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0 Executive Summary

TNEI Services has been commissioned by Scottish Enterprise, which is working in partnership with SP Energy Networks (SPEN), to undertake a review of MVDC (medium voltage direct current) technology. The study encompasses technological and market based analyses of MVDC technology, both at present and approximately 10-15 years into the future, with a view to identifying potential opportunities, primarily for Scotland.

Renewable energy generation is an important focus for Scotland. Ongoing efforts to meet considerable renewable energy and carbon reduction targets have seen the significant growth of the renewables industry in Scotland, owing to the wealth of natural resources the country affords. The integration of renewable generation onto the electrical network presents a number of challenges for the various stakeholders involved in these developments, including the renewable generation developers and the electricity network operators.

As it stands, there is considerable interest and activity ongoing in HVDC (high voltage DC) and LVDC (low voltage DC) projects however, MVDC technology has been identified as a potential enabling solution for a variety of the challenges facing the integration of renewable generation. The most useful applications have been identified as:

- MVDC collector arrays for offshore renewable generation developments such as wind, tidal and wave;
- MVDC links for distribution network reinforcement purposes; and
- De-risking of HVDC technology components and applications on a smaller and less expensive scale.

Despite being identified as a useful technology in offshore wind applications, MVDC technology is not being used in any of the current UK offshore projects owing to its lack of test and demonstration track record and the risk associated with this. Additionally, immaturity of a number of necessary components (e.g. DC circuit breaker) and the high capital costs associated with power electronics are significant barriers to the adoption of the technology as it stands. The same barriers have also had a prohibitive impact on the other identified applications.

The objectives of this project are to further assess the feasibility and perceived worth of MVDC technology for use in these applications and identify whether there is a case for the establishment of an MVDC test and demonstration facility in Scotland. The outcomes of this project look to enable Scottish Enterprise and SP Energy Networks to make an informed decision on any future investment and development plans for MVDC in Scotland.

Initial market analysis has been conducted which included research and stakeholder engagement activity. This identified feasible applications for MVDC technology. A detailed cost benefit analysis for two case study applications was then carried out which established that, under certain conditions, MVDC

technology could provide a more cost-effective option than the “business as usual” technology. The outcomes of the market analysis and subsequent cost benefit analysis formed the basis of a scoping exercise for a potential test and demonstration facility for MVDC which could meet the needs of the industry in terms of improving MVDC technology maturity and market readiness. A socio-economic impact assessment was carried out for three configurations of test and demonstration facility in order to anticipate the impacts and benefits of such a facility for Scotland and the industry.

0.1 MVDC Test Facility Proposal

As a result of the stakeholder engagement and technical case studies in parts A and B of this study, a purpose built “plug and play” hardware facility is proposed. The scope of this test facility is to facilitate DC component testing and product certification, thus providing itself with a future income stream, as well as a demonstration of whole system behaviour which will contribute greatly to industry learning for MVDC projects.

Three different test facility configurations have been proposed, ranging from a simple point to point network which, for the lowest build cost, would enable the component testing of MVDC Converters, DC Cables and DC circuit breakers, to a multi-terminal network with different DC voltage levels, which would be the first full scale multi-terminal DC hardware facility in the world. The three options are summarised as follows:

- **Option 1: Point to point at a single voltage level;**
- **Option 2: Multi-terminal at a single voltage level;**
- **Option 3: Multi-terminal at multiple voltage levels.**

The capital cost of developing such a test facility was estimated, and ranged from £13 million for a point to point facility to £25 million for a multi-terminal facility. The most significant cost items are the MVDC converters, and so it would be advisable to approach suppliers of these as potential project partners. If the converters were donated or loaned by project partners, then the capital cost of the test facility would be reduced to between £2.7million and £4.4million. Operational and ongoing research costs are not included in these figures.

Although a point to point network has been included, it is proposed that the optimal test facility configuration will be multi-terminal as this additional functionality should provide a significant increase in the benefit to transmission stakeholders, as well as better facilitating competition in the wider industry, as there are more test bays available and it would be possible for multiple suppliers to test their products simultaneously.

Based on the results of this report, TNEI recommend that Scottish Enterprise should pursue Option 3, a multi-terminal test facility incorporating two different voltage levels and DC boost technology.

0.2 Socio-Economic Benefits to Scotland

An appraisal of the potential direct and wider economic benefits to Scotland has been undertaken for the proposed MVDC Test & Demonstration facility.

Potential Scottish MVDC Market Size

In order to give an indication of the size of the potential market for MVDC, the value of Scottish Offshore projects and interconnectors in 2014 was calculated. It was found that there is a significant volume of Scottish offshore projects that will spend a total of £3.3bn on electrical infrastructure. Most of these projects are going ahead with AC transmission solutions; however this figure does indicate the potential scale of the offshore market in Scotland for MVDC, if the technology is matured and de-risked sufficiently for developers to consider it as a transmission solution. If the same projects were to use direct to shore MVDC solutions, the reduction in capital costs could amount to up to £1.7bn, based on the offshore case study considered in section B of this report. The adoption of MVDC would, however, have an adverse impact on losses and unavailability. When factoring in these lifecycle costs the potential savings would be significantly reduced. This reduction is highly dependent on assumptions about the cost of energy from offshore wind. If costs per MWh are higher (eg £140/MWh), then lifecycle costs become more significant than for lower costs of energy (eg £100/MWh).

Direct Benefits during Construction

Direct benefits during the construction of a Test & Demonstration facility have been calculated based on predicted build costs and a range of assumptions. Net GVA, depending on the chosen Test & Demonstration facility option, has been calculated as between around £0.5 and £0.8 million based on total installed costs, or £0.25 to £0.4 million taking a more conservative approach based on design and construction costs alone.

Direct, Indirect and Induced Benefits during Operation

It is predicted that direct benefits during operation will be derived from Full Time Equivalent (FTE) jobs created by operation of the test facility. Numbers of FTE jobs and GVA have been estimated as in **Table 0-1**.

Table 0-1: Estimated Economic Benefits of the Operation of the MVDC Test Facility

Option	Direct Jobs Supported	Indirect and Induced Jobs Supported	Direct GVA (£million per annum)	Indirect and Induced GVA (£million per annum)	Total GVA (£million per annum)
Option 1	14	7	0.6	0.4	1
Option 2	17	9	0.7	0.5	1.2
Option 3	17	9	0.7	0.5	1.2

Other Benefits

- One of the key benefits of the MVDC test & demonstration facility will be to encourage the development of a DC research cluster in Scotland. To quantify the impact of this agglomeration, the Manitoba HVDC research centre has been investigated as a case study.
- In Manitoba, HVDC activity, including Manitoba HVDC Research Centre, lead to the establishment of a number of R&D companies and consultancies over approximately a 20 year period. This technology cluster has been analysed and the total discounted Net GVA, which includes direct and induced effects, has been calculated as being between around £5 and £8.5 million per annum.
- The European Marine Energy Centre (EMEC) in Orkney has been operational since 2003. The establishment of a technology cluster around that facility has not been seen however the test centre has been analysed and the discounted Net GVA has been calculated as around £1.4 million.
- There is evidence of a significant skills shortage in power electronics and the activities of an MVDC T&D Centre, and anticipated spin-off activities helping to attract and train new engineers to alleviate this, is a potential wider benefit to the Scottish economy. A lack of suitable skills could lead to a reduction in economic development in this industry within Scotland, with new companies and facilities being set up elsewhere.
- De-risking MVDC technology would assist in improving grid connectivity for offshore and onshore renewable energy generation although the scale of the benefits as a result of MVDC and HVDC (which would also benefit from an MVDC T&D Centre) cannot be quantified. Option 3 would provide the greatest potential benefits, particularly relating to DC Boost technology. Potential benefits resulting from this include increased employment opportunities, increased energy generation (some of which may be exported) and reductions in consumer energy costs.
- Development of a T&D Centre would help to put Scotland at the centre of the development of this technology and could develop world recognised expertise, as has been achieved for Manitoba with PSCAD. It is considered that this could happen more quickly than was the case in Manitoba due to the current state of the industry and demand requirements. Establishment of a T&D Centre could lead to significant specialised expertise being developed and the emergence of a number of consulting and R&D spin-off companies.

The appraisal of economic benefits for Scotland concludes that the wider benefits in terms of facilitating further development of renewable generation, energy self sufficiency (and exceeding it) and reductions in consumer energy bills cannot be quantified but have the potential to provide a real and significant benefit to the Scottish economy.

0.3 Justification for MVDC Test Facility

0.3.1 Market Analysis

The market analysis carried out for this project involved a combination of research and stakeholder engagement activity. The research yielded information on previous and existing MVDC research, projects and applications within the power industry, and provided an indication of the market position of MVDC technology and its components. Through the stakeholder engagement activities, a range of technical and market barriers and challenges were expressed, with many of these being interdependent i.e. some technical barriers are preventing a market case from being successfully proven, and vice versa.

Despite the numerous challenges described by the stakeholders, there is a generally positive opinion of MVDC and its potential for use in a number of power system applications. It is clear that activity in the area remains naissant however the majority of stakeholders have expressed encouragement for its advancement to maturity.

A number of technical and market barriers were identified by the stakeholders, most prominently the issues relating to cost and reliability of power electronic and MVDC equipment were cited, as were concerns over specifications, regulation and the need for a performance/operational track record. From a technical perspective, the majority of the challenges put forward by the stakeholders could be overcome through a demonstration project. A demonstration would de-risk the technology by performing realistic demonstrations. A test and demonstration facility would also provide a means to test and develop some of the less mature MVDC technologies seen to be critical for deployment e.g. DC protection devices. Outcomes from such a venture would also increase market certainty by lending positive support and results to meeting some of the market and economic challenges being faced.

There are a number of existing DC test and demonstration laboratories and facilities which are relevant to the work in this project with the focal point of Scotland, either due to the scope of the facility or its location. Each of these facilities has been assessed and the capabilities of each have been identified to gauge any gaps an MVDC test and demonstration centre could potentially fill. It has been established that there is scope for an MVDC demonstration to be located in Scotland without the risk of duplicating any of the existing facilities, provided the following criteria are met:

- Voltage level greater than 5 kV DC;
- Hardware test capability for industrial demonstration of MVDC components;
- Point to point or multi-terminal configuration.

The estimated timeline for MVDC technology to reach the market in a state of technology readiness with sufficient demand varies from around 3 years to 20 years depending on the stakeholder group and the associated application. The belief is that a demonstration capability would take up to 4 years to provide meaningful results and from there the market could grow steadily with confidence in the technology. Although there is generally a positive opinion of MVDC and its potential, there is not an immediate appetite to adopt the technology over "business as usual" technology.

0.3.2 Technology Case Studies

Two case studies were considered to demonstrate the applications of MVDC technology:

1. Using MVDC to connect a large offshore wind farm
2. Using an MVDC link for onshore distribution network reinforcement

These case studies considered full project lifecycle costs, including capital cost, electrical losses and unavailability.

The offshore wind case study demonstrated that direct MVDC connections, with array and transmission cables operating at ±60 kV, would be a cost effective way to connect offshore wind farms over a range of distances. This connection topology eliminates the need for an offshore platform, which leads to significant reductions in capital cost. However, costs relating to electrical losses and unavailability are very significant; therefore such connections will be more attractive if the cost of electricity from offshore wind is reduced to £120/MWh or £100/MWh. To make this type of connection possible, it has been assumed that some technological improvements will be readily available, including:

- The use of AC disconnectors on DC circuits to quickly isolate faulted network components;
- Cost effective generator DC integration, which eliminates the requirement for a step-up transformer.

Many of the benefits demonstrated for offshore wind farms would also be applicable to tidal and wave energy projects.

The onshore distribution network case study showed that a DC link can be an efficient way to reinforce a network in which there are several issues which need to be addressed. It was found that in place of extensive 132kV reinforcement works an MVDC link could be installed at 33kV with much lower capital cost. In addition, the MVDC link dramatically improves the voltage profile throughout the case study network which decreases network losses. Over the asset's lifetime, the reduction in losses proves to be a significant benefit of the MVDC link, compared to the conventional reinforcement scheme.

