Melksham and Seabank from Imperial Park and Whitson respectively, and the double 275kV circuit from Whitson to Iron Acton. A boundary that separates Pembroke from the rest of the network, termed PEMB, has been modelled in this study to identify local constraints.

4.2.2 Background Generation, Interconnectors and Demand

The South Wales grid is mainly characterised by around 4oooMW of thermal generation, including the 2200MW CCGT Pembroke Power Station. Wales' largest onshore wind farm, Pen Y Cymoedd, connects 228MW at Rhigos substation. There is also around 1300MW of distribution generation connected within the South Wales network, primarily from a number of small solar and wind projects. In total approximately 5600MW of generation is currently connected within South Wales.

Several projects are contracted to connect in the South Wales region over the next decade, including 299MW Open Cycle Gas Turbine (OCGT) power peaking plants at both Swansea North and Rhigos. PV and energy storage hybrid projects are due to connect at Aberthaw (57MW) and at Whitson (285MW), while a 50MW battery storage project is also due to connect at the latter. A grid connection agreement at Baglan Bay also still exists for the Swansea Bay Tidal Lagoon project (320MW).

At Pembroke, both the Erebus (96MW) and Valorous (300MW) FLOW projects have grid connection agreements. The Greenlink interconnector is also contracted to connect at Pembroke and has been treated as a 526MW importer to the GB system in this study.

There is approximately 1000MW of distribution generation contracted to connect in the South Wales region. In total, therefore, there is approximately 2700MW of generation and a 526MW interconnector contracted to connect in the South Wales region.

There is estimated to be around 1,300MW of minimum demand within the South Wales region with 128MW located under Pembroke GSP.

4.2.3 Grid Constraints Analysis

Connected generation in South Wales already exceeds the capacity of the SW1 boundary under the SQSS methodology. However, due to the volume of renewable energy behind this boundary and the variability of its generation characteristics, the majority of expected power flows are within the capacity of the boundary. This means that reinforcements are unlikely to be required in the short term, with the network instead managed by constraining generators off during infrequent periods of high generation. The latest NOA **[13]** does not list any required grid upgrades for South Wales, supporting this viewpoint. As a result, a scaling factor of 0.5 to the estimated security planned transfer for background generation was applied in this study, providing a better representation of actual available capacity.

The contracted generation, including the Celtic Sea projects in development (Erebus and Valorous), can be realised by minor turn in works at Swansea North to the circuit that runs from Pembroke to Walham. This will involve diverting this circuit through the Swansea North substation to improve stability issues arising from its length. Beyond this, a modest amount of reconductoring to the Imperial Park-Melksham and Whitson-Seabank circuits is required to enable the additional 1GW of new FLOW capacity in the low case scenario (**Table 2**), plus it is possible that either an extension to increase the number of connection bays at the Pembroke substation or the build of a new nearby substation will be required.

The medium case scenario adds a further 2.5GW of new offshore wind (3.9GW total) to South Wales (**Table 2**). In addition to the grid works required to accommodate the low case scenario, the medium case requires considerably more reconductoring to the South Wales network (**Figure 6**), including the 4 circuits out of Pembroke as well as the Whitson to Iron Acton 275kV double circuits. The latter would either require high temperature low sag conductors or uprating to 400kV, which would involve additional substation works at Whitson, Iron Acton and Melksham. The likelihood of requiring an extension to Pembroke substation or a new nearby substation is greater in this scenario.

