SP ENERGY NETWORKS

ANGLE-DC

ANGLE-DC

2015 Electricity Network Innovation Competition

Section 1 Project Summary

1.1. Project Title	**ANGLE–DC**
1.2. Project Explanation	ANGLE-DC aims to demonstrate a novel network reinforcement technique by converting an existing 33kV AC circuit to DC operation. The technique can be used by DNOs as an efficient solution to create network capacity headroom and facilitate GB's objective for the shift towards a low carbon economy.
1.3. Funding licensee:	SP Manweb Plc
1.4. Project description:	**Problems:** The existing distribution network is increasingly strained due to growing demand and a high penetration of distributed generation. The conventional AC network has limited **controllability and flexibility**, two fundamental attributes required as the network evolves and becomes increasingly complex. **Methods:** ANGLE-DC will utilise an existing 33kV AC circuit comprising cable and overhead line sections to establish a DC link. One AC/DC converter station will be installed at each end of the circuit and the condition of AC assets under DC stress will be monitored in real time. **Solutions:** The DC link will **enable improved power flow and voltage control**. Converting AC assets to DC operation will enhance the thermal capability of the circuit in a timely manner. The Anglesey example, while complicated, is representative of many of the challenges all DNOs are facing in the transition to a low carbon economy. This pilot scheme will incorporate a novel technology as part of the toolbox of solutions for network reinforcement and renewable connections. The solution could be deployed to **interconnect two distribution networks** which would otherwise be operated split due to fault level and thermal limits. **Benefits:** ANGLE-DC will provide capital and operational benefits to the distribution systems in Anglesey and North Wales by securing a power corridor between the island and mainland, while also providing ancillary benefits to the AC distribution network by controlling power flows and regulating the voltage at both ends of the circuit. Total savings of **£18.67m** could be gained from the ANGLE-DC trial, in addition to the CO_2 emission reduction. The savings would be in the form of: • **Net capital investment** saving associated with the incremental capacity of 30.5MW; • **£7.57m for wide area loss reduction** by the end of 2030 and **£15.77m** by the end of 2050. If successful, the roll-out of the ANGLE-DC solution at **GB level could bring a total saving of £69.2m by 2030** and **£396.0m by 2050**. Important learning will be also generated for future DC projects.

1.5. Funding

1.5.1 NIC Funding Request (£k)	13,121	*1.5.2 Network Licensee Compulsory Contribution (£k)*	1,484
1.5.3 Network Licensee Extra Contribution (£k)	0	*1.5.4 External Funding – excluding from NICs (£k):*	0
1.5.5. Total Project Costs (£k)	14,839		

1.6. List of Project Partners, External Funders and Project Supporters

Project Partners
During the preparation of this proposal, SP Energy Networks has engaged with the main suppliers of MVDC technology and those who may provide engineering and consultancy support for the delivery of the project. In order to provide the best value for money, no project partner has been selected at this stage, project partners will be selected through a competitive tendering process upon funding award.

Academic Partners
Extensive engagement has been carried out between SP Energy Networks and academic institutes and consortiums. Appropriate academic partners will be identified within three months of project start.

Project Supporters
Welsh Government, Isle of Anglesey County Council, Western Power Distribution (WPD), Scottish Hydro Electric Power Distribution (SHEPD), WSP | Parsons Brinckerhoff, Anglesey Enterprise Zone, Menter Mon (tidal), Offshore Renewable Energy (ORE) Catapult, Energy Island, The National HVDC Centre (MTTE), Flexible Elektrische Netze (FEN) GmbH, Electric Power Research Institute (EPRI), Energy Networks Association (ENA), Power Electronic Society.

1.7. Timescale

1.7.1. Project Start Date	January 2016	*1.7.2. Project End Date*	April 2020

1.8. Project Manager Contact Details

1.8.1. Contact Name & Job Title	Mikel Urizarbarrena Engineer	*1.8.2. Email & Telephone Number*	murizarbarrena@ spenergynetworks.co.uk 0141–614-2626
1.8.3. Contact Address	Future Networks Ochil House 10 Technology Avenue Hamilton International Technology Park Blantyre G72 0HT		

Section 2 Project Description

2.1. Aims and objectives

ANGLE-DC is an innovative project which aims to demonstrate a smart and flexible method for reinforcing distribution networks by converting Alternating Current (AC) assets for Direct Current (DC) operation. ANGLE-DC will adapt existing power electronic technologies to build a medium voltage DC (MVDC) link which could be an effective solution to **facilitate the integration of renewable resources** and accommodate future demand growth. ANGLE-DC aims to build the confidence in deploying MVDC technologies by other UK Distribution Network Operators (DNOs) and also trigger the medium voltage DC supply chain. ANGLE-DC has the following objectives:

- Trial the first **flexible MVDC link** in the Great Britain (GB) distribution system;
- Trial **conversion of an AC circuit to DC operation** to enhance circuit capacity;
- Trial **real-time holistic circuit condition monitoring** of a DC circuit converted from AC to provide the evidence and confidence for DNOs;
- Provide **real-life data on MVDC converter operation** under various loading conditions;
- Provide **real-life data on cable ageing mechanism**;
- Develop **technical guidance, recommendations and policy documents** for planning, procurement, operation and control strategy of MVDC converters and MVDC links;
- Create a supply chain and stimulate a **competitive MVDC market**;
- To **bridge the gap** between transmission network and low voltage distribution DC technologies;
- Explore the feasibility of MVDC technology as an **enabler for the Distribution System Operator** model;
- Provide wider benefits to other industries such as shipping and railway.

2.1.1. *The Problems which need to be resolved*

Increasing demand growth and uptake of distributed energy resources place pressure on the distribution network. Electricity distribution networks need to adapt for the future energy scenarios which aim to reduce CO_2 emissions in the power sector to near zero by 2050. The UK Carbon Plan promotes the electrification of heating and transport and the use of renewable energy sources, which will mainly be connected to distribution networks. Consequently, DNOs face a challenge to accommodate a significant demand growth and Distributed Generation (DG) capacity which is predicted to nearly double with approximately 21.8 GW in the GB by 2035. Thus, extensive and prohibitively expensive reinforcement of the distribution networks is required to maintain networks within thermal, voltage and fault level constraints and comply with the electricity industry standards.

The creation of new way-leaves for additional distribution circuits and substations is difficult in the UK. Conventional reinforcements typically involve significant costs and additional land requirements. Obtaining way-leave agreements or easements could directly affect the lead time of distribution network expansion schemes. Consequently, this may result in lengthy lead times for renewable connections and a slowing down in the move towards UK Carbon Plan targets. Solutions for future distribution networks need to make the most efficient use of existing assets, this potentially defers or avoids the need for new network reinforcements.

A passive distribution network does not satisfy future network requirements. Renewable resources are intermittent and their export does not necessarily coincide with local demand requirements. This along with the inherent uncertainty of future generation and demand requires distribution networks to be flexible and controllable. The operation of conventional AC distribution networks is mostly passive and is not able to provide the necessary control of power flow magnitude and direction.

Power exchange between two distribution networks is mostly only possible through primary grids. Most GB distribution systems are traditionally operated radially; neighbouring networks are not operated with interconnection as coupling distribution systems may result in thermal ratings, fault level limits and permissible voltage levels being exceeded. However, a direct and controlled power exchange between distribution systems allows the transfer of the excessive power generated by DGs to other load centres. A reliable and controlled interconnection between distribution systems could potentially reduce network losses, enhance the reliability of the system as a whole, and reduce customer interruptions by increasing the power supply paths.

2.1.2. *The Method being trialled to solve the Problem*

ANGLE-DC aims to address the aforementioned problems by building on earlier projects and demonstrating additional benefits from the deployment of MVDC converters at both ends of an existing circuit (rather than a "back to back" (BtB) application). The **proposed method can enable power and voltage control over a wider area of influence and increase the capacity of an existing circuit**. The following three principles will be trialled in the ANGLE-DC project:

1- Insertion of a flexible MVDC link in a GB distribution system;
2- Conversion of an AC circuit to DC operation;
3- Holistic circuit condition monitoring of a DC circuit converted from AC.

The first principle is to use MVDC converters at both ends of a distribution network interconnector, to control the power through the link and voltage at both distribution systems. This solution will develop a building block for active rather than passive power control between two distribution networks which cannot be operated coupled by an AC circuit due to uncontrolled circulating power and fault levels. This will be the first GB trial of a MVDC link (to our best knowledge the first in Europe).

The second principle is to convert existing AC medium voltage (MV) distribution circuits to DC operation. This solution is anticipated to unlock capacity from the existing circuits which can be used to facilitate integration of renewable resources. This will be the first trial of the method on GB distribution networks.

The third principle demonstrates that AC assets can be used for DC operation by real-time condition monitoring of assets in pre and post DC conversion. Real-time partial discharge (PD) monitoring equipment will be deployed at both ends of the link to assess the performance of AC assets in different loading and DC stress conditions in real-time. To our best knowledge, PD monitoring of DC circuits at medium voltage has not been trialled before in the UK.

2.1.3. *The Development or Demonstration being undertaken*

An existing 33kV AC circuit between North Wales and Anglesey has been identified as a suitable location for a trial to demonstrate the application of a flexible MVDC link using existing circuits. This circuit connects Bangor (mainland) to Llanfair PG (Anglesey) 33kV substations and comprises both cable sections and overhead line sections.

In the Anglesey area, the volume of renewable generation and the demand for electricity are increasing significantly. The demand growth forecast for this area is around 11% during the RIIO-ED1 period. The connected and contracted renewable generation connections have reached around 160 MW. Consequently, voltage and thermal rating issues in several locations in Anglesey and North Wales need to be addressed. Additional headroom derived from increased capacity of circuits operating using DC will bring benefits to the wider area and reasonable provision for uncertain future developments.

Furthermore, it is necessary to control power flow on the 33kV circuits between Anglesey and the mainland connecting the two different distribution systems, as the existing 33kV network creates a parallel power flow path with the existing 400kV transmission network. Uncontrolled power flow may exceed the thermal rating of the 33kV Bangor-Llanfair PG circuit, as illustrated in Figure 2-1. Therefore, this circuit represents an appropriate location to demonstrate the viability of an attractive alternative reinforcement technique.

2.1.4. *The Solutions which will be enabled by solving the Problem*

The project aims to prove the viability of converting existing AC circuits to DC operation, by demonstrating that it is practically possible to realise improvements in the control of power flow, voltage profile and increased capacity for a real circuit. Furthermore, practical experience will be acquired (and shared) by way of a prudent approach to design; requirements for testing the existing equipment; proof of the equipment reliability and scheme availability; and improvements obtained in the wider distribution network. By the end of the ANGLE-DC trial, it is anticipated that the MVDC reinforcement solution will be significantly de-risked for future applications.

The solution will provide operational benefits to the distribution system on Anglesey by providing an up-rated power corridor to the mainland, while also providing ancillary benefits to the AC distribution network by controlling power flow and regulating voltage at both ends of the circuit. This will potentially allow further connection of low carbon renewable energy sources on the island; and defer the need for further medium voltage AC reinforcements on the island or mainland. It is expected that because the MVDC technology is able to improve the voltage control in the wider area of the distribution network, operating losses will decrease. Energy losses represent an economic cost to system operation and the savings will reduce the ultimate cost that is borne by the consumers of electricity.

2.2. Technical description of Project

2.2.5. *AC networks vs DC networks*

AC technology has been in use for over 100 years to connect generation sources to consumer loads. Although this is a well-developed technology, easily adaptable for new connections, it is somewhat difficult to control the flow of power through a network. This can make it difficult to control the voltage profile across the network and thus minimise operating losses.

With the re-emergence of High Voltage Direct Current (HVDC) transmission since the 1960's and recent developments in AC to DC converter technology, the use of DC for distribution applications is being considered. Unlike AC distribution, with DC the power flow is fully controllable.

2.2.6. *Benefits of using DC networks*

DC technology is now widely used for high voltage power transmission (HVDC) and there are a few examples of stations operating at medium voltage levels (<76.5kV). Additionally, there are some distribution applications (up to 138kV) of DC which are mainly BtB topologies or niche power supplies to off-shore oil and gas installations, see Appendix M. To date there are no known applications for MVDC links in distribution networks. The use of DC technology will bring a number of benefits to the operation of the distribution network and hence to the consumer as outlined in the following:

- Enhanced power flow through an existing circuit;
- More precise control of the flow of power in the distribution circuit;
- No possibility of overload of the circuit;
- Control of voltage at either end of the distribution circuit;
- Control of reactive power[1] flow at both ends of the distribution circuit;
- Lower losses in the wider distribution network due to the improved voltage control;
- Rapid support to the system voltage during faults;
- Fault level decoupling between distribution systems;
- Facilitating accelerated access to the network for renewable connections.

2.2.7. *Technical Overview*

ANGLE-DC aims to demonstrate the application of MVDC technology by converting an existing 33kV AC circuit between Llanfair PG substation on Anglesey and Bangor substation in North Wales to a symmetrical monopole DC circuit, with each AC circuit becoming one pole, operating at ±27 kVdc[2]. The existing circuit consists of underground cables and an overhead line section on Anglesey, cables on the Britannia Bridge over the Menai Strait, and underground cables in North Wales. The total circuit length is approximately 3km. Figure 2-1 shows the 33kV circuit (OHL + cable sections) route between Bangor and Llanfair PG substations. As discussed earlier, condition monitoring of the cables, when operating under DC stress, is a critical aspect of this project.

2.3. MVDC Converters

At each end of the DC link, a Voltage Source Converter (VSC) with an interface transformer will be used to convert 50Hz AC to DC, and back again at the opposite end of the link. The existing circuit would be re-terminated at the DC connection of the new converters. An overview of the technical details of the MVDC converters is given in Appendix H.

The notional power rating of the scheme is 30MW with a working assumption that the scheme may operate continuously at this power level with a power factor of lead/lag 0.9, i.e. a scheme rated capacity of 33MVA. This power rating will be confirmed by detailed evaluation early in the project execution phase. Bi-directional power transfer capability is required, i.e. the rated power is required in both directions. Minimum power transfer level of the scheme will be around 1% of the rated capacity. A high level functional specification of the converters is given in Appendix I.

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[1] Reactive power is an inherent feature of AC networks. It cannot provide useful "work" such as heating, lighting, motion, etc., but it must be controlled and compensated in order to operate the AC network.

[2] This is a notional voltage and the exact DC voltage will be determined in the design phase of ANGLE-DC project. We have conducted a DC voltage withstand test during proposal preparation phase and confirmed that this circuit is capable of DC operation at 27kVdc.

The scheme will be able to operate in voltage control mode, such that the operator may select a target AC bus voltage and the converter will automatically adjust converter reactive power absorption or generation to achieve the desired voltage. Alternatively the operator may select reactive power control mode to influence the voltage profile in the wider network.

In the event that the DC circuit is unavailable each converter station should be capable of operating as a static synchronous compensator (STATCOM) to support voltage on local networks.

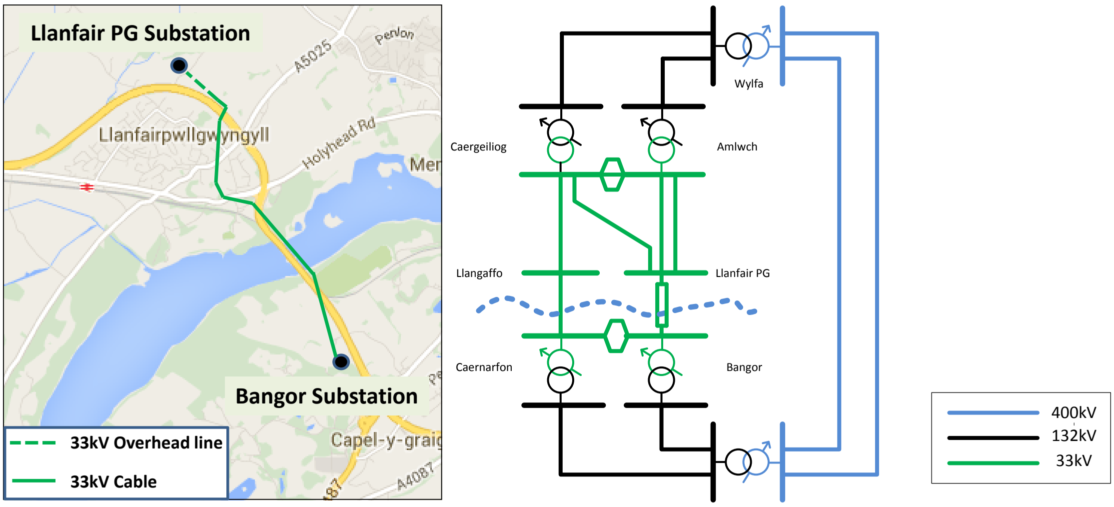

Figure 2-1: Existing 33kV circuit route and schematic diagram between Bangor and Llanfair PG

2.3.1. *Connection arrangement*

It is proposed that the three conductors of one existing AC circuit are parallel connected to form one DC pole conductor and the same for the other circuit. Cable failures are rare and so it may be decided that it is possible to tolerate the repair time on an infrequent basis in order to benefit from significantly increased capacity during normal operation. Mechanical isolators will be provided to enable any faulted phase of the cable to be removed from operation to undergo repair and reinstate the link with less capacity (approximately two-thirds of the full capacity for a fault on one phase) after a short interruption.

A simplified circuit diagram is shown in Figure 2-2 to indicate the additional equipment that is proposed, namely: two interface transformers and two power electronic converters.

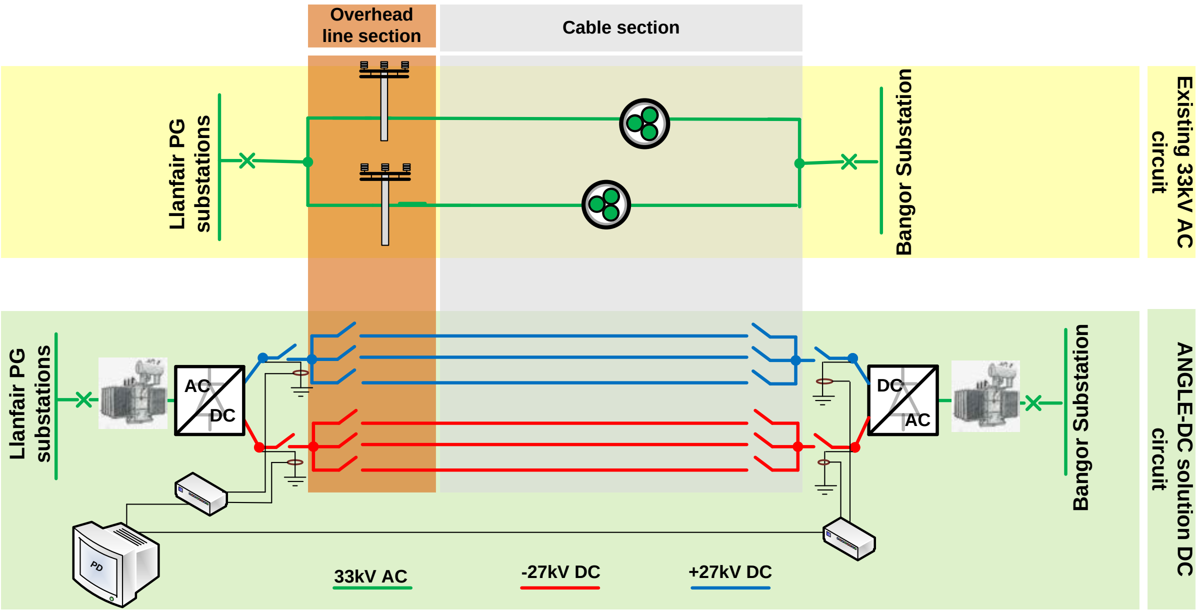

Figure 2-2: Existing and ANGLE-DC networks schematic diagram

2.3.2. *Technology choices: MVDC Converters*

In considering the choice of technology for an MVDC demonstration project, two approaches were considered:

> <u>Option 1:</u> Using the prevailing HVDC technology, called Modular Multi-level Converter (MMC), and scaling the solution (typically 1000MW at ±320kV) down to 30MW and ±27kV.
>
> <u>Option 2:</u> Using existing industrial or distribution level technology that is used for power supplies or reactive power control and adapting it for MVDC power flow for a rated power of 30 MVA and ±27kV DC operating voltage.

It should be noted that Option 1 will be associated with concerns and uncertainties about the potential high cost base implicit in this technology. An optimised and fit for purpose design needs to be defined to ensure that technology innovation is also value for money for electricity customers. SP Energy Networks is planning to develop a detailed technical specification of the MVDC converters in the design phase of this project. The final and definite choice of technology will be the outcome of a competitive tender process, **which will stimulate the supply chain and deliver a best value solution for the customer for future MVDC applications.**

2.3.3. *ANGLE-DC will unlock 30.5 MW of the existing network*

The capacity unlocked in the Anglesey area consists of two elements: i) DC allows the coupling of two distribution systems and ii) DC makes better use of the conductor than AC.

DC allows the coupling of two distribution systems: In order to avoid exceeding thermal limits in the Bangor-Llanfair PG circuit due to uncontrolled power flow, this circuit is kept open in normal conditions. Deploying the DC solution offered by ANGLE-DC, however, allows this circuit to be closed and making efficient use of stranded assets by power flow control in this corridor. This will add 24.8MVA capacity to the network.

DC makes better use of the conductor than AC: DC allows more current to flow and hence greater power transfer. DC current does not suffer from "skin effects" (discussed in Appendix J), therefore the complete cross sectional area of the conductor can be used, providing a higher current capability in a DC circuit. ANGLE-DC will enhance the thermal rating of the circuit by **around 23% from 24.8MVA (operating in AC at 65°C) to 30.5MVA (operating in DC at 50°C)** by conversion to DC operation. A potentially higher capacity release could be achieved because the capacity increase of 23% has been calculated based on the conservative assumption that the maximum operating temperature of the cable circuits when operating in DC is 50°C, whereas the cables are currently operated at a maximum temperature of 65°C, see Figure 2-3. The details of the capacity released calculation are given in Appendix K.

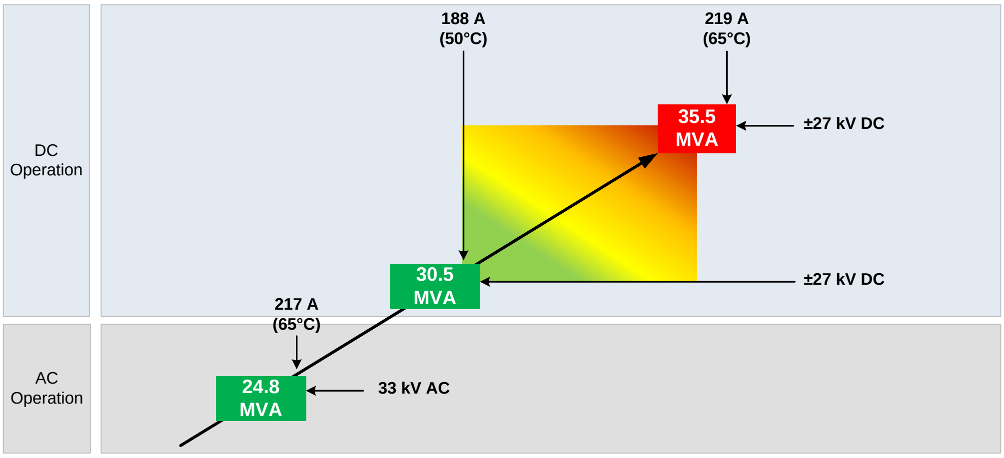

Figure 2-3: Capacity increase in Bangor-Llanfair PG corridor by converting AC to DC

2.3.4. *ANGLE-DC is an innovation project*

This project will trial the first Voltage Source Converters (VSC) for operation of a DC circuit in the GB distribution system. DC technology has been used to some degree at MV for industrial and BtB distribution applications, but it has not been widely used and exploited for commercial maturity. This project aims to develop a fit for purpose specification and encourage suppliers to offer an appropriate, cost effective and easily repeatable solution for future applications.

The re-use of existing AC assets represents a significant innovative step in the use of MVDC technology. The agreement of new easements/way-leaves for additional distribution circuits can be difficult in the UK, as in most developed countries, due to the extensive and prolonged planning and negotiation processes involved. Avoidance of the need for new circuits, resulting from the enhancement of the capacity of existing circuits when they are operated using DC, will accelerate access to the network for low carbon renewable generators because construction of converter stations is expected to be quicker than construction of a new circuit.

The project has key differentiating factors with existing or planned BtB projects (such as WPD's "Equilibrium"). In a BtB design the optimisation is to minimise the DC voltage and maximise the DC current, within the limits of the semi-conductors. For this project we maximise the DC voltage, within the cable insulation limit, and minimise the DC current, and hence losses in the circuit. A BtB station is at one location, whereas this project will prove the flexibility of operating in two electrical and physical environments and prove the communication needs between the stations. A BtB solution requires a specific location, typically a Normally Open (NO) point on the network, whereas this project will demonstrate the more general application, which could be a NO point or a Normally Closed (NC) circuit. By its nature a BtB installation does not impact on the wider environmental aspects of the distribution network.

This project will provide unique learning for the UK DNOs and other stakeholders to facilitate cutting edge research into the DC operation of existing AC circuits. The opportunity to measure the performance of MVDC converters in different conditions in terms of losses and availability can provide a valuable experience and also help evaluate the impact on network operation and maintenance requirements. A key output of the demonstration project will be **operational data to help determine the true cost-benefit of MVDC network reinforcement**, including running costs and the avoidance of future reinforcements.

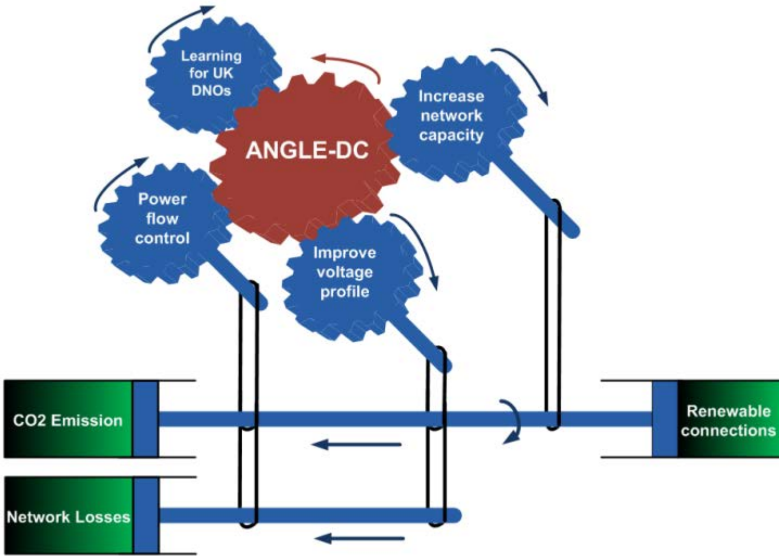

Figure 2-4: Angle-DC concept and benefits

2.3.5. *ANGLE-DC Work packages*

The ANGLE-DC project has been broken down into six work packages (WPs), see Figure 2-5, these enable the ANGLE-DC solution and provide valuable learning to the UK electricity industry. An overview of each WP and the innovation offered by them is described in the following:

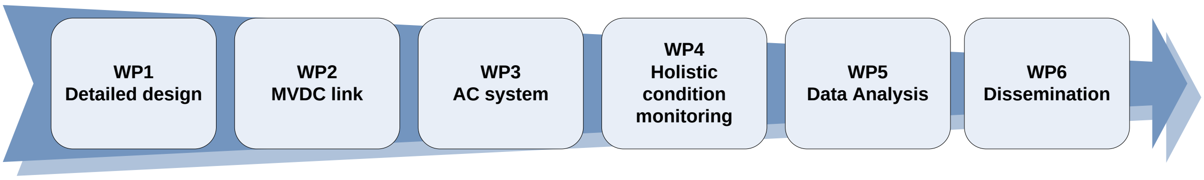

Figure 2-5: Overview of the WPs which will be carried out in the Angle-DC project

WP 1: Detailed design

A detailed system study, sample tests, a fresh review of MVDC technologies and supplier engagement will be undertaken in this WP. The main objective of this WP is to develop a technical specification for the MVDC link, including MVDC converters, interface transformers, control systems, etc. The functional specification must deliver a solution that is adequately future-proofed in order to deal with uncertainty in the precise nature of the development of the distribution systems. It will not presuppose choices of particular technologies or suppliers.

One of the main enhancements offered by the MVDC link is the power flow and voltage controllability feature. A thorough desktop study will be carried out to develop an **optimised power flow control strategy** and set points of the MVDC converters **under different generation and demand scenarios**.

A **protection scheme** for the complete MVDC link will be developed. The existing AC network protection system will be integrated into the MVDC link protection system. The protection concept is based on a series of overlapping protection zones from the existing AC networks through to the DC network.

Appropriate design consideration will be given to electromagnetic coupling (**EMC**) to inform future design requirements.

The real-time PD monitoring of a DC circuit has not previously been trialled in the UK. Initial market research which was undertaken through a Network Innovation Allowance (NIA) funded project showed that there are several companies claiming that they can provide the technology and methodology for PD monitoring of DC circuits. SP Energy Networks will develop a detailed technical specification which is fit for use on present and future MVDC links. This system needs to operate in real-time and be capable of sending valid alarms to the operators via communication systems.

WP 2: MVDC link

This WP includes all the activities required for manufacturing the MVDC link equipment, site preparation, installation and commissioning the MVDC link. Based on a market research and technical specification developed for the MVDC converters in WP 1, SP Energy Networks will select a capable supplier through a competitive tendering process. It is expected that a capable supplier, who believes in future market demand for the MVDC converters, can contribute extensively in this project. A summary of work which will be carried out in the WP is listed below:

- MVDC equipment procurement;
- MVDC manufacturing and product optimisation during factory acceptance test process;
- Developing installation method statements;
- Site preparation at both Bangor and Llanfair PG substations including civil works, wirings, protection etc;
- Shipment of the equipment to the sites;
- Installation of the equipment, site acceptance tests and commissioning;
- EMC measurement study.

There is not any similar previous experience about procurement and installation of MVDC converters in the UK, therefore it is expected that this WP will provide significant learning for future MVDC applications.

WP 3: AC system

It is also proposed that a new 33kV AC cable circuit will be installed in parallel with the DC link to enable outage and testing of the DC link under commissioning and different power flow control circumstances. The cost of this AC circuit has been included in the cost of the ANGLE-DC project. This will allow the MVDC VSC converter technology to be tested for a range of network and environmental operating conditions, whilst not adversely affecting the security of the network. SP Energy Networks plans to commission this circuit before energisation of the MVDC link described in WP2. SP Energy Networks will also develop a reliable and cost effective operational scheme for connecting the AC circuit.

WP 4: Holistic circuit condition monitoring

The circuit condition monitoring will form an important learning outcome of this demonstrator project. The project will demonstrate on-line PD monitoring systems. These will be used to give an indication of PD based degradation and trend in time with other operating stresses which can influence PD including voltage ramp up/down, over voltages and ripple from power converters. The system will also trend electromagnetic interference detected from the converters. Data will be analysed and benchmarked to inform SP Energy Networks and other DNOs about the way in which distribution circuits age. Pre and post-DC operation monitoring will allow for validation of theories about how DC impacts on cable ageing.

WP 5: Data analysis and enhanced learning

It is imperative to monitor, record and analyse the performance of the MVDC link for at least a 6 month period. This WP is designed to build confidence in the MVDC technology used in this project and capture the learning for operation of the MVDC link. SP Energy Networks will carry out several live tests on the performance of the MVDC link, including control of power flow and voltage. The withstand temperature of the cable circuits will be also assessed by a gradual increase in power through the cable circuit and monitoring their condition at the same time. SP Energy Networks is also planning to prepare the technical installation guidance and policy documents for MVDC design and operation. These documents can be used for preparation of the business case for the future and support “business as usual” MVDC applications.

WP 6: Knowledge dissemination

Significant learning is expected to be captured from the ANGLE-DC trial due to the innovative nature of the project. SP Energy Networks have consulted wider stakeholders to ensure the timing, innovative nature and value for money of the ANGLE DC proposal. We will continue to deploy various methods of communicating the lessons learnt to other UK DNOs and the project’s stakeholders during the project delivery phase and beyond. The MVDC link will be retained and dissemination will continue by making the data continuously available to interested parties. SP Energy Networks will share the data at the 2020 and 2021 LCNI conferences. Due to the importance of the knowledge sharing and dissemination, we have considered a separate WP for dissemination activities. Section 5 of this proposal describes in detail the strategy that will be used in this project for capturing and disseminating the knowledge and lessons learnt.