1 Introduction

The concept of HVDC (high voltage direct current) technology is well established within the electricity supply industry. In particular, HVDC is used to connect asynchronous transmission networks (e.g. GB and mainland Europe) and is of increasing interest to offshore renewable developers. The key benefits of HVDC for these applications are (a) losses in a DC (direct current) circuit are lower than in an equivalent AC (alternating current) circuit, (b) there is no requirement for reactive compensation in a DC circuit, (c) conversion between AC and DC allows for asynchronous grids to be connected to each other.

LVDC (low voltage direct current) is also commonly used in the electricity supply industry. For example, solar PV (photovoltaic) panels generate DC electricity and to export this to the grid, low voltage DC to AC inverters are used. Similar technologies are becoming increasingly common in wind farms; by connecting a wind turbine to the grid via an AC/DC/AC converter, it allows for the turbine to operate at varying speeds.

MVDC (medium voltage direct current) is a similar technology. The key distinction is the voltage level; HVDC is typically used for transmission applications, including offshore renewable transmission. MVDC systems, on the other hand, would be used for distribution applications and for renewable energy arrays, corresponding to AC voltages of 11 kV, 33 kV and 66 kV. MVDC systems are currently used for markets outside of the electricity supply industry such as rail electrification.

MVDC technology could potentially be used to facilitate integration of variable renewable energy sources, either by using MVDC in the design of renewable energy connections or by using the technology for onshore network reinforcement. In addition, a key application of MVDC technology could be to demonstrate and de-risk novel HVDC systems and components, such as multi-terminal systems.

There is already significant HVDC research and development (R&D) taking place in Scotland and there is potentially a very large market for this. Several offshore wind farms in Scotland have considered the use of HVDC technology, including Moray and Beatrice, although none as yet have progressed with this. In addition, an HVDC link from Caithness into Moray is currently in development, with plans for this to potentially be a multi-terminal system with a further connection into Shetland. Further HVDC links from Scotland into England & Wales are also under consideration. This market is supported by a variety of research centres, such as the Power Networks Demonstration Centre (PNDC) in Cumbernauld, the Low Voltage DC laboratory at the University of Aberdeen and the proposed Multi-Terminal Test Environment (MTTE).

Therefore, there is potential for Scotland to become a hub for DC research activities. With this in mind, Scottish Enterprise, in partnership with SP Energy Networks, is looking to understand the market potential for MVDC technologies with a view to exploring the opportunity to establish an MVDC test and demonstration project in Scotland.

1.1 Report Structure

The report is structured as follows:

- Chapter 2: This covers the work completed in Part A of this project, i.e. a review of the existing market for MVDC technology and discussion of the future direction of the market. The majority of the stakeholder engagement was completed in Part A of the work and therefore the results from this are included in Chapter 2;
- Chapter 3: This covers the work completed in Part B of this project, i.e. case studies which demonstrate the cost benefit of using MVDC technology for offshore renewable connections and onshore network reinforcement. The results of these case studies, taken with the results of Part A, are then used to inform the direction of Part C;
- Chapter 4: This covers the work completed in Part C of this project, i.e. optioneering for an MVDC test & demonstration centre, and an assessment of the economic benefits of such a test centre for Scotland.
- Chapter 5: This summarises TNEI's recommendations to Scottish Enterprise on how to progress the MVDC Test & Demonstration Facility project.

2 Market Understanding and Analysis (Part A)

Part A of this project encompasses an assessment of the market conditions for MVDC technology, both presently and looking out approximately 10-15 years into the future. This section identifies the MVDC technologies that offer the potential to integrate renewable energy generation and examines the market outlook for these technologies. This has been achieved by reviewing previous and ongoing work on MVDC projects, including research, development and the testing of technology.

This section initially introduces MVDC technology in the context of how it is considered for this project, and describes the main components detailing their function and purpose as well as their current technological maturity and perceived market readiness. Following this, a description of relevant previous and current MVDC projects is provided, also giving details of existing DC laboratory facilities where MVDC research, development and testing is carried out.

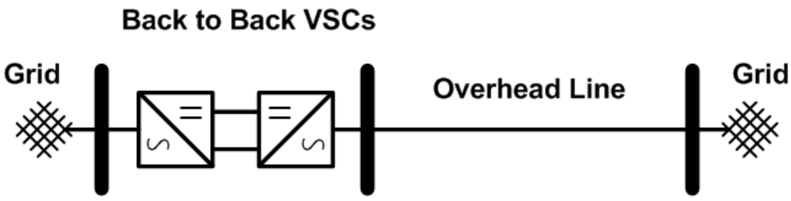
Stakeholder engagement was carried out as part of this market analysis, and the outputs are presented here according to their category, and summarised as such. A 'gap analysis' is presented at the end of this section which reviews the findings of Part A and the constraints that have been identified. These will feed into the work in Part C which involves the specification of a MVDC test and demonstration project.

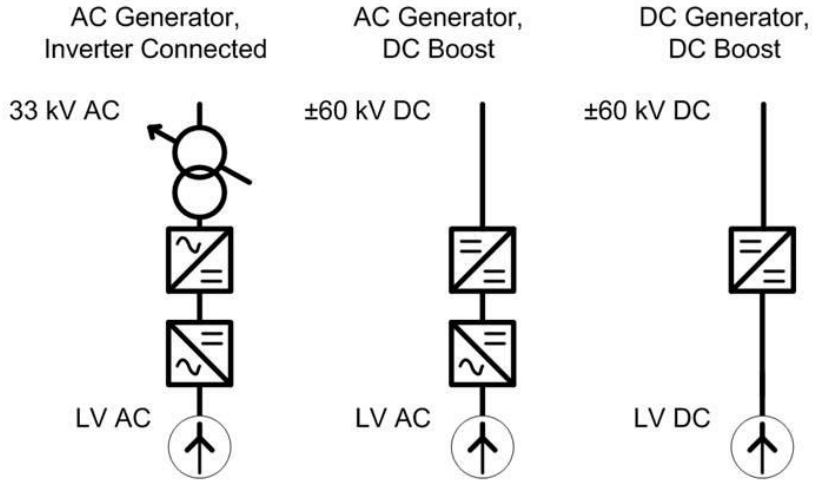
2.1 MVDC Technology and Components

For the purposes of this report MVDC technologies are those which use direct current where the DC voltage is in the range of ±1 kV to ±80 kV. However, there is no definitive answer of what is meant by MVDC technology and definitions vary within the industry. The majority of stakeholders who were engaged agreed with this voltage range, however there are exceptions. For example ABB's HVDC Light project brochure includes a project with a DC voltage as low as ±9 kV; in this report, this would be considered to be a MVDC project.

In terms of technologies, this report is primarily focused on the applications of voltage source converters at medium voltages and the novel components which could support a medium voltage DC network, such as DC circuit breakers. Table 2-1 describes some of these components in more detail.

Table 2-1: MVDC Technologies & Components Considered in the Report

MVDC Component	Description
Voltage Source Converter	"Classic" HVDC systems use Current Source Converters (CSC), where diodes or thyristors convert between DC and AC. More recently, Voltage Source Converters (VSC), which use high power Insulated Gate Bipolar Transistors (IGBT), have become more common for HVDC applications. There are significant advantages of VSC systems compared to CSC. For example, it is easier to change the direction of power flow and it is easier to control voltage on the AC side of the converter. VSC systems can also be used to "black-start" a grid which needs re-energised or where one end is a weak grid. There are limitations however, with VSC resulting in higher losses and higher costs than CSC.
VSCs in back-to-back arrangement	It is possible to put two VSC converters in a back-to-back arrangement, as in the figure below:  **Figure 2-1: Back to Back VSC Arrangement** There are no long DC circuits in this arrangement and therefore there are no benefits arising from loss reduction. However, there are numerous technical benefits which might make this an attractive tool for network reinforcement. For example, such a back-to-back VSC system could allow for two grids which operate at different frequencies to be connected to each other. It can also be used to mitigate issues relating to phase angles, fault levels, power flow control and under- or over-voltage.
DC/DC Boost Technology	Currently, to step up from one DC voltage to another would require two DC to AC converters in series with a conventional AC transformer. This arrangement would have a considerable footprint which might preclude it from being used for offshore purposes. In addition, large capacity VSC converters are very expensive and any arrangement which requires two of them is likely to be prohibitively expensive. Technology which would allow direction conversion from one DC voltage to another without requiring so much space or cost would therefore be beneficial for the development of DC grids.

MVDC Component	Description
Generator DC Integration	A variant of DC/DC boost technology, this refers to systems which allow generators (turbines in particular) to output their power directly into a DC array. Alternatively, it could be possible to have generators which output directly at low voltage DC, which is then boosted to medium voltage DC. A typical arrangement for an offshore wind farm is shown below, alongside two proposed variants:  **Figure 2-2: Typical Offshore Wind Farm Arrangements**
DC Cables	High Voltage DC cables are currently used on HVDC interconnectors, large offshore wind farms with HVDC transmission connections and long distance onshore HVDC power links. DC cable technology has to date been developed independently from AC cables, so an HVDC project today will use a purpose designed DC cable. At medium voltage however, it may be possible to utilise existing standard AC cables for MVDC systems. A 33kV AC cable has been rated to withstand an RMS AC voltage of 33kV +/- 10%. This means that the equivalent AC peak voltage it can withstand is 33 x 1.41 x 110% = 51 kV. In theory, a 33kV AC cable could therefore be run continuously at 51kV DC. The development of this concept in industry would be highly valuable as it would increase competition in the supply of DC cables and reduce the cost of DC systems.

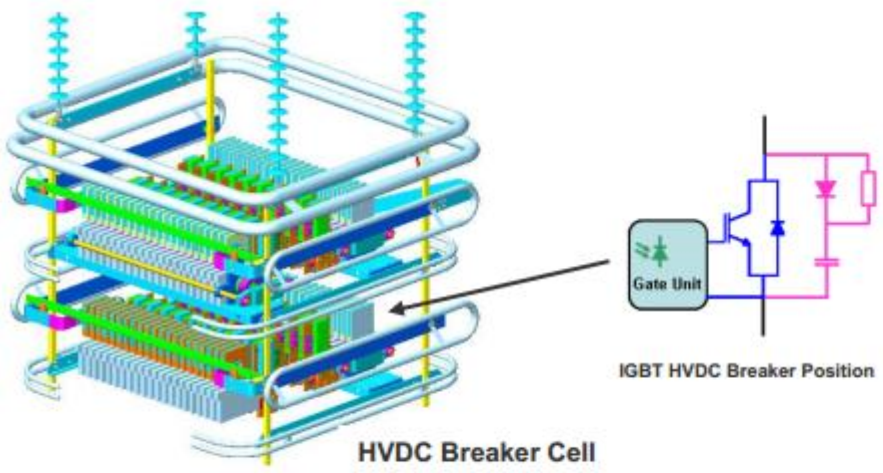
<table>
<tr><th>MVDC Component</th><th>Description</th></tr>
<tr><td>DC Circuit Breakers</td><td>
High Voltage DC breakers have long been problematic to develop, due to the difficulty in interrupting a large DC current fast enough to isolate a fault. However Circuit Breakers are critical to the design and operation of a reliable grid, and so the lack of a DC circuit breaker design was a major obstacle to the large scale development of HVDC grids.
In 2012, one supplier, ABB announced the successful development of an HVDC breaker, which has been verified at component and system levels at ABB’s high power laboratories in Sweden and Switzerland, for HVDC voltages up to +/-320 kV and rated currents of 2.6 kA.