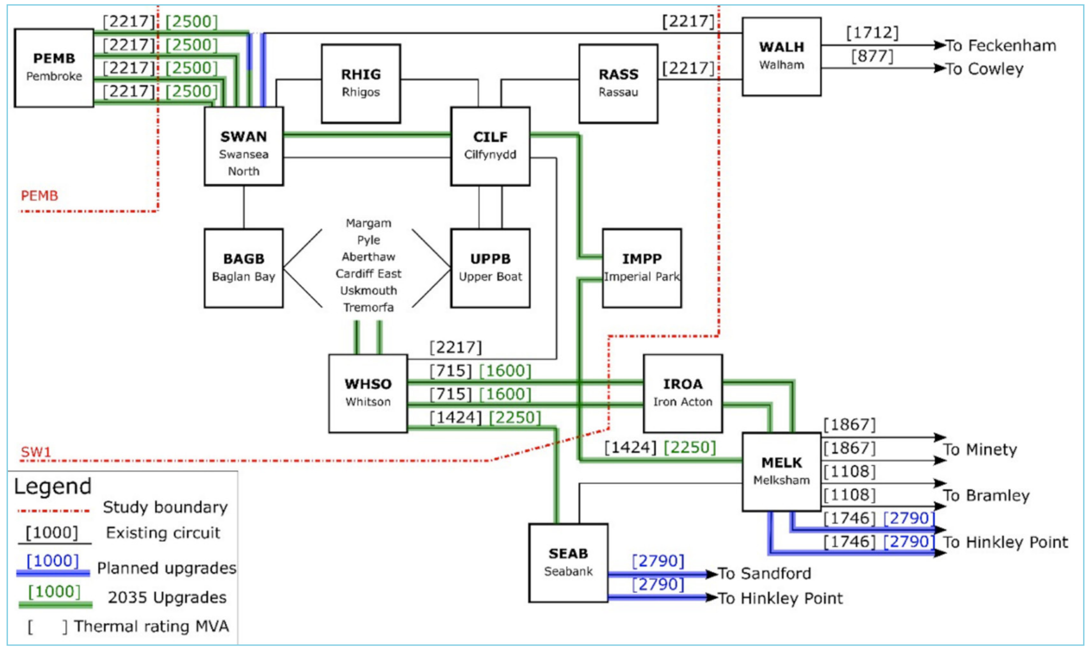


Figure 6: South Wales grid reinforcements to accommodate the medium new offshore wind scenario

The medium case scenario could also be accommodated by establishing a subsea HVDC link from Pembroke to SW England, e.g. at Alverdiscott. This would mitigate the need for much of the onshore reconductoring work, apart from that described in the low case scenario. A new HVDC converter station would need to be established in the vicinity of Pembroke for this solution. However, bootstrapping South Wales to SW England needs to consider the grid capacity in this region, which is out of the scope of this study. This is particularly true if other future FLOW projects in the Celtic Sea connect into SW England.

The high case scenario considered adds 10.4GW of new offshore wind to South Wales (**Table 2**) at Pembroke. Any onshore solution for this volume of power requires building new double 400kV circuits that run straight to Walham, which would be subject to considerable consenting and engineering risks. Additionally, new circuits out of Walham would need to be built and the entirety of the existing South Wales transmission network would need reconductoring, to a level beyond that shown in **Figure 6**.

Similar to the medium case, the amount of onshore work can be reduced via subsea HVDC link(s) from Pembroke to SW England. Given the likelihood of other future FLOW projects connected into SW England, this solution needs to be evaluated as part of a UK-wide power flow analysis. It is possible that a wider offshore bootstrap development connecting South Wales to SW England to SE England could be a viable means of managing power flows in the Celtic Sea.

5 NOVEL APPROACHES

This section discusses novel approaches that could be proposed to help manage grid constraints and evaluates at a high level their applicability to Wales.

5.1 DATA CENTRES

Data centres produce a large electrical demand which could be met through renewable energy, either from the grid, close to the connection point, or through a Power Purchase Agreement. By positioning new data centres near to the landfall of offshore renewables, a significant amount of the energy production could be diverted from the wider grid, saving on the upgrades required. Further, up to 40% of data centre energy demand is for cooling servers **[16]**. With smart management of the system, this energy demand could be lowered during times of limited renewable resource and increased during energy surpluses. This would help give an outlet for the energy production rather than sending it into the constrained grid, which might mean that the generation is constrained and wasted.

This is an area increasingly being considered by offshore wind developers. SSE Renewables recently announced that its 520MW Arklow Bank Wind Park has signed an agreement with Echelon Data Centres to provide energy to a 100MW data centre. The wind farm and data centre will connect to a new shared substation and onto the wider Irish national grid, decreasing grid reinforcements **[17]**.