2.4. Changes since Initial Screening Process (ISP)

There have been no substantive changes to the scale of the project since the ISP was submitted. No partners have been selected at this stage, however a number of collaborators have been engaged in the gestation and validation of the concepts proposed. These are:

- **Local government and policy makers**;
- **GB professional bodies** including Energy Network Association (ENA), Power Electronic Society and British Approvals Service for Cables (BASEC);

- **International professional institutes**, such as EPRI (USA), ENTSO-E (EU) and E.ON Energy Research Center (Germany);
- **GB DNO** Companies;
- Previous existing **innovation project teams** (Low Carbon Hub, Equilibrium, MTTE);
- **International DC component suppliers**;
- **Academic Institutes and Consortium**;
- **Professional Consulting Companies**: e.g. TNEI, EA Technology, WSP | Parsons Brinckerhoff.

Section 3 Project business case

3.1. Overview

Distribution networks need to adapt for future energy scenarios. The system will need to accommodate higher volumes of renewable generation and deliver more power in response to a rising demand for electrified heat and transport.

In this context passive network operation will no longer be the optimum approach to operate the system. A new mode of actively **managing the network is required to face the challenges of maintaining the network within operational limits under unpredictable generation and demand variations**. In this transition towards the smart-grid model DC solutions have been identified as an enabler for the active control of power flows whilst also maximising the utilisation of existing assets.

ANGLE-DC aims to demonstrate a novel DC network reinforcement technique to be used by DNOs as an economic solution, with the objective of facilitating the shift towards a low carbon economy. ANGLE-DC offers clear benefits in the following categories:

- Securing a **30.5 MW power transfer corridor** interconnecting two distribution systems which offers **a net capital investment saving** and enables the transport of low-carbon generation between two distribution systems[1];
- Enhancing voltage and reactive power controllability at both ends of an MVDC link and subsequently reducing losses by around 20%, which is equivalent to a **£630k saving per annum;**
- If successful in the roll-out phase replicating the ANGLE-DC solution at GB level will potentially result in **total savings of £396.0m by 2050**;
- An independent study[2] revealed that the MVDC solution can be considered in collector arrays and connections of renewables to the grid. This application can potentially **reduce capital costs** required for **offshore electrical infrastructure by up to £1.7bn**.

3.2. ANGLE-DC is in line with GB and European innovation strategy roadmaps to satisfy customers' expectations

The ANGLE-DC proposal is deploying **power electronic technologies in distribution networks**. This application has been identified as an **enabler for future smart grid** in European[3] and GB[4] innovation roadmaps. Based on these roadmaps and extensive stakeholder consultation, the SP Energy Networks' Innovation Strategy[5] was established this also considered Medium-Voltage DC (MVDC) systems as a particular area of interest. DC solutions have also been identified as an enabler for facilitating the integration of renewables through better use of system assets. In addition, MVDC networks have the potential to complement a number of other innovation activities planned in SP Energy Networks' Innovation Strategy roadmap, as listed below:

[1] A 17% factor is assumed based on the generation load factors published by DECC on renewable resources and the generation portfolio on Anglesey.
[2] TNEI, MVDC Technology Study – Market Opportunities and Economic Impact, February 2015
[3] Consolidated View of the ETP SG, April 2015.
[4] A Smart Grid Routemap, Electricity Networks Strategy Group, February 2010.
[5] http://www.spenergynetworks.co.uk/userfiles/file/201403_SPEN_InnovationStrategy_MH.pdf

- **Active Network Management:** MVDC links as a technology enabler for more active distribution network control to form part of distribution system operator role.
- **Monitoring and managing fault levels:** MVDC links maintaining the fault levels within circuit breaker capabilities by de-coupling different areas of the network.

3.3. ANGLE-DC's innovation nature warrants NIC funding

ANGLE-DC falls into a category of what should be funded through the NIC funding mechanism given the following reasons:

- It fits into the **unproven** category but has significant potential benefits and can reasonably be expected to be considered among viable reinforcement options in the near future;
- It builds on the learning generated by previous **NIA** projects e.g. HVDC Cable Condition Monitoring System and Investigation into the Development of a MVDC Demonstration Project;
- It complements existing **LCNF** projects to deliver enhanced benefits e.g. Low Carbon Hub and Network Equilibrium.

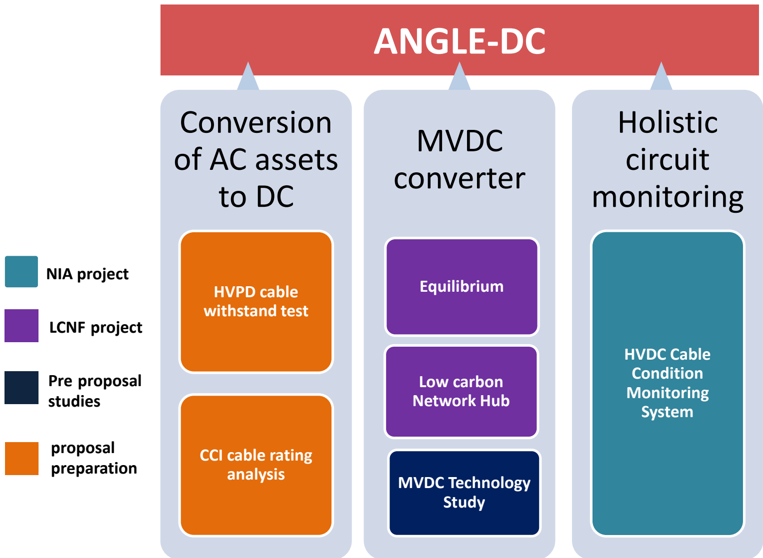

Figure 3-1: Knowledge gained from other projects to support ANGLE-DC innovation aspects

3.4. MVDC links Benefits

The simplicity of AC equipment has always made AC the preferred choice for distribution networks. Nevertheless the recent cost reduction experienced in the field of power electronics together with major advances in semiconductor technologies are, for the first time, enabling the advantages of AC systems and DC systems to be combined. Using both AC and DC technologies could bring significant benefits to consumers, renewable generators, electricity licensees and the wider society as outlined below:

- MVDC technology allows for **full controllability of power flows** and improved voltage regulation capability thus **reducing network losses** in the wide area. Over the lifetime of the assets, this reduction in network losses is significant, and will help network operators deliver power to end customers as efficiently as possible;
- The use of AC circuits at DC could increase the thermal capability allowing for more power to flow across the circuit. This additional headroom would be released without any new circuits, and therefore at a **reduced environmental**

impact. The headroom could be used to connect more generation from renewable sources leading to **reduced carbon emissions**;

- An AC to DC conversion scheme could be delivered **faster** than a conventional reinforcement where way-leaves are likely to be an issue. MVDC technology could **expedite the connection of renewable generation**;
- The degree of controllability offered by DC solutions could enable network normally-open points to be closed in circumstances that would otherwise lead to unacceptable thermal overloads or fault levels. As a consequence **reliability** of the network could be improved and **network assets are used more efficiently**;
- The establishment of a DC link could in some situations **avoid or defer** the need for wider **distribution network reinforcement**;
- Establishing a controllable path between distribution systems provides an alternative route for power to be transferred between neighbouring networks without necessarily going through the transmission system. Thus, some complexities in transmission network operation could be alleviated and **transmission reinforcements avoided or deferred**.

3.5. The ANGLE-DC case

3.5.1. *Anglesey Problem*

The nature of the comprehensive challenges in the Anglesey area mirrors the issues of the evolving GB distribution network. The Anglesey example, while complicated, is representative of many of the challenges all DNOs will face in the transition to a low carbon economy.

The 33kV system on the Isle of Anglesey, North Wales (within the licensed area of SP Manweb) is currently approaching both thermal and voltage limits. The demand in Anglesey is anticipated to increase significantly over the next 10 years due to various regeneration and development projects by the Welsh Government and the Horizon Nuclear Power station development. The level of generation connection activity in the area is extremely high and it is anticipated to increase during the RIIO-ED1 period.

A 33kV circuit connecting Anglesey (Llanfair PG) to other parts of the North Wales distribution network (Bangor) has been identified where **uncontrolled power flows are forecast to exceed thermal limits**. Additionally the circuit is located in an area where voltage management is becoming increasingly difficult. In order to **partly avoid these issues, the Bangor-Llanfair PG link would be operated in open circuit in normal conditions**. The network issues in the Anglesey area are discussed in further detail in Appendix C.

3.5.2. *ANGLE-DC solution for Anglesey*

ANGLE-DC proposes to convert the Bangor-Llanfair PG circuit to DC by installing two converters at both ends of the circuit. This technique allows better utilisation of existing assets. **Network capacity can also be unlocked by keeping this link connected (rather than normally open) and performing optimised power flow and voltage control**. Figure 3-2 shows a theoretical conventional method to deliver 30.5MW of generation capacity.

By using DC technology a 24.8MW corridor can stay connected between Bangor and Llanfair PG. Additionally the conversion of an existing AC circuit to a DC circuit will increase the power transfer capability of the existing assets by 5.7 MW. In other words,

using the ANGLE-DC solution will increase the power transfer capability between Bangor and Llanfair PG by 30.5MW (24.8MW+5.7MW). This headroom can be used to facilitate the integration of low carbon generation. Assuming only 17%[1] of this capacity will be used by local renewable generators, **45.4GWh of green energy** can be transported across the link annually**.**

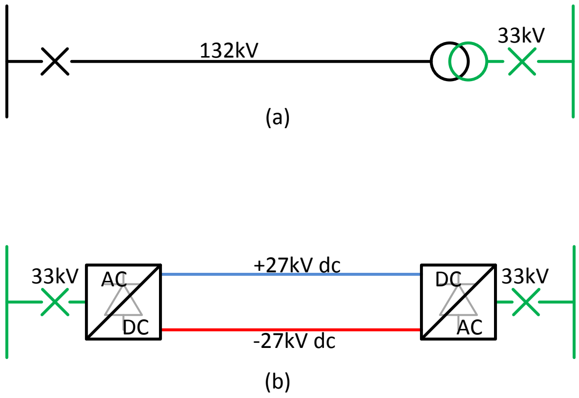

Figure 3-2: (a) Theoretical conventional base case and (b) ANGLE-DC method

3.5.3. *Capital investment (CAPEX)*

The investment costs required for ANGLE-DC have been estimated following a bottom-up approach, using the estimated costs received from the manufacturers, SP Energy Networks' unit costs and required site works costs. Our market engagement in the proposal preparation phase was used to inform the initial investment (CAPEX) requirement for commissioning MVDC equipment including research and development (R&D) activities undertaken during the course of the project. It is envisaged that the MVDC solution will become more attractive in terms of CAPEX after successful demonstration of the ANGLE-DC project. The expected CAPEX for the post ANGLE-DC trial is discussed in Appendix D.

3.5.4. *Capital investment saving*

Deploying the ANGLE-DC solution would create a 30.5MW power transfer capability between Bangor and Llanfair PG. Releasing the capacity by a theoretical conventional alternative involves the installation of a new grid transformer, a 132kV circuit, 132kV switchgear and 33kV switchgear. The ANGLE-DC trial represents a net avoided capital investment when compared against the theoretical conventional option.

3.5.5. *Operational and maintenance benefits*

Traditional reinforcements do not offer any functionality for power flow and voltage control. The reactive power controllability offered by the ANGLE-DC solution could radically improve network voltage and reduce network losses. Savings from losses reduction directly benefit the electricity customers through a reduction in Distribution Use of System (DUoS) charges. Calculations indicate that wider **distribution network losses could reduce by around 20%** (MVDC converter losses are included) by using the ANGLE-DC solution. The benefit gained from loss reduction is estimated to be **£630k annually.**

[1] The 17% factor is calculated based on the generation load factors published by DECC on renewable resources and the generation portfolio in the Anglesey area.

3.5.6. *Financial analysis*

The financial benefit of the ANGLE-DC solution is compared against a theoretical conventional solution. This solution represents the industrial practice by installing a new grid transformer at Anglesey and corresponding circuits (Figure 3-2a) to release the same level of generation capacity. Financial analysis shows that ANGLE-DC compared to the conventional alternative offers significant benefits to the Anglesey and North Wales areas. Table 3-2 summarises the benefits gained from the ANGLE-DC project.

Table 3-1: Benefits of ANGLE-DC

	2030	2050
Total benefits	£10.47m	£18.67m

3.6. Rollout

AC to DC conversion of existing assets has already been considered for transmission voltages and low-voltage network applications, these examples are shown in Appendix M. A demonstration at 33kV will increase the maturity of MVDC technology and provide an opportunity to realise benefits on medium-voltage networks. Based on our literature survey and initial market engagement, we estimate that the technology readiness level (TRL) of DC technology at medium voltage is 5-6 currently. **ANGLE-DC aims to increase the TRL of MVDC converters to 7-8 and make this solution ready for commercial deployment**. The ANGLE-DC solution will be an attractive solution for future reinforcement applications because this project will:

- Provide a **clear understanding about benefits (capital, operational, social, etc.) of an MVDC** solution, this can be used by GB DNOs for future cost benefit analysis against conventional reinforcement;
- Provide significant learning in terms of the **optimum design and operation of MVDC technologies, this can be directly adopted by other GB DNOs** with a significantly reduced cost compared with that required for the R&D phase for unproven technologies;
- **Stimulate competition in the supply chain** which will consequently reduce the cost of MVDC technology;
- Provide a clear understanding about considerations required for the conversion of existing AC assets to DC operation, this understanding will **significantly reduce implementation costs for GB DNOs and the end consumers.**

The solution proposed in this project is envisaged to be deployed for two distinctive applications in the future: i) As an alternative reinforcement in medium voltage distribution networks and ii) As an application in offshore wind farms' electrical infrastructure.

3.6.1. *Application by GB electricity licensees*

Upon successful demonstration of the MVDC solution by 2020 in the ANGLE-DC project, it is expected that this solution will compete with conventional reinforcement techniques. For the post ANGLE-DC trial applications, the cost of power electronics is assumed to decrease with time as per the cost curves described in the Work Stream 3 report published by the Smart Grid Forum, see Appendix D for further details.

For the roll-out phase, we assume that the ANGLE-DC reinforcement solution could release, on average, **30.5MW** of capacity on the converted circuits, the same level of headroom as this trial. This additional capacity can be used for **reducing total emission costs.** The average **network loss reduction** is also assumed to be **20%**, similar to the ANGLE-DC case, given the enhanced voltage control capability MVDC offers.

We estimate that potentially there can be at least one more site in SP Manweb and approximately 25 sites (See Appendix D) within the GB where the ANGLE-DC method could be replicated. By extrapolating the expected benefits to the 25 sites, we estimate that a **total benefit of £396.0m can be achieved by 2050 across GB**. The level of expected financial benefits is shown in Table 3-2.

Table 3-2: Expected Benefits (See Appendix D for rollout methodology)

	2030	2050
Licensee scale	£18.4m	£39.2m
GB rollout scale	£69.2m	£396.0m

3.6.2. *Application in offshore connections*

The previous study commissioned by Scottish Enterprise suggested that MVDC solutions can be considered in collector arrays and connections of renewables to the grid. A significant volume of investment, around £3.3bn, will be spent in total on that electrical infrastructure of Scottish offshore projects. Most of these projects use AC transmission solutions; however if the MVDC technology is matured and de-risked, potentially through the ANGLE-DC trial, DC may be used as an offshore transmission solution. If Scottish offshore projects were to use direct to shore MVDC solutions, the reduction in capital costs could be up to £1.7bn.

3.7. Project risks

In order to ensure successful delivery of expected benefits and learning objectives of the ANGLE-DC project, we will proactively identify risks to the project and provide mitigation plans. The risk register will be updated regularly during the course of the project. The three major risks (commercial, technical and resourcing) are listed in Table 3-3, see Appendix G for a complete lists identified in the proposal preparation stage.

Table 3-3: Three major risks in different categories

Risk Category	Risk Description	Probability (1-5)	Financial Impact (1-5)	Reputation Impact (1-3)	Overall Risk (2-45)
Technical	Existing cable may be severely damaged when operates in DC	3	5	2	21
Commercial	Cost of MVDC equipment is significantly higher than estimated	3	5	3	24
Resources	Lack of experience of project staff	2	5	3	16

Section 4 Benefits, timeliness, and partners

4.1. Response to (a) Accelerates the development of a low carbon energy sector and/or delivers environmental benefits whilst having the potential to deliver net financial benefits to future and/or existing Customers

4.1.1. *Impact on the Carbon Plan*

The Carbon Plan presents plans for the reduction of emissions from a range of sectors in the UK. There is a common theme that reductions in emissions will be obtained through the use of low carbon electricity for more purposes, including: shifting to heat pumps for heating buildings; increasing the use of modes of transport that use electricity, including the charging of batteries for electric vehicles; and electrification of a range of industrial processes.

The Carbon Plan's emphasis on low carbon electricity provides significant motivation for ANGLE-DC's proposal to make best use of existing distribution network assets. The Carbon Plan recognises that increasingly variable demand profiles mean that "our electricity system will need to become smarter at balancing demand and supply." Conversion of an existing AC circuit to MVDC will considerably enhance the ability to control voltages and manage the flow of power between areas of generation and demand, and the effect of the improvement will be felt across a diverse area. Enhancement of the electricity network using MVDC as proposed in **ANGLE-DC will implicitly support electrification to facilitate emissions reductions in buildings, transport and industry**.

As well as an increasingly variable electrical demand profile, the magnitude of the demand is predicted to increase, requiring additional generation capacity, as recognised in the Carbon Plan's statement: "we are likely to need 100 GW or more of new low carbon generation capacity in 2050". The economic justification for renewable generation is inextricably linked with the ability of the distribution system to provide a route to export low carbon electrical power at reasonable cost.

Conversion of existing circuits to MVDC will provide capacity increases as well as a reduction of losses. The proposed technology is likely to unlock 30.5 MVA capacity on the existing Llanfair PG to Bangor corridor. MVDC enhances the power flow controllability in the network, this can be used to release additional capacity in a wider area.

A recent study commissioned by SP Energy Networks to investigate the potential for MVDC as part of the preparation of this proposal indicates that it will be possible to achieve greater capacity increases from subsequent deployment of the technology, and that there are **25 circuits around the UK that would be suitable for the ANGLE-DC solution**.

The release of capacity is expected to be available earlier than a new circuit could be constructed. Also, it is suggested that due to the uncertainty regarding the uptake of electrification and distributed generation, the additional capacity available through the application of MVDC is a suitable "stopgap" measure, appropriate for the resolution of imminent issues, until the ultimate changes in demand become clearer and are realised. Without conversion from AC to DC, the capacity of the existing network is conventionally enhanced by the addition of new circuits with considerable effort and environmental impact. It is therefore believed that MVDC provides benefits for the connection of low carbon electrical power.

4.1.2. *Release of network capacity by the demonstration*

The release of network capacity from deployment of the ANGLE-DC solution is **around 30.5 MVA** which comes from two elements: i) better use of stranded assets and ii) better use of conductors.

- **Better use of stranded assets or circuits which should be kept normally open:**
  The controllability of the size and direction of power flows in AC networks is very little. Conventionally, some circuits in AC networks need to be kept open because closing them creates a path for uncontrolled power flows which may exceed the thermal limits of the circuit. Examples for this condition can be those circuits connecting two different distribution systems or distribution circuits creating parallel paths with transmission networks. Using DC, however, provides full control over power flow in a circuit as well as the wider network. Therefore, normally open circuits can be closed and an efficient use of stranded assets can be achieved. The ANGLE-DC solution will facilitate keeping the Bangor – Llanfair PG circuit connected, consequently creating a 24.8MVA intact capacity on the network.

- **Better use of conductors:**
  DC current uses the complete cross sectional area of a conductor. This is an improvement on AC which only uses the outer portion of the conductor due to skin effects. The increase of the cross section available for carrying DC electricity reduces the effective resistance of the conductor, in a DC circuit, and means that it is capable of carrying more current with the same heating effect. Coupled with the optimum choice of DC voltage, a higher power transfer can be achieved in DC operation in comparison with that achieved in AC operation. A recent study commissioned by SP Energy Networks confirms the theoretical advantage of converting AC circuits to DC. In particular where two AC three-phase circuits are available, because DC requires only two conductors (positive and negative), the three conductors of each AC circuit can be connected in parallel to provide the DC conductors. In the ANGLE-DC project, we estimate that at least 5.75 MVA of Bangor - Llanfair PG can be released through better use of the conductors.

The 30.5MVA capacity release estimated in this project is **based on prudent assumptions** for secure operation. Studies indicate that it will be theoretically possible to achieve greater capacity increases from subsequent deployment of the technology, but this depends on the learning from this project, information about the existing cables to be converted and prudent decisions about how to operate them.

The recent study indicates that there are around 25 circuits in the UK that would be suitable for conversion to MVDC over a 20 year period. Assuming that the capacity released is the same as the 30.5MVA capacity release estimated for this trial, this equates to a total of **762.5MW of unlocked capacity by using only the existing assets in GB**.

Enhancing network capacity by building new overhead or underground distribution circuits requires the network licensee to go through a rigorous planning process and obtain easements/way-leaves prior to the commencement of construction. Thus, the addition of extra capacity from conversion to MVDC, by adding equipment at each end of an existing circuit resulting in diminished planning requirements by avoiding new lines, should mitigate problems in the short-term and defer or avoid the need for other new circuits. This proposal offers the opportunity to test the application of MVDC technology to an existing distribution circuit for the first time, and the significant learning associated with it.

4.1.3. *Environmental benefits*

In addition to the problem of network capacity for increasing demand and renewable generation, there is also an opportunity to reduce losses in the distribution systems. The connection of two areas of a network using an MVDC link to control the flow of power and maintain electrical separation supports network voltages on both sides of it. The effect of this support at each end of the link is to manage voltages at locations across a wider area, minimise current through circuits and, therefore, network losses in the affected area. For this demonstration project, the **losses in Anglesey and North Wales are anticipated to be reduced by approximately 13,030 MWh annually**.

Over the lifetime of the assets, this reduction in network losses is significant. Reduction of distribution losses reduces the amount of power that the generators and the transmission system are required to deliver, potentially providing additional loss reduction in the transmission network, enabling the network operators to deliver power to customers more efficiently. According to a recent study, commissioned by SP Energy Networks, the lifecycle cost of losses associated with the option to convert an existing circuit to MVDC is in the region of £15.77m. **By extrapolating this figure to the 25 sites in the GB, the ANGLE-DC solution offers £252.4m savings as a result of loss reduction across GB by 2050.**

The enhanced capacity of a circuit that is converted to operate with DC allows the network to accommodate higher power flows without the need for an additional circuit to be built, and the associated environmental impact and damage to nature.

4.1.4. *Potential to deliver net financial benefits*

The ANGLE-DC solution will deliver a significant financial benefit in the form of avoided cost of network reinforcement and reduction in network losses. The benefit gained from this project materialises in two elements:

i) **Benefit to Anglesey and North Wales** area only as a result of ANGLE-DC trial will be **£18.67m by 2050**. ANGLE-DC is an **enduring** solution for Anglesey that will provide network support beyond the ANGLE-DC project completion;

ii) **Benefit to GB** in the roll-out phase by deploying the ANGLE-DC solution at 25 sites in the GB distribution network will be **£396.0m by 2050**.

Figure 4-1 shows the total financial benefit is expected to be gained after ANGLE-DC trial across GB.

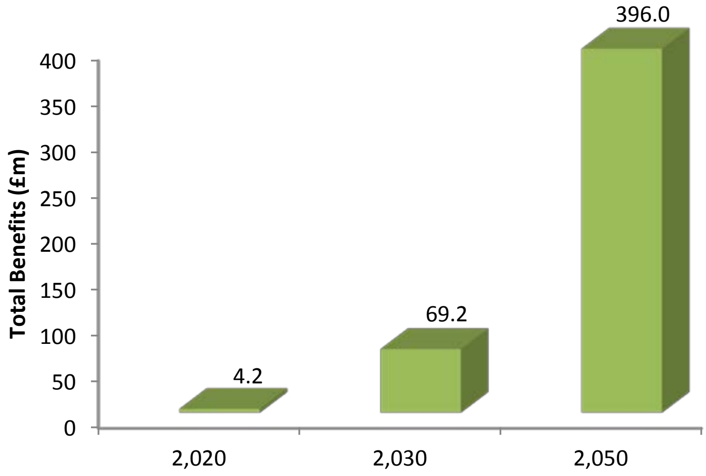

Figure 4-1 Total financial benefit in roll-out period of ANGLE-DC solution

4.2. Response to (b) Provides value for money to electricity distribution customers

4.2.1. *Potential direct impact on the network*

The existing GB distribution network is expected to be under stress during the transition to a low carbon economy. The voltage, thermal and stability issues associated with the integration of low carbon technologies require a step change towards smart and flexible reinforcement solutions. In line with this requirement, the ANGLE-DC solution provides a direct positive impact on our network as below:

Impact on Anglesey network:

- The release of capacity in the Anglesey network is expected to facilitate the connection of distributed generation and new demand **in a shorter timescale**;
- This reduction of the delay and cost of connection faced by renewable energy schemes will help to **ensure that already committed investment** in low carbon generation will be exploited at the earliest opportunity;
- In addition, the **reduction of losses** will also **reduce** the cost of operating the distribution network, this is passed on to customers through the **Distribution Use-of-System (DUoS) charges;**
- Additional reactive and voltage support offered by MVDC technology will **alleviate the existing post-fault voltage step** issues in the Anglesey area;

Impact on other GB networks:

ANGLE-DC will serve as a valid reference for other GB Electricity Licensees for areas with similar network constraints. Planning of electricity systems has become more challenging due to significant constraints on development, and decisions have to be made without certain knowledge of generation and demands. This means that flexible solutions are required in order to avoid investment in technologies that are unsuitable if unforeseen changes occur. The MVDC technology that is proposed represents a flexible solution that will not prejudice other developments. ANGLE-DC will provide valid data and operational experience for network owner/operators and their stakeholders.

4.2.2. *Justification of the scale of the project*

The following key criteria were considered when deciding the scale of the project:

- **Needs of the Anglesey distribution network -** Our planning studies showed that due to increasing integration of renewables and load growth, there will be various thermal and voltage issues in the 33kV network in Anglesey and North Wales. We also expect Bangor-Llanfair PG to exceed its thermal limits in contingency conditions due to uncontrolled power flowing between two different groups Anglesey (Bangor) and North Wales (Llanfair PG). This project, ANGLE-DC, is designed to enhance the performance of Anglesey (Bangor) and North Wales distribution networks and alleviate the existing network issues.
- **Learning Objectives -** The key learning objective of this project is to demonstrate how converting existing AC assets to DC operation at medium voltage can be an alternative solution to future reinforcement. In particular, this application would be most viable when two neighbouring distribution systems need to be connected in a controlled way. Bangor-Llanfair PG circuit provides the exact condition where we can demonstrate our learning objectives of the project. This circuit consists of both cable (with different cable types) and overhead line conductor, thus allowing us to show the impact of DC conversion on different asset types.
- **Balance between Innovation and Risks –** The trial of any unproven technology is associated with various technical risks. We aim to demonstrate the ANGLE-DC solution in a real-life system and not in a laboratory environment.

4.2.3. *Justification of the cost of the project*

Consultations were carried out during the proposal preparation to ensure that the cost information is an accurate estimate and serves the interest of existing and future electricity customers. The costs of different elements in the ANGLE-DC project are detailed below:

- **Cost of MVDC equipment** was estimated based on consultation carried out with major high voltage and industrial DC suppliers to understand available technologies and identify suitable technology for medium voltage application. We then developed a high level functional specification for the MVDC link and requested manufacturers to informally provide cost estimates;
- For estimation of the **site preparation activities** a separate consultation was carried out. The sites at Bangor and Llanfair PG were inspected and, based on the estimated size of MVDC equipment, the amount of works required for civil works, cabling works and electrical works were estimated;
- The **cost of holistic monitoring equipment** was also estimated based on the existing available monitoring technologies, the engagement with one of the PD monitoring suppliers, and our previous experience of the cost required for integration of the monitoring system;
- The **cost of the AC system** was estimated based on the unit costs of typical cable installations and also after specific site visits carried out between Bangor – Llanfair PG to identify possible routes and way-leaves requirements;
- The **cost of labour, consultation services and contractors** for each WP was also estimated based on our experience in previous projects. These costs were internally reviewed by SP Energy Networks.

The total estimated project cost includes 8% contingency due to the innovative nature of the project. A complete project breakdown cost is given in Appendix B.

4.2.4. *Provide the most economical solution*

We will endeavour to ensure the project cost represents the best value for the customer by considering the two following elements:

- **Optimal design of the equipment –** The use of DC technology at medium voltage is not a mature technology. Nonetheless, there are many DC applications at high voltage and industrial voltage levels. The initial engagement indicates the consensus between the "pull" from the MVDC market and the "push" from technology. HVDC is inherently an expensive technology with high project engineering costs. The detailed design and specifications of the DC technologies at medium voltage is not necessarily similar to the specification of high voltage or industrial applications. In order to provide the best value for the customer, we have considered a dedicated WP to provide the most optimum and reliable design for MVDC application. In another words, we aim to avoid the costs associated with some specifications that may only be required for HVDC applications while not compromising the system reliability by selecting a pure industrial DC solution.

- **Robust procurement process -** SP Energy Networks uses a robust procurement process to ensure that the best value for money is achieved for the equipment and services required in the ANGLE-DC project. In addition to the work undertaken in the proposal preparation phase, we will continue to carry out extensive market research and due diligence to identify capable suppliers and project partners. These activities will be carried out during the first year of the project under WP 1 (Detailed design). The equipment and services will also be purchased through a competitive tendering process at the lowest cost and highest quality.

4.2.5. *The proportion of benefits that accrue to the electricity network*

ANGLE-DC is aiming to **drive the innovation needed to deliver a sustainable energy network at value for money to existing and future customers, including providing fair access to the network to facilitate competition for distributed low carbon generation**. The principal benefits that arise from the conversion of an existing circuit to MVDC have a direct impact on network investment, operational expenditure and will contribute to future planning. These benefits are the network capacity released and the reduction of wider network losses. Low carbon generation technology is likely to be accommodated as a result of this proposed project, but will be charged for connection in line with conventional reinforcement costs and without a burden for new technology in the distribution network.

This project is an **innovative demonstrator** of MVDC technology in the GB and EU. It will **provide significant learning** to other GB DNOs for DC operation of existing assets including power electronic optimal design, enable functions in Active Network Management and provide, technical feedback into professional bodies (such as CIGRE) on MVDC standards. A criteria list and a decision flow chart with detailed guidance will also be provided at the end of this project for electricity licensees and other stakeholders to enable them to select and apply this novel technology in a simple, easy to understand manner. WP 6 has been designed to ensure the relevant learning is captured and disseminated in accordance with the knowledge dissemination strategy.

4.2.6. *AC System*

The cost has been included in the submission request to cover the costs of the AC circuit that is proposed to be installed in parallel with the existing circuit to be converted to MVDC. This is the principal measure for protection of customer supplies in the event that the existing cable is irrevocably damaged and the connection to Anglesey seriously compromised. The function of this circuit is to:

- Provide circuit redundancy during the commissioning of ANGLE-DC;
- Enable the necessary testing on a DC Link and measurement during the ANGLE-DC project life time;
- Provide an enduring arrangement for additional interconnector capability.

4.3. Response to (d) Is innovative (i.e. not business as usual) and has an unproven business case where the innovation risk warrants a limited Development or Demonstration Project to demonstrate its effectiveness

The extensive nature of power distribution systems and their proximity to population centres means that simply installing a new circuit, whether AC or DC, will entail significant planning and environmental difficulties. However, the complexity associated with the changing nature of power generation, particularly from low carbon sources, and changing demand patterns, which will result from electric vehicle charge/discharge and domestic photo-voltaic generation, triggers the need for a flexible distribution network. ANGLE-DC addresses these issues by introducing the following innovative aspects:

- To introduce for the **first time an optimum designed DC technology at medium voltage** to achieve a power "up-lift" and allow active control of the power flows and voltage profiles in the wider AC network;
- To **re-use the existing AC asset in a more efficient DC manner**, thus avoiding the need for a new build of distribution circuits;
- To **provide unique learning** from real-time monitoring of DC operation of AC assets and performance of the MVDC converter in different loading conditions.

In the implementation phase the scheme will be designed to maximise the availability of the asset, but being mindful that the cost base of the technology is a critical factor in its future acceptance as a viable solution. Hence, many of the design methodologies common for HVDC projects may not be valid for MVDC.

Whereas the insertion of DC power flow controllers in distribution networks has been demonstrated, this concept coupled with conversion of AC assets to DC operation to release capacity on a circuit has not been achieved to date. Thus there is no body of experience to draw upon and hence many aspects of the project implementation and scheme operation must of necessity entail risks.