Figure 2-3: Design of ABB 80kV main HVDC breaker cell [1]
The next step is to deploy the breaker in a real HVDC transmission line to test under continuous full load conditions.
</td></tr>
<tr><td>DC Disconnector</td><td>
Mechanical disconnectors work as a switch to isolate components within the electrical system. Once a fault is detected and isolated by a circuit breaker (see above), a disconnector can be used to isolate the faulty component and the rest of the system can be re-energised. This can be done in a matter of minutes which would significantly reduce the down-time as a result of any faults.
Development of DC disconnectors (or the proven use of AC disconnectors on DC systems) would therefore provide significant improvements in availability.
</td></tr>
</table>

MVDC Component	Description
DC Wet-mate connectors	Wet mate connectors allow electrical connections to be made between cables under water. This means that installation and maintenance activities can take place without being brought to the sea surface. This can increase the efficiency of offshore operations and is an important development for the wave and tidal industry in particular.  **Figure 2-4:Example of a Wet Mate Connector [2]**

Certain components which might be classed as MVDC technology have not been considered further in this report. In particular, STATCOMs (static synchronous compensator) have not been included in the market analysis, even though these utilise DC technology and could be connected at medium voltages. In fact, there are many similarities between STATCOMs and VSC devices; STATCOMs utilise IGBT based VSCs in their design. However, STATCOMs are only used to provide reactive power support to an AC grid and STATCOM technology is already relatively mature with tens of installations of STATCOMS in the UK alone at both generation and grid substation sites, and a wide product offering from the key electrical suppliers. Therefore, further market research for medium voltage STATCOMs is likely to be of limited value at this stage, however lessons learned and knowledge from STATCOM technology growth and roll-out should be a useful resource at a later stage.

2.2 Market Use

Some of the current and proposed market applications of MVDC technologies include:

1. **Offshore Renewables**: MVDC can potentially be used in the design of arrays for offshore renewable energy sources, including offshore wind, wave and tidal. Use of direct current will reduce losses and remove the requirement for reactive power compensation equipment. In some cases the use of MVDC could preclude the need for expensive offshore substation platforms;
2. **Distribution Networks:** MVDC technologies can be used to make the most of existing network assets and potentially avoid costly reinforcements at

higher network voltages. Some of the benefits of MVDC for distribution networks include reductions in fault level, control of power flow, control of power factor and improvements in voltage profile;

3. **De-risking HVDC:** Another potential application for MVDC, in the short- to medium-term will be to provide scaled down hardware demonstrations of HVDC technologies and their applications. For example, a multi-terminal MVDC project could be constructed which is representative of a multi-terminal HVDC arrangement. Using medium voltage equipment would be cheaper and potentially easier for maintenance purposes, however many of the lessons learned would be applicable for a higher voltage project.
4. **Transmission Networks:** One of the key applications of MVDC for transmission networks will be de-risking technologies and applications of HVDC which can then be applied directly on the transmission network, as above. However, there are also potential applications for MVDC to be used directly on Scotland's 132 kV transmission network; with a 132 kV AC voltage network it is likely that the DC system would be operated at <±80 kV;
5. **Rail Electrification:** DC systems are used for rail electrification (particularly light rail such as trams) throughout the world, sometimes at voltages greater than 1kV DC. Railways and trams need to be able to operate at variable speeds and variable speed drives which are not synchronised to the AC grid can therefore be supplied directly by DC systems;
6. **Shipping and Harbours:** One of the key applications of MVDC converters, particularly in a back-to-back configuration, is the connection of two asynchronous grids. This is of relevance to the shipping industry, as it would allow a large vessel to connect to a harbour's electrical system even if it was not operating at the same frequency. More recently, work has been done to explore the potential for MVDC distribution systems within ships.

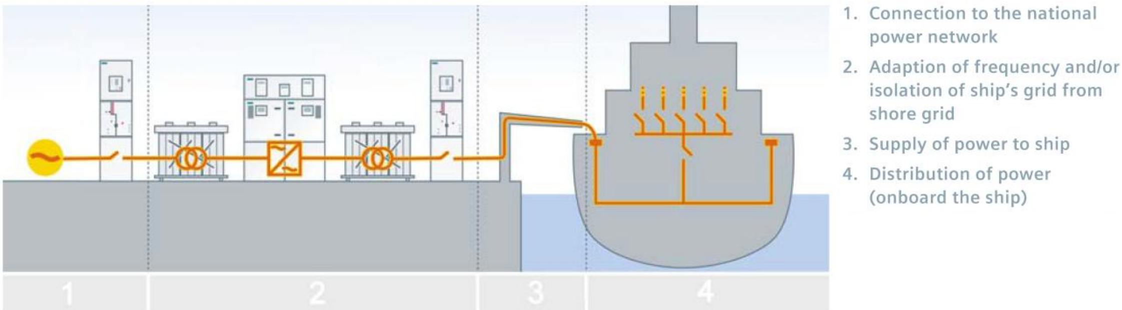


Figure 2-5: Siemens SIPLINK System for Ships [3]

For the purposes of this report, applications 5 (rail electrification) and 6 (shipping and harbours) are considered to be of less relevance, as they are not related to smart grids or integrating variable energy sources. The markets in these industries are already mature, however they are critically specialised and there is little or no experience of cross-selling this technology into other sectors. Case studies which demonstrate potential market applications for 1 (offshore renewables) and 2 (distribution networks) are presented in Part B (Section 3). A test & demonstration centre, which would de-risk HVDC applications as per application 3 and help the development of MVDC technology, is discussed in Part C (Section 4). Potential applications to transmission networks, as per application 4, are discussed throughout the report, where appropriate.

2.2.1 Market Drivers

The main market drivers for MVDC technology can be considered as:

- A reduction in costs for applications which look to facilitate the integration of renewable generation, such as offshore generation sites and smart grids for maximising use of existing network capacity; and
- Acceleration and reduction in cost of the testing/demonstration of HVDC which will improve bulk transfer of power over long distances

2.3 Review of Relevant MVDC Projects and Demonstrations

Interest in MVDC technology and potential applications for power systems has been evident for a number of years. It has been considered, studied or deployed in a small number of previous projects, and there continues to be ongoing work in the area. Some of the most relevant previous and current projects, demonstrations and work in the area are described in the following sections. Relevant LVDC and HVDC demonstrations are also included where synergies have been identified.

2.3.1 PNDC Scoping Project for MVDC Demonstration Capability

Prior to the work carried out as part of this project, the Power Networks Demonstration Centre, funded jointly by Scottish Power Renewables (SPR), SP Eenergy Networks, Iberdrola Renewables and Scottish Enterprise, carried out an investigation into the development of an MVDC demonstration project. This work focused on understanding the present and future requirements that would bring MVDC technology to the attention of the industry, with a view to extending the existing facilities at PNDC to include MVDC demonstration capability, where presently it houses only an LV AC network.

An interim report was published on the project findings in late 2013 [4], and this presented a number of applications for MVDC technology, an also identified existing research projects and demonstration capabilities. In terms of potential uses of MVDC technology, five main applications were identified in this study;

1. DC networks for buildings and data centres which have a high proportion of DC load;
2. DC distribution networks onboard ships;
3. Distribution network reinforcement solutions;

4. Offshore renewable generation collection (wind, wave, tidal); and
5. DC interconnection of HVDC transmission networks and scaling of HVDC technologies for testing.

Based on the findings noted above, and taking on board the outcomes from stakeholder engagement discussions, three potential demonstration activities were scoped to meet the needs of options 3 and 4 above, which were seen as the most promising applications. These three demonstration activities were:

- An offshore multi terminal HVDC transmission system down-scale demonstrator;
- An onshore multi terminal MVDC distribution system real-scale demonstrator; and
- An offshore multi terminal MVDC distribution system (collector system) down-scale demonstrator.

The work being carried out in this study follows on from the PNDC project and takes an additional view of the potential wider socio-economic impacts and benefits such a facility would bring to Scotland.

2.3.2 University of Aberdeen – DC Laboratory and Research

The Power Systems Research Group at the University of Aberdeen has a Low Voltage DC laboratory rated at 1 kV/30 kW [5]. Within the lab, a number of projects focused on equipment prototyping are carried out, such as DC/DC converters [6]. Work on DC grids, including MVDC grids for offshore and subsea collector systems [7], [8], DC hubs and DC protection [9] is also carried out in the department.

2.3.3 University of Nottingham – DC Laboratory and Research

The Power Electronics, Machines and Control Group at the University of Nottingham received EPSRC (Engineering and Physical Sciences Research Council) funding towards setting up a scaled (medium voltage) VSC-HVDC laboratory [10]. The facility is a 3.3 kV AC/5 kV DC/3 MW grid which has a flexible topology inclusive of six converters, three of which are programmable. Real-time simulation is achieved using Opal-RT processors and allows for hardware-in-the-loop functionality. Much of the research planned for this facility will focus on VSC (Voltage-Source Converter) technology as it increases in prevalence and becomes the preferable method of HVDC systems.

2.3.4 RWTH Aachen University and the E.ON Energy Research Centre – DC Laboratory and Research

The Institute for Power Generation and Storage Systems (PGS) at E.ON Energy Research Center (ERC) of RWTH Aachen University put forward a proposal to start a research group focused on MVDC technology. This was met with high levels of interest and the “Flexible Elektrische Netze FEN-Konsortium” was formed with 12 industry partners, with the FEN GmbH being the foundation as the legal entity, was created in October 2014. Research will be carried out on low, medium and high voltage systems. However, initially there is a clear focus on medium voltage technologies as the most urgent problems in the electrical supply are seen in medium voltage distribution grids. The German government has granted €2m funding each year for the next 5 years up to 2019, possibly longer, dedicated to this. There are four main MVDC project themes that will be explored initially;

- DC grid planning, which looks at planning procedures for pure DC and mixed AC/DC grids. Also, elements of non-technical research are included e.g. acceptance research, landscape architecture and legislation;
- MVDC components e.g. power electronics, medium frequency transformers, cables, hybrid switches;
- Automation and control, including real-time simulation;
- Setting up an MVDC research grid.

The MVDC research grid is intended to connect up to power existing DC nodes (test benches) as part in a campus DC grid such that it will not only facilitate work on the other three themes noted above, but also on wider DC research. More information on the MVDC demonstration grid can be found in the joint E.ON ERC/RWTH Aachen University report [11].

The final specifications of the MVDC research grid have not yet been finalised, however a minimum voltage of 5 kV DC is being considered. The topology of the MVDC grid will be flexible such that different configurations can be studied in terms of equipment set up as well as protection and control philosophies.

Among other work ongoing at the PGS institute, development of a prototype high-power DC/DC converter in a 5 MW dual active bridge topology is underway. Research on this demonstrator is looking to improve operational and spatial efficiencies of converters.

2.3.5 SHE-T Multi-Terminal Test Environment - HVDC Demonstration Facility

Scottish Hydro Electric Transmission (SHE-T) (in conjunction with National Grid Electricity Transmission Ltd (NGET) and Scottish Power Transmission Ltd (SPT)) are currently developing the Multi-Terminal Test Environment HVDC facility following the award in 2013 of £11.82m Network Innovation Competition (NIC) funding from Ofgem.

The MTTE is intended to provide greater understanding of HVDC systems to the transmission operators (TOs) at various levels and at all stages throughout a project lifecycle.

The facility will focus on studying the control behaviour of HVDC systems, initially for a multi-terminal project which is in the pipeline to connect to the SHE-T network, and then other HVDC projects in the future. To this end, when it is constructed, the MTTE will be a 5-terminal HVDC system which will be used to develop and validate control schemes for HVDC operation. Studies and simulations will be carried out offline in power system analysis software (likely PSCAD/EMTP or Matlab) and these will be replicated in real-time simulations (using RTDS (real time digital simulation) equipment) which will include plug-in HVDC control panels allowing validation of control schemes. Within the MTTE, it will also be possible to study the interoperation of high voltage AC and DC networks which is an area of growing interest.

The facility is planned to be delivered in 2017 and will run until at least 2021, at which time a business plan for continuation of the facility will be produced.