5.2 ENERGY STORAGE

Energy storage can absorb some of the generation peaks and reduce its impact on the wider grid. This stored energy can then be released back into the grid at times of low generation, helping smooth the peaks and troughs inherent to intermittent sources of generation like offshore wind. If relatively large scale energy storage is implemented, this could somewhat reduce the upgrades required to the grid. Furthermore, energy storage can complement renewables by providing the rapid response capabilities that intermittent renewables cannot.

Pumped storage is already utilised in Wales and can play a useful role in harnessing renewable resources. North Wales has a unique opportunity in this respect, with the Dinorwig Power station located in Snowdonia connecting into Pentir. These power stations however have already been considered in the analysis presented in Section 4.1. If additional facilities were to be constructed, this could provide a store for the energy generated by offshore wind, however, there are significant technical and consenting risks to the construction of new pumped storage.

The UK has recently relaxed planning legislation for large battery storage projects, creating a pathway to their implementation alongside offshore wind. The cost of battery storage has reduced dramatically over the past few years with costs set to reduce even further **[18]**. By combining offshore wind with utility scale battery storage, grid constraints can be reduced by lowering export peaks. Furthermore, a number of other benefits can be provided to the grid, complementing offshore wind generation. These include frequency regulation, peak shifting, and power management **[19]**.

5.3 ELECTRIFICATION OF OIL & GAS ASSETS

With the drive to Net-Zero and maximising economic recovery, oil companies within the Douglas Fields off Rhyl and Cardigan Bay could benefit from electrification, with power supplied by offshore wind. Electrification means replacing a fossil-based power supply with renewable energy, enabling a reduction in greenhouse gas (GHG) emissions. Today, most offshore assets produce their own electricity using gas turbines, which accounts for 67% of UK Oil & Gas (O&G) assets' GHG emissions, being released into the atmosphere. O&G production is responsible for 3% of the UK's GHG emissions.

A recent study by ORE Catapult found that there is an early market opportunity for FLOW to provide electricity to O&G assets in the North Sea [20], although the economic attractiveness depends on a combination of the power requirements, wind resource and the remaining asset life.

5.4 HYDROGEN PRODUCTION

Hydrogen production has often been discussed as a solution to the intermittency of offshore wind generation, and renewables in general. The principle is that when renewable generation exceeds grid capacity, the excess energy is converted to hydrogen and stored. ORE Catapult have explored this scenario in its 'Solving the Integration Challenge' (STIC) report [21]. This would mean the expensive curtailment fees that the transmission operator pays to wind farm operators could be eliminated. This in turn means that fewer upgrades to the grid are potentially required, while a greater proportion of renewable energy is harnessed to reduce emissions in sectors such as heating, transport and industry.

While hydrogen has long been proposed as a key element of a zero-carbon economy, it has until recently been assumed that 'blue hydrogen' (hydrogen produced from fossil fuels, but with carbon capture and storage used to mitigate CO_2 emissions) would provide the major share due to cost advantages over 'green hydrogen' (true zero carbon hydrogen, generated from renewable energy) until around 2050. The STIC report [21] suggests, however, that with accelerated deployment alongside offshore wind, green hydrogen could reach cost parity with blue hydrogen by the early 2030s.

Even though many parts of the UK are well-suited to blue hydrogen, South Wales lacks the geography necessary for local CO_2 storage, meaning that captured CO_2 must be transported elsewhere for storage, increasing costs substantially. Green hydrogen, by contrast, can leverage the huge potential for FLOW in the Celtic Sea, and the existing O&G expertise and infrastructure in the region, particularly at Milford Haven, with its existing methane import and transmission infrastructure. There is already a market for hydrogen in the steel-making industry in the region, an industry that faces its own decarbonisation challenges. The Milford Haven Energy Kingdom project [22] is developing a decarbonisation roadmap for the area through the design of a hydrogen and renewables smart local energy system.

5.5 INTERCONNECTORS

As discussed in Section 3.2, interconnectors with other countries can both help and increase grid constraints. In the case of interconnecting with Ireland, the Irish grid is already relatively constrained, meaning that it is unlikely to be a viable means of reducing constraints in Wales. Larger interconnectors from Wales to continental Europe may instead offer a greater opportunity for power export.