In the operation phase careful records will be kept, in line with the Cigre TB 590 protocol, to monitor and share details about the operational performance of the scheme in relation to reliability and availability. A key aspect of the project will be condition monitoring of the AC assets whilst they are operated under DC conditions. SP Energy Networks will work with companies who specialise in such work to develop and install systems which can give advanced warning of incipient damage to the assets. **This demonstration of the conversion of an existing circuit to MVDC is only possible with NIC funding as a result of the various technical and commercial risks.**

4.4. Response to (e) Involvement of other partners and external funding

4.4.1. *Project partners*

As described, SP Energy Networks has engaged with a number of suppliers of DC converters and related equipment. In order to promote competitive tendering in the implementation phase, for what will be the first project in a potentially attractive market, no formal partnerships have been established. However, mutually beneficial dialogue with several suppliers has resulted in testing of the functional specification and consideration of the suitability of technologies for this application. We have developed weighting factors for evaluating the future project partners for the services and contributions they will provide in ANGLE-DC project, as outlined in Table 4-1.

Table 4-1: Weighting factors for evaluating ANGLE-DC project partners

Evaluation Criteria Category	Weighting
Engineering and Technology	65%
Commercial	25%
In Kind Contribution and Innovation	10%

In addition to the large number of individual stakeholder engagements listed in Sections 2.4 and 6.1, various activities to engage internal and external stakeholders are being undertaken by SP Energy Networks, including:

- Announcing the intention to prepare this 2015 NIC proposal to the industry and interested parties in the 2014 LCNI conference in Aberdeen;
- Seeking feedback on this proposal at a stakeholder engagement event linked to the Protection, Automation and Control conference in Glasgow in June 2015;
- Organising two internal stakeholders meetings to identify the business needs;
- SP Energy Networks further organised two internal R&D panels to shortlist the NIC proposal among over ten proposals each of which has both technology push and business pull.

Such a **wide and in-depth stakeholder engagement and the consistent message received** convinced SP Energy Networks that this project will provide added value to address the genuine challenges faced by distribution networks and their consumers.

The overwhelming support from those stakeholders has been valuable in project scope evolvement, feasibility studies, benefits tracking and lessons learnt intake.

Strong support has been received from the Welsh Government, equipment suppliers and renewable developers among others. There is considerable enthusiasm to progress the project to ensure that the network does not become a bottleneck to connect further renewables and help to achieve the government's carbon reduction targets. The letters of support provided by different organisations are presented in Appendix N.

4.5. Response to (f) Relevance and timing

The ANGLE DC proposal is a direct result of on-going and recently concluded innovation projects, strong customer demands and the in-depth understanding of future smart grid requirements. While this trial is designed for ANGLE DC, a criteria list and a decision flow chart with detailed guidance will be available at the end of this project for electricity licensees and other stakeholders to enable them to select and apply this novel technology in a simple and easy to understand manner.

4.5.1. *Need for the technology in the UK*

Moving towards a zero carbon future in the UK drives a significant load growth and integration of renewables into distribution networks. This increases the complexity of the future networks and triggers considerable network investment. Conventional approaches can no longer be the only solution to keep up with these rapid changes in our grid. Instead, new solutions offering a better utilisation of the existing assets and increasing flexibility of the network need to be deployed. ANGLE-DC will be a timely demonstrator of an innovative solution addressing the UK distribution network issues because it:

- Enhances the controllability of network for both power flow and voltage;
- Facilitates the connection of the two distribution systems which should operate split due to fault level and unwanted power flow issues;
- Reduces network losses in a wide area (not only in the DC link) by controlling the active and reactive power.

Our initial studies showed that potentially the **ANGLE-DC solution is applicable to up 25 circuits in the UK**. We envisage that, **if ANGLE-DC is successful, by creating a competitive supply chain**, the future MVDC equipment cost reduces and competes with conventional approaches.

There is also a lack of technical guidance and policy documents on MVDC applications in the UK. **ANGLE-DC aims to partly fill this gap** by developing technical specifications, installation method statements and policy documents for design and operation of the MVDC links.

4.5.2. *Previous NIC, NIA and LCNF projects*

Several innovation projects are working in areas that relate to MVDC, including:

- The WPD Network Equilibrium LCNF project that is due to install a MVDC back-to-back system into their distribution network before the end of 2018. The system will connect previously isolated parts of the WPD network, demonstrate control of power flow in the network and avoid an unacceptable increase in short circuit current;
- The SHE Transmission Multi-Terminal Test Environment (MTTE) for HVDC Systems NIC project is developing a collaborative facility housing a real-time simulator system;
- The WPD Low Carbon Hub LCNF project deployed a STATCOM Flexible AC Transmission (FACT) device;
- The SP Energy Networks HVDC Cable Condition Monitoring System NIA project is developing a prototype for a holistic online condition monitoring system.

As such, and with the addition of market research exercises under NIA, **there is a body of work that explores related issues and points to MVDC as a viable solution for reinforcement. The next practical step is to test this on an actual circuit embedded in the distribution network**, having adopted all measures for prudent operation. This is an opportune time to derive benefit from learning that is being received shortly in advance of our project.

4.5.3. *State of market for MVDC Converters*

The present market for MVDC schemes can be characterised as follows:

- A limited number of niche projects implemented on a "one off" basis;
- Solutions provided by a limited number of major HVDC suppliers;
- Technology derived from HVDC requirements and scaled down;
- Conventional mind set of distribution companies, when compared with the level of activity from transmission companies;
- New suppliers have a strong will and ambition to enter the market.

There is limited experience of MVDC projects and very little is reported on their operational performance, e.g. reliability and availability statistics and utilisation data. Few owners of HVDC assets report on maintenance aspects (timescales, resources, etc) or mention failures and repairs on their assets. Conversion of existing AC lines or cables to DC operation has never been implemented for commercial operation, although there is renewed interest in overhead line conversion, due to the difficulty of acquiring new easements/wayleaves.

To encourage the DC technology suppliers to develop their product to an optimum MVDC solution a number of outcomes need to be achieved to respond to converging market needs and available technical solutions. **It is now appropriate to bring together these converging elements**, and the proposed demonstration project strives to make headway in all of these aspects:

- Successful demonstration of MVDC technology embedded in a distribution system;
- Successful conversion of existing AC assets to DC operation;
- Entrance into the market of new suppliers to enhance competition and innovation;
- Selection of optimum DC technology for MVDC application;
- Dissemination of the results of the operational experience of MVDC schemes;
- Identification of future MVDC opportunities in the GB distribution networks.

The history of modern HVDC technology has shown a convergence of solutions to the optimum design which achieves the required functionality with minimum capital costs and operating losses. As MVDC is in its infancy the market will propose different technology solutions, with different cost and loss bases. However, over time this may be anticipated to converge to an optimised solution, driven by competition in the market and innovation from the suppliers. So long as this commercially optimised solution can be offered at competitive cost, then the adoption of MVDC will be attractive to network licensees for inclusion in future business planning.

Section 5 Knowledge dissemination

Knowledge dissemination and stakeholder engagement have been core activities in the innovation projects which SP Energy Networks has conducted to date. Based on previous experience, SP Energy Networks has set a robust knowledge management methodology to capture and disseminate the knowledge created in the ANGLE-DC project in order to ensure that all available learning is collected and made available to interested parties in an appropriate format. Due to the importance of knowledge dissemination, a separate WP has been proposed for knowledge sharing activities in the ANGLE-DC project.

5.1. Learning generated

It is recognised that the project must have a clearly defined procedure for capturing generated knowledge in its entirety. A robust knowledge capture strategy will be deployed in the ANGLE-DC project to ensure that all possible learning is captured, analysed and documented. A designated Knowledge Coordinator (KC) role will be included in the ANGLE-DC project team. The KC will support the project manager (PM) in collating all learning points.

5.1.1. Methodology for Learning Capture

The knowledge, including learning, technical documents, issues and risks, created by each WP will be captured in the first instance by WP leaders and will be reported to the PM and KC. The KC will document and categorise the information in a knowledge repository and communicate it within the delivery team.

In addition, learning from other relevant innovation projects will be reviewed at the outset and pertinent conclusions recorded and shared to inform the delivery team. The principal projects that are likely to provide relevant learning are:

- The WPD Network Equilibrium project is due to deploy two power electronic devices in a back-to-back application;
- The SHE Transmission Multi-Terminal Test Environment (MTTE) for HVDC Systems project is developing a collaborative facility housing a real-time simulator system;
- The WPD Low Carbon Hub project deployed a STATCOM Flexible AC Transmission system (FACT) device.

A summary of the knowledge capture methodology, which is shown in Figure 5-1, is as follows:

- Include separate learning, issues and risk sections in the monthly progress reports created by WP leaders;
- Maintain knowledge and lessons learnt in a knowledge repository with advanced searching and information retrieval features;
- Establish regular communication between the project manager, project WP leaders and knowledge coordinator to ensure that all of the planned and unplanned learning points in each WP are captured;
- Categorise the learning points based on their usefulness to different interested parties.

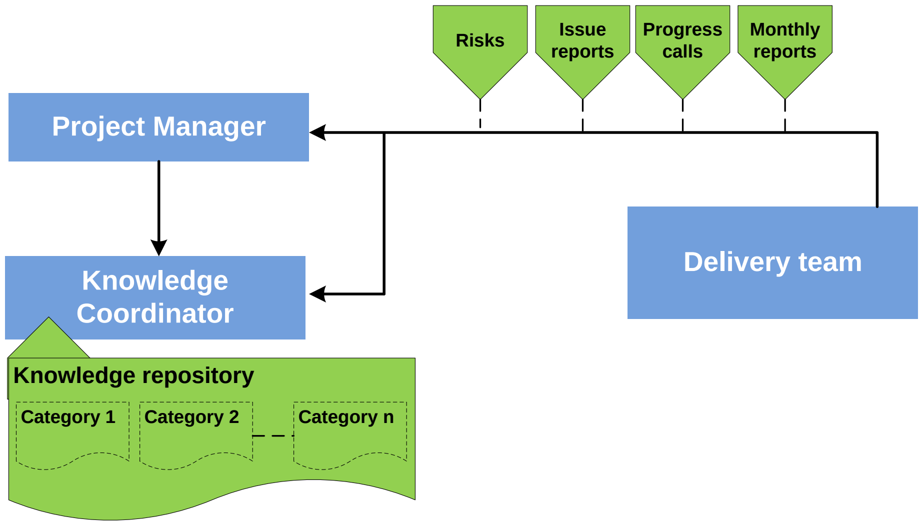

Figure 5-1: Methodology for learning capture

5.1.2. *Learning Objectives*

ANGLE-DC will generate new learning applicable for network operators and offshore developers by demonstrating the first ever DC operation of a medium-voltage AC circuit. The expected learning outcomes from the ANGLE-DC project have been divided into the project WP categories for clarity. Table 5-1 outlines the expected learning from ANGLE-DC.

Table 5-1: Expected learning in ANGLE-DC project

WP	Learning objectives
Detailed Designed	• Manufacturers' capabilities in AC/DC converter technologies • Suitable MVDC technology for medium voltage applications • Technical specification of the MVDC converters • Investment cost and operating cost of the MVDC equipment • Suppliers' capabilities for monitoring condition of DC circuits • Technical specification of a real-time condition monitoring system for DC circuits • Data from laboratory test of cable capability under extreme DC voltage and cyclic loading • Protection strategy for a MVDC circuit • Optimised power flow control of a MVDC link under real AC distribution network conditions • Voltage and reactive power control strategy of the MVDC link
MVDC Link	• Detailed site layout • Method statement for factory acceptance test (FAT) of MVDC link equipment • Method statement for installation of the MVDC link • Health and safety considerations when converting AC assets to DC • Method statement for site acceptance test (SAT) of MVDC link
AC System	• Method statement for installation of the medium voltage cable • Operation strategy for switching in the AC system as a back-up for MVDC link

Table 5-1: Expected learning in ANGLE-DC project (continued)

WP	Learning objectives
Holistic circuit condition monitoring	• Method statement for installation of a real-time holistic condition monitoring system • AC assets performance under a DC voltage and the associated stress • Availability and ageing data for cable and OHL assets operated at AC • Availability and ageing data for cable and OHL assets operated at DC
Data analysis and enhanced learning	• Operational experience of the application of DC to AC cables and overhead lines • Unlocked network capacity and reduced losses across a wider area • Impact of the MVDC link on transmission power control • Availability data for MVDC converters in various operating conditions • Technical guidance and policy documents for day-to-day operation of an MVDC link

5.2. Learning dissemination

Following the knowledge capture, the learning will be disseminated both externally and internally. Learning will also be communicated within the delivery team to efficiently progress the work. It is recognised that knowledge sharing is a separate and important topic from knowledge capture and a separate strategy and methodology has been devised to ensure that all captured knowledge will be shared to the fullest. It is also acknowledged that internal learning is an important part of innovative projects, so any discovered issues can be made known and, therefore, avoided in the future.

5.2.1. *Methodology for Knowledge Dissemination*

In order to achieve maximum dissemination, several techniques have been outlined below. While some techniques may overlap in their target audience, each individual method can provide a unique outlook and further information about the project to the appropriate audience. SP Energy Networks will endeavour to collect feedback from the relevant stakeholders during the course of the project through the various dissemination events.

Regular Progress Reports – Every six months, SP Energy Networks will provide updates to Ofgem which will document the project progress to date with a section dedicated to outline the captured learning for that period. These reports will be available through the ENA portal for anyone who has an interest to follow the project course.

Workshops – Several internal and external workshops will be organised during the course of the project to update interested parties. These workshops will be focused on both technical and non-technical learning aspects of the project. These events will also be opportunities to receive feedback about the project and the disseminated material from other interested parties e.g. network operators and universities, creating a path of two-way communication.

Webinars – Webinars will be arranged over the course of the project to update those who are unable to attend the aforementioned workshops. Webinars will also aim to reduce the need for travelling which will contribute to total carbon footprint reduction.

Webinars will also be recorded and published on the SP Energy Networks innovation website for access by any interested party.

Low Carbon Network Innovation Conferences (LCNI) – LCNI conferences are held every year and will provide opportunities to present ANGLE-DC project updates and the latest learning to other LCNI attendees. The MVDC link will be retained after project completion and data will continuously be made available to interested parties. Additionally, SP Energy Networks will share the data at the 2020 and 2021 LCNI conferences.

SP Energy Networks Innovation Website Update – The learning outcomes that will be documented in the progress reports will also be available in a categorised format through the SP Energy Networks Innovation website. This information will be available to everyone and will provide an overview, rather than detailed technical content. Other information such as webinar recordings will also be available through this website.

Close-down Report – The close-down report will be available after project completion. This report will document all learning outcomes captured during the project, rendering a complete detailed description of the project and what has been achieved. Like the progress reports, this will be available through the ENA portal to be accessed by interested parties.

5.2.2. *Interested Parties*

It is acknowledged that different groups will have different interests in the learning outcomes generated from the project; different information will become available at various points in time; and knowledge should be shared as it becomes available. Furthermore, it is recognised that knowledge sharing is most effective when the data is tailored to suit the interested parties' background and requirements. The methods of dissemination will focus on the following groups:

Network Operators – Distribution Network Operators (DNOs) are the primary focus for learning from ANGLE-DC as they operate the present medium-voltage network and they will undertake future MVDC projects. We have spoken with each GB DNO and identified the general learning benefits. These learning outcomes will primarily aid DNOs in understanding how a MVDC link operates as part of an AC network; what availability can be achieved; and its impact on the cables, OHL, and the wider AC network. To facilitate the future rollout of the technology, a MVDC Best Practice Guide will be developed, including an evaluation criteria for DNOs to evaluate the suitability of the technology prior to the detailed design phase. National Grid and transmission owners will also be interested to learn the impact of power flow and voltage control from an MVDC link on the transmission system. Learning about the design of MVDC converters will also potentially influence future HVDC converter designs.

Offshore Developers - Preliminary market studies have foreseen applications of MVDC technology within collector arrays in offshore renewable generation developments. These will also be supported by the project learning outcomes.

Developers of Standards and Network Codes – The core of this proposal is to operate existing assets with DC. This will deliver learning outcomes that may indicate necessary changes to how the surrounding network is operated in future. Increasing deployment of MVDC will mean that network codes need to be altered in order to accommodate this change. Therefore, the regular reports and close-down report will hold some interest with these bodies.

General Public – Project developments will be of interest to stakeholders who perceive some impact from the project, especially the Anglesey and North Wales communities in close proximity to the link. Local authorities who have responsibility for planning decisions, such as the Anglesey Council, and those who have interest in enabling the connection of low carbon technologies, such as the Welsh Government will be kept informed about project developments.

Academics – ANGLE-DC will provide valuable real-life data and results of laboratory tests for further academic work in different areas such as cable ageing mechanisms and operation of AC assets under DC stress.

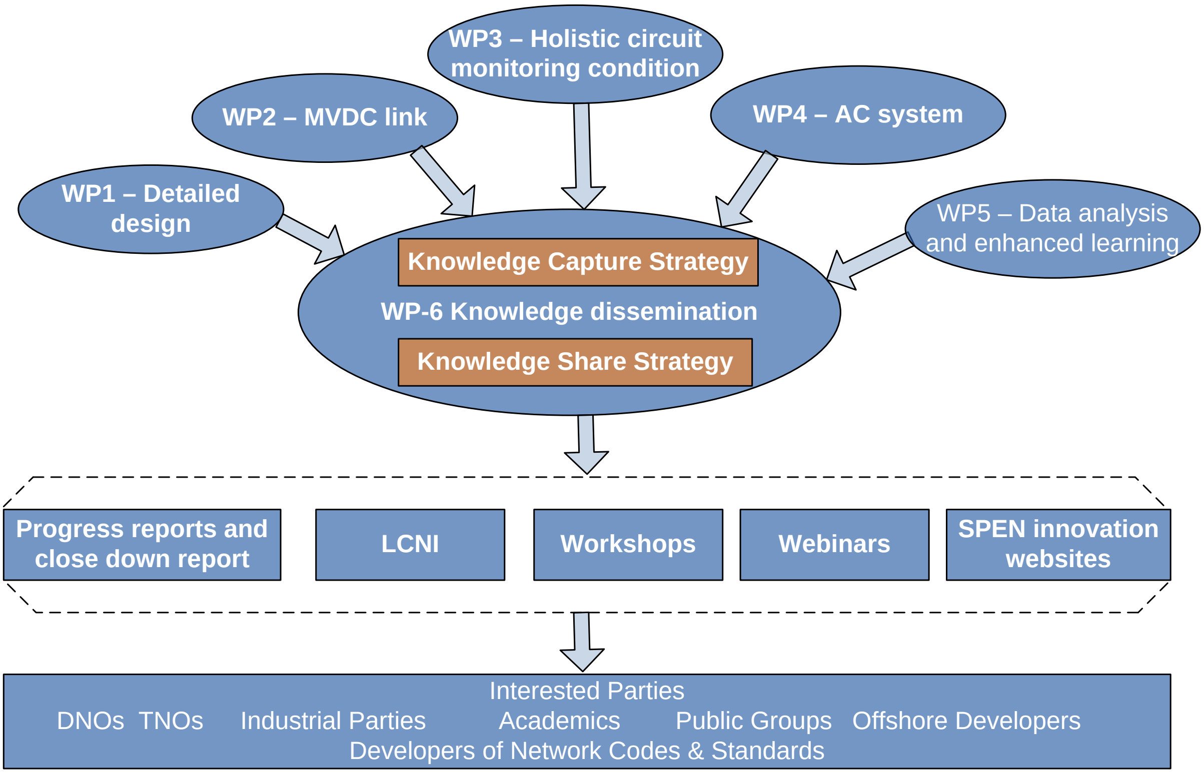

Figure 5-2: Knowledge Capture and Dissemination Methodology in ANGLE-DC

5.3. IPR

ANGLE-DC will conform to the default NIC IPR principles outlined by Ofgem. The project is not expected to develop foreground IPR which will be outside of these default IPR requirements.

Section 6 Project Readiness

Requested Level of Protection against cost over-runs: 5%
Requested Level of Protection against unrealised Direct Benefits: n/a

6.1. Evidence of why the Project can start in a timely manner

We are confident that the ANGLE-DC project can start in a timely manner based on the significant information and learning we have gathered and a strong project team we have in place. The evidence that the project is ready to start after the required funding is provided, is outlined below:

- Strong commitment from SP Energy Networks to deliver this innovative project;
- Effective engagement with interested parties;
- Knowledge and learning gained from other DNO's NIA and NIC projects;
- Knowledge gained from independent studies carried out by various institutes;
- Sufficient engagement with suppliers market at international level;
- In-house project management capability to deliver large-scale innovation projects;
- Comprehensive handover plan from proposal team to delivery team;
- Well-developed project plan, scope of work and risk register;
- Well-defined project structure and roles and responsibilities.

6.1.1. *Strong commitment from SP Energy Networks to deliver this innovative project*

The concept and benefits of ANGLE-DC have been discussed extensively at different stages of the proposal preparation, with different (and relevant) managerial levels within SP Energy Networks. There has been strong support within the senior management team including the Director of Engineering Services to fully provide the required resources for starting the ANGLE-DC project immediately after the project funding is secured.

6.1.2. *Effective engagement with interested parties*

While there is no formal partnership document signed, SP Energy Networks has been mindful about the balance between novelty and risk. Formal consultation with important stakeholders has been carried out and fed into the proposal, including:

- Visiting Nottingham University and understanding their on-going power electronic research;
- Informing and consulting Top & Tail Consortium (EPSRC funded Higher Education research project);
- Informing and consulting Professional bodies including Energy Network Association (ENA), Power Electronic Society and British Approvals Service for Cables (BASEC);
- Meeting with Western Power Distribution to clarify differences between ANGLE-DC learning objectives and existing R&D activities such as Equilibrium
- Meeting with WPD, Scottish Hydro Electricity Power Distribution on potential roll-out opportunities;
- Liaising with HVDC Multi Terminal Testing Facility (MTTE) team to consult on project scope and future collaboration opportunity;
- Informing and consulting ENTSO-E member companies to identify the novelty of ANGLE-DC and the alignment of the EU R&D routemap;

- Informing and consulting EPRI (USA) to confirm their feasibility studies on AC-DC conversion;
- Visiting Isle of Anglesey County Council to clarify potential planning application;
- Delivery of presentation and a poster to the audience in the PAC World Conference, held in Glasgow in June 2015;
- Liaising with local community including renewable developers to identify their requirements.

Such a wide and in-depth stakeholder engagement and the consistent message received convinced SP Energy Networks that this project will provide added value to address the genuine challenges faced by distribution networks and their consumers. The overwhelming support from those stakeholders is key to ensure an up-to-date scope, implementation of risk mitigation measures and access to expertise.

6.1.3. *Knowledge and learning gained from other DNOs NIA and NIC projects*

An extensive review of existing and previous LCNF, NIC and NIA projects was carried out **to fully gather relevant lessons learnt, avoid duplication and ensure ANGLE-DC's learning objectives can be distinctively differentiated from previous projects**. Equilibrium (WPD Tier 2 LCNF), The Low Carbon Hub (WPD Tier 2 LCNF) and Flexible Plug and Play (UKPN Tier 2 LCNF) projects were paid special attention, as in these projects DC and power electronic applications were trialled.

6.1.4. *Knowledge gained from independent studies carried out by various institutes*

SP Energy Networks has commissioned various institutes and companies to provide background and feasibility studies supporting the ANGLE-DC proposal. These studies have been conducted before and during the proposal preparation phase:

<u>Work carried out to support the NIC proposal preparation</u>

- ✓ In February 2015 an MVDC Technology Study report, following six months of preparation, was published as the result of work commissioned by Scottish Enterprise in partnership with SP Energy Networks through the NIA. This high-level study sought to identify the potential to build upon previous HVDC research and development. It presented case studies to demonstrate the cost benefit analysis of using MVDC technology for offshore renewable connections and onshore network reinforcement, as well as consideration of the case for an MVDC test and demonstration centre.
- ✓ During the course of the NIC proposal development SP Energy Networks conducted more in-depth analysis of the system for the onshore reinforcement application of the technology. This resulted in a detailed business case and indication of the potential scale of the opportunities for national roll-out.
- ✓ Learning to ensure the timely start of the proposed ANGLE-DC project is being delivered by another on-going SP Energy Networks NIA project, by HVPD and other partners. It is developing a system for "holistic" condition monitoring of critical subsea HVDC cable networks and will establish a system that is suitable for implementation on onshore MVDC circuits that are converted from AC. The system will provide information to indicate insulation defects and faults ahead of failure, to facilitate preventative maintenance and mitigate technical risks associated with the conversion of the cables to DC operation.

Work carried out during NIC proposal preparation

The following activities were undertaken during the preparation of the ANGLE-DC bid to facilitate the efficient transition from bid to delivery phases to ensure a timely start.

- ✓ A study of the 'Feasibility of Conversion of AC Cable Circuits for DC Operation was commissioned and carried out by Cable Consulting International (CCI) to address the potential risk of cable condition. This investigation considered the actual cables that are proposed for conversion in this submission. Prudent voltage and temperature limits were recommended to determine the cable's appropriate current rating and resultant power transmission capability. Additionally, this study recommended selected testing of sample cables, joints and terminations, as included in the ANGLE-DC proposal.
- ✓ Specifically commissioned diagnostic and withstand tests of samples of the AC cables to be used with DC were carried out by HVPD at the Bangor substation. The tests gave valuable information that may be supplemented at a later date. Short duration tests showed that both cables were able to withstand DC voltages of at least 27kV, but they cannot indicate the long term effects of DC voltages. Recommendations were made for additional tests of the cables at higher voltages having made necessary preparations for repairs; and for prolonged ageing tests or destructive testing on samples of service-aged cable.
- ✓ SP Energy Networks has benefitted from cooperation from several suppliers of DC converter technology who have been engaged during the proposal preparation phase. While not having yet entered into any formal partnering relationships, the suitability of a range of MVDC technologies has been considered in some detail. Notwithstanding future contractual negotiations, it may be said that the thinking of SP Energy Networks and several suppliers has evolved rapidly through steps that realistically mirror the gestation of a genuine project.

6.1.5. *Sufficient engagement with suppliers market at international level*

During the development of the proposal SP Energy Networks has engaged with converter suppliers to ensure that the technological solutions being considered are viable and that there would be multiple suppliers able to deliver the necessary equipment. Initial engagement with suppliers suggested that those working in the industrial or distribution areas had solutions which could be easily adapted to MVDC application. The suppliers of MV power electronic equipment are able to adapt their existing schemes to deliver an MVDC solution of the required power and voltage level, without fundamental research and development. Based on these considerations and to ensure timely start, the specific technological solution described in this proposal is an up-scaling of an existing modular solution, but it is not considered to be a unique solution and its functional requirements are believed to be well within the capabilities of multiple suppliers. The up-scaling approach means that the solution may not achieve the ideal level of functionality, but cost and time are key factors in delivering the project and any significant R&D requirements placed on the suppliers were not considered warranted in terms of the gains which could be delivered. The modular nature of the converters is well adapted to connections at different DC voltages, hence similar solutions could be considered for other distribution systems, from 11kV to 132kV.

It is anticipated that other projects in the distribution networks will use similar suppliers, e.g. for STATCOM projects. The proposed ANGLE-DC project is likely to benefit from the suppliers experience gained in delivering MVDC to these other projects. By avoiding the need for significant development, the supply chain should be ready to deliver the ANGLE

DC project in the required timescales and take part in the future market for projects in distribution networks using DC technologies.

One of the key features of the ANGLE-DC project is the condition monitoring of the existing AC cables, which will be operated under DC stress. This is essential to ensure that a valuable asset is not put at risk by its incorporation into this project. The specific technique to be used is the monitoring of partial discharge[1] within the cable insulation, which is considered to be a sensitive indication of incipient damage to the cable. The inception of partial discharge and its potential increase over time can be indicative of a potential major failure of the insulation of the cables. Engagement with several suppliers indicates that an on-line monitoring system can be installed at both ends of the cables, this can detect the presence of partial discharge and provide an indication of the location of the problem. An initial "fingerprint" of the cable will be performed to act as a baseline for assessment of future measurements of partial discharge.

6.1.6. *In-house project management capability to deliver large scale innovation projects*

SP Energy Networks is equipped with the knowledge, experience and resources to successfully conduct large scale innovation projects such as ANGLE-DC. The ability to succeed in such pioneering schemes is derived from previous achievements in similar large scale innovation projects, some of these projects are listed below:

- Flexible networks for future low carbon future (FLEXNET): This project had a total budget of £6.4m. In this project, we demonstrated our **capability to deliver a multi-vendor project** which **involved trials of different innovative methods** at different parts of distribution networks located in both Scottish Power Manweb and Scottish Power Distribution areas;
- Accelerating Renewable Connections (ARC): This project had a total budget of £8.0m. We demonstrated our capability to **trial a real-time active network management system** which required a reliable **communication architecture and control strategy** to adjust the outputs of generators. We **developed several technical guidance and policy documents** which will be used for full business adoption;
- Visualisation of Real Time System Dynamics using Enhanced Monitoring (VISOR): This is a NIC project with a total budget of £7.37m and it involves **complicated real-time modelling and analysis** of transmission network dynamic conditions.

The above examples are evidence that we have **managed a delivery team from a variety of backgrounds**, including consultants and suppliers, and set-up a strong communication structure to **ensure successful management, delivery and knowledge dissemination**. These strengths will be passed onto ANGLE-DC and will enable us to deliver ANGLE-DC successfully, as well as generate and capture all learning outcomes within the estimated time and budget.

6.1.7. *Comprehensive handover plan between bid preparation team and delivery team*

We have considered a comprehensive handover plan for an efficient, effective and smooth knowledge transfer between bid preparation team and delivery team. We will

[1] The term "partial discharge" refers to a small localised electrical breakdown within the insulation material, but which does not bridge the full insulation structure from the central medium voltage core to the outer grounded sheath of the cable. However, with time the level of discharge can increase and if not attended to can ultimately lead to the end of life of the insulation.

use the same Interim Team model previously used in our NIC VISOR project. ANGLE-DC Interim Team will have the following main responsibilities for around a six month period during which the handover process will be completed (see Figure 6-1):

- Ensure the continuity in the project progress and avoid any impact on the project due to delay in availability of permanent resources;
- Transfer knowledge, project background and contacts created during the proposal preparation phase to the ANGLE-DC permanent team;
- Provide recommendations and support for recruitment of the ANGLE-DC permanent team in terms of knowledge, skills and responsibilities required;
- Provide recommendations on the project steering committee and project management structure;
- Provide recommendations on project partners selection process;
- Liaise with the legal department to produce, review and approve collaboration agreements.

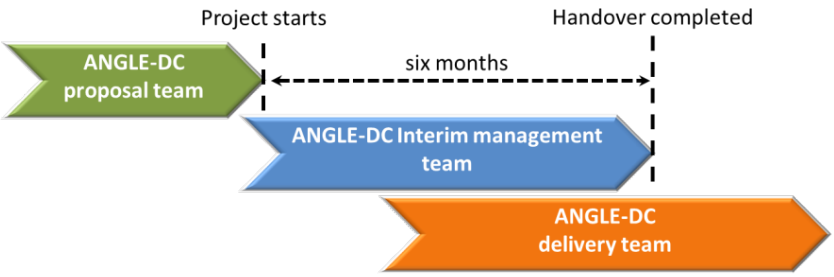

Figure 6-1 ANGLE-DC handover process to delivery team

6.1.8. *Well-developed project plan, scope of work and risk register*

We have developed a robust project plan and scope of work to ensure the successful delivery of the project. The project will be run in six WPs each of which provides distinctive learning to other DNOs and interested parties. The dependencies between activities within WPs and between WPs have been also identified and are reflected in our project programme. The complete project programme is given in Appendix E.

Based on the information gathered from supplier engagement, our experience from previous projects, and consultations undertaken with stakeholders **we have identified the potential risks to the project**. Risks were categorised based on the relevance to different aspects of the project (project management, equipment and procurement, installation etc). The impact of each risk was also evaluated and mitigation plans were identified. Appendix G shows a complete list of risks identified in the proposal preparation phase. **The risk register will be a live document in the course of the ANGLE-DC project and we will endeavour to continue identifying risks and mitigation plans**. We have also planned a process to halt the project in the event that high impact risks materialise and impact the overall delivery of the project within the time and budget planned (see Section 6.6 for more details)

6.1.9. *Well-defined project structure roles and responsibilities*

Through extensive stakeholder engagement carried out during the proposal preparation we developed a clear understanding about the distinctive workload and activities required for each of the WPs. Based on this information and experience from previous projects we propose a project structure shown in Figure 6-2. The delivery team will mainly consist of two technical teams, namely MVDC technical team and circuit condition monitoring technical team. The roles and responsibilities of these two technical teams are described in Appendix F. Although we have identified a number of potential academic partners based on their core research specialities and laboratory facilities, the academic partners will be selected within three months after project starts.