2.3.6 RXPE Deployed MVDC Projects

RXPE are a manufacturer of power electronic equipment, specialising in medium voltage technologies such as harmonic filters and reactive compensation equipment. As a result of their area of expertise, they have already been involved in the deployment of three MVDC projects to date; two of which involved the point to point connection at 10 kV DC of two oil platforms separated by a distance of approximately 30km; and the third project, located in southern China, was part of a demonstration intended to prove the use of MVDC technology to supply a busy urban network with a requirement for a low short circuit level infeed.

2.3.7 ABB HVDC Light Projects

Global power system equipment manufacturer, ABB, has the HVDC Light product which employs VSC technology. The HVDC Light technology was launched in 1997 as an adaptation of classic HVDC, and its appeal comes from its ability to transmit lower powers over shorter distances using DC technology [12]. The HVDC Light product has been used in a number of projects for applications such as back to back integration of AC grids and point to point connections to offshore oil platforms and wind farms. Its capability to transmit lower powers over shorter distances has resulted in its deployment at voltages as low as 9 kV DC, and as stated in Section 2.1, this study is considering the range of voltages attributed to MVDC as between 1 kV and 80 kV.

The most relevant project examples of use of HVDC Light technology at MV are:

- Tjaereborg onshore wind farm in Denmark, which was connected to the grid via a 4.3km 9 kV point to point HVDC Light link. This project was completed in 2000 and was intended as a small scale demonstration to determine the technology's ability to support the deployment of offshore wind in Denmark (expected to be up to 4 GW by 2030). This mirrors one of the identified applications for MVDC technology in this study; scaled-down demonstration of HVDC.
- More recently, the Mackinac project in the USA has been installed. This project seeks to increase controllability of power flows within the grid in Michigan, and facilitate integration of renewables in the area through the use of a back to back converter. The 200 MW converter station operates on the 138 kV AC network with a DC voltage range of ±71 kV. The use of back to back converter stations to support the integration of renewables

and management of power flows has been a focal point of this study, with a case study presented in Section 3.

2.3.8 Carbon Trust DC Technology Scoping Studies

TNEI carried out an investigation in 2012 on behalf of the Carbon Trust which investigated DC technology being applied for offshore generation collector array systems such as those used in wind, tidal and wave developments. The investigation performed a technology review of DC collector array systems over a range of voltages and compared these with the "business as usual" (BAU) AC array solutions using a cost benefit analysis. The range of voltages considered in the study was between ±30 kV and ±60 kV which is considered to be within the MVDC operating range.

The report summarised that overall, the technology is feasible for use in offshore collector systems, however there is very little activity (at the time of writing) in terms of deployment and use as there was no needs case to prompt manufacturers to build MVDC equipment. When looking at short distances offshore, direct MVDC connection to shore is marginally more cost effective when compared to 132 kV AC but this saving is lost when 220 kV AC is considered. As transmission distances increase further offshore, a case was made for connection via an offshore platform and an HVDC link, however the cost benefit analysis of this option comes out worse than the AC alternatives.

2.3.9 Western Power Distribution Funding to Build MVDC Demonstration

Western Power Distribution (WPD) submitted a bid this year for Low Carbon Network Fund (LCNF) Tier 2 funding from Ofgem for their project "Network Equilibrium". This bid was recently successful and WPD have been awarded £11.48m towards the project. The Network Equilibrium project seeks to trial three methods of managing power flows and controlling voltages across WPD's South West distribution networks, one of which involves the use of MVDC technology. An AC-DC-AC MVDC converter will connect two separate 33 kV networks which have previously not been connected due to issues encompassing fault level, circulating current and phase angles. Work on the project is due to commence in March 2015 and will run for four years.

2.3.10 Tidal Array Concept Study

In 2012, SSE Renewables, with the support of Scottish Enterprise and other sector stakeholders, contracted ABB, GE Power Conversion and Siemens Subsea to carry out a concept engineering exercise to investigate the electrical infrastructure required to connect commercial scale tidal arrays to the network [13]. Each of the companies was provided with the same specifications (cost, scope, programme) and was asked to investigate optimal connection designs and any potential for standardisation. Three tidal farm capacities were studied: 30 MW, 100 MW and 200 MW, in both surface piercing (e.g. floating, fixed) and fully submerged topologies.

ABB concluded that DC collection is preferable for the various tidal array configurations studied, with the 30 MW solution proving the most cost effective by employing two 15 MW DC ring main circuits. In the floating solution, the power is collected from the rings by three subsea hubs operating at ±7.5 kV DC and transported to shore at 33 kV AC, while a fully subsea solution sees the two ring main circuits running the full distance to shore. At capacities greater than 100 MW, ABB identified the most economic solutions to be surface piercing platforms where either AC or DC connections can be used.

GE Power Conversion's preferred solution is also a DC collection system which incorporates a DC transmission link to a shore side collection/converter station and grid connection. The 1 MW turbines are assumed to operate at 6.6 kV and the DC transmission link operates at ±5 kV DC. GE propose to collect the power from four offshore collector/converter stations, each capable of taking power from nine turbines thus giving a total power of 36 MW, which is transmitted to the onshore collector/converter station. At capacities greater than 100 MW, this solution can be scaled or other options are explored.

Siemens did not consider a DC array configuration as the assumption has been made that the tidal turbines will be designed much like their wind turbines and therefore have built-in conversion with an AC output, such that there would be little benefit in converting the power again for collection.

More information on the projects and the specifications and assumptions made are available in the individual reports [14], [15] and [16]. The work carried out here is being taken forward by ORE Catapult who is commissioning further research on the subject to be conducted in 2015.

2.4 Future Direction of MVDC

The future direction of MVDC for the various applications identified in Section 2.2 will be shaped by a range of benefits, constraints and external factors. A number of constraints are universal to all MVDC applications, these include the capital cost of the power electronic equipment, the lack of operational track record or demonstration for the majority of the components, and the risk associated with both of these. Acceleration of MVDC deployment is also constrained by the need for further technological advancements in DC/DC voltage level transformation and DC protection. Supply chain issues are another factor, where manufacturers won't build or invest in MVDC technology or components in an absent market.

The application of MVDC technology for offshore renewable developments (over BAU AC solutions) would bring the benefits of reduced losses over the collector system, and also would remove the requirement for reactive power compensation equipment, both of which can prove costly on large offshore projects. In tidal and wave (and near shore wind) developments, there is potentially an additional cost saving to be made by using MVDC and thus removing the need for an expensive offshore platform. The use of MVDC as the collector technology in offshore wind farms that will have an HVDC link to shore, and their connection point, could also bring some efficiencies. In addition to those described above, constraints for MVDC technology being used in offshore developments are recognised as including the operational reliability of power electronics in high risk environments, and the subsequent cost of failure encompassing repairs and time when unable to generate. One major external factor that will influence the uptake of MVDC on offshore projects, specifically wind, in the UK, is how the market for offshore wind will endure high capital costs and an uncertain subsidy regime with Contracts for Difference [17] replacing the Renewable Obligation Certificate (ROC) [18] incentives.

The main benefits of deploying MVDC technology as a reinforcement solution on distribution networks are associated with the deferral of costly and time-consuming reinforcements. Other technical benefits include the ability of MVDC to solve problems that cannot be as easily solved by the BAU approach e.g. MVDC can provide power flow control or be applied in areas where high fault levels are an issue. The constraints include those described above, and probably most significantly the lack of track record/demonstration has limited the deployment thus far. This is because DNOs have a responsibility to operate a safe and reliable network and there is not yet enough evidence or confidence in the reliability of MVDC technology to support an effective business case, and it is not known if and what wider implications there will be on networks. External factors which will influence the roll-out of MVDC in this application include money awarded for innovation and developments e.g. Ofgem funding initiatives, and the knowledge sharing between network operators that this promotes.

In terms of using MVDC as a means to de-risk HVDC technology, there are several benefits to speak of. The de-risking of HVDC technology could be achieved on a much smaller and cheaper scale, potentially in shorter timescales. The learning can not only be applied to HVDC but also to the MVDC technology itself, providing de-risking and also a track record/demonstration such as those required for the offshore developments and distribution network reinforcement applications detailed above. Interest in HVDC for bulk power transfer is much higher than in MVDC so this would be a useful way for it to gain momentum and build a portfolio of evidence while also meeting the primary requirements of HVDC de-risking. The benefits are similar for MVDC use on Scottish transmission networks (where 132 kV is a transmission voltage in Scotland) with technology de-risking and learning for both MVDC and HVDC being achieved. MVDC for network reinforcement, similar to that on the distribution network as described above, could also be accomplished on the 132 kV network. Use of MVDC on transmission network applications would open the technology up to the availability of funding intended for transmission projects.

2.5 Stakeholder Engagement

A significant aspect of this investigation into MVDC technology and its potential for development was the undertaking of stakeholder engagement activity. A range of stakeholders were consulted to ascertain opinions and views on the potential opportunities of MVDC and establish what, if any, projects have been or are presently being undertaken in the area.

2.5.1 Stakeholder Categories

Six main categories of stakeholder were identified as key players whose business would be directly affected by the deployment of MVDC technology. These six categories are:

- Renewable Developers (onshore and offshore)
- Equipment Suppliers
- Turbine (predominantly wind) Manufacturers
- Distribution Network Operators (DNO)
- Academia
- Existing Test & Demonstration Facilities/Other Facilitators

2.5.2 Method of Engagement

The most effective method of engagement for this project, which would ensure the timeline was respected, was agreed to be telephone discussions with key personnel within each of the stakeholder organisations. A list of contacts was finalised and an introductory email, which included a brief description of the project, was sent to each contact and they were asked if they would be willing to engage, or offer a more appropriate person in their organisation to engage, with TNEI on the subject.

Where positive responses were received, a telephone discussion was scheduled and a list of questions was sent to the stakeholder prior to the call such that they understood the line of questioning and could prepare accordingly. This also allowed for maximum use of time on the calls for more detailed discussion.

2.5.3 Questions to All Stakeholders

A standard set of six questions was asked of each stakeholder:

- What voltage level/range would you consider preferable for MVDC?
- What do you see as the main MVDC application for your business?
- What still has to happen for MVDC to become an effective solution; technologically and from a business point of view?
- What do you think is a reasonable timeline for this?
- Do you think the biggest barriers are/will be technical or business/market factors for suppliers?
- Do you think there is enough interest, and also knowledge/expertise in your organisation to support activity in such a venture?

These questions aimed to gather a broad perspective on MVDC and how each type of stakeholder sees the technology developing, over what timescales, and what barriers they anticipate to be the most onerous.

Additional questions, tailored for each category of stakeholder, were also set which delve into some of the anticipated issues specific to the different types of business and explored the potential economic benefits. These questions are detailed in Appendix A.

2.5.4 Stakeholder Responses

The table below, **Table 2-2**, lists the stakeholder organisations that engaged with TNEI on the projects and in what capacity. It should be noted that many more stakeholders were contacted for questioning as part of this project's engagement activities, however there was a great deal of difficulty in getting responses and/or scheduling a suitable time for discussion. Of notable absence are the majority of offshore renewable developers active in the UK, PNDC, ORE Catapult and the Carbon Trust.

Table 2-2: List of Stakeholders Engaged as part of the Market Analysis

Organisation	Stakeholder Type	Engagement Method
Aachen University/E.ON ERC	Existing T & D Facility	Telephone Call
ABB	Equipment Supplier	Telephone Call/Brief Face to Face Discussion
Gamesa	Turbine Manufacturer	Brief Face to Face Discussion
GE Power Conversion	Equipment Supplier	Telephone Call
Heriot-Watt University	Academia	Written Responses
MTTE	Planned T & D Facility	Telephone Call
Nexans	Equipment Supplier	Brief Face to Face Discussion
Ofgem	Funding Body/Facilitator	Telephone Call
Repsol	Renewable Developer	Telephone Call
RES	Renewable Developer	Telephone Call
RXPE	Equipment Supplier	Telephone Call
Siemens	Equipment Supplier	Brief Face to Face Discussion

Organisation	Stakeholder Type	Engagement Method
SSEPD (SSE Power Distribution)	DNO	Telephone Call
University of Aberdeen	Academia	Telephone Call
University of Nottingham	Academia/Existing T & D Facility	Visit to the University
University of Strathclyde	Academia	Telephone Call
WPD	DNO	Telephone Call

The following sections summarise the responses gathered from the stakeholders during the engagement activities and telephone discussions. The summaries attempt to capture the most relevant outcomes of the discussions and are not a transcript. More detailed accounts of the stakeholder responses are provided in Appendix A.