6 WELSH OFFSHORE WIND AND ENERGY DIVERSITY

Energy security from renewable sources can be improved through diversification, both by varying the type of generation, e.g. by combining solar and wind power, and by varying the geographic location of generation of the same type. Given that currently the majority of offshore wind projects in the UK have been developed along its East coast, increasing the amount of offshore wind in Wales could improve UK energy security, provided that wind resources between these two areas are not strongly correlated. **Table 3** shows the results from a preliminary investigation that compares wind data from the World Meteorological Organisation (WMO) at sites in Wales and the UK's East Coast. The low coefficients of correlation found between these two locations suggest differing wind resource characteristics.

This is further highlighted in **Figure 7**, where the breakdown of wind speeds above a typical 5m/s cut-in speed for a wind turbine is shown. While the majority of the time (57%) it is found that wind conditions at both locations would enable simultaneous turbine generation, 18% of the time the turbines in Wales would be the only source of wind power, compared with 8% on the UK's East Coast.

Location	Sites in Wales		Sites on the UK's East Coast		
	Aberdaron	Milford Haven	Weybourne	Donna Nook	Boulmer
Aberdaron	1				
Milford Haven	0.683	1			
Weybourne	0.420	0.324	1		
Donna Nook	0.333	0.289	0.660	1	
Boulmer	0.348	0.259	0.399	0.403	1

Table 3: Coefficients of correlation for wind data in Wales and the UK's East Coast

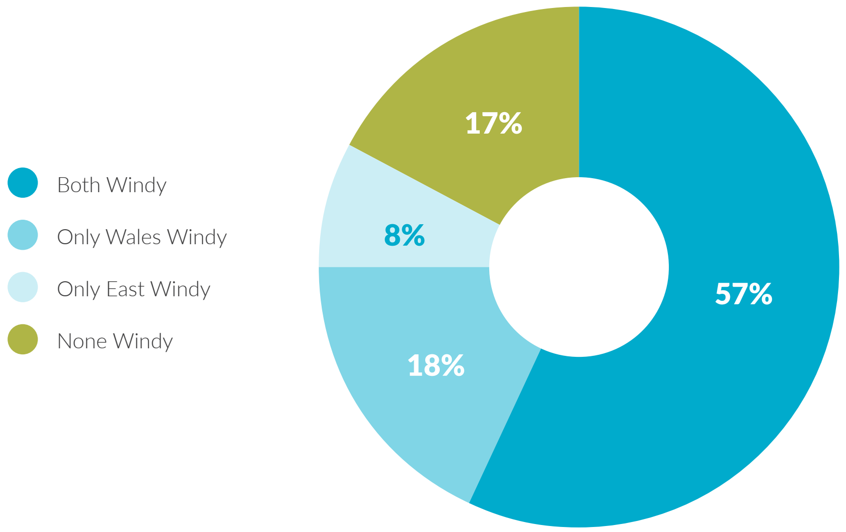


Figure 7: Breakdown of wind speeds above cut-in for Welsh and East Coast locations

7 RECOMMENDATIONS

- **Remommendation 1.**
  We recommend that engagement with BEIS is increased to ensure that the Celtic Sea area is considered as part of its OTNR. The work to date does not appear to recognise that this area could feature a significant amount of FLOW in the future, likely due to the fact that there is no clear pipeline of projects (see Recommendation 2). Preliminary work by the OTNR has suggested that bootstrapping North Wales to South Wales could be a viable way of managing power flows and coordinating future networks in Wales, but the work in this study has shown that this is not a suitable way of managing grid constraints if considerable amounts of generation are added to both North and South Wales. Furthermore, given that no offshore wind development has taken place in South Wales to date, this represents an opportunity to incorporate the lessons learned from existing projects, rather than continue the trend of point-to-point offshore connections, which is inefficient and has considerable environmental and local impacts. The OTNR needs to look at the UK as a whole and not just where existing project pipelines exist.