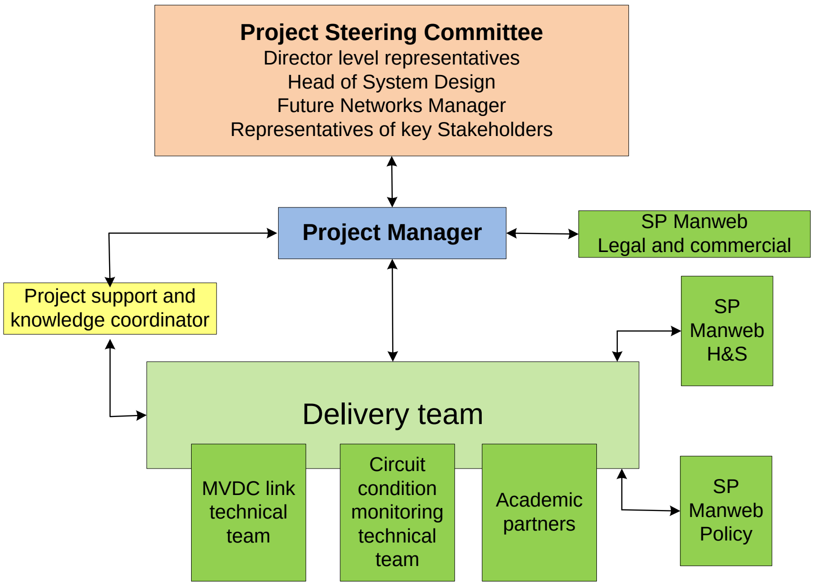

Figure 6-2: ANGLE-DC project structure

6.2. Evidence of how the costs and benefits have been estimated

- A bottom-up approach was used to estimate the cost associated with the delivery of each WP. The total estimated project cost includes 8% contingency due to the innovative nature of the project. A complete project breakdown cost is provided in Appendix B;
- Cost of MVDC equipment was estimated based on a consultation carried out with major high voltage and industrial DC technology suppliers after understanding available technologies and identifying suitable technologies for medium voltage application;
- Site preparation costs were estimated based on specific site inspections in Bangor and Llanfair PG and the estimated size of MVDC equipment;
- Cost of holistic monitoring equipment was also estimated based on the engagement with one of the PD monitoring suppliers, and our previous experience of the cost required for integration of the monitoring system into the corporate system;
- The cost of the AC system was estimated based on the unit costs of typical cable installations and also after specific site visits carried out between Bangor – Llanfair PG to identify possible routes and way-leave requirements;
- The cost of labour, consultation services and contractors for each WP was also estimated based on our experience in previous projects. These costs were internally reviewed by SP Energy Networks;
- For the benefits associated with losses, load flow studies carried out at different loading conditions in the Anglesey area with MVDC and without MVDC were used

to calculate annual loss reduction. The benefit of loss reduction was calculated assuming £48.42/MWh losses cost as per Ofgem CBA spreadsheet;

- For the benefit in the roll-out phase in the GB, load flow and voltage heat maps of different distribution networks in the GB were taken into account. 25 sites were identified as suitable for the ANGLE-DC solution replication. An extrapolation technique was used to estimate the future GB benefits taking into account specific benefits estimated in the ANGLE-DC case.

6.3. Evidence of the measures the Network Licensee will employ to minimise the possibility of cost overruns or shortfalls in Direct Benefits

We will use robust methodologies throughout the lifetime of the project to ensure that the risk of cost overruns is minimised. The methodologies we use are outlined as follows:

- **Equipment cost estimation and optimisation:** The greatest potential uncertainty lies around the budget for the MVDC equipment, consequently to reduce the risk of cost overruns we have actively engaged with the potential MVDC suppliers during the proposal preparation phase to make a practical estimation of the equipment cost and have allowed a contingency. We have considered a separate WP (Detailed design) to continue market research, technology review and supplier engagement in the first year of the project to ensure an optimised design of the product will be specified by SP Energy Networks to avoid any expensive but unnecessary specifications.
- **Project breakdown into WPs:** ANGLE-DC is a large-scale project and we will split it into separate WPs with allocated budget and tolerances. A stage control strategy will be used to define the activities in each WP by stages. In this way we can monitor the cost of activities at each stage. Monthly project cost review and cost at completion forecast will be also conducted for each WP to provide an accurate picture of total project cost.
- **Focus on SDRCs and learning objectives**: Due to the innovative nature of the project, there is always a temptation to trial new ideas and new methods which are not in the main project objectives while the project is progressing. We acknowledge that we need to stay focused on our learning objectives and SDRCs as defined at the outset to avoid unplanned expenditures.
- **Risk management process and mitigation plans:** We recognise that identifying risks and putting appropriate mitigation plans in place is an effective methodology to avoid possible overspent on the project. We have already identified risks in ANGLE-DC especially those which will have a financial impact on the project. We will continue to actively update the risk register and mitigation plans during the course of the project.

6.4. A verification of all information included in the proposal (the processes a Network Licensee has in place to ensure the accuracy of information can be detailed in the appendices)

The following process was undertaken to ensure that the information included in this proposal and associated appendices, prepared by an experienced technical team led by a full-time dedicated proposal manager, is up-to-date and reflects the best knowledge:

- **Supplier engagement** to ensure the MVDC cost estimated for the financial analysis and the lead time considered in the project plan are close to the expected reality.
- **External consultants**, TNEI, CCI, HVPD and WSP | Parsons Brinckerhoff, experts in the various associated technical fields were engaged during the development of this proposal to verify the proposed design concept, the technical

assumptions, the project risks, the project delivery programme and the costs, both CAPEX and OPEX, used in the Cost Benefit Analysis.
- **A thorough quality control** and independent peer-review of the proposal was carried out by different technical experts outside of the proposal preparation team. The proposal is subject to the SP Energy Networks data assurance policy and has been reviewed before submission.
- As part of **stakeholder engagement activities**, various consultations were organised to confirm the innovation aspects and feasibility of the ANGLE-DC projects.

6.5. How the Project plan would still deliver learning in the event that the take up of low carbon technologies and renewable energy in the trial area is lower than anticipated in the Full Submission

ANGLE-DC will still deliver its learning objectives in the unlikely event of a low uptake of renewables and low carbon technologies in the area affected by the trial (Anglesey and North Wales). Although the ANGLE-DC solution will offer significant benefits in terms of facilitating the integration of renewables, the focus of learning objectives will be mainly around the trial of new methods and new technologies. The conversion of the existing AC assets for DC operation and the application of voltage source converters in both ends of a medium voltage circuit to create a MVDC link are the main sources of the learning objectives in this project. We will demonstrate whether the conversion of AC to DC is possible and what technical and safety aspects should be considered. We will also develop a Best Practice Guide for technical design and specification of a MVDC link. **These learning points do not rely on the level of uptake of renewables.**

We will also monitor the performance of the MVDC link in different loading conditions. The peak electricity demand in the Anglesey island is already high enough to allow us to test the MVDC link under high load conditions e.g. up to the rating of the MVDC link. **The learning from day-to-day operation of the MVDC link would not rely on the rate of progress of low carbon technology developments on Anglesey. The same is the case with the learning from the ageing mechanism of AC cables after conversion to DC.**

The expected learning from this project is explained in detail in Section 5 and none of this would be dependent on low carbon technology developments in the Anglesey and North Wales areas.

6.6. The processes in place to identify circumstances where the most appropriate course of action will be to suspend the Project, pending permission from Ofgem that it can be halted

We will set and continuously monitor the key performance indicator (KPIs) of the ANGLE-DC project to evaluate how well we perform in delivering the Successful Delivery Reward Criteria (SDRCs). The following process will be in place to identify circumstances where the project should be halted:

ANGLE-DC is a large-scale project. In order to effectively monitor the KPIs, we will define stages in each WP and will evaluate the project performance at the end of each stage. This methodology will enable us to evaluate the project progress in a controlled manner to ensure that we deliver SDRCs within the time and budget as planned in this proposal.

For each WP we will set tolerances in terms of budget, time and quality. If a stage evaluation shows that the WP will exceed its tolerances an issue report will be submitted to the project manager by the WP leader. Depending on the impact on the project as a whole the project manager may escalate the issues to the steering committee by submitting an exception report. The exception report will contain the information for the project board to decide if the project should be stopped or remedial actions are required. The steering committee will issue a formal report to Ofgem to request permission to discontinue or delay the project, detailing the issues, meeting minutes and recommendations. Figure 6-3 shows the process to identify situations where the most appropriate course of action is to halt the project. This process will comply with the NIC Governances and will be delivered in the best interests of customers.

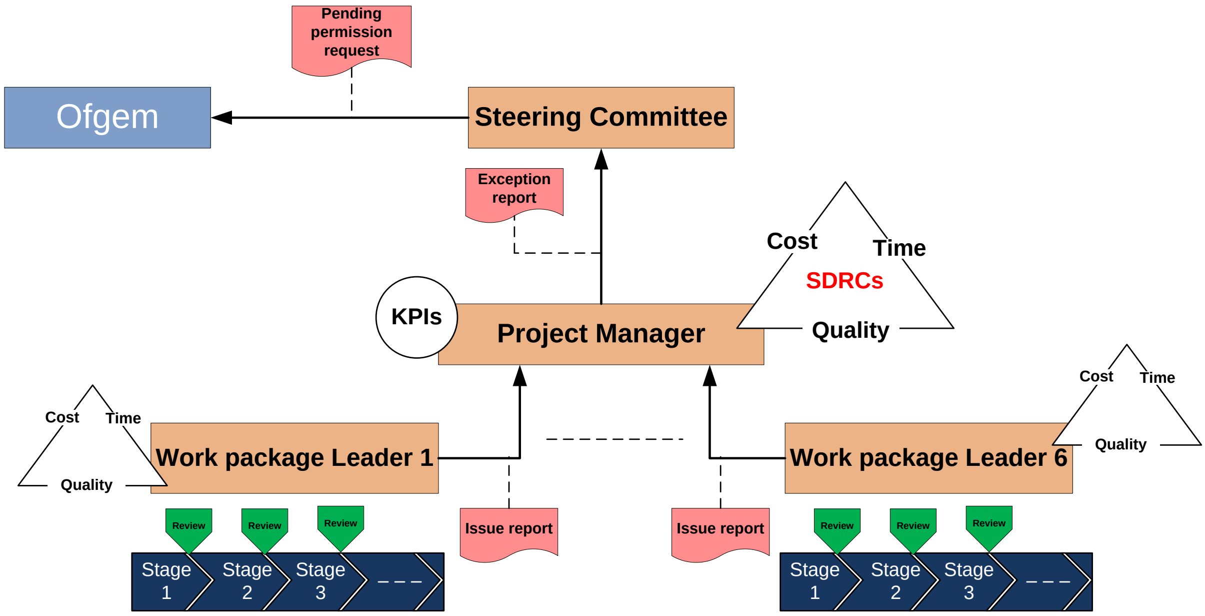

Figure 6-3: Process in place to identify if project should be halted

Section 7 Regulatory issues

The ANGLE-DC project is within the scope of the regulation.

7.1. Derogations

No derogations have been identified to be required for the project.

7.2. Licence Consents

No license consents have been identified to be required for the project.

7.3. Licence Exemptions

No license exemptions have been identified to be required for the project.

7.4. Changes to Regulatory Arrangements

No changes to regulatory arrangements have been identified to be required for the project.

Section 8 Customer Impact

8.1. The Project

ANGLE-DC proposes to convert existing AC assets for DC operation thus making more efficient use of the existing infrastructure. The method represents a significant innovative step which, if successfully demonstrated, could avoid or defer significant network reinforcements and their subsequent impact on customers in the near future.

8.2. Minimising Customer Impact

ANGLE-DC represents a novel solution and as such all mitigation measures will be put in place to ensure the project can be delivered whilst minimising the risk to the customers.

Where new equipment has to be installed SP Energy Networks' procedures will be followed. The operation of the network will not be affected by the project.

8.2.1. *Permanent Monitoring*

Initial testing completed on the proposed circuit has demonstrated the cables are able to withstand a DC voltage of 27kV for a short duration. Nevertheless the long term effect of DC stress on AC cables is not yet well understood and constitutes one of the key learning outcomes from the project. For this purpose permanent condition monitoring devices will be installed at each end of the circuit.

Besides the long term trending of deterioration data the devices will also provide instantaneous partial discharge readings which could be used to identify weak points in the insulation in advance of fault occurrence. The data could be used to identify the fault location and minimise recovery time.

8.2.2. *AC system*

Additionally, customer's risk exposure is minimised with the establishment of a new 33kV AC circuit between sites. The circuit will form an integrated part of the project to enable:

1- DC circuit outage during commissioning and testing;
2- Optimal power flow control between AC and DC.

In the project design phase, the optimum strategy for the operation of the AC link will be considered with the aim of ensuring a reliable power transfer corridor between the mainland and island. By establishing an operating plan for the AC link, the installed system will be able to provide the minimum number of possible interruptions to the customers and will result in no overload to the circuits, after switching to AC.

The project programme detailed in Appendix E has been built to ensure the AC circuit is installed before the conversion work commences on the DC link. This is illustrated in Figure 8-1:

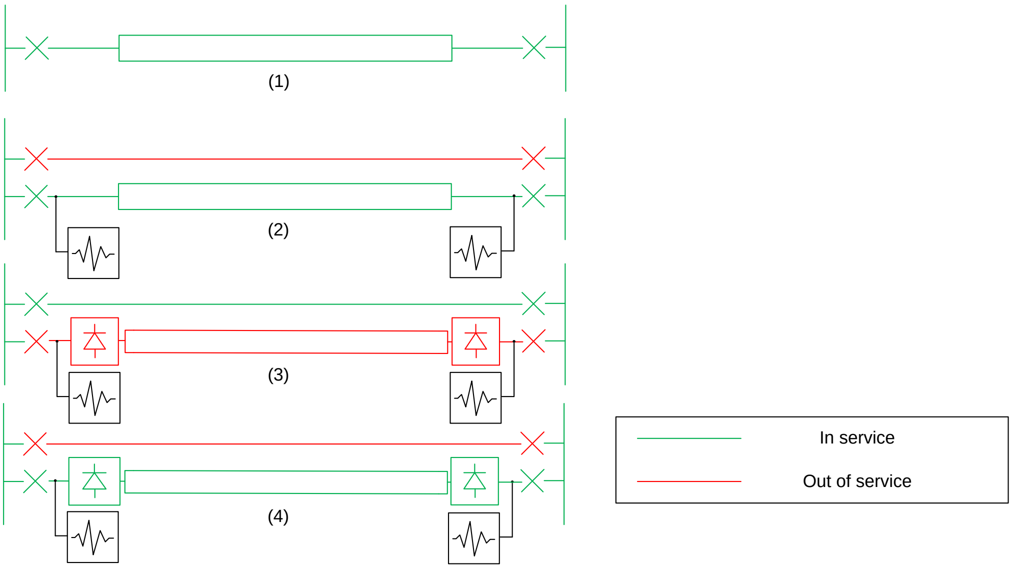

Figure 8-1: The sequence of energisation

The sequence for energisation is detailed as follows:

(1) Existing AC circuit in operation;

(2) Construction of AC circuit while the existing circuit is in operation. Condition monitoring equipment is installed to monitor the AC cable status. The equipment will be placed at either end of the cable;

(3) The AC circuit will be in service while the existing AC circuit is converted for DC operation;

(4) The normal running arrangement will have the DC circuit in service and the AC circuit will be normally open.

8.2.3. *Power Quality*

Power electronic devices are likely to introduce harmonic distortion in their operation. The level of harmonic distortion will not exceed the levels indicated in Engineering Recommendation G5/4 as per the distribution code. No adverse impact on customers is anticipated.

8.2.4. *Electromagnetic Fields*

A key aspect of the project will be the impact of electromagnetic fields (EMF) and potential concerns about public safety. Relevant epidemiological and biological studies have been reviewed in reports by the independent Advisory Group on Non-ionising Radiation (AGNIR, 2001a,b, 2003). These conclude that there is no firm evidence of such adverse health effects at the levels of EMFs to which people are normally exposed. In the light of ongoing research, and major health risk assessments being carried out by the World Health Organization (WHO), the ANGLE-DC Team will continuously review the guidelines on limiting exposure to EMFs and recognises the need to adopt a cautious approach in the interpretation of scientific knowledge and the benefits of common international guidelines. The ANGLE-DC team will:

1) Adopt a cautious approach in the interpretation of scientific knowledge;

2) Make full use of the benefits of common international guidelines;
3) Take on the overall responsibility of controlling the risk due to EMF for customers and third parties, and takes into account the international efforts in the following documents: IEC: 61000-1-2, IEC: 61582.

HSE will be an integral part of our stakeholder engagement plan, and we will ensure HSE is well informed and proactively consulted by the work on going.

8.3. Planned Interruptions

The extension of the switchboards to accommodate new circuit breakers for the AC circuit requires taking planned interruptions on the busbars at each end. SP Energy Networks' standard procedure will be followed for scheduling outages to ensure the risk to customers is minimised.

8.4. Unplanned Interruptions

No unplanned interruptions are anticipated.

8.5. Engagement with Customers

Customers will not be affected by the project and no formal engagement is anticipated.

8.6. Interaction with Customer's Premises

There is currently no intention to interact with customer's premises.

8.7. Protection from Incentive Penalties

No protection from incentive penalties is required.

Section 9 Successful Delivery Reward Criteria (SDRCs)

We have set out eight SMART[1] SDRCs in line with the outputs that will be expected to be delivered through the ANGLE-DC project. Figure 9-1 shows an overview of the delivery time of SDRCs and the link between SDRCs and work packages.

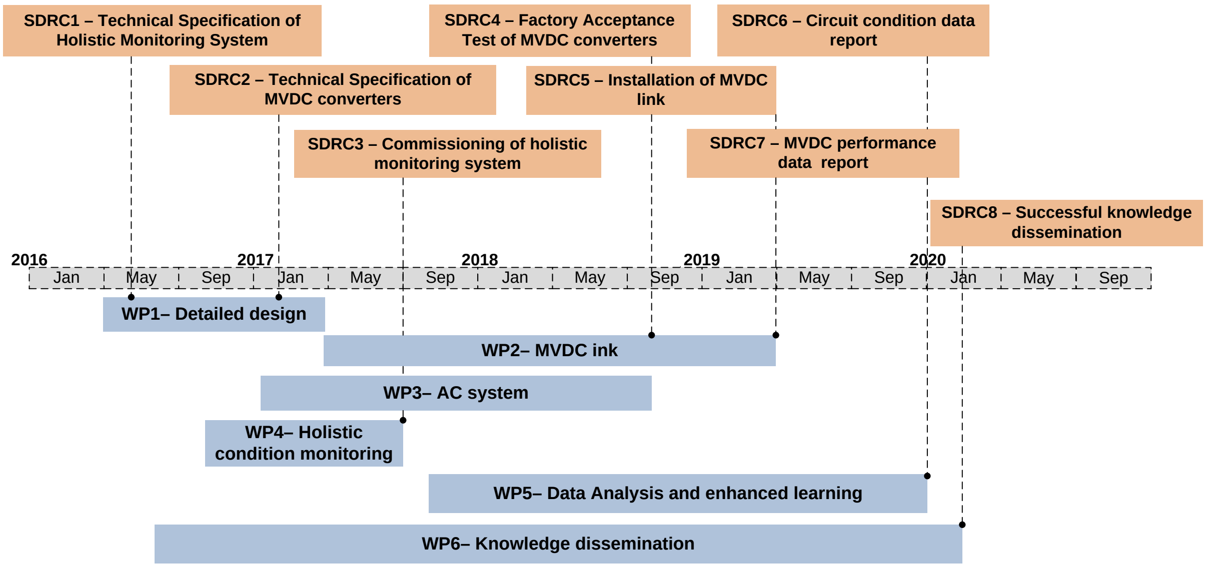

Figure 9-1: Overview of the SDRCs and their delivery time

9.1. Criterion 1

Specific: Development of the Technical Specification for Holistic Circuit Condition Monitoring systems.

Measurable: The Technical Specification will be published in the form of a document which will include a description of the Scope and Objectives, Functionality, Architecture and Design of the system.

Achievable: Initial scoping and preliminary market research has been conducted in parallel with the development of the NIC proposal to identify suppliers which can provide equipment for monitoring the circuit condition both in DC and AC voltage. The outcomes of a previous NIA project – HVDC Cable Condition Monitoring Systems – will inform the requirements on the Technical Specification.

Relevant: One of the key learning lessons from the project is the understanding of the ageing mechanism of AC cables under DC stress. It is important to ensure the monitoring equipment is adequately specified to capture and store the data, which will allow logging, benchmarking and trending the insulation condition. This technical specification is an essential requirement for starting WP 4.

Time-bounded: The Technical Specification will be completed by the 17th June 2016.

Evidence: Share the Technical Specification for the Holistic Circuit Condition Monitoring systems with other project stakeholders, principally other DNOs.

[1] SMART = Specific, Measurable, Achievable, Relevant and Time Bound

9.2. Criterion 2

Specific: Development of the Technical Specification for MVDC Converter Stations.

Measurable: The Technical Specification will be published in the form of a document which will include a description of the scope and objectives, electrical specifications, control strategy and site installation requirements. This will also include the operating parameters for the scheme, which will be the subject to commercial guarantees.

Achievable: Initial scoping and preliminary supplier engagement has been conducted to understand the challenges of MVDC converter stations. A high level Functional Specification for the converters has already been developed – see Appendix I– and will be developed further, to include specific requirements as informed by the studies undertaken at the Detail Design phase (WP1).

Relevant: MVDC converter stations constitute the main hardware deliverables to be installed as part of the project. It is fundamental that the converter stations are specified in detail to ensure the desired functionality can be achieved. This technical specification is an essential requirement for starting WP3.

Time-bounded: The Technical Specification will be published by the 24th February 2017.

Evidence: Share the Technical Specification for MVDC converters with other project stakeholders, principally other DNOs.

9.3. Criterion 3

Specific: Commissioning of the Holistic Circuit Condition Monitoring Systems.

Measurable: A report will be published in the form of a document describing the characteristics of the equipment installed, including the functionality and architecture and its integration in to the SP Energy Networks monitoring systems. Photos of the devices at the sites will be provided as well as evidence of the data being recorded and the trend information being stored.

Achievable: Upon successful development of the Technical Specification for the Holistic Circuit Condition Monitoring systems, a formal procurement exercise will be conducted. The chosen vendor will be required to install and commission the equipment, before handing over to SP Energy Networks.

Relevant: Timely commissioning of the permanent circuit condition monitoring systems is fundamental to allow for sufficient time to understand the condition of the existing AC circuit, as a "benchmark" before being converted to DC.

This is the main output from WP4.

Time-bounded: The permanent circuit condition monitoring systems will be commissioned by 15th November 2017.

Evidence: Publish report demonstrating the on-site installation of the monitoring systems has been completed including photos of the devices at the sites and evidence that data is being recorded. Formal service support contract will be also signed with the supplier for analysis of the data.

9.4. Criterion 4

Specific: Factory Acceptance Test of MVDC converters.

Measurable: A report will be produced describing the testing procedure as well as findings from the testing.

Achievable: Upon development of the Technical Specification for the MVDC converters, a formal procurement exercise will be conducted. The chosen vendor will be required to develop a programme to enable the Factory Acceptance Test being completed within the given timescales.

Relevant: Conducting the Factory Acceptance Test of MVDC converters on time is a major milestone to ensure the project will successfully be delivered on time.

Time-bounded: The Factory Acceptance Test will be completed by 30th November 2018.

Evidence: Share report describing the testing procedure and highlighting the key findings during the Factory Acceptance Test.

9.5. Criterion 5

Specific: Installation of the MVDC circuit.

Measurable: A report will be produced and published in the form of a document describing the on-site installation of the MVDC converter stations process. The report will incorporate photos of the installed equipment and a description of the installation procedure.

Achievable: Initial market engagement has been carried out as part of the development of the NIC proposal to define the timescales for the supply and installation of the MVDC converters.

Relevant: The MVDC link will be the first UK demonstration of a combined medium-voltage overhead and underground AC circuit conversion to DC. This is the main output of WP2.

Time-bounded: The MVDC circuit will be installed by 12th April 2019.

Evidence: Share report demonstrating the on-site installation of the DC circuit has been completed, including photos of the sites.

Share design of how the converters have been installed and key considerations for the future installations of MVDC converters.

9.6. Criterion 6

Specific: Publication of circuit condition data report.

Measurable: A report will be published on the project website summarising the data collected by the Holistic Circuit Condition Monitoring systems. The report will describe the condition of the circuit while in AC operation and how the condition changed, if at all, after conversion to DC. Data trending and conclusions will be presented.

Achievable: The publication of the circuit condition data follows the commissioning of the Holistic Circuit Condition Monitoring systems.

Relevant: Analysis of the effect of DC voltages on AC cables is one of the main learning lessons from the project. The data will be published to ensure access to the learning for all interested parties. This is one of the main outputs from WP5.

Time-bounded: The data will be published by 23rd January 2020.

Evidence: Share report documenting the data gathered by the Holistic Circuit Condition Monitoring Systems. All incidences in the circuit since Holistic Cable Condition Monitoring system installation will be described, including the severity and mitigation measures.

9.7. Criterion 7

Specific: Publication of operational performance of MVDC converter stations.

Measurable: A report will be published on the project website summarising the MVDC performance. The report will target the availability and reliability of the system. Outages rates and energy availability figures will be provided. A differentiation will be made between forced and planned outages. The report will include information on the maintenance regime, in terms of time and resources required.

Achievable: The systems in place will record the performance of the converters.

Relevant: Previous analysis has identified the lack of delivery and operational track-record as one of the challenges for adopting MVDC technology. The project offers the opportunity to measure the performance of MVDC converters in different conditions which can provide a valuable experience and help evaluate the impact on the network operation and maintenance requirements. This is one of the main outputs from WP 5.

Time-bounded: The MVDC performance data will be published by 23rd January 2020.

Evidence: Share the report documenting the performance of the system. The report will summarise the reliability and availability of the converters after the initial adjustment period. The report will differentiate between the forced outage rate (FOR), scheduled energy unavailability (SEU), forced energy unavailability (FEU) and energy availability (EA).

9.8. Criterion 8

Specific: Successful dissemination of knowledge generated.

Measurable: The knowledge and lessons learnt will be maintained in a knowledge repository where all learning points will be categorised based on their usefulness to different interested parties.

Achievable: SP Energy Networks has experience in disseminating the knowledge from previous LCNF/NIC innovation projects. Knowledge dissemination constitutes a separate WP in the project. Necessary resources will be allocated to ensure access to the learning is facilitated to all interested parties.

Relevant: This is the main outcome from WP6.

Time-bounded: Knowledge dissemination will be completed by 16th April 2020.

Evidence:

- Timely delivery of project progress reports;
- Bi-annual knowledge dissemination workshops;
- Presentations at annual innovation conferences;
- Establishment and up-to-date maintenance of online project portal;
- Publication of the close-down report.

Appendix	Title
Appendix A	Benefit Tables
Appendix B	Project cost
Appendix C	Anglesey Reinforcement
Appendix D	Financial Analysis
Appendix E	Project Plan
Appendix F	Roles and Responsibilities
Appendix G	Risk Register
Appendix H	MVDC Converter Technology
Appendix I	High Level Functional Specification for MVDC Distribution Link
Appendix J	Skin Effect in Cables
Appendix K	Capacity Released Calculation for Bangor-Llanfair PG Circuit
Appendix L	NIA SPT 1307 – MVDC. Project Close Down Summary
Appendix M	Existing Non-UK AC to DC Conversion Projects
Appendix N	Letters of Support
Appendix O	Glossary of Terms

Method	Method name
Method 1	Medium – Voltage DC (MVDC)

A.1 Electricity NIC – financial benefits

				Financial benefit (£m)				
Scale	Method	Method Cost	Base Case Cost	Benefit			Notes	Cross-references
				2020	2030	2050		
Post-trial solution *(individual deployment)*	MVDC	[redacted]	[redacted]	0.0	9.98	20.1	It is assumed that first post-trial application will take place in 2021 with a cost reduction of %6 on power electronic equipment. Cost variations of both DC and conventional elements are according to technology cost curves published by Work Stream 3 Smart Grid forum. The theoretical conventional base case assumes the installation of one new grid transformer with the corresponding 132kV circuit, 132kV and 33kV switchgear.	Appendix D, page 63
Licensee scale *If applicable, indicate the number of relevant sites on the Licensees' network.*	MVDC	[redacted]	[redacted]	4.2	18.4	39.2	One further site has been assumed within the licensee area by 2025.	Appendix D, page 63
GB rollout scale *If applicable, indicate the number of relevant sites on the GB network.*	MVDC	[redacted]	[redacted]	4.2	69.2	396.0	A total of 25 MVDC projects have been assumed by 2040.	Appendix D, page 63

A.2 Electricity NIC – carbon and/or environmental benefits

Scale	Method	Method Cost	Base Case Cost	Environmental benefit (GWh) 2020	2030	2050	Notes	Cross-references
Post-trial solution *(individual deployment)*	MVDC	[redacted]	[redacted]	0	45.4	45.4	It is assumed that both the base case and the method will deliver the same capacity. The method is expected to deliver the capacity at least one year earlier.	Appendix D
Licensee scale *If applicable, indicate the number of relevant sites on the Licensees' network.*	MVDC	[redacted]	[redacted]	45.4	90.8	90.8	It is assumed that both the base case and the method will deliver the same capacity. The method is expected to deliver the capacity at least one year earlier.	Appendix D
GB rollout scale *If applicable, indicate the number of relevant sites on the GB network.*	MVDC	[redacted]	[redacted]	45.4	454.2	1135.5	It is assumed that both the base case and the method will deliver the same capacity. The method is expected to deliver the capacity at least one year earlier.	Appendix D

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RIIO NIC NETWORK INNOVATION COMPETITION