2.5.4.1 Renewable Developer Responses

Renewable developers were consulted to gauge their level of interest in MVDC as a collector system technology for their generation developments. Also of interest is what the main barriers (technical and otherwise) are to the use of MVDC for renewable developers both presently and in the coming years, specifically in the offshore industry. The developers were also asked what evidence they would require from a demonstration to give them the confidence to use the technology.

2.5.4.2 Renewable Developer Response Summary

Both Repsol and RES highlighted an interest in using MVDC technology for their offshore collection systems, however it has been ruled out thus far for their projects. From the offshore wind perspective, Repsol’s view was that the technology was not well enough established and the resulting lack of cost information meant it was not considered past the concept stage. From a tidal perspective, RES stated compatibility issues with the tidal turbine to be the main barrier. This, coupled with the complexity of subsea engineering with power electronics, means the use of MVDC as a collection technology is neither feasible nor cost effective at present.

Use in future projects however, was not discounted providing the technical barriers are overcome and the TRL of the technology is increased (likely through onshore tests and applications). More testing and information is required on the reliability of the technology, especially in high risk offshore environments.

Specific turbine interfacing issues would also have to be solved for MVDC to be feasible for tidal projects.

2.5.4.3 Equipment Supplier Responses

Equipment suppliers were engaged to establish what, if any, MVDC products they currently develop, and for what purpose and industry. The adaptability of any product to the applications identified in this project they do produce is also of interest here to try and establish the maturity and readiness of MVDC technology. The technical and market barriers that must be overcome from a supplier perspective are probed as are their perceptions of what MVDC equipment will be the most 'important' in terms of initial market demand.

2.5.4.4 Equipment Suppliers Response Summary

The equipment suppliers all offer MVDC products to other industries encompassing the rail, mining and oil and gas sectors. Each of the companies believes that they have the expertise to support the adaptation of their MVDC technology offering for use in the power systems applications being investigated in this study. They are also convinced that their supply chain would adapt without much difficulty, again owing to their existing portfolio of MVDC products. The adoption of MVDC technology is therefore dependent on market factors facilitating buy-in from these additional industries.

Until there is a market for MVDC products (from a power system perspective), equipment suppliers are unlikely to provide off-the-shelf equipment, rather they will continue to respond to bespoke requests for project-specific equipment. When the MVDC market does start to grow, converters and DC protection (both devices and philosophies) have been identified as the most important technologies for wide-spread deployment of MVDC schemes, and as those which will be demanded first.

Each of the equipment suppliers expressed an interest in collaborating with any potential MVDC test and demonstration centre that may be set up, with the level of involvement depending on the specifics of the facility and its capabilities.

2.5.4.5 Turbine Manufacturer Responses

Turbine manufacturers were consulted to establish what the implications of MVDC collector systems would be on turbine design and with what ease/difficulty this could be achieved should the technology be adopted for offshore arrays.

2.5.4.6 Turbine Manufacturer Response Summary

From a turbine manufacturer perspective, there is minimal activity in the area, with only some R&D being carried out. The turbine manufacturers will realistically only make changes to their turbine design should the market demands MVDC collector systems, and this is not expected to be feasible until at least 10 years into the future.

2.5.4.7 DNO Responses

DNOs were consulted to determine whether MVDC technology is, or would be, considered as a network reinforcement solution on distribution networks, and what are seen as the main challenges of implementing MVDC onto distribution networks in this context. DNOs were also asked what value they would seek to gain from a demonstration project in terms of increasing their confidence in considering the technology as a reinforcement option.

2.5.4.8 Summary of DNO Responses

As is evident, the opinion of DNOs on MVDC varies a great deal. This can be easily explained with different networks in different areas having different problems and priorities. WPD have identified areas of their network which could benefit from an MVDC reinforcement solution and have successfully won funding to investigate the technology further, while SSEPD have yet to establish a business case for using MVDC.

The LNCF projects work on the premise that any and all learning will be shared among other DNOs such that SSEPD, and indeed all other DNOs, should benefit from the outcomes of the WPD Network Equilibrium project, including an increased TRL for the technology used, and potentially deploy MVDC as a reinforcement solution on their own networks in future.

The operation of MVDC technology on the distribution network is of interest to both DNOs in the context of how it will perform and integrate with existing equipment, and whether there will be any undesirable impacts. The protection and control of any MVDC equipment is of significant importance to network operators and the testing of this equipment and associated philosophies is worthy of a demonstration.

Both DNOs have expressed an interest in potential involvement with any MVDC demonstration project however the extent of their involvement would be dependent on project specifications of the facility and its capabilities.

2.5.4.9 Academia Responses

Academics from a number of universities were engaged here, specifically those with interest and involvement in DC research projects and groups, to determine what research on MVDC technology or MVDC grids has been undertaken, and any outcomes of this work. Academia can often provide useful insights into early work and developments in a specific area which can give a good indication of future prospects for a technology or idea.

2.5.4.10 Summary of Academia Responses

The responses from the three academic institutions are varied, as is to be expected with each focusing on their own areas of strength and interest.

The University of Aberdeen is working on the premise that MVDC will be a facilitator/subsidiary for HVDC grid development and deployment, where their

HVDC research is scalable to MVDC level voltages. Work on LVDC is also carried out in their 1 kV DC laboratory so they see MVDC as bridging the gap between HVDC and LVDC.

The DC research ongoing at Heriot-Watt is focused on asset management and the improvement of monitoring for reliability purposes.

The research at the University of Strathclyde is primarily focused on HVDC however MVDC has been studied and indentified as useful, with multi terminal capability requiring more development.

There is a general understanding that market factors are more of a barrier than technical challenges and all agree that a demonstration centre or project would be a worthwhile endeavor with technology validation and de-risking the main priorities to reduce market uncertainty. Clustering with a facility such as MTTE would bring benefits however care must be taken to manage the separate ambitions of each project and prevent duplication.

2.5.4.11 Existing Test & Demonstration Facility Responses

Existing test and demonstration facilities were engaged here to investigate what existing text facilities there are and what their set up is from both technical and business model perspectives. Technically, the voltage level, topology and test objective aspects are of interest as it is important that any demonstration borne of this work does not duplicate already-offered capability. Funding options, lessons learned and business models for the facilities were also points of interest in the discussions to assess potential longevity of a demonstration centre with a sustainable business model.

2.5.4.12 Existing Test & Demonstration Facility Response Summary

Each of the three facilities described above have been set up in different ways; the University of Nottingham is funded jointly by EPSRC and the university; the Aachen University/E.ON ERC is funded by the German government and run by a consortium of industry and academic partners; and the MTTE is being constructed using funding awarded by Ofgem. Their business models also vary considerably.

Knowledge and resource clustering is encouraged by all three groups with potential synergies to be found between MTTE and an MVDC demonstration.

2.5.4.13 Funding Body/Facilitator Responses

Ofgem

As the gas and electricity regulator of the UK, Ofgem maintains a ‘technology neutral’ stance. The price control process for the network operators uses, amongst other techniques, a benchmarking approach. This delivers a degree of competition between the network operators as it shows how they are performing in relation to their peers in terms of providing savings to customers through innovation and efficiency measures. Ofgem monitors the performance of the network operators in relation to one another on an ongoing basis. Where one is performing well using a specific technique or technology, the others are encouraged to do the same by the incentive mechanisms embedded in the RIIO price control model. Transparency between operators through reporting helps this process significantly.

Consequently, there is no need for the MVDC technology and solutions to be explicitly endorsed by Ofgem. Its adoption will be dependent on evidence to support the case that its deployment would provide efficiency savings on the network and cost savings to customers.

2.5.5 Overall Summary of Stakeholder Responses

The stakeholder engagement undertaken for this project, presented in the preceding sections, was met with generally positive opinion of MVDC and its potential for use in a number of power system applications. It is clear that activity in the area remains naissant however the majority of stakeholders have expressed encouragement for its advancement to maturity.

A range of technical and market barriers were identified throughout the discussions. These are summarised in the table below, Table 2-1.

Table 2-3: Summary of Technical and Market Barriers to MVDC

Technical Barriers to MVDC	Market/Economic/Commercial Barriers to MVDC
Tidal turbine compatibility with DC connection	Need for proof of cost effectiveness of MVDC (over business as usual solutions)
Complexity of subsea engineering with power electronics	Need for incentive to investors
Reliability of technology (especially in high risk environments)	Need for appropriate demonstration or case study
Regulations & specifications for MVDC components	Cost of power electronics
Future proofing of power electronics	Need for a proven business case
Buy-in from turbine manufacturers	Need for technology de-risking to reduce market uncertainty
DC protection devices and control schemes	Creation of demand for MVDC products
Audible noise from converter stations	Behaviour of related markets and industries e.g. offshore wind

Technical Barriers to MVDC	Market/Economic/Commercial Barriers to MVDC
Wider impacts on surrounding equipment e.g. on a distribution network	More interest in HVDC projects than MVDC scale projects

The majority of the technical barriers cited by the stakeholders could be overcome through a demonstration project, and this is expressed clearly in the sections above. And the solving of some of these technical challenges, alongside other tests and demonstrations would also provide the evidence required, such as improved TRLs, to overcome a number of the market barriers. For instance, if the reliability/availability of MVDC components could be measured and verified, this would de-risk the technology from the perspective of offshore developers which could in turn result in a positive business case for the offshore collector array application and thus create demand.

A timeline for MVDC technology to reach the market in a state of technology readiness with sufficient demand varies from around 3 years to 20 years depending on the stakeholder group and the associated application. The belief is that a demonstration capability would take up to 4 years to provide meaningful results and from there the market could grow steadily with confidence in the technology.

2.6 Gap Analysis

Throughout the research and stakeholder engagement activities carried out and presented in the preceding sections, a number of constraints have been identified in the context of MVDC technology and its development.

2.6.1 Gaps in Technology Availability

The most commonly identified, and indeed critical, technology gaps are listed here:

- DC/DC voltage level transformation
- DC circuit breakers
- DC protection and control philosophies

It is understood that, for MVDC to be considered for use in the applications identified, and on any sort of scale, these technology challenges must be overcome. Presently, DC/DC voltage level transformation is highly inefficient and is achieved by a DC voltage being converted to an AC voltage (through a DC/AC converter) which is then fed through an AC transformer where the voltage level is stepped up or down as necessary, and finally converted back to DC (through an AC/DC converter).

DC circuit breakers, and their associated protection and control philosophies, present another set of challenges to the widespread use of MVDC. It is possible to use AC devices to protect DC sections of equipment and/or network, and there are in fact DC protection devices available that have been developed for other industries e.g. the ENVILINE Automatic Grounding System (AGS) developed for use in the rail industry. However, for large scale applications such as the use of MVDC as a collector technology for an offshore wind farm, this protection would be inadequate and ineffective.

2.6.2 Gaps in Existing Test & Demonstration Capability

The existing test and demonstration facilities presented in this report are those that have been considered relevant in relation to the project focal point of Scotland, either in terms of scope or location. These include:

- The University of Nottingham DC laboratory
- The University of Aberdeen DC Laboratory
- The Aachen University/E.ON Energy Research Centre DC Demonstration
- The Multi-Terminal Test Environment

What is known of the specifications of the facilities has been described in Section Review of Relevant MVDC Projects and Demonstrations2.3 (the specifications of some facilities are not yet finalised). The table below, Table 2-4, summarises these specifications.