- **Remommendation 2.**
  In order to trigger investment into transmission network upgrades, National Grid needs confidence of a clear pipeline of projects before it will begin works. Despite the significant potential of the Celtic Sea, an auction round is needed to pave the way for deployments of the scale outlined in this study. TCE's recent announcement that it will commence work to deliver a leasing opportunity for early commercial-scale FLOW projects in the Celtic Sea is an encouraging development **[4]**. We recommend that engagement between all stakeholders and TCE be stepped up to ensure that the Celtic Sea's potential is realised. Even if such a pipeline can be credibly established, there may be the need for the 'buying down' of risks associated with anticipatory investments (see Recommendation 4) by National Grid.

- **Remommendation 3.**
  The latest NOA, published in January 2021 **[13]**, recommends delaying the construction of a second 400kV circuit between Pentir and Trawsfynydd, work it estimates will take 6 years to complete. Provided that the work commences by 2023, this should be timely for the indicative 2030 operational date for the Awel y Môr project. However, the recent announcement of a further 1.5GW of new offshore wind for North Wales could mean that grid works are needed sooner, and the very high option fees being paid by developers suggests that they believe projects can be built at an unprecedented rate. We recommend that these project development timescales are checked against National Grid's plans, and if required, the relevant policy support is put in place to ensure that grid is not a barrier.

- **Remommendation 4.**
  Significant cost savings could be achieved if onshore reinforcement works are completed on an anticipatory basis. This is particularly true for the North Wales scenarios, where in some cases the results in this study show the same circuits being upgraded on multiple occasions. NGET cannot make anticipatory investments due to the risk of assets being underutilised, although a small amount of strategic investment is possible. We recommend that the mechanisms for underwriting these upgrades are fully understood, and all opportunities to incentivise anticipatory investments are explored to present an alternative to prospective developers.

- **Remommendation 5.**
  The assessment of wind speeds across the UK in this study, while not extensive, has highlighted that there are considerable periods of time when wind resources in Wales and the East Coast of the UK are not correlated, which supports the findings from other related studies **[23]**. This negative correlation of wind speeds could be invaluable in the management of the UK's future transmission network, which is easier to operate with a diverse mixture of generation connected to it and with geographic diversity in generation of the same type. Offshore wind in Wales could power much of the UK when wind speeds on the East Coast collapse, or in the event of a fault in offshore wind networks elsewhere. When lobbying the case for offshore wind in Wales, particularly for the Celtic Sea, we recommend that these benefits to the management of the future transmission network are highlighted. Through the Floating Wind Centre of Excellence (FLOW CoE), ORE Catapult is currently undertaking a study to further quantify the benefits to the energy system that FLOW brings by opening up new offshore wind sites around the UK.

- **Remommendation 6.**
  Related to Recommendation 1, we recommend that further work is undertaken to increase the study boundary for the Celtic Sea to incorporate potential FLOW projects connecting into Cornwall. This study only looked at FLOW projects connecting into South Wales and identified potential solutions that involved bootstrapping Pembroke to South West England. These solutions may not be suitable if additional FLOW generation connects to Cornwall.

- **Remommendation 7.**
  It is recommended that further work is undertaken to quantify how TNUoS tariffs may change in the event of significant new renewable generation in Wales, which is known to be a concern that potential developers share. ITPE has an in house TNUoS model that can be used to evaluate how the charges may change under the low, medium, and high scenarios and the reinforcements they require. In future work, ITPE could use the in house TNUoS model to make predictions of TNUoS charges. This could be a valuable resource in effective planning for the Welsh wind industry.

- **Remommendation 8.**
  In addition to the conventional grid upgrades that Wales needs to facilitate the rollout of an offshore wind industry at scale, there are a number of novel solutions that we recommend should be explored and supported in parallel. Hydrogen production, in particular, is gaining considerable traction in Wales and the UK, and could be a means of not only alleviating grid constraints but could also have a key role in the decarbonisation of several energy intensive sectors, further supporting the transition to net-zero. Developing a larger hydrogen industry in Wales would also have several wider economic benefits, including the creation of high value jobs and the development of a supply chain that will attract other businesses to Wales.

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