Appendix B Project cost

	A	B	C	D	E	F	G	H	I	J	K	L
1	**NIC Funding Request**											
2			2015/16	2016/17	2017/18	2018/19	2019/20	2020/21	**Total**			
3	**Cost**	*From Project Cost Summary sheet*										
4		Labour	163,870.01	553,740.51	564,877.65	252,258.37	280,020.42	-	1,814,766.95			
5		Equipment	-	210,000.00	3,139,084.97	2,625,000.00	100,000.00	-	6,074,084.97			
6		Contractors	5,256.11	592,766.11	3,884,267.86	144,593.61	738,767.50	-	5,365,651.20			
7		IT	-	-	-	-	-	-	-			
8		IPR Costs	-	-	-	-	-	-	-			
9		Travel & Expenses	21,444.63	115,368.90	75,757.97	75,453.40	56,620.19	-	344,645.08			
10	Payments to users & Contigency		9,670.36	72,364.71	643,946.72	416,136.20	57,639.52	-	1,199,757.50			
11		Decommissioning	-	-	-	-	-	-	-			
12		Other	4,800.00	8,800.00	8,800.00	8,800.00	8,800.00	-	40,000.00			
13		**Total**	205,041.11	1,553,040.22	8,316,735.17	3,522,241.57	1,241,847.62	-	14,838,905.70			
14												
15	**External funding**	*Any funding that will be received from Project Partners and/or External Funders - from Project Cost Summary sheet*										
16		Labour	-	-	-	-	-	-	-			
17		Equipment	-	-	-	-	-	-	-			
18		Contractors	-	-	-	-	-	-	-			
19		IT	-	-	-	-	-	-	-			
20		IPR Costs	-	-	-	-	-	-	-			
21		Travel & Expenses	-	-	-	-	-	-	-			
22	Payments to users & Contigency		-	-	-	-	-	-	-			
23		Decommissioning	-	-	-	-	-	-	-			
24		Other	-	-	-	-	-	-	-			
25		**Total**	-	-	-	-	-	-	-			
26												
27	**Licensee extra contribution**	*Any funding from the Licensee which is in excess of the Licensee Compulsory Contribution - from Project Cost Summary sheet*										
28		Labour	-	-	-	-	-	-	-			
29		Equipment	-	-	-	-	-	-	-			
30		Contractors	-	-	-	-	-	-	-			
31		IT	-	-	-	-	-	-	-			
32		IPR Costs	-	-	-	-	-	-	-			
33		Travel & Expenses	-	-	-	-	-	-	-			
34	Payments to users & Contigency		-	-	-	-	-	-	-			
35		Decommissioning	-	-	-	-	-	-	-			
36		Other	-	-	-	-	-	-	-			
37		**Total**	-	-	-	-	-	-	-			
38												
39	**Initial Net Funding Required**		*calculated from the tables above*									
40		Labour	163,870.01	553,740.51	564,877.65	252,258.37	280,020.42	-	1,814,766.95			
41		Equipment	-	210,000.00	3,139,084.97	2,625,000.00	100,000.00	-	6,074,084.97			
42		Contractors	5,256.11	592,766.11	3,884,267.86	144,593.61	738,767.50	-	5,365,651.20			
43		IT	-	-	-	-	-	-	-			
44		IPR Costs	-	-	-	-	-	-	-			
45		Travel & Expenses	21,444.63	115,368.90	75,757.97	75,453.40	56,620.19	-	344,645.08			
46	Payments to users & Contigency		9,670.36	72,364.71	643,946.72	416,136.20	57,639.52	-	1,199,757.50			
47		Decommissioning	-	-	-	-	-	-	-	Check Total = to Initial Net Funding request		
48		Other	4,800.00	8,800.00	8,800.00	8,800.00	8,800.00	-	40,000.00	in Project Cost Summary		
49		**Total**	205,041.11	1,553,040.22	8,316,735.17	3,522,241.57	1,241,847.62	-	14,838,905.70	**OK**		
50												
51	**Direct Benefit:**	*from Direct Benefits sheet*										
52		Total	-	-	-	-	-	-	-			
53												
54												
55												
56	**Licensee Compulsory Contribution / Direct Benefits** *from Project Cost Summary sheet*											
57		Labour	16,387.00	55,374.05	56,487.76	25,225.84	28,002.04	-	181,476.70			
58		Equipment	-	21,000.00	313,908.50	262,500.00	10,000.00	-	607,408.50			
59		Contractors	525.61	59,276.61	388,426.79	14,459.36	73,876.75	-	536,565.12			
60		IT	-	-	-	-	-	-	-			
61		IPR Costs	-	-	-	-	-	-	-			
62		Travel & Expenses	2,144.46	11,536.89	7,575.80	7,545.34	5,662.02	-	34,464.51			
63	Payments to users & Contigency		967.04	7,236.47	64,394.67	41,613.62	5,763.95	-	119,975.75			
64		Decommissioning	-	-	-	-	-	-	-	of Total Initial Net Funding Required		
65		Other	480.00	880.00	880.00	880.00	880.00	-	4,000.00	**OK**		
66		**Total**	20,504.11	155,304.02	831,673.52	352,224.16	124,184.76	-	1,483,890.57	Check that **Total** is = or > than		
67										Total Direct Benefits		
68										**OK**		
69	**Outstanding Funding required**		*calculated from the tables above*									
70		Labour	147,483.01	498,366.46	508,389.88	227,032.53	252,018.38	-	1,633,290.26			
71		Equipment	-	189,000.00	2,825,176.47	2,362,500.00	90,000.00	-	5,466,676.47			
72		Contractors	4,730.50	533,489.50	3,495,841.08	130,134.25	664,890.75	-	4,829,086.08			
73		IT	-	-	-	-	-	-	-			
74		IPR Costs	-	-	-	-	-	-	-			
75		Travel & Expenses	19,300.17	103,832.01	68,182.17	67,908.06	50,958.17	-	310,180.57			
76	Payments to users & Contigency		8,703.32	65,128.23	579,552.05	374,522.58	51,875.56	-	1,079,781.75			
77		Decommissioning	-	-	-	-	-	-	-	Check that Total is =to		
78		Other	4,320.00	7,920.00	7,920.00	7,920.00	7,920.00	-	36,000.00	Total Outstanding Funding required		
79		**Total**	184,537.00	1,397,736.20	7,485,061.66	3,170,017.42	1,117,662.86	-	13,355,015.13	**OK**		
80												
81	balance	13,121,436.21	0.00	11,539,163.01	4,177,404.35	1,085,969.77	(5,376.22)	26.75	13,121,436.21			
82	Interest		0.00	123,303.00	78,582.84	26,316.87	5,402.97	(26.75)	233,578.92			
83									13,355,015.13	-		
84											click this button to calculate the NIC funding request	
85		Bank of England interest rate		0.5%		**NIC FUNDING REQUEST £**			**13,121,436.21**			
86		Interest rate used in calculation		1.0%								
87		RPI adjustment	2015/16	2016/17	2017/18	2018/19	2019/20	2020/21	2021/22	2022/2023	2023/2024	
88		Index	267.6	275.9	284.4	293.2	302.3	311.7	321.4	331.3	341.6	
89		Annual inflation	3.10%	3.10%	3.10%	3.10%	3.10%	3.10%	3.10%	3.10%	3.10%	
90	*n.b the Second Tier Funding Request calculation should use the Bank of England Base rate plus 1.5% on 31 June of the year in which the Full Submission is made.*											

Appendix C Anglesey Reinforcement

The 33kV system on the isle of Anglesey, North Wales, is currently approaching both thermal and voltage limits. The Amlwch, Caergeilliog 33kV demand group on Anglesey is supplied by two 132/33kV transformers. There are two 33kV circuits that run under the Menai Strait and interconnect the group with the 33kV system on the mainland. The schematic diagram of the Anglesey network is shown in Figure C-1.

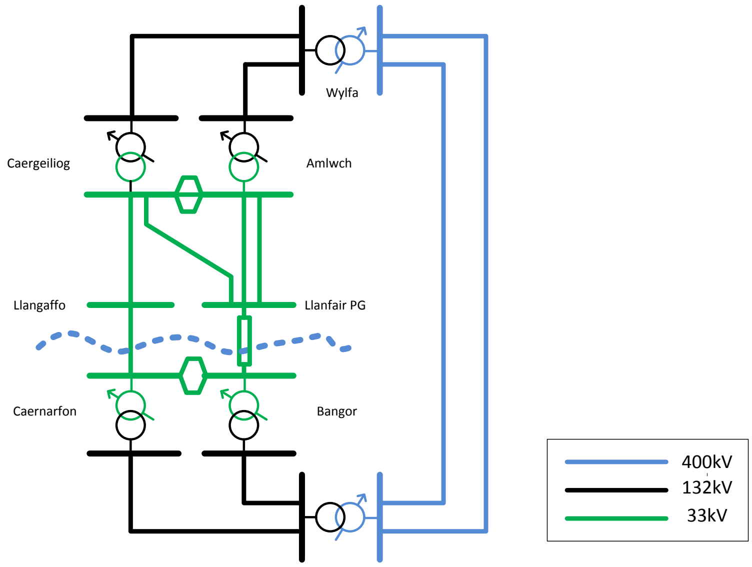


Figure C-1: Schematic network diagram

The demand in Anglesey is anticipated to increase significantly over the next 10 years due to various regeneration and development projects. There is currently approximately 80MW of low carbon generation connected to the 33kV system on Anglesey with a further 83MW that is currently contracted. The level of generation connection activity in the area is extremely high and it is anticipated to increase significantly throughout the RIIO- ED1 period. The coloured circles in Figure C-2 show the connection points of renewables to the Anglesey network.

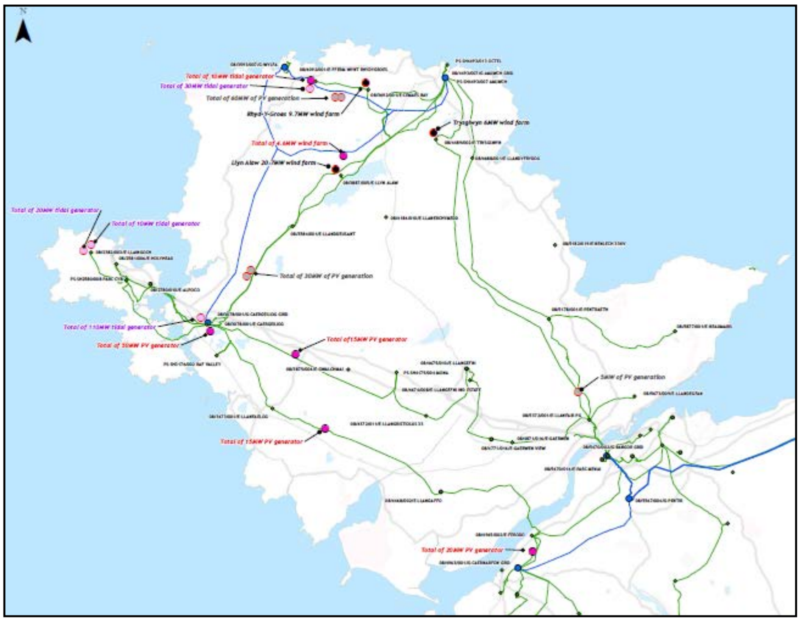


Figure C-2 : Anglesey Distributed Generation, 132kV and 33kV assets

With the existing pressures on the network, the two grid transformers operate close to thermal limits during outage conditions and will exceed thermal limits with forecast demand growth during RIIO-ED1. A scheme to reinforce the demand group on Anglesey was designed in 2011/12 and submitted as part of the RIIO-ED1 business plan. The proposal was to establish a new grid transformer at Llanfair PG and a new 33kV circuit on the island. The submitted scheme was expected to significantly increase the thermal demand capacity on Anglesey and facilitate the separation of the Anglesey 33kV group from the mainland. This would in turn maintain fault level limits and provide an additional 132kV infeed to the island from the mainland that would improve operational security.

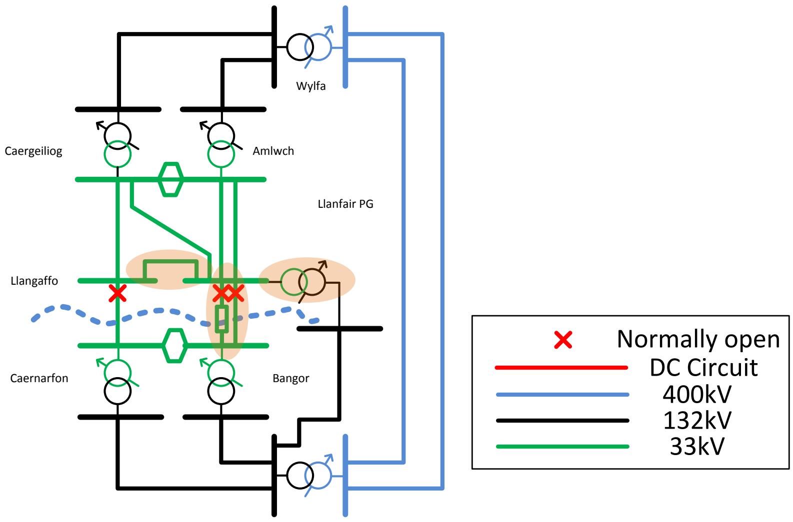


Figure C-3: Anglesey Distributed Generation, 132kV and 33kV assets

In recent years, this area of the network has undergone very high levels of generation and demand connection activity. The requirement for reinforcement of the distribution network on Anglesey has been re-assessed in order to satisfy the existing demand and generation requirements and accommodate future load growth. As a result Caergeiliog has been identified as the optimum location for the proposed grid transformer where most of the activity has been concentrating in recent years.

With the generation growth in Anglesey together with the potential for imposed 400kV parallel flows, the power flows between the island and mainland are forecast to exceed the capability of the existing circuits. For this reason, options still need to be considered to separate the 33kV electrical network on the Isle of Anglesey from the mainland. Additionally voltage problems are expected in Bangor towards the end of the regulatory period.

Among the different options including phase-shifting transformers, STATCOMs, DC etc. the ANGLE-DC method was identified as a viable solution which maintains the link between Bangor and Llanfair PG in service and at the same time provides an upgraded power corridor between Anglesey and the North Wales mainland. Figure C-4 shows the proposed network arrangement with DC link established between Anglesey and mainland. In addition to the MVDC link the wider Anglesey reinforcement works include the addition of a new grid transformer at Caergeiliog and a 33kV circuit between Caergeiliog and Llanfair PG substations.

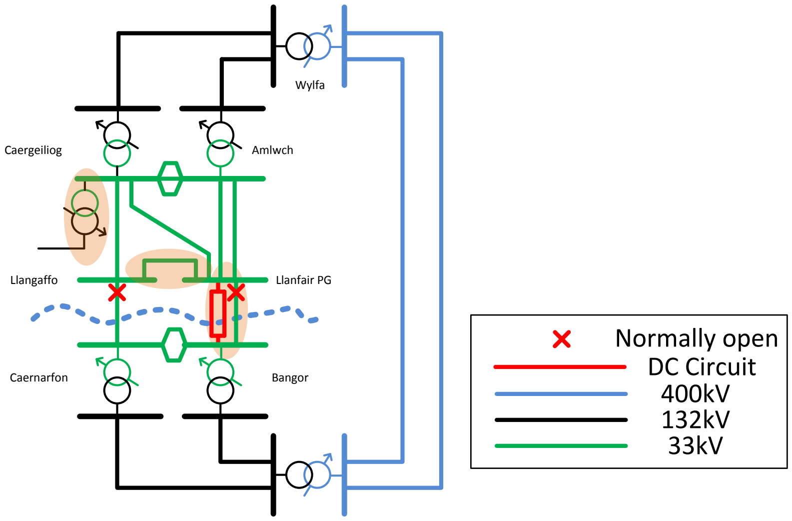


Figure C-4: Proposed DC link

The method will provide an efficient and enduring reinforcement solution to meet the long term energy needs of the island.

Appendix D Financial Analysis

Significant load growth and integration of renewable resources have increased the network complexity and put stress on distribution networks. These issues can be tackled by the ANGLE-DC solution which offers an innovative approach to enhance the flexibility of the network and unlock the full capacity of the existing assets. A 33kV circuit connecting Anglesey (Llanfair PG) to other parts of the North Wales distribution network (Bangor) has been identified where uncontrolled power flows are forecast to exceed thermal limits. Additionally the circuit is located in an area where voltage management is becoming increasingly difficult. As a consequence the link between Bangor-Llanfair PG would be operated in open circuit during normal conditions.

ANGLE-DC will convert the Bangor-Llanfair PG AC circuit to DC by installing MVDC converters at both ends of the existing circuit. This Appendix provides details of the cost benefit analysis for the ANGLE-DC case. The expected benefits after rolling out the solution across GB are also presented.

D.1 Methodology

For the purposes of the capital expenditure assessment we have compared the ANGLE-DC method with a theoretical conventional method of releasing network capacity by installing a collector station in Anglesey (see figure D-2).

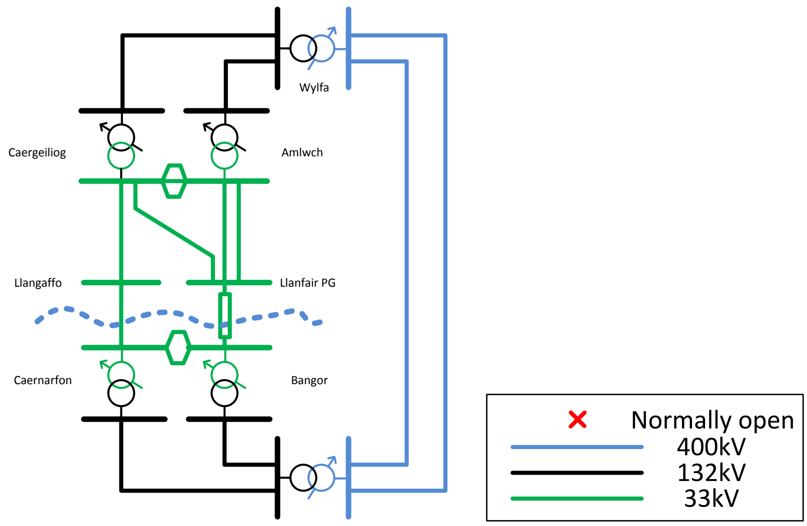


Figure D-1: Existing running arrangement;

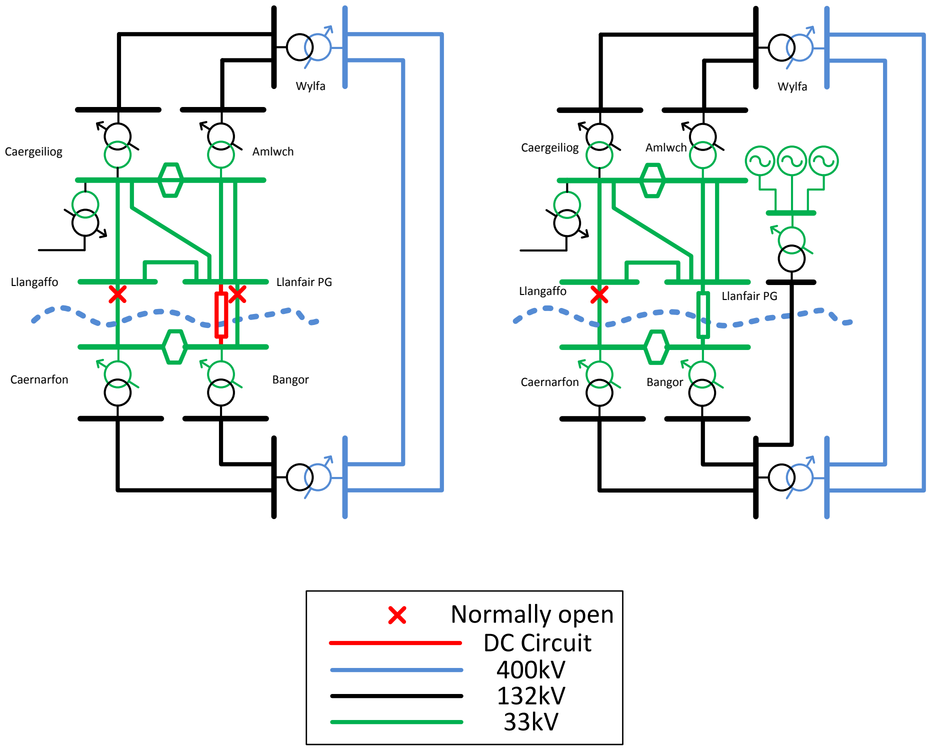


Figure D-2: Left: MVDC option;

Right: Theoretical conventional solution providing the same generation capacity (by creating a new 132kV collecting hub for renewable generation in Anglesey)

All the benefits and investments are calculated by the end of 2030 and 2050. For the GB roll-out phase and ANGLE-DC post-trial replications we have assumed the MVDC technology cost will reduce but the same benefit as ANGLE-DC project would be achieved.

D.2 Business case options

- **Option 1 (Base case): Installation of a new grid transformer**
  The theoretical alternative conventional method to deliver 30.5MW of generation capacity involves the installation of a new grid transformer with the associated 132kV circuit, 132kV switchgear and 33kV switchgear.

- **Option 2: MVDC link**
  This option represents the ANGLE-DC solution which will convert the Bangor-Llanfair PG AC circuit to DC by using MVDC converters at both ends. As there is no market for MVDC at this time, the technology solutions proposed by different suppliers can be anticipated to be quite different in detail design and consequently cost. The initial supplier engagement was utilised to inform the cost of the MVDC link including the two converters, interface transformers and associated elements We have also considered civil works, site preparation and resources**. It should be noted that the cost estimation reflects the trial cost and MVDC technology will become cheaper when it is proven successful.**

D.3 Benefits

The following benefits are expected to be gained by deploying the ANGLE-DC (Option2) solution:

- Increase the network capacity by around 30.5MW;
- Achieve capex saving compared with the theoretical conventional base case**;**
- Reduction of losses by around 20% in North Wales and Anglesey area which is equal to a saving of £630k annually.

Capital benefit

As described in section 2.3.3, the ANGLE-DC solution will use DC technologies to secure a link between Bangor and Llanfair PG whereby 30.5MW of network will be released. A theoretical alternative conventional means to release 30.5MW of generation capacity involves the installation of a new grid transformer. The ANGLE-DC method results in a net capital saving when the two options are compared**.**

Losses reduction

SP Energy Networks have commissioned a desktop study comparing the network losses for two cases:

1-Network with conventional reinforcement in Anglesey which does not offer any power flow and voltage controllability;

2-Network with ANGLE-DC solution.

The results showed that the network losses can be reduced for different loading conditions and in total a reduction of 20% is expected in losses on the North Wales area. Table D-1 shows a summary of the results of losses calculated for the two aforementioned cases.

Table D-1: Reduction in losses

	Conventional	30MVA MVDC link
Network condition	Real Power Losses (MWh/year)	Real Power Losses (MWh/year)
Winter Max	2473	1633
Winter Min	10347	11823
Summer Max	28730	17767
Summer Min	24153	16545
Converter losses	-	4905
Total	**65703**	**52673**

The unit cost for losses is assumed to be £48.42/MWh as given in the Ofgem CBA spreadsheet. The annual savings associated with loss reduction are estimated to be £630k.

CO_2 Emission reduction

Additionally both options will create headroom that can be used to transport renewable generation between Anglesey and North Wales. The ANGLE-DC solution can be used to transport up to 45.4GWh of renewable generation across the link annually. This value has not been monetised for the purposes of the financial analysis.

D.4 Financial analysis

For the purpose of the financial benefit analysis, as explained in the methodology, we have compared the MVDC solution (Option2) against Option1. Our financial analysis showed that Option 2 will be more attractive. Table D-2 shows the benefits and investment compared with the Base Case by 2030 and 2050 if the ANGLE-DC solution is deployed.

Table D-2 : Financial benefits

	2030	2050
Total benefits	£10.47m	£18.67m

D.5 Rollout across GB

In line with the spirit of NIC, if ANGLE-DC is proven successful, the benefits from ANGLE-DC will not stop at this application but will add value to strategically unlock the potential of existing network assets and facilitate competition in the supply chain of power electronic converters. For future applications it is expected that MVDC will compete with other conventional reinforcement schemes.

SP Energy Networks commissioned a study to estimate the number of sites in the UK where the ANGLE-DC solution may be replicated in future. This study included an assessment of the voltage profile and circuit loading heat maps on UK DNOs' networks and suggested that 20 to 25 sites could benefit from the enhanced benefits offered by MVDC circuits across the UK by 2040. The number of UK replications is shown in Figure D-3.

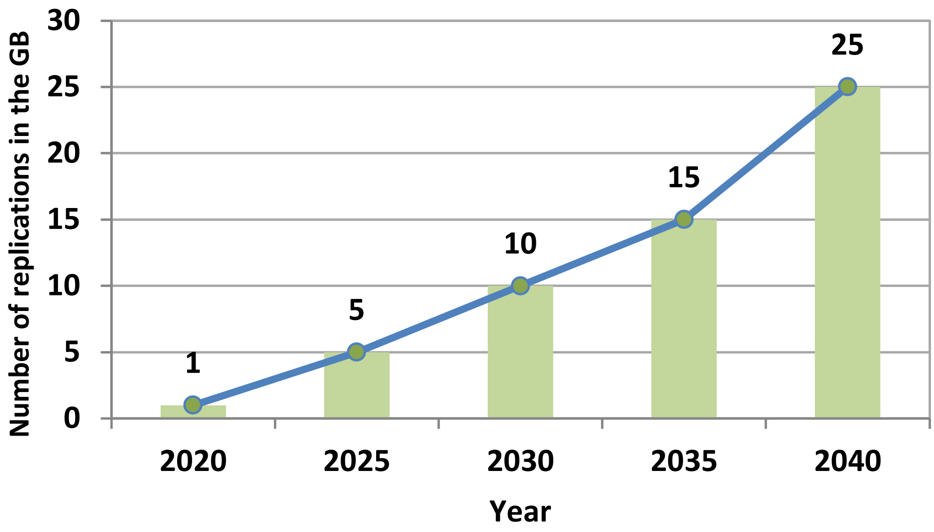


Figure D-3: Number of sites in the GB where ANGLE-DC solution will be replicated

The capital investment of MVDC for the trial will be reduced in post-trial phases:

i) R&D activities will be minimised due to learning, knowledge and optimum design created in the ANGLE-DC trial;
ii) The MVDC supply market will be more competitive after the ANGLE-DC trial;

iii) The maturity of the technology will be enhanced and the power electronic devices will be cheaper.

In order to model the cost reduction of MVDC, a type 3 cost reduction curve as per the Work Stream 3 report – "Assessing the Impact of Low Carbon Technologies on Great Britain's Power Distribution Networks" – has been used for the power electronics elements. Figure D-4 shows the cost reduction curves presented at the Work Stream 3 report.

The real benefit of the ANGLE-DC project can be revealed by comparing with the conventional approach of installing additional transformers and circuits. The MVDC solution could be installed at least one year faster than the base case alternative.

In order to model the cost variation of conventional solutions, a type 1 cost reduction curve as per the Work Stream 3 report – "Assessing the Impact of Low Carbon Technologies on Great Britain's Power Distribution Networks" – has been used. Figure D-4 shows the cost curves presented at the Work Stream 3 report

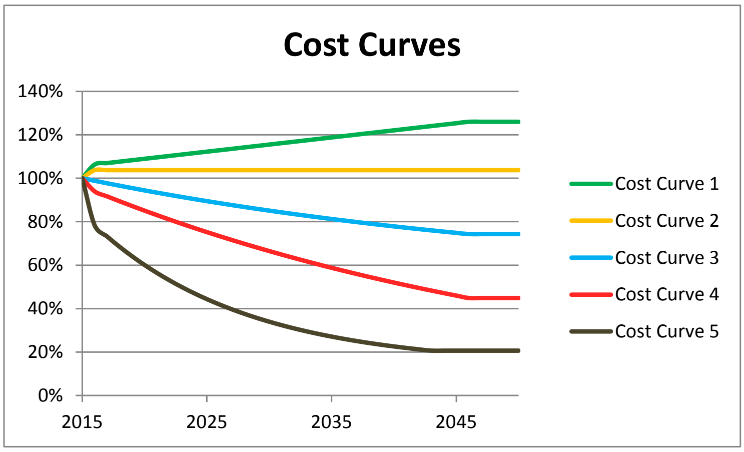


Figure D-4: Cost Curves

- Cost Curve 1 – conventional solutions with a high aluminium, steel or copper content;
- Cost Curve 2 – the default position, flat profile;
- Cost Curve 3 – New solutions where volumes are expected to be low (EHV);
- Cost Curve 4 – New solutions where volumes are expected to be moderate (HV, LV);
- Cost Curve 5 – New solutions where volumes are expected to be high.

The financial benefits accruing to MVDC links including capital savings and reduction in network losses are summarised in Table D-3.

Table D-3: Financial benefits of ANGLE-DC rollout

	2020	2030	2050
Total benefits	£4.2m	£69.2m	£396.0m

The same level of capacity release has been conservatively assumed for each future replication of the ANGLE-DC project. This released capacity can be available at least one year faster than the conventional reinforcement approach. Table D-4 shows the total estimated capacity released in the roll-out phase of ANGLE-DC[11].

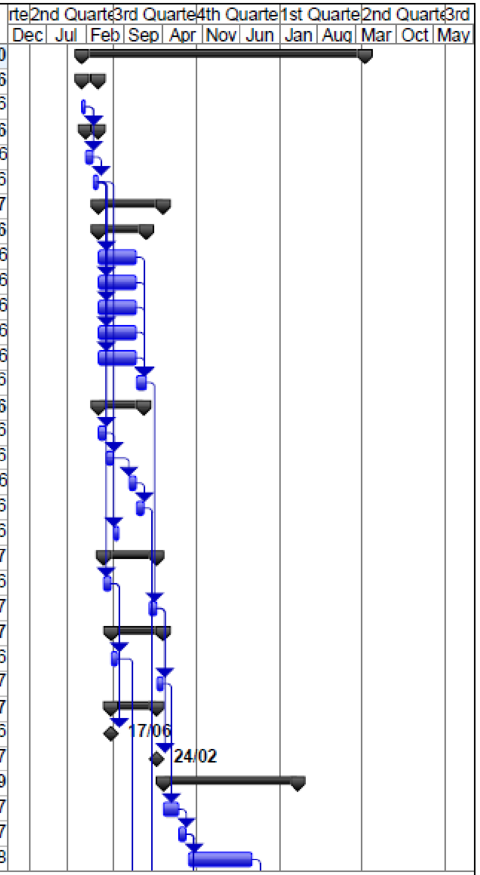
Table D-4: Carbon benefits of ANGLE-DC rollout

	2020	2030	2050
GWh	45.4	454.2	1135.5

[11] A 17% factor is calculated based on the generation load factors published by DECC on renewable resources and the generation portfolio in the Anglesey area.