Table 2-4: Summary of Existing Test & Demonstration Facility Configurations

Facility	Voltage	Configuration	Primary Test Type	Location
University of Nottingham	MV – 5kV DC	Point to Point	Hardware/Academic Research	England
University of Aberdeen	LV – 900V DC	DC Test Rig	Hardware/Academic Research	Scotland
Aachen University/E.ON ERC	MV – TBC Likely 5kV DC	DC Grid connecting existing DC test benches	Hardware/Industrial Testing & Academic Research	Germany
MTTE	HV - >80kV DC	Multi-Terminal	Software/Industrial	Scotland

It can be derived from the information given in Table 2-4, and also from the stakeholder engagement, that there is scope for an MVDC demonstration to be located in Scotland without the risk of duplicating any of the above, provided the following criteria are met:

- Voltage level greater than 5 kV DC;
- Hardware test capability for industrial demonstration of MVDC components; and
- Point to point or multi-terminal configuration

2.6.3 Gaps in Stakeholder Opinions

As stated in Section 2.5.4, there was difficulty in engaging with all of the stakeholders originally contacted as part of this project, and as a result the opinions of many important stakeholders were not obtained. Of notable absence were the majority of the offshore wind developers active in the UK, the existing T&D facility PNDC, and the facilitating organisations ORE Catapult and the Carbon Trust.

It would be strongly recommended to consult with these organisations in any future MVDC endeavours to gather a well rounded opinion of:

- The adoption of the technology in offshore applications from the perspective of offshore developers;
- The set up of a T&D facility including justifications, objectives, funding and business plans from the experience of setting up PNDC; and
- The potential routes to market for new technologies from the perspective of facilitators who have been through this process with previous technologies.

2.6.4 Other Areas of Concern

An area of concern which has been identified in the course of this work, but is not receiving a high level of attention at present is the issue of tidal turbine interfacing with a DC network. This was highlighted by RES in the stakeholder engagement and is seen as the primary barrier for DC collection arrays being used in tidal developments. Encouragingly, further work on DC tidal arrays is being commissioned in 2015 by ORE Catapult; it is hoped this will yield some positive outcomes for these interfacing issues.

The ability to test the integration issues expressed here would be a valuable feature of an MVDC demonstration centre and this is considered in the specification of Part C (Section 4).

3 Technology Overview (Part B)

Part B of this project shows the potential future applications for MVDC technology and describes potential test and demonstration project options. Case studies are presented which robustly demonstrate the cost efficiencies of MVDC over full project lifecycles. The two applications which are considered further in this section are (1) offshore renewable energy connections and (2) onshore distribution network reinforcement. Various test & demonstration project options are described, and the learning benefits to different sector stakeholders are quantified.

The results of the stakeholder engagement, and supporting industry reports (eg from the Carbon Trust and PNDC [22]), identified the key applications of MVDC, which are applicable to Scotland, as follows:

- Offshore renewable energy connections;
- Distribution network reinforcement;
- Demonstration of DC concepts to de-risk HVDC.

Based on these applications, case studies were investigated to help determine the potential benefits of MVDC technology in (1) the offshore renewable sector, and (2) the onshore power networks sector. For both case studies, a novel MVDC solution was developed and the costs compared to the existing technology solutions in a cost benefit analysis exercise. The two case studies developed were:

1. A 1000MW Offshore Wind Farm
2. A Distribution Network reinforcement scenario

An early decision was made not to proceed with a case study relating to the demonstration of DC concepts to de-risk HVDC, as this would be considered further in Part C of the project, in which a Test & Demonstration Project is scoped and an economic impact assessment is performed.

3.1 Case Study Approach

In order to capture the full extent of a project's costs and benefits throughout its lifetime, a lifecycle approach was used which considered:

- Capital cost (capex);
- Operational costs (opex), including:
  - Cost of electrical losses; and
  - Cost of losses due to unavailability.

To facilitate the comparison between capital costs and operational costs, operational costs were capitalised by calculating the net present value (NPV) of lost energy, as well as any penalties for unavailability, such as customer interruptions (CIs) and customer minutes lost (CMLs) for the onshore network case study. NPV was calculated using the following formula:

$$NPV_{Cost} = \pounds Cost\ x \sum_{i=1}^{N} \left(\frac{1 + Inf}{1 + Int}\right)^{i-1}$$

- £Cost is the cost of lost energy, or the cost of CIs and CMLs;
- *N* is the financing period of the project, assumed to be 25 years for the offshore wind project and 40 years for the onshore reinforcement project;
- *Inf* is the % annual rate of inflation, assumed to be 1.5%; and
- *Int* is the interest rate of the financing, assumed to be 8% for the offshore wind project and 5% for the onshore reinforcement project.

3.1.1 Data and Assumptions

A variety of data sources were used to input into the case studies. This included data from industrial stakeholders, TNEI's internal data sources, published data source, and partner data from SP Energy Networks where required. Data sources are summarised in Table 3-1.

Estimated costs of MVDC components were gathered through engagement with industrial stakeholders in the supply chain, in particular converter manufacturers who anonymously provided cost data.

There was considerable variation in the availability data and capital cost data which was used in the offshore wind case study. To mitigate the uncertainty arising from this variation, best-case, medium-case and worst-cast scenarios were explored for both capital cost and availability. The impact of improvements to converter cost and availability was also explored.

Table 3-1: Data Sources for Offshore and Onshore Scenarios

	Offshore Scenario	Onshore Scenario
Technical Data	• Electrical parameters for components from TNEI databases	• Operational network model provided by SPEN
Cost & Financial Data	• TNEI databases • National Grid's Electricity Ten Year Statement 2013[23] • Stakeholder Engagement	• TNEI databases • Scottish Power Investment Papers [24] • Stakeholder Engagement
Availability Data	• TNEI databases	• CI & CML data from SPEN • Supplementary data from Ofgem [25]

3.2 Offshore Array Application Cost Benefit Analysis

The offshore case study compared lifecycle costs for a 1000 MW wind farm using 5 electrical connection topologies:

1. Conventional 220 kV AC connection with 33 kV AC offshore array
2. Conventional ±320 kV HVDC transmission link with AC offshore array
3. Direct ±60 kV MVDC connection
4. ±320 kV HVDC transmission link with ±60 kV MVDC offshore array
5. 16.67 Hz 220 kV Low Frequency AC connection

An overview of these connection topologies is given in Figure 3-1.

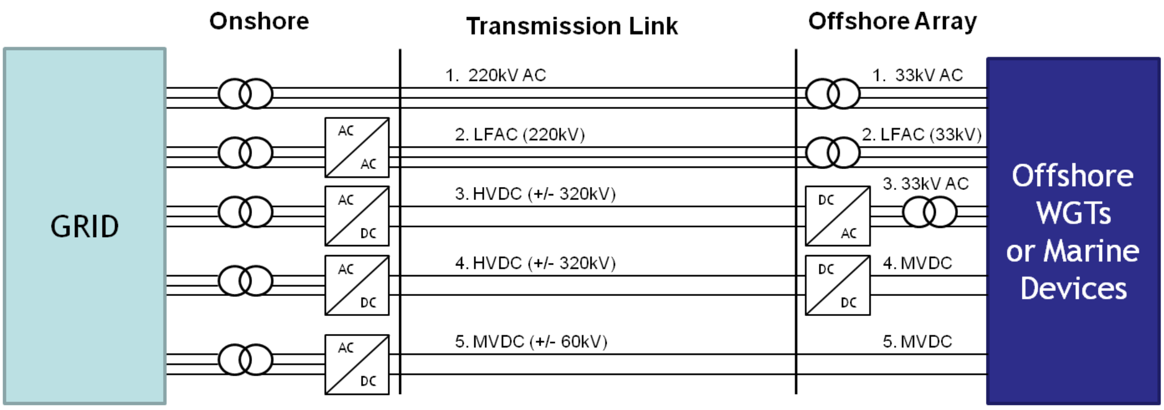


Figure 3-1: Five Electrical Connection Topologies Considered for the Offshore Cost Benefit Analysis

Connection distances from 50 km to 200 km were considered. Results were considered for three different costs of energy from offshore wind, £140 /MWh (the 2017/19 strike price [26]), £100 /MWh (the Offshore Wind Cost Reduction Task Force target [27]) and £120 /MWh (a more conservative cost reduction target).

The results demonstrate that the topology which is potentially of greatest interest is the direct MVDC topology. This topology is shown in more detail in Figure 3-2.

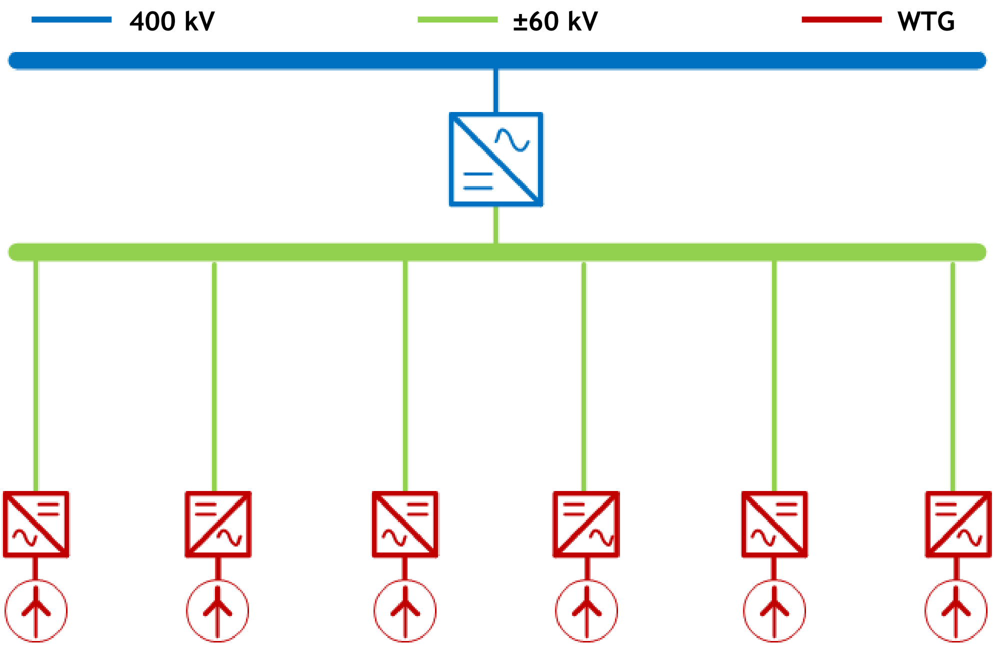


Figure 3-2: Direct MVDC Topology

Note on Redundancy

Throughout the case study it has been assumed that both AC and DC disconnectors are readily available, so that faulted components anywhere in the offshore arrays, or offshore transmission networks can be isolated. This minimises the impact of energy losses due to unavailability. In practice, it is likely that AC disconnectors could be used on DC circuits to isolate faults, with a single DC circuit breaker on the whole system to protect against faults. However, such a use of AC disconnectors for DC systems is not yet proven.

It has been assumed that each converter consists of two units operating in parallel. In every topology, converters share a common DC bus; therefore this is not "redundancy" in the conventional sense as a fault will cause a loss of both of the converter units. However, it has been assumed that in the onshore converter stations the faulted unit can readily and easily be isolated from the electrical system, allowing the rest of the electrical system to be promptly re-energised. This reduces the lost revenue due to unavailability of the onshore converters. This assumption is also dependent on the availability of DC disconnectors.

Figure 3-3 demonstrates the DC protection philosophy which is assumed to be used in the wind farm connections. The entire DC system is protected by a single circuit breaker, and therefore, a fault in the DC system will cause the entire DC system to be cut off from the network. However, the isolators allow for the faulty component to quickly be disconnected from the network, so that the rest of the system can quickly be reenergised. For example, if one of the paralleled converters fails, it can be quickly disconnected from the system using isolators and then the rest of the DC system can be reconnected, albeit with a lower export capacity. Reenergising the system is not problematic, as the VSC converters have black start capability.

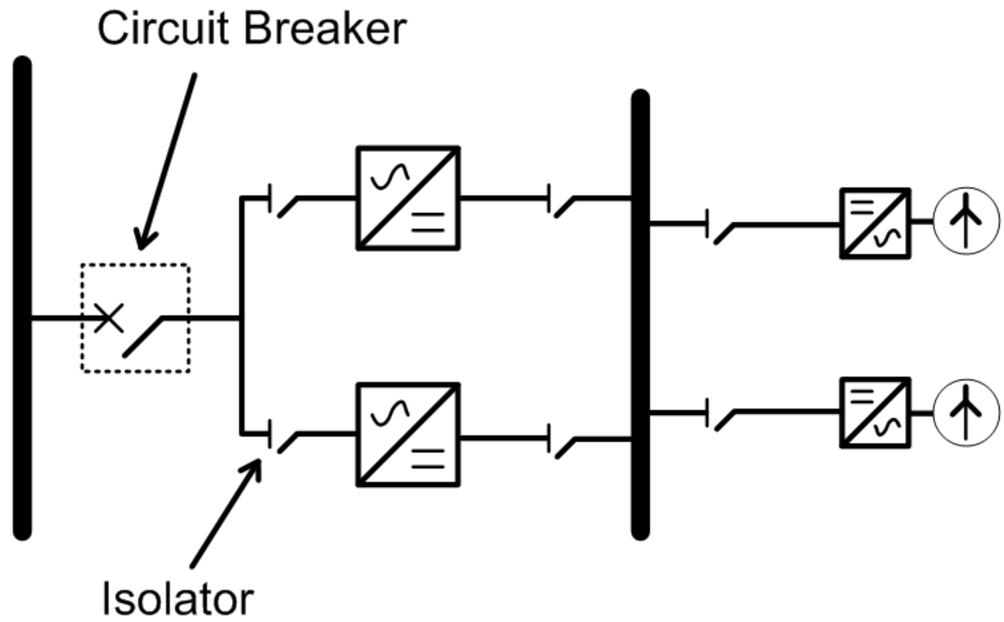


Figure 3-3: DC Protection Philosophy

3.2.1 Cost Benefit Results

In every instance, the capital cost of the Direct MVDC topology was found to be considerably cheaper than all other topologies. See Figure 3-4 for an example, which assumes 100 km distance and mid-case capex/availability for converters. At this distance MVDC offers a potential reduction in capital cost of over 50%. Direct MVDC has the lowest capital cost as (a) less conductor is required in the transmission cables than for the conventional HVAC topology, and (b) there is no need for any offshore substation platforms.

The costs of losses and unavailability are very significant for the Direct MVDC topology. If mid-case capex/availability for converters and a cost of energy from offshore wind of £140 /MWh are assumed, then Direct MVDC is 8.4% more expensive over the total lifecycle cost than conventional HVAC at a distance of 100 km (see Figure 3-5, with a detailed breakdown of the sources of lost revenue provided in Figure 3-6 and Figure 3-7).

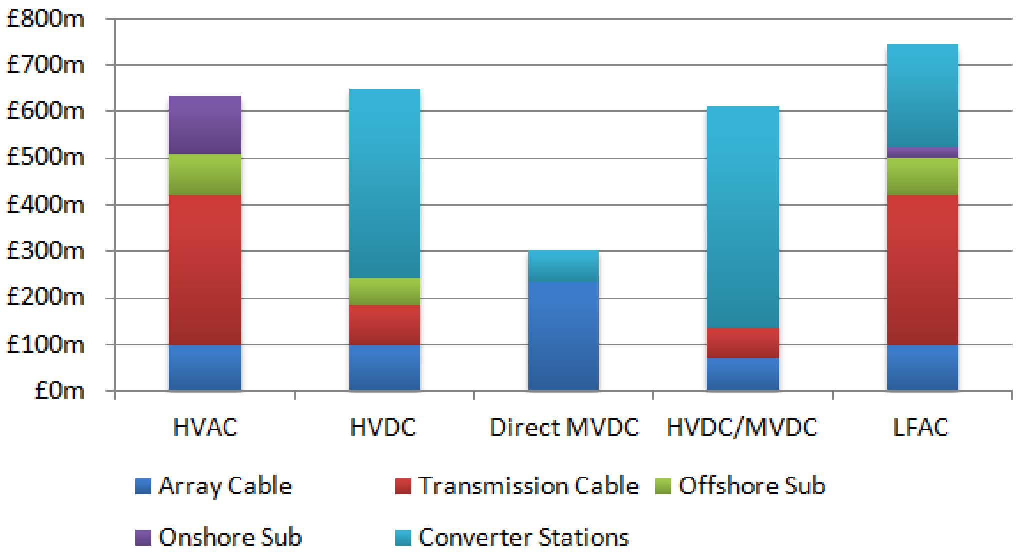


Figure 3-4: Capital Cost, 100 km, Mid-case[1]

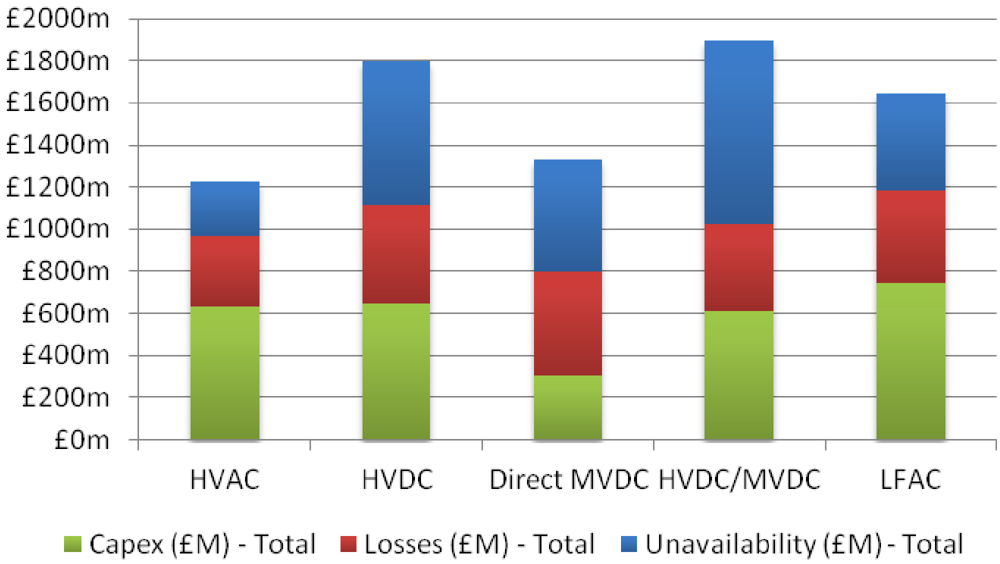


Figure 3-5: Electrical System Cost, 100 km, £140 /MWh, Mid-case

[1] Note that converter stations include onshore and offshore substation elements, such as transformers, but do not include reactive compensation (if required)

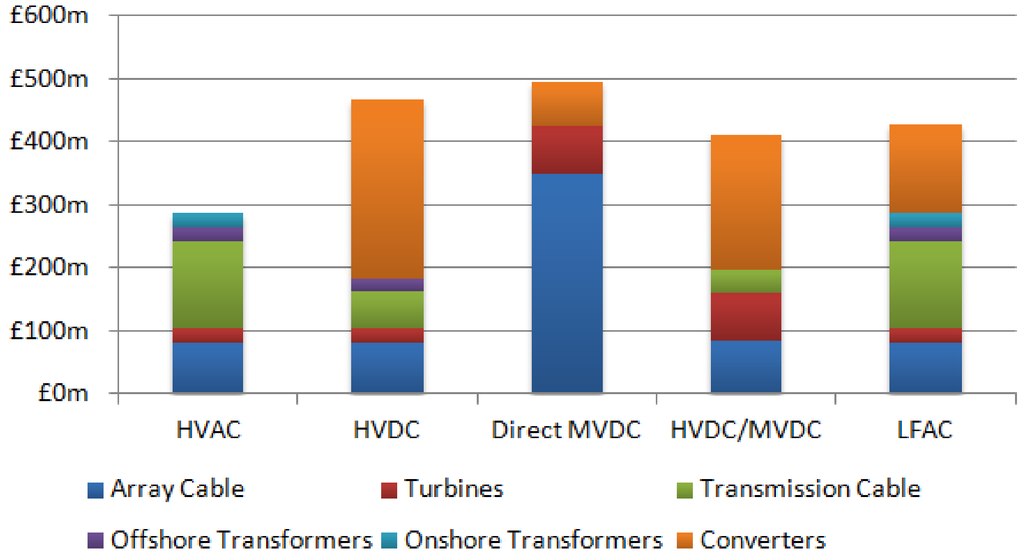


Figure 3-6: Cost of Electrical Losses, 100km, £140/MWh, Mid-case

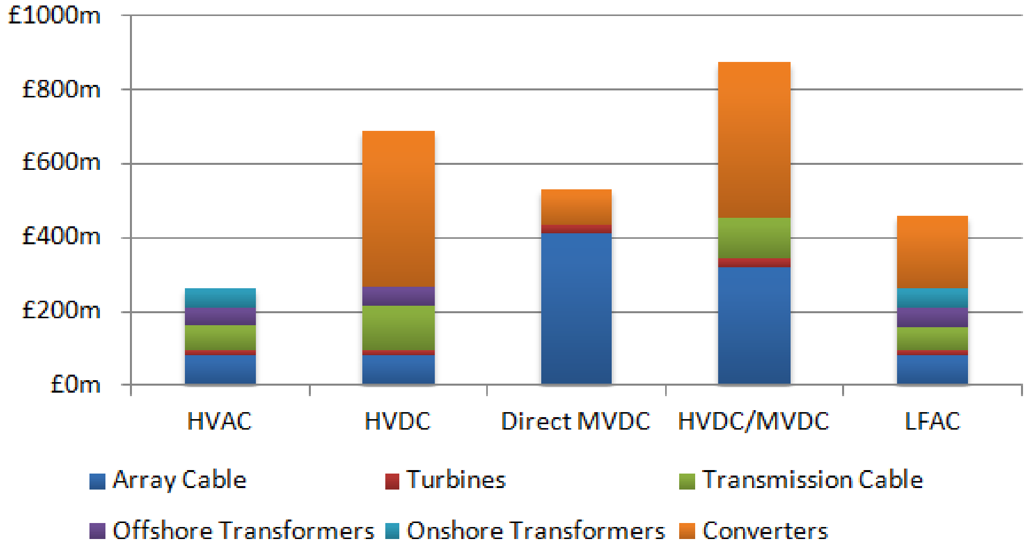


Figure 3-7: Cost of Unavailability, 100 km, £140 /MWh, Mid-case

153 km is the breakeven distance at which Direct MVDC becomes cost effective as compared with conventional HVAC, when considering losses and unavailability at a cost of £140 /MWh and mid-case severity for converter capex/availability (Figure 3-8).