Appendix E Project Plan

ID	Task Name	Duration	Start	Finish
1	**ANGLE-DC**	**1115 days**	**Mon 11/01/16**	**Thu 16/04/20**
2	**Project setup**	**65 days**	**Mon 11/01/16**	**Fri 08/04/16**
3	Project initiation document	15 days	Mon 11/01/16	Fri 29/01/16
4	**Formalise team structure: Project manager, Project board, Delivery team**	**50 days**	**Mon 01/02/16**	**Fri 08/04/16**
5	Identify project partners	30 days	Mon 01/02/16	Fri 11/03/16
6	Develop collaboration agreement with project partners	20 days	Mon 14/03/16	Fri 08/04/16
7	**WP1 - Detailed design**	**255 days**	**Mon 11/04/16**	**Fri 31/03/17**
8	**Detailed system analysis**	**190 days**	**Mon 11/04/16**	**Fri 30/12/16**
9	Generation, demand scenarios analysis	150 days	Mon 11/04/16	Fri 04/11/16
10	Normal and fault conditions analysis	150 days	Mon 11/04/16	Fri 04/11/16
11	Harmonic analysis	150 days	Mon 11/04/16	Fri 04/11/16
12	Development of control strategy	150 days	Mon 11/04/16	Fri 04/11/16
13	Development of protection strategy	150 days	Mon 11/04/16	Fri 04/11/16
14	Q&A and approval	40 days	Mon 07/11/16	Fri 30/12/16
15	**Cable capability evaluation**	**180 days**	**Mon 11/04/16**	**Fri 16/12/16**
16	Development of test specification	30 days	Mon 11/04/16	Fri 20/05/16
17	Procurement for cable test	30 days	Mon 23/05/16	Fri 01/07/16
18	Cable capability test	30 days	Mon 26/09/16	Fri 04/11/16
19	Cable capability evaluation report	30 days	Mon 07/11/16	Fri 16/12/16
20	MVDC market research update	20 days	Mon 04/07/16	Fri 29/07/16
21	**Development of technical specifications**	**210 days**	**Mon 09/05/16**	**Fri 24/02/17**
22	Develop holistic condition monitoring equipment technical specification	30 days	Mon 09/05/16	Fri 17/06/16
23	Develop MVDC link technical specification	30 days	Mon 16/01/17	Fri 24/02/17
24	**Develoment of invitation to tender documents**	**205 days**	**Mon 20/06/16**	**Fri 31/03/17**
25	Develop invitation to tender documents for holistic condition monitoring equipment	25 days	Mon 20/06/16	Fri 22/07/16
26	Develop invitation to tender documents for MVDC link	25 days	Mon 27/02/17	Fri 31/03/17
27	**SDRCs**	**180 days**	**Fri 17/06/16**	**Fri 24/02/17**
28	Publication of technical specification for monitoring system	0 days	Fri 17/06/16	Fri 17/06/16
29	Publication of technical specification for the MVDC link	0 days	Fri 24/02/17	Fri 24/02/17
30	**WP2 - MVDC Link**	**530 days**	**Mon 03/04/17**	**Fri 12/04/19**
31	Procurement and vendor evaluation	60 days	Mon 03/04/17	Fri 23/06/17
32	Sign the contract	30 days	Mon 26/06/17	Fri 04/08/17
33	Equipment production	250 days	Mon 21/08/17	Fri 03/08/18



Project: ANGLE-DC Project Plan
Date: Tue 20/10/15

Task	External Milestone	Manual Summary Rollup
Split	Inactive Task	Manual Summary
Milestone	Inactive Milestone	Start-only
Summary	Inactive Summary	Finish-only
Project Summary	Manual Task	Progress
External Tasks	Duration-only	Deadline

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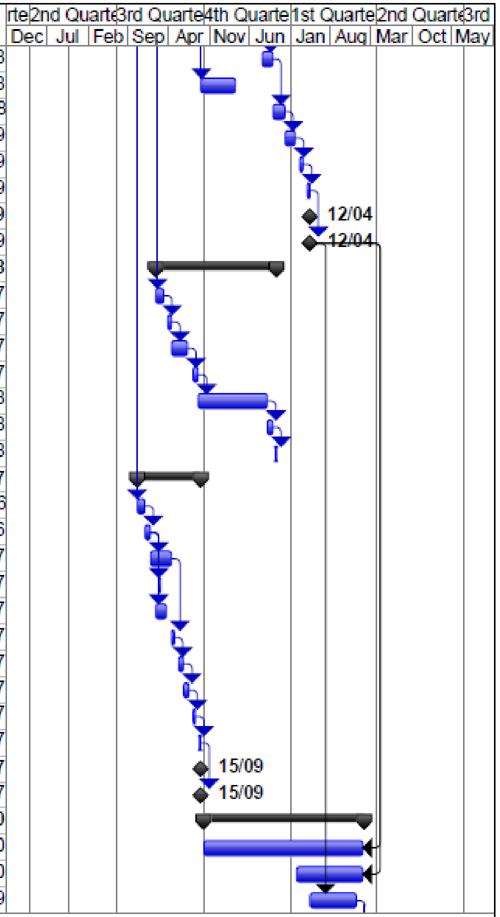
ID	Task Name	Duration	Start	Finish
34	Factory acceptance test	40 days	Mon 06/08/18	Fri 28/09/18
35	Site preparation, civil, communications and electrical	130 days	Mon 18/09/17	Fri 16/03/18
36	Equipment delivery	45 days	Mon 01/10/18	Fri 30/11/18
37	Equipment installation	40 days	Mon 03/12/18	Fri 25/01/19
38	Site acceptance test	15 days	Mon 18/02/19	Fri 08/03/19
39	Commissioning	10 days	Mon 01/04/19	Fri 12/04/19
40	**SDRCs**	**0 days**	**Fri 12/04/19**	**Fri 12/04/19**
41	Installation of MVDC link	0 days	Fri 12/04/19	Fri 12/04/19
42	**WP3 - AC System**	**455 days**	**Mon 23/01/17**	**Fri 19/10/18**
43	Detailed circuit design	30 days	Mon 23/01/17	Fri 03/03/17
44	Procurement	15 days	Mon 27/03/17	Fri 14/04/17
45	Wayleaves	60 days	Mon 17/04/17	Fri 07/07/17
46	Equipment delivery	20 days	Mon 07/08/17	Fri 01/09/17
47	Installation	260 days	Mon 04/09/17	Fri 31/08/18
48	Protection settings	20 days	Mon 03/09/18	Fri 28/09/18
49	Commissioning	5 days	Mon 15/10/18	Fri 19/10/18
50	**WP4 - Holistic Condition Monitoring**	**240 days**	**Mon 17/10/16**	**Fri 15/09/17**
51	Procurement and vendor evaluation	30 days	Mon 17/10/16	Fri 25/11/16
52	Sign the contract	20 days	Mon 28/11/16	Fri 23/12/16
53	Equipment production	80 days	Mon 26/12/16	Fri 14/04/17
54	Factory acceptance test	10 days	Mon 06/02/17	Fri 17/02/17
55	Site preparation	40 days	Mon 23/01/17	Fri 17/03/17
56	Equipment delivery	10 days	Mon 17/04/17	Fri 28/04/17
57	Equipment installation	20 days	Mon 22/05/17	Fri 16/06/17
58	Communications	20 days	Mon 19/06/17	Fri 14/07/17
59	Site acceptance test	10 days	Mon 07/08/17	Fri 18/08/17
60	Commissioning	5 days	Mon 11/09/17	Fri 15/09/17
61	**SDRCs**	**0 days**	**Fri 15/09/17**	**Fri 15/09/17**
62	Commissioning of Holistic Condition Monitoring systems	0 days	Fri 15/09/17	Fri 15/09/17
63	**WP 5 - Data Analysis**	**605 days**	**Mon 02/10/17**	**Thu 23/01/20**
64	Gather Holistic Condition Monitoring data	600 days	Mon 02/10/17	Thu 16/01/20
65	MVDC system setting adjustments	250 days	Mon 04/02/19	Thu 16/01/20
66	Develop policy documents for MVDC applications	175 days	Mon 15/04/19	Thu 12/12/19



Project: ANGLE-DC Project Plan
Date: Tue 20/10/15

Task		External Milestone		Manual Summary Rollup	
Split		Inactive Task		Manual Summary	
Milestone		Inactive Milestone		Start-only	
Summary		Inactive Summary		Finish-only	
Project Summary		Manual Task		Progress	
External Tasks		Duration-only		Deadline	

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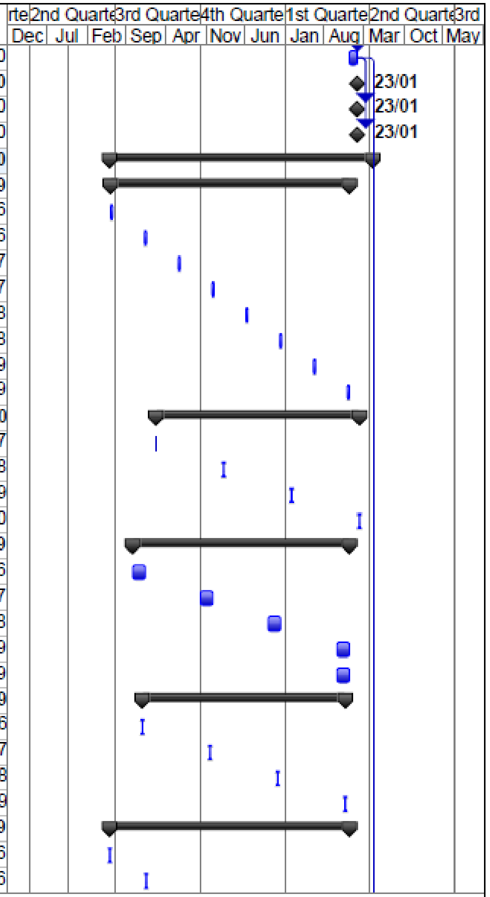
RIIO NIC NETWORK INNOVATION COMPETITION

ID	Task Name	Duration	Start	Finish
67	Report writing	30 days	Fri 13/12/19	Thu 23/01/20
68	**SDRCs**	**0 days**	**Thu 23/01/20**	**Thu 23/01/20**
69	Publication of Holistic Condition Monitoring data	0 days	Thu 23/01/20	Thu 23/01/20
70	Publication of operation performance of MVDC converters	0 days	Thu 23/01/20	Thu 23/01/20
71	**WP 6 - Dissemination**	**1013 days**	**Wed 01/06/16**	**Thu 16/04/20**
72	**6 monthly progress report**	**921 days**	**Mon 06/06/16**	**Fri 13/12/19**
73	Report 1	10 days	Mon 06/06/16	Fri 17/06/16
74	Report 2	10 days	Mon 05/12/16	Fri 16/12/16
75	Report 3	10 days	Mon 05/06/17	Fri 16/06/17
76	Report 4	10 days	Mon 04/12/17	Fri 15/12/17
77	Report 5	10 days	Mon 04/06/18	Fri 15/06/18
78	Report 6	10 days	Mon 03/12/18	Fri 14/12/18
79	Report 7	10 days	Mon 03/06/19	Fri 14/06/19
80	Report 8	10 days	Mon 02/12/19	Fri 13/12/19
81	**Workshops**	**783 days**	**Mon 06/02/17**	**Tue 04/02/20**
82	MVDC Technical Design	2 days	Mon 06/02/17	Tue 07/02/17
83	Real-Time Circuit Condition Monitoring	2 days	Mon 05/02/18	Tue 06/02/18
84	MVDC Manufacturing and Site Preparation	2 days	Mon 04/02/19	Tue 05/02/19
85	MVDC Link Performance Review	2 days	Mon 03/02/20	Tue 04/02/20
86	**Webinars**	**836 days**	**Mon 03/10/16**	**Fri 13/12/19**
87	MVDC technoloigy and Supplier Engagement	50 days	Mon 03/10/16	Fri 09/12/16
88	Real-Time Circuit Condition Monitoring systems for AC and DC applications	50 days	Mon 02/10/17	Fri 08/12/17
89	MVDC manufacturing	50 days	Mon 01/10/18	Fri 07/12/18
90	Cable ageing mechanism in AC and DC conditions	50 days	Mon 07/10/19	Fri 13/12/19
91	MVDC performance in real-life and data analysis	50 days	Mon 07/10/19	Fri 13/12/19
92	**LCNI conference**	**784 days**	**Wed 23/11/16**	**Fri 22/11/19**
93	LCNI 2016	3 days	Wed 23/11/16	Fri 25/11/16
94	LCNI 2017	3 days	Wed 22/11/17	Fri 24/11/17
95	LCNI 2018	3 days	Wed 21/11/18	Fri 23/11/18
96	LCNI 2019	3 days	Wed 20/11/19	Fri 22/11/19
97	**SPEN innovation website update**	**924 days**	**Wed 01/06/16**	**Fri 13/12/19**
98	6 monthly update 1	3 days	Wed 01/06/16	Fri 03/06/16
99	6 monthly update 2	3 days	Wed 14/12/16	Fri 16/12/16



Project: ANGLE-DC Project Plan
Date: Tue 20/10/15

Task		External Milestone		Manual Summary Rollup	
Split		Inactive Task		Manual Summary	
Milestone		Inactive Milestone		Start-only	
Summary		Inactive Summary		Finish-only	
Project Summary		Manual Task		Progress	
External Tasks		Duration-only		Deadline	

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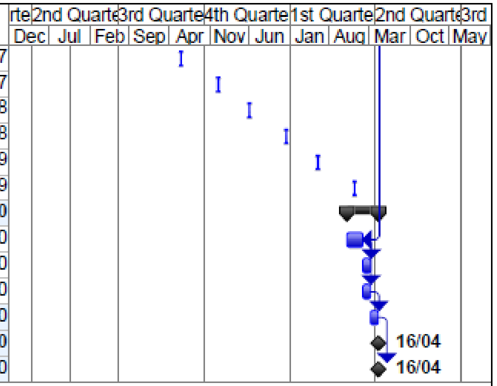
RIIO NIC NETWORK INNOVATION COMPETITION

ID	Task Name	Duration	Start	Finish
100	6 monthly update 3	3 days	Tue 30/05/17	Thu 01/06/17
101	6 monthly update 4	3 days	Thu 14/12/17	Mon 18/12/17
102	6 monthly update 5	3 days	Wed 30/05/18	Fri 01/06/18
103	6 monthly update 6	3 days	Wed 12/12/18	Fri 14/12/18
104	6 monthly update 7	3 days	Wed 29/05/19	Fri 31/05/19
105	6 monthly update 8	3 days	Wed 11/12/19	Fri 13/12/19
106	**Close-down report**	**120 days**	**Fri 01/11/19**	**Thu 16/04/20**
107	First draft preparation	60 days	Fri 01/11/19	Thu 23/01/20
108	Internal review	30 days	Fri 24/01/20	Thu 05/03/20
109	External consultation	30 days	Fri 24/01/20	Thu 05/03/20
110	Final submission	30 days	Fri 06/03/20	Thu 16/04/20
111	**SDRCs**	**0 days**	**Thu 16/04/20**	**Thu 16/04/20**
112	Effective Knowledge Dissemination	0 days	Thu 16/04/20	Thu 16/04/20



Project: ANGLE-DC Project Plan
Date: Tue 20/10/15

Task		External Milestone		Manual Summary Rollup	
Split		Inactive Task		Manual Summary	
Milestone		Inactive Milestone		Start-only	
Summary		Inactive Summary		Finish-only	
Project Summary		Manual Task		Progress	
External Tasks		Duration-only		Deadline	

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Appendix F Roles and Responsibilities

The ANGLE-DC project structure team was introduced in Section 6.1.9. The delivery team mainly consists of two distinctive technical teams, namely the MVDC link technical team and the Circuit condition monitoring technical team.

The MVDC link technical team will be comprised of SP Manweb Design Engineers, consultant specialist in DC technology and MVDC equipment supplier. This team will be responsible for:

- Desktop modelling of the MVDC link performance under various network conditions;
- Developing detailed MVDC converters technical specifications;
- Carrying out detailed site design at Bangor and Llanfair PG substations and providing all drawings and documentation;
- Conducting site preparation activities including civil works, electrical wirings etc;
- Providing protection settings in conjunction with MVDC link voltage and power control strategy;
- Liaise with SP Manweb Health and Safety (H&S) to ensure the compliance of designs and installation procedures with approved policies;
- Developing a detailed method statement for the MVDC link installation;
- Carrying out factory acceptance test of MVDC equipment;
- Conducting site acceptance test for MVDC link and commissioning;
- Developing policy documents, technical guidance and recommendations for planning, procurement and operation of the MVDC link;
- Carrying out diagnostic or maintenance measures required on the MVDC link after commissioning and during the life-time of the ANGLE-DC project;
- Providing data analysis on the performance of the MVDC link at different loading and network conditions;
- Liaise with the ANGLE-DC Knowledge Coordinator to capture and disseminate the lessons learned.

The Circuit condition monitoring technical team will be comprised of the SP Energy Networks IT team, consultant specialist in assets DC operations and cable monitoring systems and equipment supplier. This team will be responsible for:

- Developing real-time holistic condition monitoring system architecture;
- Developing specifications for monitoring equipment;
- Developing a site specific method statement for the installation of the monitoring equipment;
- Conducting factory acceptance tests;
- Installation of the monitoring equipment ;
- Conducting site acceptance tests, end-to-end diagnostic tests and commissioning;
- Providing analysis on recorded partial discharge data under different loading (or conductor temperature) conditions;
- Liaise with the ANGLE-DC Knowledge Coordinator to capture and disseminate the lessons learned.

Appendix G Risk Register

Risk No.	Issue	Risk Description	Potential Impact	Inherent Risk: Probability (1-5)	Inherent Risk: Financial Impact (1-5)	Inherent Risk: Reputation Impact (1-3)	Inherent Risk: Overall Risk (2-40)	Control and Contingency Measures	Residual Risk: Probability (1-5)	Residual Risk: Financial Impact (1-5)	Residual Risk: Reputation Impact (1-3)	Residual Risk: Overall Risk (2-40)
1. Technical risks												
1.01	Existing cables integrity with DC	Cables are unsuitable for DC operation at 27kV either due to age or type.	Project halted; delayed reinforcement and no demonstration of conversion to MVDC.	3	5	2	21	1. System operating DC voltage level kept at or below peak AC voltage level (27kV). 2. Conductor temperature limited to a maximum of 50°C for all cables. 3. Short time 27kV DC testing completed on the circuit with no problems.	1	3	2	5
1.02	Existing cable joints integrity with DC	Joints are unsuitable for DC operation at 27kV due to age or type.	Project halted; delayed reinforcement and no demonstration of conversion to MVDC.	3	4	2	18	1. System operating DC voltage level kept at or below peak AC voltage level (27kV). 2. Conductor temperature limited to a maximum of 50°C for all cables types. 3. Short time 27kV DC testing completed on the circuit with no problems	2	3	2	10
1.03	Harmonic interference	Superimposed high frequency interference on MVDC in existing cables couples with third party services.	Delay and additional cost to project in order to resolve problems for third parties.	3	3	3	18	Perform a study of VSC converter harmonics and determine likely interference on telecom and transport signalling after a study of installed services and harmonics to be generated. VSC converter filters to be designed to be adequate by converter supplier.	1	2	3	5
1.04	Earthing with DC	High DC earth return currents.	Discontinued operation and additional cost to project to improve earthing arrangements.	2	4	2	12	VSC converter study required to determine the best converter arrangement for this application to reduce the level of earth return currents during normal and abnormal operation.	1	3	2	5
1.05	Existing cables integrity with DC	Cable fails on first energisation	Project halted; additional costs to move MVDC converters for use elsewhere as converters or STATCOMS.	3	4	2	18	1. Short time 27kV DC testing completed on the circuit with no problems. 2. All cables to be fully discharged over an extended period (at least 24 hours) before DC energisation.	2	3	2	10
1.06	Existing OHL integrity with DC	Suitability of existing OHL for DC operation	Flashovers across the insulators that provide structural support between the conductors and towers are likely to necessitate switching off the whole of the MVDC scheme for a period of time.	3	2	1	9	Perform study of OHL insulation requirements for designed DC voltage, visually inspect insulators on existing line and replace if necessary.	3	2	1	9
1.07	Practical realisation of capacity gain	Theoretical capacity gain with DC cannot be achieved.	Anticipated further deployments in the UK will be discouraged by less attractive business case.	2	3	3	12	Prior to decisions to proceed, pre-engineering studies will be carried out for the identified circuit to determine requirements for prudent operation and resulting anticipated capacity release	1	1	1	2
1.08	Practical flexibility for replication of technology	Ambitious advancement of a combination of technologies from TRL in the region of 5 to TRL 7 cannot be achieved to facilitate project replications.	Anticipated further deployments in the UK will be discouraged by prohibitive cost to overcome unproven aspects.	2	2	2	8	Informal discussions have taken place with several potential vendors to understand the range of technology available for MVDC converters and constraints. A realistic functional specification has been developed in the proposal phase, and will be developed in the initial design phase to produce a detailed technical specification for the procurement process.	1	2	1	3
			Summative Risk Scores	21	27	17	116		12	19	14	49
2. Procurement, manufacturing and installation risks												
2.01	Few suppliers of MVDC equipment	Limited number of tender returns from vendors for procurement of MVDC converters.	Receipt of uncompetitive tenders that are not in line with principles of good value for money for customers; decision to halt innovation project.	2	3	3	12	Informal discussions have taken place with several potential vendors and we are confident that we will receive several tender returns through the conventional competitive bid process. Efforts will continue to be made to ensure that the specification requirements are reasonable and realistic for commercial offerings to be received.	1	2	2	4

				Inherent Risk					Residual Risk			
Risk No.	Issue	Risk Description	Potential Impact	Probability (1-5)	Financial Impact (1-5)	Reputation Impact (1-3)	Overall Risk (2-40)	Control and Contingency Measures	Probability (1-5)	Financial Impact (1-5)	Reputation Impact (1-3)	Overall Risk (2-40)
2.02	Size of equipment	Insufficient available space and/or site access for installation of large plant items	Significant loss of investment in large equipment that cannot be installed; delays to reinforcement.	2	4	2	12	Preliminary assessments indicate that access is possible for plant and space is available at both sites.	1	3	2	5
2.03	Cost of installation of AC system is significantly higher than estimated	Prohibitive cost of cable installation for AC system. These costs are site-specific and heavily dependent on excavation costs (in this case directional drilling costs), with a high variance.	High cost of crucial mitigation measure delays entire innovative demonstration project.	3	5	3	24	1. Perform thorough pre-engineering studies before defining the detailed cable route. 2. Pause the project if there is no space available on the bridge.	2	3	2	10
2.04	Easements/ wayleaves	Inability to obtain a wayleave / easement for the parallel subsea AC standby circuit.	Lack of wayleave / easement for crucial mitigation measure delays entire innovative demonstration project.	3	5	3	24	Perform thorough pre-engineering studies before defining the detailed cable route and liaise closely with planning authorities.	2	3	2	10
2.05	Cost of MVDC equipment	Prohibitive cost of MVDC equipment which is significantly higher than the estimated cost in proposal stage.	Project budget is not enough for delivery of the project objectives and project should be halted	3	5	3	24	1. Develop an optimum design for MVDC equipment and ensure unnecesary and expensive specifications will not be part of final specifications 2. Carry out competetive tendering process to ensure the best value for money	2	3	2	10
2.06	Damaged equipment	Equipment arrive on site are damaged due to improper packaging and shipment	Significant effect on delivery time and project programme	3	5	3	24	1- Ensure proper packaging and shipment with supplier 2- include appropriate penalties in terms and conditions to protect the project againt damage or late delivery of the products	2	2	2	8
2.07	Delay in commissioning of monitoring equipment	Holistic monitoring equipment is not in place before energisation of the MVDC link	The impact of conversion from AC to DC, the stress on the cables and possible damaged to the cable circuits cannot be monitored	3	4	3	21	1- Commissioning of the holistic monitoring system iis planned to take place before commissioning of the MVDC link (at least 6 month earlier) 2- Early IT engagement to ensure incorporating monitoring system in SP Energy Networks infrastructure comply with IT security requirements	2	1	2	6
2.08	Delay in delivery of converters	Delay in delivery of the MVDC equipment	The overall impact on timley delivery of the SDRCs and work in other work packages	4	5	3	32	1-Considering contigency time for production of the converters 2- Effective monitoring of the manufacturing process and define set dates for factory acceptance tests at time of contract 3- include approperiate penalties in terms and conditions to protect the project againt damage or late delivery of the products	2	2	2	8
			Summative Risk Scores	23	36	23	173		14	19	16	61
3. Operational risks												
3.01	Landowners	Opposition to the conversion of the AC cable to operate with DC.	Discontinued operation and loss of significant investment.	2	4	3	14	Engage carefully and thoroughly with landowners to explain the change of technology and safe operation of cables under DC.	1	4	2	6
3.02	Reliability of the scheme	Inadequate reliability and availability of MVDC converters	Operation of the link is compromised.	3	4	3	21	1. Efforts will continue to be made to ensure that the specification requirements are reasonable and realistic for commercial offerings. 2. An AC link between Anglesey and Bangor will be commissioned.	1	3	2	5
3.03	Maintenance requirements	Complex system installed that is impossible to maintain in reasonable timescales.	Likely interruptions of supply to customers; and increased costs for additional resources in maintenance teams.	2	3	2	10	Seek to work with the manufacturers to understand maintenance requirements and the impact on the design or selection of components; as well as ongoing training and development of staff.	1	2	2	4
			Summative Risk Scores	7	11	8	45		3	9	6	15

				Inherent Risk					Residual Risk			
Risk No.	Issue	Risk Description	Potential Impact	Probability (1-5)	Financial Impact (1-5)	Reputation Impact (1-3)	Overall Risk (2-40)	Control and Contingency Measures	Probability (1-5)	Financial Impact (1-5)	Reputation Impact (1-3)	Overall Risk (2-40)
4. Project Management risks												
4.01	Higher costs	Cost of scheme higher than anticipated	Exceedance of project budget; and risk of halting the demonstration project.	2	4	2	12	1. FIDIC contract terms should be used, such that the contractor takes on the risk; 2. Commodity price to be hedged. 3. Contingency funding deemed to be reasonable and sufficient.	1	3	1	4
4.02	Experience and HSE	Staff lack of experience and knowledge of new equipment	Inefficient working and errors.	2	5	3	16	1. Support from competent resources in technical design details and project management. 2. Careful selection of the competent staff through interview process 3. Specialist tools and training required for maintenance activity. Procedures to be developed.	1	4	2	6
4.01	Resources	Sufficient resources are not available in SP Energy Networks to deliver the project	Delay in delivery of the project and impact on quality of deliverables	3	4	3	21	1- Effective engagement with Director level in SP Manweb to provide clear understanding about project size and resource required 2- Use competent external resources where necessary	1	2	2	4
			Summative Risk Scores	7	13	8	49		3	9	5	14

Appendix H MVDC Converter Technology

Discussions with technology providers have indicated that there are two alternatives to design a MVDC solution: to scale up an existing medium voltage converter or scale down an HVDC converter. The technology description below is known as a Voltage Source Converter (VSC).

This VSC concept is known as a Modular Multi-level Converter (MMC), which is shown in Figure H-1. The three-phase AC supply (at 33kV) is connected via a transformer to a power electronic circuit which consists of multiple sub-modules. In each phase a series connection of sub-modules (typically 30 - 35) connects the AC bus to the +V DC bus and another series connection to the –V DC bus.

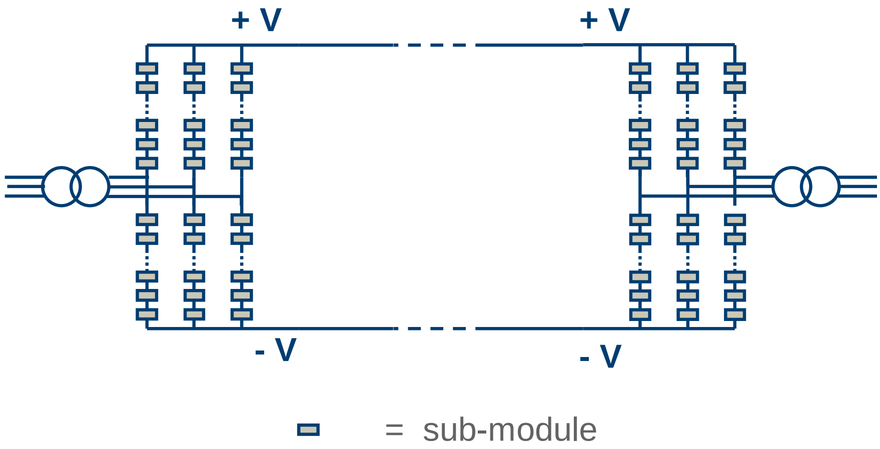


Figure H-1 : MVDC scheme topology

This VSC - MMC arrangement is also the one most widely used for HVDC projects, having completely displaced earlier variants, due to its low operating losses. Thus it is a technology which is widely familiar to the supply chain.

Each sub-module consists of a DC capacitor and an arrangement of power electronic switches, based on Insulated Gate Bi-polar Transistor (IGBT) technology. As simplified sub-module arrangement is shown in Figure H-2 alongside the output voltage waveform available. Each sub-module can only generate one polarity of voltage, either positive in the upper part of the circuit or negative in the lower part. However, there is no requirement to change the converter polarity, as reversing the power flow direction can be achieved by reversing the current flow direction, leaving the voltage polarity constant.

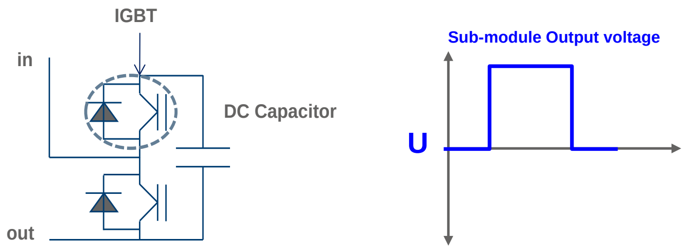


Figure H-2: Sub-module arrangement (left), output voltage waveforms (right)

At any instant one of the IGBT devices in the upper part of the circuit is switched on to inject the positive voltage and in the lower part of the bridge one IGBT is switched on to inject the negative voltage. If required a by-pass IGBT can be closed to give zero output voltage. By controlling the switching pattern, both on and off, of the multiple sub-modules a voltage sinewave can by synthesised as shown in Figure H-3.

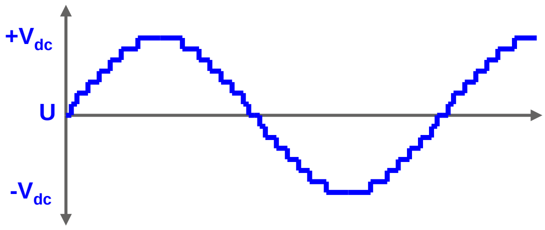


Figure H-3: Output AC voltage from the MMC

With enough sub-modules switched in and out in the correct sequence, an acceptable fundamental frequency voltage sinewave can be produced. By controlling the phase angle of this voltage waveform, with respect to the measured 33kV system voltage, power flow through the MMC can be controlled as required. By controlling the amplitude of this voltage waveform, with respect to the measured 33kV system voltage, reactive power absorption and generation can be controlled as required. This gives the MVDC converter a "4-quadrant" capability, as shown in Figure H-4.

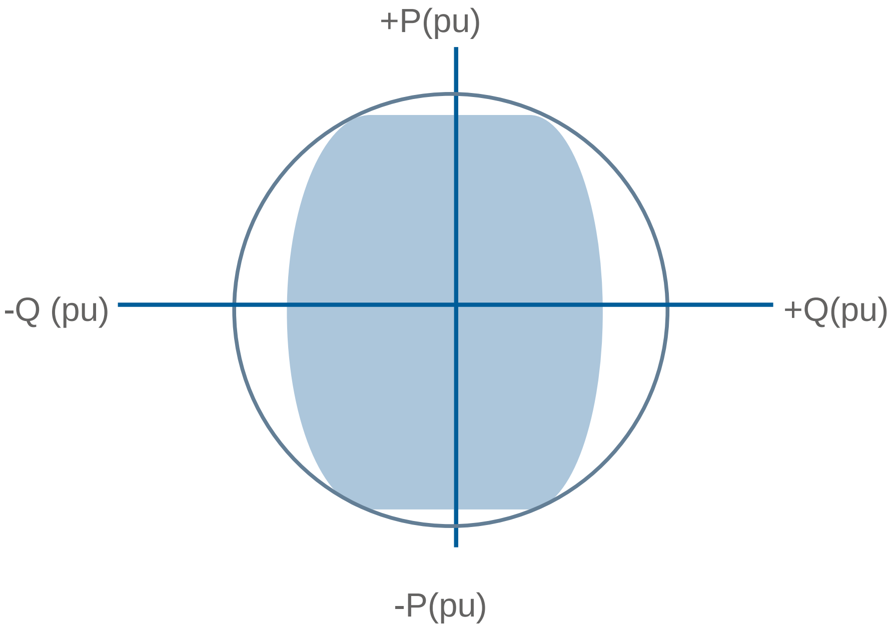


Figure H-4 : Active and Reactive Power Capability

In the ideal case the converter can operate anywhere within the constant MVA circle, but in reality constraints imposed by the voltage and current stresses on the power electronic equipment, limit the operation to the central shaded portion shown in Figure H-4. However, the supplier will be able to adjust the design to achieve the power and reactive power levels required by SP Energy Networks to meet the Distribution Grid Code.

The level of harmonic distortion present in the voltage, which is determined by the number of small steps used to create the sinewave, should be suitable for direct connection to the distribution network, without the need for additional harmonic filters. However, this needs to be checked against the requirements of Engineering Recommendation G5/4, or local SP Energy Networks limits.

As the switching frequency of the IGBTs is low, typically <150Hz, the operating loss is low, approximately 1% per converter station.

The arrangement shown in Figure H-4 is known as a symmetrical monopole, which requires only two conductors (positive and negative) and a single interface transformer at each end of the link. This is the arrangement used in most HVDC schemes, which use the MMC technology. This arrangement has the advantage of simplicity in both the converter design and the transformer design, but during maintenance and any major equipment fault, all power transfer is lost through the link.

Appendix I High Level Functional Specification for MVDC Distribution Link

I.1 Introduction

SP Energy Networks is proposing to convert an existing double circuit 33kV AC circuit to operate at Medium Voltage Direct Current (MVDC). The scheme will link the existing Llanfair PG sub-station on the island of Anglesey to the Bangor sub-station on the Welsh mainland. Figure I-1 shows the location of the sub-stations and the route of the 33kV circuits.

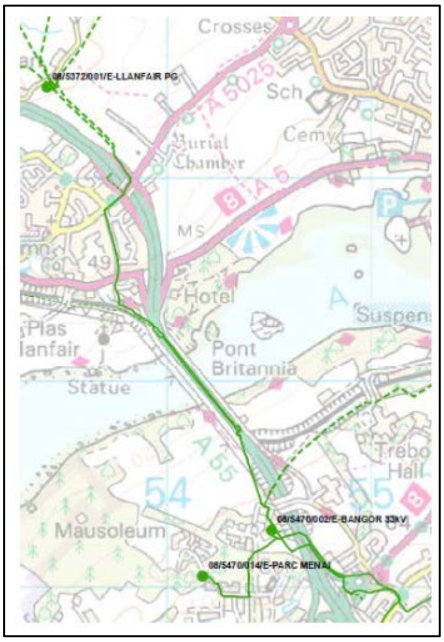


Figure I-1: Proposed MVDC link

The project has a number of aims, including:

- Enhancing the power flow between Anglesey and North Wales;
- Providing more control of the power flow;
- Providing control of reactive power flows, hence influencing wider area voltage profile;
- Reducing operating losses in the wider distribution area;
- Providing additional ancillary services from the link;
- Demonstrate the use of DC technology for distribution applications;
- Demonstrate the conversion of existing AC assets to DC operation;

This specification provides the functional requirements of the MVDC scheme which will be required to achieve the above aims. General electrical and environmental details for the distribution system and location will be provided in separate documents as required.

I.2 Existing AC circuits

The route length between Llanfair PG and Bangor is approximately 3km, which consists of a mix of land cables and short sections of overhead line. The schematic diagram in Figure I-2 illustrates the two AC circuits. Each circuit has multiple sections, with several designs of cables (3-core, 1-core, copper, aluminium) being used. The cables were originally installed in the 1960's, although many, but not all, sections have been replaced with more modern designs.

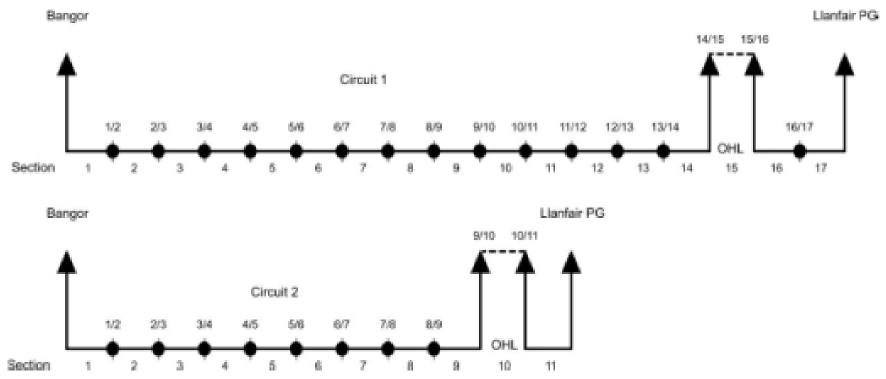


Figure I-2: Existing 33kV AC circuits

Although both circuits are approximately the same length, the DC resistance of the two circuits is not the same.

I.3 Conversion to DC operation

The MVDC scheme should operate as a symmetrical monopole, i.e. with one positive MV terminal and one negative MV terminal, or as a bi-pole, with positive and negative MV terminals and a neutral point. In the latter case a neutral connection between the converter stations is not required, but the neutral at one station shall be grounded. The supplier should indicate if and how they intend to provide a ground reference for a symmetrical monopole scheme.

It is proposed that the three conductors of one existing AC circuit are parallel connected to form one pole conductor and the same for the other circuit. Thus the scheme topology would be as shown in Figure I-3.

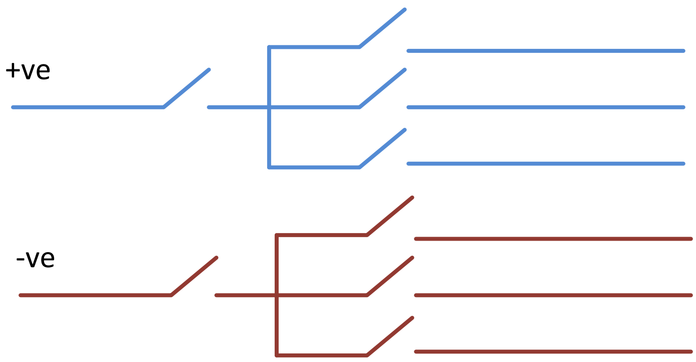


Figure I-3 : Conversion of three phases to two poles

The impact on this arrangement is an unbalance in the resistances of the pole conductors.

The MVDC equipment supplier should comment on the impact the unbalance in the pole conductor resistances would have on the operation of the scheme.

In the event of prolonged loss of one conductor, due to a cable fault, it is proposed that a complimentary conductor on the other pole is taken out of service, by mechanical isolation, to maintain, as close as possible the resistance balance between circuits. The scheme would operate at approximately 67% of normal power under this condition.

I.4 Power rating

The notional power rating of the scheme is 30MW. The supplier should assume that the scheme may operate continuously at this power level with a power factor of lead/lag 0.9, i.e. a scheme rated capacity of 33MVA.

This power rating will be confirmed by detailed evaluation early in the project execution phase and the supplier is requested to comment on how higher power levels could be achieved from their designs.

Bi-directional power transfer capability is required, i.e. the rated power is required in both directions.

The target minimum power transfer level of the scheme shall be 0MW. The supplier shall comment on any difficulty in achieving this level and if not possible, the minimum continuous power level which can be achieved.

Over-load rating of the scheme, i.e. operating at higher DC current, is not required. However, the supplier should comment on which items of equipment in their supply would be the limiting factor for short time overload.

I.5 DC voltage rating

The DC voltage is constrained by the insulation capability of the existing cables. The age of the cables is also a factor in the consideration of the DC voltage.

The notional DC voltage for the scheme is ±27kV.

This voltage rating will be confirmed by detailed evaluation early in the project execution phase and the supplier is requested to comment on how higher voltage levels could be achieved from their designs.

Due to the presence of overhead line sections and the proximity to the sea coast, operation at reduced DC voltage (50 – 80%) may be a requirement under certain climatic conditions. The supplier should comment on how this can be achieved from their equipment.

I.6 Scheme operation

The scheme should be designed for un-manned operation, with remote control via a SCADA system from SP Energy Networks operation centre.

SP Energy Networks operators should be able to dispatch power through the link, either as,

- Pre-set power transfer levels, e.g. 100%, 80%, 60%, etc;
- Vernier control from full load to minimum power.

The power ramp rate shall be adjustable by design, but the operator would implement a fixed rate anticipated to be 30MW/minute. This ramp rate would apply to steps between pre-set power levels and to vernier control.

This ramp rate will be confirmed by detailed evaluation early in the project execution phase and the supplier is requested to comment on what limits on ramp rate could be achieved from their designs.

I.7 Control Modes

a) Power

The primary control mode for the scheme will be power control, i.e. the scheme is able to operate from minimum power to maximum power, transferring power in either direction through the link. By operator selection, each terminal may function as a rectifier (exporting power) or an inverter (importing power).

b) DC voltage

The inverter terminal should control the DC voltage and the rectifier terminal should control the DC current and hence power flow.

c) Reactive power

The scheme should be able to control reactive power absorption and generation at each terminal independently and also independent from the direction of power flow. Thus a full “4 – quadrant” capability is required for real and reactive power, as illustrated in Figure 5.

It is anticipated that the voltage or and/or current ratings of the equipment may introduce a limitation on the full 4 – quadrant operation of the converter, as indicated by the inner shape in Figure I-4. The supplier is requested to confirm the converter operating capability at the points indicated in Table I-1.

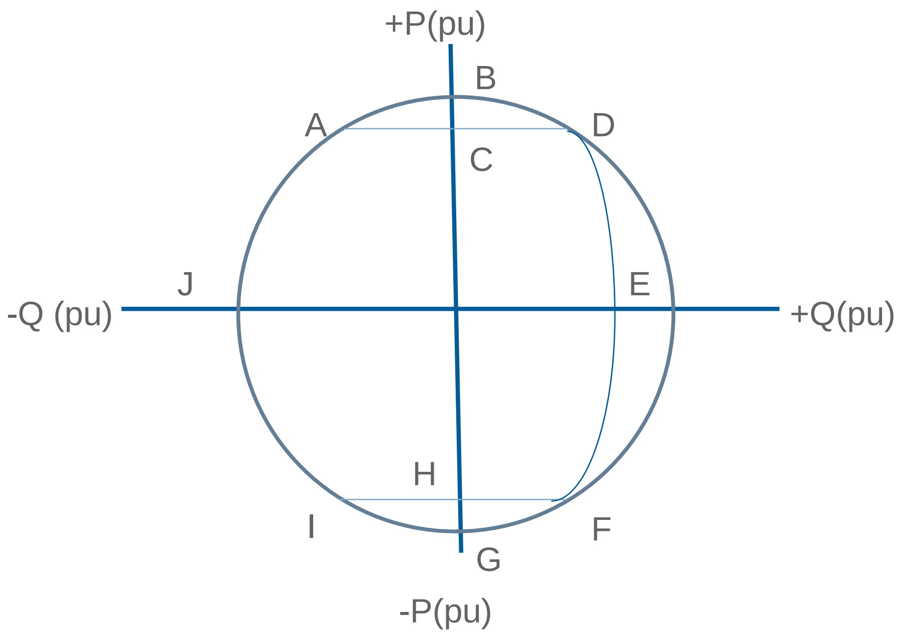


Figure I-4: Real/reactive power capability diagram

In the following table operating points B, E, G and J are requested To Be Confirmed (TBC) by the supplier. All other operating points are a mandatory requirement of this specification.

Table I-1 : Scheme operating points

Operating point	Power (pu)	Power factor (pu)	Comment
A	1.0	-0.9	Required
B	TBC	0	Requested
C	1.0	0	Required
D	1.0	0.9	Required
E	0	TBC	Requested
F	-1.0	0.9	Required
G	TBC	0	Requested
H	-1.0	0	Required
I	-1.0	-0.9	Required
J	0	TBC	Requested

d) AC bus voltage

The scheme should be able to operate in a voltage control mode, such that the operator may select an AC bus voltage and the converter will automatically adjust converter reactive power absorption or generation to achieve the desired voltage.

Normal operating range of the 33kV distribution system is ±6%.

e) STATCOM operation

In the event that the DC circuit is unavailable, e.g. due to a major cable fault, each converter station should be capable of operating as a STATCOM, i.e. providing reactive power output at points E and J in Figure I-4. This will require that any equipment required for initial energisation, e.g. pre-insertion resistors, is installed at both terminals.

f) Power run-back

Under certain contingencies on the distribution system, e.g. the loss of a key circuit or generator, there may be the need to instigate a power "run-back" from the present operating power transfer level to a pre-defined operating level. Studies in the early project execution phase will determine if this facility is required and to what levels power run-back would be set. Note that "run-back" can imply power reduction and power increase, the latter limited by the rating of the scheme.

g) Black start

Not required.

h) Power oscillation damping

Not required.

I.8 Reliability and Availability

As a single DC link will replace one existing AC link (the 2 circuits being connected in parallel), the reliability of the scheme and the availability of energy are critical. The following target performance figures are requested:

- Forced outage rate (FOR) <3 trips per annum
- Scheduled energy unavailability (SEU) <1%

- Forced energy unavailability (FEU) <1%
- Energy availability (EA) >98%

The supplier shall indicate what reliability and availability can be achieved from their design. Converter operation will be monitored for a period of 5 years after the start of commercial service. It is a requirement that the above requirements are met in each of the 5 years.

Outages of the converters as a result of failures on the cable and overhead line distribution circuits are excluded from this evaluation, unless it is clear that such a failure was a direct result of a mal-operation of the converters.

I.9 Operating losses

The following target operating losses are requested for each converter station and if not considered to be achievable the supplier should confirm what level of operating losses can be achieved.

No-load losses <0.2% of scheme rated power

Load losses <1.0% of scheme rated power

I.10 Harmonic distortion

The level of harmonic distortion created by the MVDC link at the Point of Common Coupling at Llanfair PG and Bangor shall not exceed the levels indicated in Engineering Recommendation G5/4.

I.11 Auxiliary power

The supplier shall confirm the maximum level of auxiliary power required to operate each converter station. It is anticipated that the primary source of auxiliary power (at 415V) will be supplied by SP Energy Networks from the local distribution network. The supplier shall indicate what back-up power supplies are provided to allow the MVDC scheme to ride-through momentary disturbances to the auxiliary power supply.

I.12 Relocation

The complete MVDC installation should be capable of being re-located from the Llanfair PG and Bangor sub-stations to other locations on the SP Energy Networks distribution network. To achieve this it is anticipated that the power electronic converters, plus cooling, control, protection and auxiliary power equipment will be housed in a series of portable buildings. These, together with the transformers, should be capable of being transported on normal freight vehicles, without the need for the special measures required for an “exceptional load”. The cables between the converter stations at the existing and new locations does not form part of this re-location requirement.

Appendix J Skin Effect in Cables

MV electricity cables, whether for AC or DC application consist of three main components, as shown in the cross-section drawings in Figure J-1. These are:

- A central metallic core, normally copper or aluminium, which carries the current;
- An insulation layer, either oil impregnated paper or extruded plastic;
- An outer sheath which is connected to ground potential.

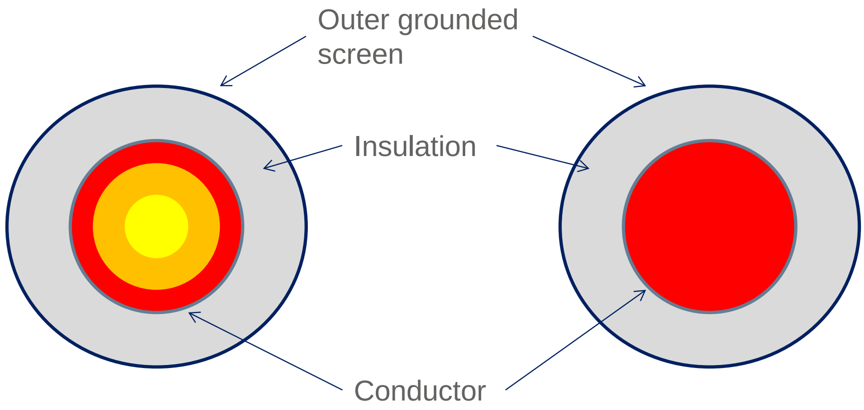


Figure J-1 : AC cable (left) and DC cable (right)

For AC applications the alternating current creates an electromagnetic field, which has the unwanted effect of forcing the current to flow in the outer layers of the conductor, rather than equally across the complete cross-section. This causes the outer layer to become hotter (red colour) than the inner layers (orange and yellow colours), which are colder. This is known as the “skin effect” and effectively means that full use is not mad of the conductor material and the magnitude of Ac current has to be limited to avoid over-heating of the outer layer of conductor and hence of the insulation.

For DC applications, there is no alternating field and the skin effect does not apply. Thus the full cross-section of the cable conductor material can be used, allowing more current to be carried in the cable before the temperature of the outer layer reaches the critical point for the insulation. This introduces the possibility of an up-lift of current in the link and hence an up-lift in power flow in the existing cables.

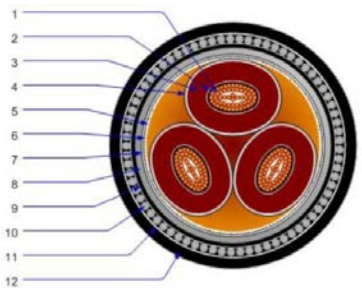
Appendix K Capacity Released Calculation for Bangor-Llanfair PG Circuit

The Bangor to Llanfair PG 33kV circuit is comprised of a combination of underground and overhead sections covering an approximate length of 3km. The underground section is made up of a number of cables with different types of construction, insulation and age.

- Cable Type A – H Paper Oil Rosin Insulated Cable;
- Cable Type B – HSL Impregnated Paper Insulated Cable;
- Cable Type C - XLPE Insulated Cable.

K.1 Cable Type A – H Paper Oil Rosin Insulated Cable

This type of cable contributes the longest length of the installed cable for each circuit. If the circuits are to operate successfully at DC without significant cable replacement then the withstand capability of this cable type, which is the oldest of the types installed will be crucial to the success of the conversion project.

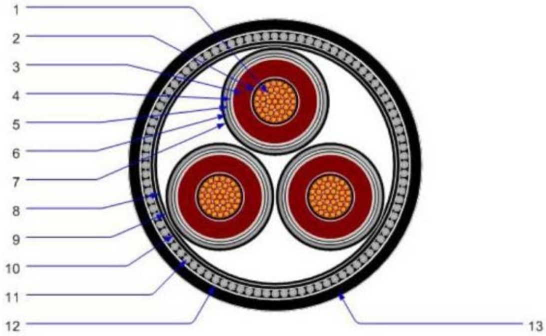


(1) Conductor
(2) Conductor screen
(3) Insulation
(4) Core screen
(5) Laid-up cores
(6) Binder
(7) Radial clearance
(8) Lead sheath
(9) Armour bedding
(10) Armour wires
(11) Binder
(12) Serving

Figure K-1: H Type A Impregnated Paper Cable Design

K.2 Cable Type B – HSL Impregnated Paper Insulated Cable

These cables form the second largest cable type installed on the double circuit connection. Although the exact type of impregnant used is not known it is likely to be a mass impregnated non-draining compound (paraffinic oil mixed with a microcrystalline wax). The maximum AC operating conductor temperature for this cable design type is 65ºC.



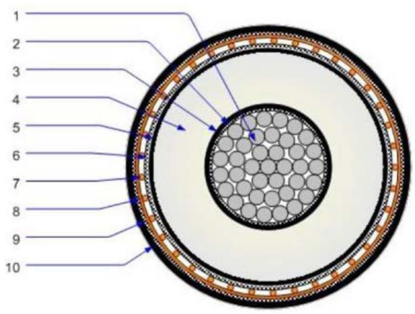
(1) Conductor
(2) Conductor screen
(3) Insulation
(4) Core screen
(5) Radial clearance
(6) SL lead sheath
(7) SL taping
(8) Laid-up cores
(9) Binder
(10) Armour bedding
(11) Armour wires
(12) Binder
(13) Serving

Figure K-2 : Impregnated Paper HSL Cable Design

K.3 Cable Type C - XLPE Insulated Cable

XLPE insulated single core cables make up the smallest portion of each circuit. The maximum allowable conductor temperature for most XLPE cables operating at an AC voltage is 90°C.

XLPE insulation when subjected to a high DC voltage field has been proven to be affected by the phenomenon of space charge. The 33kV XLPE cables and accessory materials are likely to have a high propensity to develop space charge at stress levels above 10kV/mm. Nevertheless 33kV cables on AC systems are still being tested using a DC site withstand test voltage and a high level of post-test energisation failures resulting from such testing at this voltage level is not being reported. If the DC electric stress is less than the threshold value of 10-12kV/mm then the effect is small and at the level of 5-7kV/mm expected in the XLPE cable space charge would not be expected to limit the cable system performance.



(1)	Conductor
(2)	Conductor binder
(3)	Conductor screen
(4)	Insulation
(5)	Core screen
(6)	Screen bedding
(7)	Wire screen
(8)	Equalisation tape
(9)	Screen binder
(10)	Serving

Figure K-3 : XLPE Cable Design

K.4 Current rating

The maximum temperature limit on the cable conductor is set by the maximum allowable temperature of the insulation. Mass impregnated paper insulation is still in production for very long length subsea cable DC interconnectors and temperature limits are set between 50ºC and 55ºC depending upon the manufacturer. This compares with the AC voltage working temperatures on the 33kV cables being considered of 50ºC to 65ºC where the temperature limits are set by void formation leading to partial discharge within the insulation.

It is considered reasonably conservative to operate the paper insulated cables at a maximum conductor temperature of 50ºC. As the XLPE cables have a lower electrical DC resistance than the paper cables and a lower external thermal resistance, being single core rather than 3-core cables, the XLPE cables will be operating at a significantly lower operating temperature than 50ºC when carrying the same load. This is significantly lower than the 70ºC applied to modern materials and is considered to be a prudent maximum temperature.

Cable Type A will have the lowest rating of all cable types. This is due to its higher conductor DC resistance and three core construction. The rating of the AC circuit when operated at a maximum conductor temperature of 65°C is calculated at 217A.

For testing purposes, it is deemed prudent to limit the conductor temperature to 50°C resulting in a current carrying capability of 188A. Studies demonstrated the maximum DC rating for 65°C operation could be increased up to 219A.

K.5 System Voltage

There are several considerations with regard to determination of a practical DC working voltage which might be applied to the 33kV cables. Factors concerning a lower risk practical working voltage will be:

- The DC strength of the cable and joint insulation;
- The condition of the insulation.

The insulation thickness of the paper cable designs is expected to be between 6.8 and 7.1mm. The estimated maximum voltage for the Type A cable is lower than Type B cables due to the use of shaped (oval) conductors.

Table K-1 : Estimated Maximum Geometric DC Voltage for existing paper cables

Cable Design	Max DC Voltage (kV)
Cable Type A	95
Cable Type B	129

Whilst the maximum estimated DC voltage is up to 95kV. The cables considered in this study are not new. It is thus prudent to limit the maximum voltage to a level at which there is a reasonable degree of certainty that the cables and accessories will withstand the continuously applied DC voltage. The Cigre paper[12] suggests that on the basis of electric mean stress the cable insulation could withstand up to twice the AC voltage as an applied DC voltage, i.e. 38kV.

The cables and accessories have been operating at an AC line voltage of 33kV and an RMS phase to earth voltage of 19kV AC. The AC peak voltage which the insulation is currently experiencing is thus 27kV which is proposed as a conservative operating voltage at which all cable and accessory types would be expected to be comfortable to operate at.

Initial testing completed on the circuit indicated the insulation is able to withstand a DC voltage of 27kV but long term degradation effects were not considered.

K.6 Power Transfer Capability

The power rating of the circuit under AC voltage for the two circuits in parallel are calculated as follows:

$$S_{AC}\,(65^0C) = \; 2\,x\,\sqrt{3}\,x\,33{,}000\,x\,217 = \; 24.8MVA$$

The power rating of the circuit under DC voltage for the two circuits in parallel is calculated as follows:

$$P_{DC}\,(50^0C) = \; 2\,x\,3\,x\,27{,}000\,x\,188 = \; 30.5MW$$

Assuming a power factor of 1.0 under AC operation the thermal capacity of the circuit is increased by 5.75MVA i.e. 23% of the AC rating.

[12] Cigre, "Upgrading and Uprating of Existing Cable Systems", Section 5, Working Group B1.11, Paris, Jan 2015

Appendix L NIA SPT 1307 – MVDC. Project Close Down Summary

An NIA project was completed by SP Energy Networks during the last regulatory year. This Appendix summarises the key conclusions from the project which identified significant potential for MVDC technology in the following areas:

- Distribution network reinforcement to provide a comprehensive support on voltage and power flow;
- Enabler role in DSO due to its transient controllability;
- Renewable Energy resource integration; and
- Other industries such as shipping and railway.

The existing research can be found at either transmission level (>132kV AC system) or low voltage (i.e. households). Due to the continued performance improvement and cost reduction of power electronics, MVDC should be considered and trialled to be part of the tool box for DNOs. This project, when it was initialised, was to identify the need: both commercially and technically and develop the roadmap to deployment towards Business as Usual (BaU).

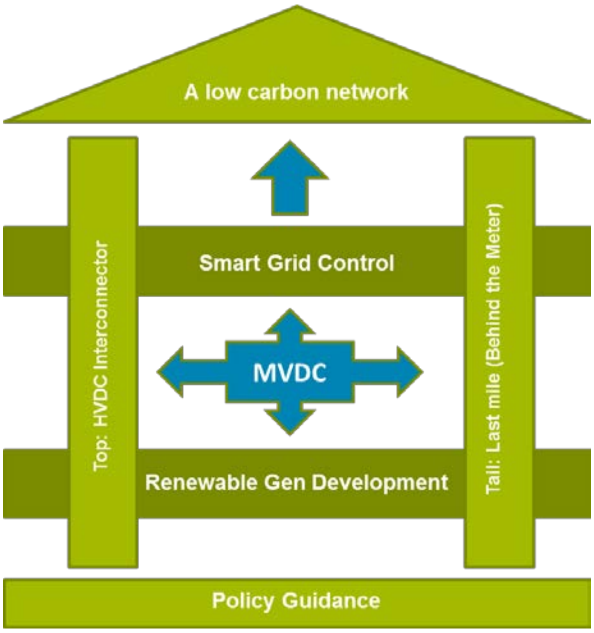


Figure L-1 : Facilitating the transition to a low carbon future

An MVDC project was consequently shaped with the following findings being still valid:

1. This technology is close to being commercially available and laboratory tests or simulation will have limited contribution to improving the TRL;

2. The stakeholders and suppliers are keen to see a trial on the distribution network to provide operational experience and serve as a valid example to provide market and user confidence; and

3. The market potential of this technology can only be realised if the full operational configuration is analysed where locations prohibit the installation of one back-to-back convertor.

Appendix M Existing Non-UK AC to DC Conversion Projects

Our literature survey shows that there have been a limited number of applications of DC technology in distribution systems. **None of the known examples in medium voltage distribution networks** have transmitted power over distance through an intervening circuit, i.e. the back-to-back application which will be trialled in LCNF Equilibrium project is a prevail application. The off-shore power supplies link the generation source to a remote load and use new cable assets. **To our best knowledge, to date there is no known application which embeds a DC link within a medium distribution network and re-uses existing network assets**. Nonetheless, we have identified three example projects which convert the existing AC assets for DC operations. These projects have been implemented in high voltage (transmission), low voltage (distribution) network and medium voltage offshore cable.

M.1 Conversion of AC assets for DC operation

Transmission example[1]

Amprion and TransnetBW, two of the four Transmission System Operators in Germany, are planning to convert a 400kV AC circuit to a DC connection on existing overhead line (see Figure M-1). The rated power of the DC circuit will be in the range of 2GW to 3GW, depending on the environmental conditions. In this way it is possible to increase the transmission capacity over a long distance without additional corridors for overhead lines.

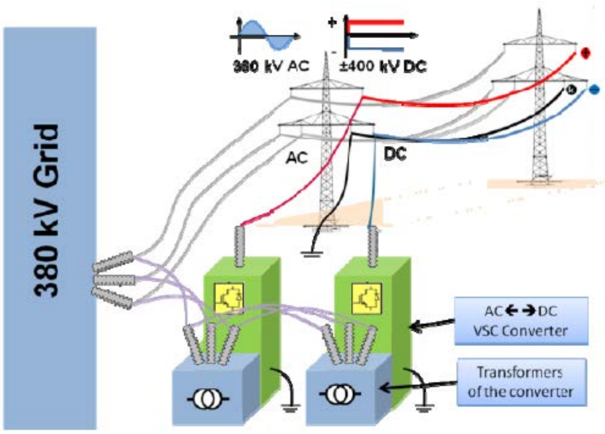


Figure M-1: Concept of the Ultranet

Low-Voltage distribution example[2]

Tampere University in Finland has trialled a low voltage DC (±750V) distribution network concept that challenges the traditional 400V AC network applications (see Figure M-2). This trial project developed a testing program to study the main considerations of the DC suitability of typical low-voltage AC cables. Tested cables included a combination of different cable types. DC withstand voltage of all the tested cable types was concluded to be high enough for the low-voltage DC system but no long term ageing phenomena were covered.

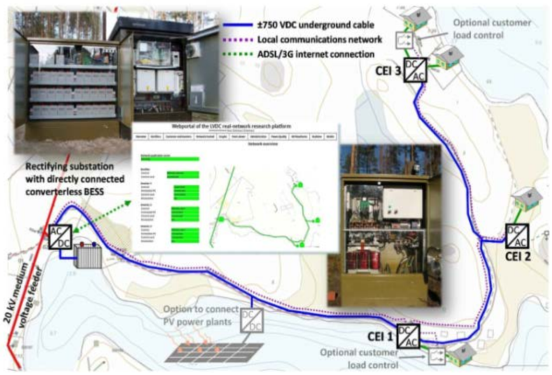


Figure M-2 : Example of bipolar +/- 750VDC LVDC system setup

1 "Control Concept Including Validation Strategy for an AC/DC Hybrid Link. Amprion.

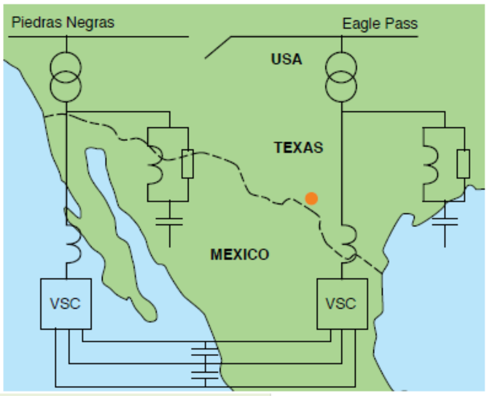
2 Feasibility of Low Voltage Cables for Use at 1500V DC Distribution Networks. Tampere University
Low-voltage DC Electricity Distribution – On Technological and Economic Immaturities and Development Needs. Nordac.

Offshore example[1]

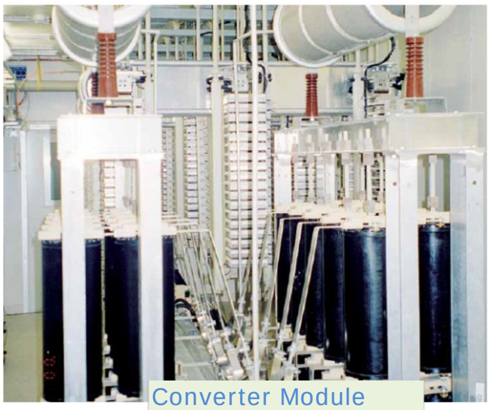
Rongxin Power Engineering Co. (RXPE) converted an existing AC cable supplying an offshore drilling platform for DC operation. This project aimed to maintain the supply to the offshore platform after one core out of the three cores of AC cable was damaged. The remaining cables (two cores) were used to build an 8MVA ±15kV DC link between shore and offshore platform.

M.2 Back-to-Back converters applications

Project Name: Eagle Pass	Location: USA-Mexico	Date: October 2011
Supplier: ABB		
Description: interconnects two 138kV distribution systems, with a back-to-back converter rated at 38MW and operating at ±16kV		
Additional information: http://new.abb.com/systems/hvdc/references/eagle-pass https://library.e.abb.com/public/aaf03e894d40146bc1256fda003b4d19/A02-0174_Eagle%20Pass_LR.pdf		



Schematic diagram



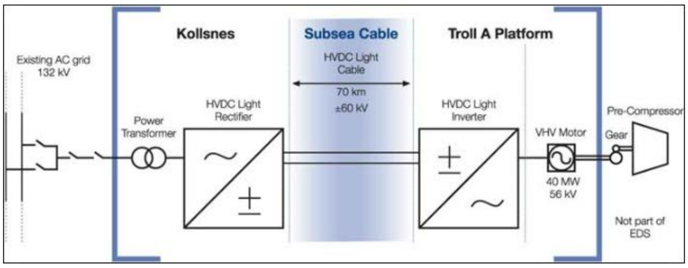
Converter Module

Eagle Pass substation

[1] www.rxpe.co.uk

Project Name: Mackinac	Location: USA	Date: Ongoing
Supplier: ABB		
Description: A back-to-back converter embedded in a 138kV distribution system to control power flow and is rated at 200MW and operates at ±71kV;		
Additional information: http://new.abb.com/systems/hvdc/references/mackinac		

Project Name: Troll A	Location: Norway	Date: 2005
Supplier: ABB		
Description: A power supply to an off-shore oil and gas installation rated at 88MW and operated at ±60kV		
Additional information: http://www.mena.abb.com/cawp/seitp202/cf86c94ac420344c85257a670045e7b7.aspx		



Appendix N Letters of Support

Welsh Government

We have worked closely with SP Energy Networks and the Anglesey Energy Island Programme to develop a distribution network that suits the increasing future demand and generation needs.

The development of renewable energy and establishing Anglesey as a world leader in this technology is a crucial part of the long term economic future for the Island…

Adran yr Economi, Gwyddoniaeth a Thrafnidiaeth
Department for Economy, Science and Transport

Llywodraeth Cymru
Welsh Government

23 July 2015

Mikel Urizarbarrena
Future Networks
SP Energy Networks
Ochil House
10 Technology Avenue
Hamilton International Technology Park
Blantyre
G72 0HT
United Kingdom

Date

Ref: ANGLE-DC NIC Project

Dear Mr Urizarbarrena

Welsh Government are pleased to provide a letter of support for your application to OFGEM Network Innovation Competition funding for the ANGLE-DC Project. We have worked closely with SPEN and the Anglesey Energy Island Programme to develop a distribution network that suits the increasing future demand and generation needs.

Anglesey is a key priority area for us and has been given Enterprise Zone status with the aim to maximise the benefits of all the low carbon renewable projects that have been attracted to the Island. There are a number of major strategic projects presenting skills opportunities for local people, supply chain opportunities and inward investment.

The development of renewable energy and establishing Anglesey as a world leader in this technology is a crucial part of the long term economic future for the Island and I am pleased the SPEN is proposing to develop a project that will enable the connection of increasing volumes of low carbon generation.

Yours sincerely

Gwenllian Roberts
Deputy Director Energy Wales Unit

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INVESTOR IN PEOPLE

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Gwenllian.roberts@wales.gsi.gov.uk

Menter Môn

Menter Mon on behalf of Crown Estate is working hard to build a tidal stream industry on the island as part of its contribution to low carbon energy generation. Given its attractive tidal resource and our work in progressing grid capacity and consent matters, we currently have twenty eight developers from around the globe formally expressing interest in locating in the MORLAIS zone. Early conservative indications are that the zone and its allied sites will produce 160 MW of power by 2022.

We are fully committed to realising the true economic potential of low carbon generation on Anglesey and believe that the ANGLE-DC project.

Menter Môn Cyf

Neuadd y Dref, Sgwâr Bulkeley,
Llangefni, Ynys Môn. LL77 7LR

Gerallt Llewelyn Jones
Rheolwr Gyfarwyddwr - Managing Director

01248 725700 01248 725735 www.mentermon.com

Mikel Urizarbarrena
Future Networks
SP Energy Networks
Ochil House
10 Technology Avenue
Hamilton International Technology Park
Blantyre
G72 0HT
United Kingdom

24.07.2015

Ref: ANGLE-DC NIC Project
Dear Mikel,

I wish to provide this letter of support on behalf of Menter Mon for the ANGLE-DC project.
Menter Mon, through its MORLAIS West Anglesey Demonstration Zone leasehold management status on behalf of Crown Estate is working hard to build a tidal stream industry on the island as part of its contribution to low carbon energy generation. Given its attractive tidal resource and our work in progressing grid capacity and consent matters, we currently have twenty eight developers from around the globe formally expressing interest in locating in the MORLAIS zone.
Early conservative indications are that the zone and its allied sites will produce 160 MW of power by 2022

We are fully committed to realising the true economic potential of low carbon generation on Anglesey and believe that the ANGLE-DC project will allow up to 350MW of additional capacity. This is critical to our plans for marine energy renewables growth.

We believe that the project will benefit the Isle of Anglesey and will enable the connection of increasing volumes of low carbon generation.
Kind regards,

Gerallt Llewelyn Jones MD
Menter Mon Ltd and MORLAIS

Rhif y cwmni - Company number: 3160233
Cwmni cyfyngedig drwy warant - A Company limited by guarantee

ISLE of Anglesey City Council, Director of Sustainable Development	ISLE of Anglesey City Council, Energy Island Programme Director
… We are also fully aware that the true renewable opportunities for Anglesey far outweigh this with another 350MW of generation connections in the immediate pipeline … We, Isle of Anglesey County Council, believe ANGLE-DC will directly benefit the electricity customers and community, including local generators and consumers.	…Anglesey Energy Island recognises that in order to support low carbon energy developments it is necessary to promote the modernisation of and improvements to local infrastructure… ANGLE-DC is in line with the Energy Island strategy and contributes Anglesey Energy island by innovation … we recognise the value of the ANGLE—DC project…

CYNGOR SIR YNYS MÔN
ISLE OF ANGLESEY COUNTY COUNCIL

Arthur Wyn Owen, Dip.E.P., M.R.T.P.I.
Cyfarwyddwr Datblygu Cynaliadwy /
Director of Sustainable Development
Adran Datblygu Cynaliadwy / Sustainable Development Directorate
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Eich Cyf./Your Ref -

Mikel Urizarbarrena
Future Networks
SP Energy Networks
Ochil House
10 Technology Avenue
Hamilton International Technology Park
Blantyre
G72 0HT

17 July 2015

Dear Mikel

Letter of support for ANGLE-DC NIC Project

I am pleased to provide this letter of support on behalf of Isle of Anglesey County Council for the ANGLE-DC Project.

Isle of Anglesey County Council have worked closely with Welsh Government for a number of years to develop low carbon and renewable opportunities that will regenerate the area and provide crucial employment opportunities for our future generations.

Isle of Anglesey County Council have worked closely with SP Energy Networks to develop a distribution network that suits the increasing future demand and generation needs of the island and we are pleased that SP Energy Networks have significant investment plans across Anglesey, which includes 132KV reinforcement works at Caergeiliog Grid Substation. Whilst we recognize that there is currently 150MW of generation that is connected or contracted to be connected on the island, we are also fully aware that the true renewable opportunities for Anglesey far outweigh this with another 350MW of generation connections in the immediate pipeline. Isle of Anglesey County Council are committed to realising the true economic potential of low carbon generation on Anglesey and we believe that developing new technologies to actualize these opportunities is instrumental in securing the long term economic future for the Isle of Anglesey.

We, Isle of Anglesey County Council, believe ANGLE-DC will directly benefit the electricity customers and community, including local generators and consumers. Such a technology, if proven successful, will accelerate the generation/demand connection in the island, and facilitate a low carbon economy.

SWYDDOGOL / OFFICIAL

CYNGOR SIR YNYS MÔN
ISLE OF ANGLESEY COUNTY COUNCIL

YNYS YNNI MÔN
ANGLESEY ENERGY ISLAND

DR JOHN IDRIS JONES BSc, MCMI, MInstP, CPhys
Cyfarwyddwr Rhaglen – Programme Director

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Ein Cyf / Our Ref:
Eich Cyf / Your Ref:
Dyddiad / Date: 16th July 2015

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10 Technology Avenue
Hamilton International Technology Park
Blantyre
G72 0HT
United Kingdom

Dear Mikel,

Ref: Letter of support for ANGLE-DC NIC Project

The Anglesey Energy Island Programme is a collective effort between several stakeholders within the public and private sector working in partnership to put Anglesey at the forefront of energy research and development, production and servicing. Within the Energy Island Programme, opportunities offered by low carbon energy development are of critical importance to the wider economic development and diversification of Anglesey and North Wales. Anglesey Energy Island could contribute nearly £12billion to the Anglesey and North Wales economy over the next 15 years. It undoubtedly offers a once in a generation opportunity to give the economy a tremendous boost and this must be collectively grasped.

Anglesey Energy Island recognises that in order to support low carbon energy developments it is necessary to promote the modernisation of and improvements to local infrastructure. It is key to make full utilisation of the opportunities offered by new technologies and investigate innovative options to overcome the limitations of the existing infrastructure. The proposal of ANGLE-DC is in line with the Energy Island strategy and contributes Anglesey Energy Island by innovation: by getting at least 20% increment from the existing circuit, the technology will have significant contribution to achieving the renewable generation aspirations for the Isle of Anglesey. Harnessing a rich mix of energy streams at distribution level, including wind, tidal biomass and solar; together with associated servicing projects provides major potential to achieve economic, social and environmental gains for Anglesey and the wider North Wales region.

ISLE of Anglesey City Council, Director of Sustainable Development (in Welsh)

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17 Gorffennaf 2015

Annwyl Mikel

Llythyr o gefnogaeth i Brosiect ANGLE-DC NIC

Rwy'n falch o ddarparu'r llythyr hwn o gefnogaeth ar ran Cyngor Sir Ynys Môn i'r Prosiect ANGLE-DC.

Mae Cyngor Sir Ynys Môn wedi gweithio'n agos gyda Llywodraeth Cymru am nifer o flynyddoedd i ddatblygu cyfleoedd carbon isel ac ynni adnewyddadwy a fydd yn adfywio'r ardal ac yn darparu cyfleoedd cyflogaeth hollbwysig i genedlaethau'r dyfodol.

Mae Cyngor Sir Ynys Môn wedi gweithio'n agos gyda SP Energy Networks i ddatblygu rhwydwaith dosbarthu sy'n gweddu i anghenion cynyddol yr ynys o ran y galw am ynni a chreu ynni yn y dyfodol, ac rydym yn falch fod gan SP Energy Networks gynlluniau buddsoddi sylweddol ar draws Ynys Môn, sy'n cynnwys gwaith atgyfnerthu 132KV yn Is-orsaf y Grid yng Nghaergeiliog. Er ein bod yn cydnabod fod gwerth 150MW o gynhyrchiant ynni ar hyn o bryd wedi'i gysylltu neu dan gontract i'w gysylltu ar yr ynys, rydym hefyd yn llwyr ymwybodol fod y cyfleoedd posib am ynni adnewyddadwy i Ynys Môn ym mhell tu hwnt i hyn gyda gwerth 350MW o gysylltiadau ynni pellach ar y gweill yn fuan iawn. Mae Cyngor Sir Ynys Môn yn ymroddedig i wireddu'r potensial economaidd gwirioneddol sy'n deillio o gynhyrchu ynni carbon isel ar Ynys Môn a chredwn fod datblygu technolegau newydd i wireddu'r cyfleoedd hyn yn hanfodol er mwyn sicrhau dyfodol economaidd tymor hir Ynys Môn.

Rydym ni, Cyngor Sir Ynys Môn yn credu y bydd ANGLE-DC yn dod â **buddion uniongyrchol i'r cwsmeriaid trydan a'r gymuned**, gan gynnwys cynhyrchwyr a phrynwyr lleol. Bydd technoleg o'r fath, os profir ei fod yn llwyddiannus, yn cyflymu'r cysylltiad rhwng cynhyrchiant /galw ar yr ynys, ac yn hwyluso economi carbon isel.

ISLE of Anglesey City Council, Energy Island Programme Director (in Welsh)

SWYDDOGOL / OFFICIAL

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Annwyl Mikel

Llythyr o gefnogaeth i Brosiect ANGLE-DC NIC

Mae'r Rhaglen Ynys Ynni Môn yn ymdrech ar y cyd rhwng llawer o gydranddeiliaid yn y sector cyhoeddus a phreifat sy'n gweithio mewn partneriaeth i roi Ynys Môn ar flaen y gad gydag ymchwil a datblygu ynni, a chynhyrchu a gwasanaethu. O fewn y Rhaglen Ynys Ynni, mae cyfleoedd sydd ar gael trwy ddatblygu ynni carbon isel yn hollbwysig i ddatblygiad ac amrywiaeth economaidd ehangach Ynys Môn a Gogledd Cymru. Gallai Ynys Ynni Môn gyfrannu bron i £12 biliwn i economi Ynys Môn a Gogledd Cymru dros y 15 mlynedd nesaf. Nid oes amheuaeth nad yw'n cynnig cyfle arbennig ac unigryw i roi hwb anferthol i'r economi ac mae'n rhaid i ni fanteisio ar hyn gyda'n gilydd.

Mae Ynys Ynni Môn yn cydnabod, er mwyn cefnogi datblygiadau ynni carbon isel, bod rhaid hybu'r gwaith o foderneiddio a gwella'r isadeiledd lleol. Mae'n allweddol ein bod yn gwneud defnydd llawn o'r cyfleoedd sy'n cael eu cynnig trwy dechnolegau newydd a'n bod yn ymchwilio i opsiynau arloesol i oresgyn cyfyngiadau'r isadeiledd presennol. Mae bwriad y prosiect ANGLE-DC yn unol â'r strategaeth Ynys Ynni ac yn cyfrannu at arloesedd rhaglen Ynys Ynni Môn; trwy gael ychwanegiad o 20% o leiaf o'r cylched presennol, bydd y dechnoleg yn cyfrannu'n sylweddol at gyflawni'r dyheadau i greu ynni adnewyddadwy ar gyfer Ynys Môn. Trwy ddefnyddio cymysgedd gyfoethog o ffrydiau ynni ar lefel dosbarthu, gan gynnwys ynni gwynt, llanw, biomas a solar; ynghyd â phrosiectau gwasanaethu cysylltiedig, mae potensial mawr i gael enillion economaidd, cymdeithasol ac amgylcheddol i Ynys Môn a rhanbarth Gogledd Cymru yn ehangach.

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Western Power Distribution, UK	Scottish and Southern Energy PD
…these discussions have focussed on the ANGLE DC project scope, as well as the key differentiators and the sharing of learning already generated from the Network Equilibrium Flexible Power Link (MV BZBVSC) section of the project… We understand that the ANGLE DC project would have specific requirements, providing additional technical innovation on the optimal design of MVDC converter, the existing AC assets converted into DC operation and the enduring DC system monitoring.	…SSEPD's view is that the ANGLE DC project is interesting and innovative in addressing the voltage and thermal constraints within distribution networks, and that ANGLE DC could facilitate the transition to a low carbon economy whilst enabling financial savings for consumers… We look forward to sharing learning from the project's outputs and we will participate in ANGLE DC stakeholder consultation and knowledge dissemination activities…I also confirm that I will represent SSEPD in the Project Steering Group.

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SP Energy Networks
Ochil House, 10 Technology Avenue,
Hamilton International Technology Park,
Blantyre,
Scotland
G72 0HT

Tuesday, 21st July 2015

Dear Mikel,

Re: ANGLE DC Proposal

I can confirm that during the development of the ANGLE DC bid we have met and held open discussions on SP Energy Network's proposal several times. These discussions have focussed on the ANGLE DC project scope, as well as the key differentiators and the sharing of learning already generated from the Network Equilibrium Flexible Power Link (MV B2BVSC) section of the project. We understand that the ANGLE DC project would have specific requirements, providing additional technical innovation on the optimal design of MVDC converter, the existing AC assets converted into DC operation and the enduring DC system monitoring.

WPD remains confident that MV power electronics could play a significant role in the future network reinforcement and the flexible operation of the distribution networks.

We would also welcome the opportunity to be involved in the ANGLE DC project, including accepting a role on the steering team. There, we would continue to mutually share our power electronics experience and the knowledge generated from the Network Equilibrium and ANGLE-DC projects.

Yours faithfully

PBale

Philip Bale
Network Equilibrium Project Manager

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Western Power Distribution (West Midlands) plc
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Scottish and Southern Energy
Power Distribution

James Yu
Future Networks Manager
SP Energy Networks
Ochil House,
Glasgow, Scotland
G72 0HT

Stewart Reid
Head of Future Networks
Inveralmond House
200 Dunkeld Road
PERTH
PH1 3AQ

Our Reference: NIC/SP/ANGLEDC/210715

Date: 21 July 2015

Dear James,

Network Innovation Competition – SP Manweb- ANGLE DC

Thank you very much for your request of a letter of support for the ANGLE DC project. I am pleas to confirm Scottish and Southern Energy Power Distribution's (SSEPD) position as project supporte

SSEPD's view is that the ANGLE DC project is interesting and innovative in addressing the volta and thermal constraints within distribution networks, and that ANGLE DC could facilitate the transit to a low carbon economy whilst enabling financial savings for consumers. We believe that ANGLE warrants further development and demonstration with Network Innovation Competition supp Should the trials be successful, we would be interested in the possibility of using the project outputs assist with future distribution network planning.

We look forward to sharing learning from the project's outputs and we will participate in ANGLE stakeholder consultation and knowledge dissemination activities. I also confirm that I will repres SSEPD in the Project Steering Group.

Overall, we perceive ANGLE DC to be a worthwhile and beneficial project which could o distribution network owners a suitable alternative to traditional methodology. We look forward collaborating with you as you develop the project in more detail and wish you every success with NIC funding request.

Yours faithfully

Stewart Reid
Future Networks and Innovation Manager

The National HVDC Centre	WSP| Parsons Brinckerhoff
…SP Energy Networks has engaged with the MTTE Project/The National HVDC Centre to inform us of their proposals and discuss potential synergies … There is no overlap in the scopes of the ANGLE-DC Project and the MTTE Project … There are opportunities for The National HVDC Centre to undertake the study work to support the ANGLE-DC Project … The ANGLE-DC Project is of interest to us, and we keenly anticipate the outcomes.	The key innovation is that they will re-use the existing 33kV circuits and operate them under DC voltage, by the introduction of AC – DC converters at either end of the link… There are a number of examples …including WPD's "Equilibrium" project. However, these operate in a back – to – back mode, with no electrical circuit between the two power converters… WSP Parsons Brinckerhoff strongly supports this initiative from SP Energy networks…

The National HVDC Centre

The National HVDC Centre
Scottish Hydro Electric Transmission
Inveralmond House
200 Dunkeld Road
Perth, PH1 3AQ

Telephone: 01738 516 588
Email: simon.marshall@hvdccentre.com

17th July 2015

James Yu
Future Networks Manager
SP Energy Networks
Ochil House, 10 Technology Avenue,
Hamilton International Technology Park,
Blantyre, G72 0HT

Dear James,

Based on the information in your Initial Screening Process proforma, and the presentation at your event on 30th June 2015 on your proposed ANGLE-DC Project, I confirm that:

- Scottish Power has engaged with the MTTE Project/The National HVDC Centre to inform us of their proposals and discuss potential synergies;
- There is no overlap in the scopes of the ANGLE-DC Project and the MTTE Project; and
- There are opportunities for The National HVDC Centre to undertake the study work to support the ANGLE-DC Project, which we would be keen to explore.

The ANGLE-DC Project is of interest to us, and we keenly anticipate the outcomes. Please let me know if we can be of further assistance.

Yours sincerely,

Simon Marshall
The National HVDC Centre Project Manager

WSP | PARSONS BRINCKERHOFF

Your Ref: -

Our Ref: 3514160A

22 July 2015

CONFIDENTIAL

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www.pbworld.com

Dear Madam/Sir,

Subject: SP ENERGY NETWORKS – ANGLE DC PROPOSAL

WSP Parsons Brinckerhoff, as a world-wide consultancy, with a long history in the power business, has been pleased to work closely with SP Energy Networks during the development of this innovative proposal, the conversion of an existing Alternating Current (AC) distribution asset to operate using Direct Current (DC). We have been involved in High Voltage Direct Current (HVDC) transmission projects for many years, covering projects from initial concepts and feasibility studies, through the design and construction phases, to commissioning and on-going operation and maintenance support. These many projects have shown the benefits of using DC technology for the efficient and controllable transmission of power over long distances, using overhead lines, or over relatively short distances using underground or submarine cables. As a consultancy we have been closely involved in projects using the most recent development of DC technology, the Voltage Source Converter (VSC). The modular nature of this VSC technology and its application in HVDC and also in industrial drives and power control devices such as Static Synchronous Compensators (STATCOM), has now opened up new possibilities in the field of power distribution.

SP Energy Networks has recognised that DC technology can provide a controllable and efficient solution to resolve issues on their network, where thermal and voltage constraints limit the operational facility on some existing circuits. For this Network Innovation Competition proposal, they have identified a specific circuit in North Wales which would be an ideal candidate for a demonstration of a DC link embedded within the distribution network. The key innovation is that they will re-use the existing 33kV circuits and operate them under DC voltage, by the introduction of AC – DC converters at either end of the link. Although the concept of conversion of AC assets to DC operation has been discussed in the field of HVDC for many years, to the best of our knowledge, this has not yet been implemented. There are a number of examples of DC technology used for power flow control in distribution networks, including WPD's "Equilibrium" project. However, these operate in a back – to – back mode, with no electrical circuit between the two power converters.

The combination of the new VSC technology now becoming widely available from multiple suppliers and the acknowledged difficulty of creating new rights of way for power distribution networks makes this proposal very timely.

Flexible Elektrische Netze, Aachen, Germany	Offshore Renewable Energy Catapult
…we are supporting your plan to develop a fit for purpose DC technology for distribution (11kv—132kV), by converting a 33kV circuit into DC operation. We believe that this is the first project of its kind at EU level …. we are clear that ANGLE DC comes with specific requirements to provide additional technical innovation aspects …	Medium Voltage DC technology (i.e. less than 132kV ac voltage) has been noted as a valid option for the connection of renewable power generation … We would echo the step change you are proposing and trust that such a project will not only benefit the distribution network owners, but will also benefit the electricity customers and the general public by its function in facilitating renewable power connections.

Flexible Elektrische Netze

Flexible Elektrische Netze FEN GmbH

Dr. Christian Haag
Geschäftsführer

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21. Juli 2015

ScottishPower Energy Networks
Dr. James Yu
Ochil House, 10 Technology Avenue
Hamilton International Technology Park
Blantyre, G72 0HT
SCOTLAND

Letter of Support

Dear Dr. Yu

with this letter we are supporting your plan to develop a fit for purpose DC technology for distribution (11kv-132kV), by converting a 33kV circuit into DC operation. We believe that this is the first project of its kind at EU level.

1. Project Scope Consultation: SP Manweb has made a transparent approach during the proposal development, started in September 2014. Among this process, you participated at the Integrated Offshore Wind Conference in Germany in Oct. 2014 and visited our institute (EON ERC/FEN) in Aachen. We carried out various conversations later on to clarify the scope and defined existing new innovation projects.
2. Difference: we are clear that ANGLE DC comes with specific requirements to provide additional technical innovation aspects including:
   a. Optimal design of MVDC converter;
   b. Existing AC assets converted into DC operation;
   c. Enduring DC system monitoring
3. Project business case: we remain convinced that power electronic technology will have a significant role in the distribution network reinforcement and active management. Other Distribution Network Owners and Distribution System Operators will benefit, from effective knowledge sharing, when/whether to consider this technology as part of their toolbox for future reinforcement. There are wider benefits, should this proposal be successful.

Kind regards

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Christian Haag

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11th June 2015

Letter of Support for the project "ANGLE-DC"

Dear Mikel,

We are writing to confirm our support to your proposed ANGLE- DC project under 2015 Electricity NIC mechanism.

Offshore Renewable Catapult has a mission to drive down the cost of renewable generation as a whole, among which electrical connection and power conversion are the key elements impacting on the capital investment, reliability and operation/maintenance costs.

Medium Voltage DC technology (i.e. less than 132kV ac voltage) has been noted as a valid option for the connection of renewable power generation. It can serve a niche market with right power rating and voltage. However, the industry as a whole is lacking the confidence due to the absence of a full system demonstration at engineering level, which can address the needs comprehensively and complement the existing R&D on this topic. Your ANGLE-DC proposal is an ideal demonstration to reflect the potential phenomena and performance, such as electrical interface, AC/DC power flow optimisation and potential extension to transmission level both onshore and offshore, which might only be revealed in an enduring arrangement as you proposed.

Therefore, we would echo the step change you are proposing and trust that such a project will not only benefit the distribution network owners, but will also benefit the electricity customers and the general public by its function in facilitating renewable power connections.

We are also of the view that the customers will benefit from a more transparent and competitive power converter supply chain. Your proposal with future expansion feature will certainly contribute to this aspect.

We look forward to working with you at different stages of your project, and will be keen to share the learning to benefit to maximise the output of this novel project.

Yours faithfully,

Dr. Chong Ng, BEng(Hons), PhD, CEng, MIET
Research and Development Manager, Power Conversion

Offshore Renewable Energy Catapult is a company limited by guarantee, registered in England and Wales with company number 4659351.
Registered office: Offshore House, Albert Street, Blyth, Northumberland, NE24 1LZ.

… need is to increase the transmission and distribution capacity by converting AC circuits for DC operation. EPRI studies on ac-to-dc line conversion provide a circumspect analysis of technical, economic and operational incentives for conversion…

EPRI is currently looking for utilities who are interested to participate in field demonstration of AC to DC line conversion. (EPRI) is committed to support the Proposed ANGLE-DC project

EPRI | ELECTRIC POWER RESEARCH INSTITUTE

July 5, 2015

Mikel Urizarbarrena
SP Energy Networks
Future Networks
3rd Floor, Ochil House
10 Technology Avenue
Hamilton International Technology Park
Blantyre G72 0HT
United Kingdom

REF: Proposed ANGLE- DC project under 2015 GB Electricity NIC Mechanism

Dear Mikel:

This letter is to inform you that the Electric Power Research Institute (EPRI) is committed to support the Proposed ANGLE - DC project under 2015 GB Electricity NIC Mechanism.

The Electric Power Research Institute, Inc. conducts research, development and demonstration (RD&D) relating to the generation, delivery and use of electricity for the benefit of its members and the public. An independent, nonprofit organization, we bring together scientists and engineers as well as experts from academia and the industry to help address challenging issues in the electricity industry.

Electric utility transmission and distribution system is facing new challenges, requiring new line component design and maintenance as well as solutions for issues related to lightning strikes, grounding, and live working. Research can help utilities address these issues by improving diagnostics, inspection and assessment methods, and providing tools and techniques that can lead to safer work environments, improved asset management, and greater operational performance.

There is a growing need for more transmission and distribution capacity in the utility industry but it is difficult to get new rights-of-way to accommodate this need. One way of addressing this need is to increase the transmission and distribution capacity by converting AC circuits for DC operation. EPRI studies on ac-to-dc line conversion provide a circumspect analysis of technical, economic and operational incentives for conversion. It includes both the software (DC Convert program) necessary for preliminary assessment of the dc capability of specific ac lines and an actual system example showing feasibility of conversion. The work has shown that conversion to dc of an ac line that is part of a parallel ac path, may, in addition to its own boost in capability, also increase the allowable loading on that ac path.

The EPRI study [1] assists system planners in assessing economic feasibility of conversion, the implications in the surrounding ac system, e.g. parallel ac flows and reactive power demands. It aids the system planner in identifying opportunities where dc conversion is most likely to be

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feasible, and cites a number of practical implementation issues, including suggestion of a non-disruptive approach to conversion.

DC Capability of Specific Tower / Conductor Configurations

EPRI studied the gain in MW transfer that might be expected from conversion of specific example transmission lines ranging from 115 kV to 765 kV.

The dc voltage sustainable by a particular ac circuit will be the lesser of:

- The voltage above which conductor surface gradient exceeds an established criterion
- The voltage above which the earth surface gradient exceeds an established criterion
- The voltage above which inadequate insulation and clearance can be provided at the tower.

Figure , which recognizes all dc voltage constraints, shows the boost in total path transfer achieved by conversion, in pu of the original MW rating of circuit which was converted. It shows extremely high multiples achievable where both circuits of a double circuit tower are converted to dc, though the opportunities for such conversions may be quite rare in as much as many such circuits have intermediate taps and/or different destinations. However even for single circuit lines, most conversions showed an increase over 2:1 at 138 kV and over 1.5:1 at 230, 345 and even 500 kV. Once again the actual multiple will depend on the conductor, tower configuration, and line length.

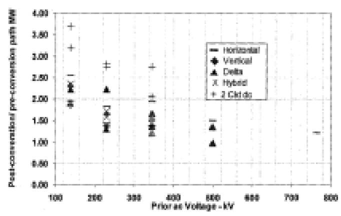

Figure 1: Ratio of post-conversion path loading to pre-conversion loading

Major Findings [1]

In addition to providing system planners with easy-to-use methods for assessing the impact of ac to dc conversion, the overall program is summarized as follows:

- Conversion from ac to bipolar dc is simple and takes advantage of countless operating precedents. However, the removal of one phase position from active power transfer weighed heavily against the bipole in economic studies.
- It is possible to construct and operate a monopole and bipole convertor in parallel such that the full thermal rating of all three phase positions of an ac line are used for dc, and to do so without requiring a ground return path or the use of any unproven equipment.
- The dc voltage supportable by an ac line will generally be higher than the line-to-ground operating voltage. The dc-to-ac crest voltage, normally limited by conductor gradient, will be highest for the lower transmission voltages.
- Converting an ac line to the tripole configuration results in converted circuits with a capability 37% greater than a bipole system that uses two of the same conductors actively, and the third as a metallic ground return. The tripole configuration favors the economics of achieving a high ratio of emergency to continuous power rating.
- The resulting "tripole" terminal will be about 84% redundant compared to 57% for the bipole system using the same three conductor array.
- Where the converted line is part of a parallel ac path, conversion to dc will tend to increase (N-1)-constrained ac dispatch by at least the ratio of the emergency capability of the dc to the emergency power assumed by the line in its ac state.
- DC conversion was far more effective in increasing transfer than the installation of a large block of capacitive compensation or installation of a phase-shifting transformer.
- The tripole configuration can be adapted to either LCC (Line Commutated Converters) or VSC (Voltage Source Converters) bridges.

EPRI is currently looking for utilities who are interested to participate in field demonstration of AC to DC line conversion.

Reference:

[1] *AC to DC Power Transmission Line Conversion.* EPRI, Palo Alto, CA, and Bonneville Power Administration, Vancouver, WA: 2010. 1020114.

Though EPRI's AC to DC line conversion studies focused so far on transmission circuits, EPRI thinks that the power electronic technology can be an accelerator for Medium Voltage Distribution Circuits also to integrate more Distributed Renewable Energy (DRE); an enabler for Distribution System Operator (DSO) for its added controllable dimension, including:

- Management of the interconnection queue;
- Analysis of feeder operations with different levels and types of DER;
- Functional requirements and standards development for DER interconnection, reliability and safety;
- Strategies for managing and integrating customer-sited renewable generation;

The proposal you are presenting is the first of its kind at demonstration level and it will have significant contribution to the existing R&D in this area.

Based on the existing expertise within EPRI, EPRI will be able to support you by providing consulting, guidance, testing facilities, and software tools necessary to conduct your project successfully.

Please contact me if you need further information.

Sincerely,

Rambabu Adapa

Dr. Ram Adapa, P.E., Fellow IEEE
Technical Executive, HVDC & Power Electronics
Power Delivery & Utilization
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Anglesey Enterprise Zone Board	Cable Consulting International
… we believe that the ANGLE-DC project will facilitate the connection of the further 350MW of generation capacity that the island of Anglesey is enriched with. We believe that the project will benefit the Isle of Anglesey and will enable the connection of increasing volumes of low carbon generation.	… The operation of 33kV … cables and accessories … at 27kV DC will give a valuable insight and second life use to old cables. Following implementation we would be pleased to see, or assist in preparing, an international paper such that this innovation may be more widely known to the technical community at large.

Mikel Urizarbarrena
Future Networks
SP Energy Networks
Ochil House
10 Technology Avenue
Hamilton International Technology Park
Blantyre
G72 0HT
United Kingdom

21 July 2015

Dear Mr Urizarbarrena

Ref: ANGLE-DC NIC Project

I am pleased to provide this letter of support on behalf of the Anglesey Enterprise Zone Board for the ANGLE-DC project.

Anglesey has an established reputation for low carbon energy generation including nuclear, wind and biomass. Given its natural resources (wind, solar and marine), skilled workforce (especially nuclear related skills), supply chain and research and development capability, the island already attracts major interest from the low carbon energy sector.

Anglesey Enterprise Zone has a number of major strategic investment projects in the pipeline, presenting exciting supply chain opportunities for local companies and future companies locating to the Enterprise Zone, including the Skerries Tidal Generation Project that is already in production and the new Menter Mon Tidal Development Zone that plans to connect 160MW of tidal generation onto the local distribution network.

Anglesey Enterprise Zone Board is fully committed to realising the true economic potential of low carbon generation on Anglesey and we believe that the ANGLE-DC project will facilitate the connection of the further 350MW of generation capacity that the island of Anglesey is enriched with.

The development of renewable energy and establishing Anglesey as a world leader in this technology is a crucial part of the long term economic future for the Isle of Anglesey, having a direct benefit for the local communities and their economic survival.

I am delighted that SP Energy Networks is proposing to develop a project for a technology which has the potential to benefit the Isle of Anglesey and help us meet the long term energy needs of the island.

We believe that the project will benefit the Isle of Anglesey and will enable the connection of increasing volumes of low carbon generation.

Yours sincerely

Neil Rowlands
Chairman of Anglesey Enterprise Zone

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27th July 2015

Scottish Power Energy Networks
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PO Box 1
Sevenoaks
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United Kingdom

Dear Mr Urizarbarrena,

Ref: ANGLE-DC Project

We understand that Scottish Power Manweb Plc are submitting the ANGLE DC project to Ofgem for the Electricity Network Innovation Competition.

Cable Consulting International Ltd employs six power cable engineers who have been involved in the design, manufacture, installation or inspection of the types of 33kV cables which are prominent on the 33kV circuits included in your project. Our engineers have power cable technical papers published by International bodies such as CIGRE and JICABLE and we have a contributed and are present on a CIGRE B1 working group. Whilst we are aware of circuits that have been designed to operate either as an AC or as a DC system, to our knowledge there has not been a conversion of an existing MV AC circuit to DC operation. The operation of 33kV impregnated paper cables, which are in the order of 60 years old, as well as much younger XLPE cables and accessories at 27kV DC will give a valuable insight and second life use to old cables and reveal the potential of DC operation on MV XLPE cables and accessories.

Following successful pre-energisation testing and inspection we fully expect the cables and accessories to operate successfully. Having assessed the risks and developed a coherent inspection and testing strategy prior to implementation, we are pleased to support this project. Following implementation we would be pleased to see, or assist in preparing, an international technical paper such that this innovation may be more widely known to the technical community at large.

Yours faithfully,

Simon Lloyd BTech MIET
Director

Cable Consulting International Ltd
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Registered office: 74 College Road, Maidstone, Kent, ME15 6SL, United Kingdom
enquiries@cableconsulting.net

Term	Definition
AC	Alternating Current
BASEC	British Approvals Service for Cables
BtB	Back to Back
CAPEX	Capital Expenditure
CBA	Cost Benefit Analysis
CCI	Cable Consulting International
DC	Direct Current
DG	Distributed Generation
DNOs	Distribution Network Operators
DUoS	Distribution Use of System
EA	Energy Availability
ENA	Energy Network Association
EU	European Union
FACT	Flexible AC Transmission
FAT	Factory Acceptance Test
FEU	Forced Energy Unavailability
FOR	Forced Outage Rate
GB	Great Britain
GHG	Greenhouse gas
GW	Giga-Watts
HVDC	High Voltage Direct Current
HVPD	High Voltage Partial Discharge Ltd
IFI	Innovation Funding Incentive
IGBT	Insulated Gate Bi-Polar Transistor
ISP	Initial Screening Process
KC	Knowledge Co-ordinator
km	Kilometres
KPIs	Key Performance Indicators
kV	Kilo-Volts
kVdc	Kilo-Volts as DC
LCNF	Low Carbon Network Fund
LCNI	Low Carbon Network Innovation

Term	Definition
LV	Low Voltage
MMC	Modular Multi-Level Convertor
mt	Metric tonnes
MTTE	Multi-Terminal Test Environment
MV	Medium Voltage
MVDC	Medium Voltage DC
MVA	Mega-Volt Amps
MW	Mega-Watts
NC	Normally Closed Circuit
NIA	Network Innovation Allowance
NIC	Network Innovation Competition
NO	Normally Open Circuit
NPV	Net Present Value
OHL	Overhead Line
OPEX	Operational Expenditure
PD	Partial Discharge
PM	Project Manager
R&D	Research and Development
RIIO-ED1	Electricity Distribution 1 Regulatory Period
SAT	Site Acceptance Test
SDRCs	Successful Reward Delivery Criteria
SEU	Scheduled Energy Unavailability
STATCOM	Static Synchronous Compensator
TRL	Technology Readiness Level
UK	United Kingdom
VSC	Voltage Source Convertor
Wh	Watt-hour
WP	Work Package
WPD	Western Power Distribution