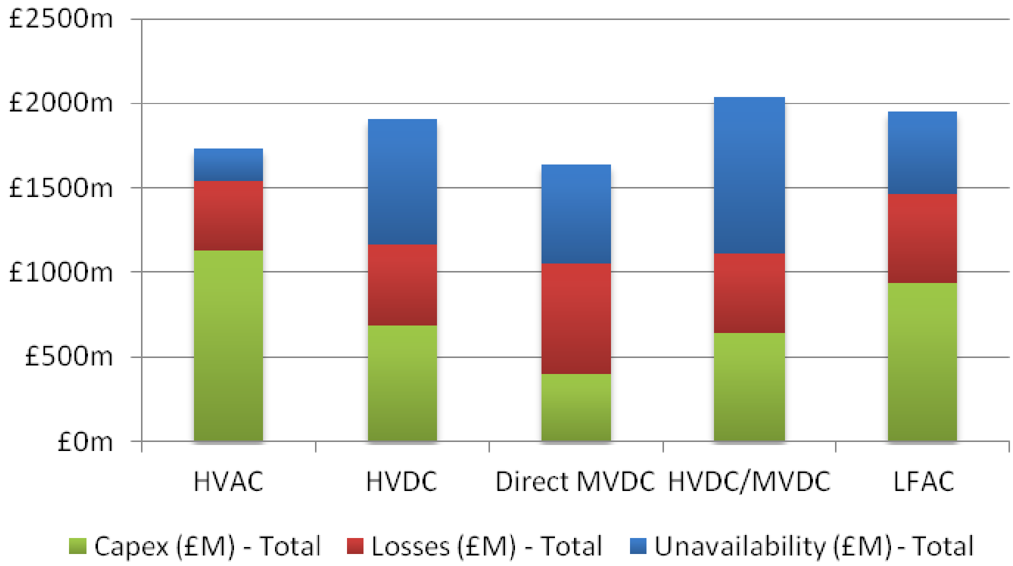


Figure 3-8: Electrical System Cost, 153 km, £140 /MWh, Mid-case

The most obvious way to reduce this breakeven distance is to improve the availability of the DC converters and reduce their capital cost. If best-case is assumed, then the breakeven distance is 119 km (Figure 3-9).

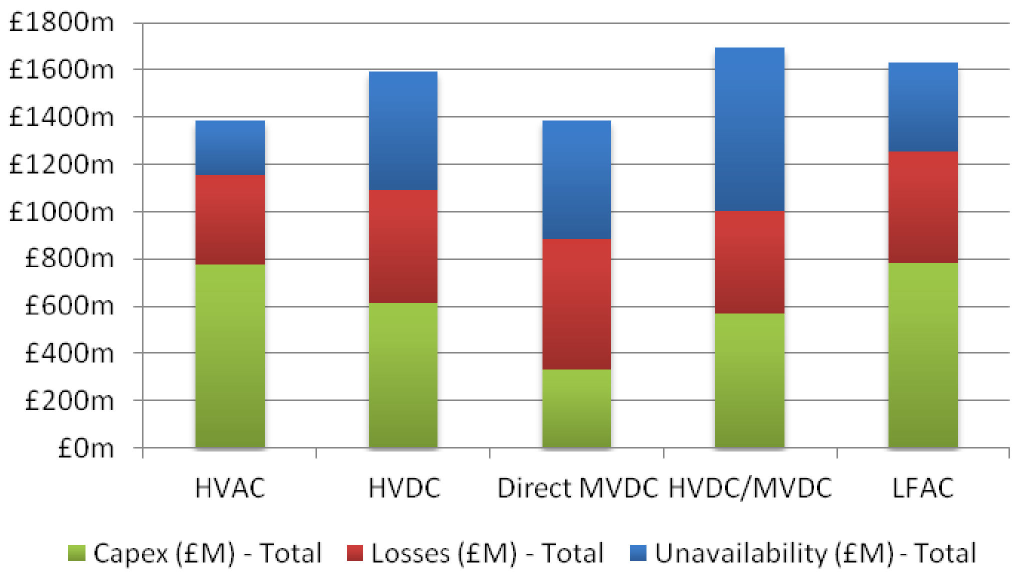


Figure 3-9: Electrical System Cost, 119km, £140/MWh, Best-case

Alternatively, Direct MVDC will prove more attractive if the per MWh cost of the lost energy is reduced, which will lower the impact of both electrical and unavailability losses. Figure 3-10 shows the total electrical system cost for an assumed electricity cost of £120 /MWh at a distance of 105 km and Figure 3-11 shows the total electrical system cost with an assumed electricity cost of

£100 /MWh, which is the Offshore Wind Cost Reduction Task Force's target, at a distance of 61km.

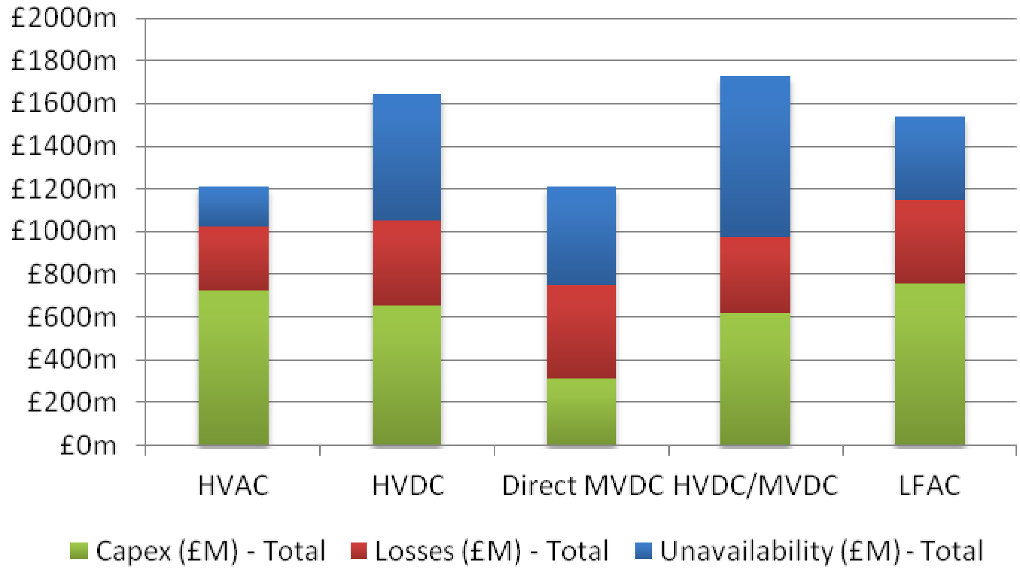


Figure 3-10: Electrical System Cost, 105km, £120/MWh, Mid-case

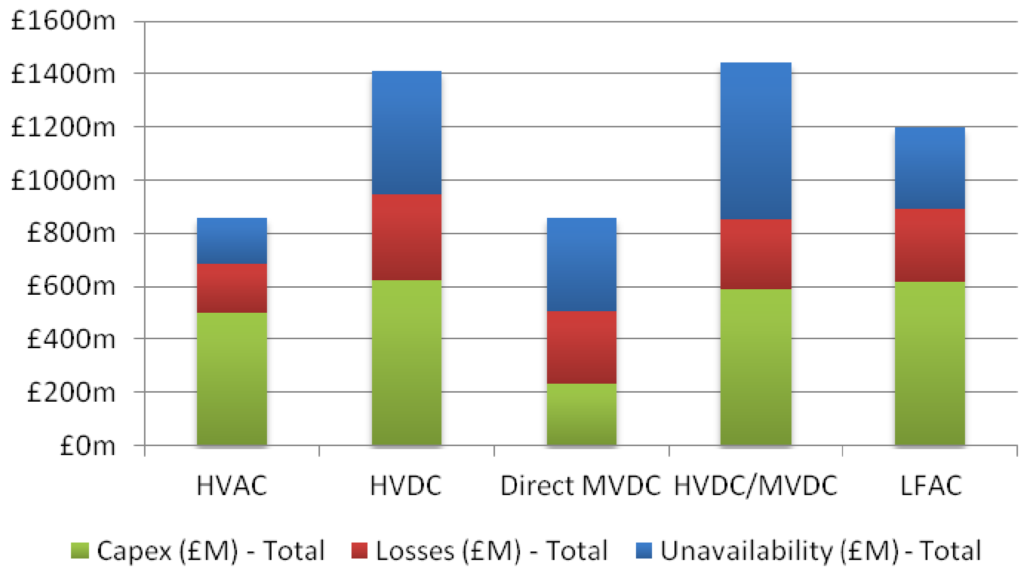


Figure 3-11: Electrical System Cost, 61km, £100/MWh, Mid-case

Further reductions in cost would be observed if the best-case assumptions for capex and availability were used.

Table 3-2 summarises the breakeven distances at which the Direct MVDC topology becomes the cheapest.

Table 3-2: Breakeven Distances for Direct MVDC Topology

		Capital Cost & Availability		
		Best-case	**Mid-case**	**Worst-case**
Cost of Energy	**£140/MWh**	119 km	153 km	153 km
	£120/MWh	72 km	105 km	153 km
	£100/MWh	50 km	61 km	105 km

The significance of 105 km and 153 km are:

- When going from 104 km to 105 km there is a step change in cost for the conventional HVAC topology, as this is the distance at which six 500 mm^2 cables must be used, rather than four 1000 mm^2 cables, due to cable compensation limits;
- When going from 152 km to 153 km there is a step change in cost for the conventional HVAC topology, as this is distance at which eight 500 mm^2 cables must be used rather than six, due to the thermal capacity required. There are further technical design considerations (e.g. relating to platform design) which would result from the use of a large number of cables.

3.2.2 Discussion

Results

The case study results demonstrate that there is always an offshore distance at which a direct MVDC topology may be the most cost effective type of array connection. Reductions in the cost of converters and improvements in converter availability are likely to make direct MVDC more cost competitive at shorter distances. In addition, direct MVDC is more competitive when a lower cost of energy is assumed. Initially, £140 /MWh has been assumed, as this is the CFD strike price for 2017/18 and 2018/19. In practice, it is unlikely that any offshore wind farms using DC arrays will be built in such a short timeframe, and therefore it is likely that the results which consider lower costs of energy (£120 /MWh and £100 /MWh) will be of greater relevance.

The case study also demonstrates that hybrid MVDC/HVDC arrays are unlikely to be cost effective, as the benefits arising from reduced array losses are minimal compared to the costs due to converter unavailability. Potential applications for hybrid MVDC/HVDC arrays are likely to only exist at greater distances, however in most cases conventional HVDC will prove to be cheaper.

Capital Costs

It is unlikely that developers will consider the operational costs presented here (losses and unavailability) with the same priority as capital cost. For example, TNEI are aware of one major offshore wind farm developer which does not consider unavailability in their design choices; they either consider that equipment failures are unlikely enough to not be of any significance, or that insurance will cover the cost of any lost energy.

It is therefore possible that, in practice, developers would be very interested in any topology which significantly reduces the capital cost of their project. In addition, with a reduced capital cost it is likely that a developer would have access to cheaper financing, allowing them to fund the project at a lower rate of interest and reducing risk for investors.

Losses and Unavailability

It is worth noting that there are many ways of interpreting the value of lost energy throughout the electrical system, due both to electrical losses and unavailability. For example, under the OFTO regime, the generator would only be interested in losses in the assets downstream from the offshore substation (eg the interface point); this includes the wind farm array cables and turbines themselves. However, losses in the OFTO system, including in the transformers, converters, transmission cables and reactive compensation equipment, will not directly lead to lost revenue. Therefore, it would be possible to consider the value of these losses in a different manner.

For example, electrical losses should be considered as typical transmission losses and therefore the value of these would be set by the market electricity price. On the other hand, unavailability losses could be evaluated in terms of the availability incentive scheme for OFTOs. This sets an availability target of 98%, rewarding those OFTOs which exceed this and penalising those which fail to meet it.

In this report, all losses have been valued as per the cost of electricity from offshore wind. This has been done to allow for comparison between all the different topologies. Specifically, in the direct MVDC topology, it is unclear how ±60 kV MVDC circuits would be categorised under the OFTO regime, which does not provide for a topology without an offshore interface point. It is possible that in such a topology, the MVDC circuits would not be categorised as offshore transmission assets and would instead belong to the generator, in which case losses would be valued at the cost of electricity from offshore wind as in this analysis.

Design Improvements

The offshore design proposed for the direct MVDC topology could potentially be improved so as to reduce losses and decrease revenue lost due to unavailability. For example, arrays could be connected as rings, so that if there is a fault on any one cable section, that cable section can be isolated and the rest of the array can be quickly re-energised. In addition, losses could be reduced by using transmission cables with larger cross sectional areas (CSA), which would have lower impedances. If larger cables were used then fewer of them would be required which could further reduce capital cost. The OWA previously looked at direct ±60 kV connections like this, where offshore platforms were used as hubs to connect smaller ±60 kV array cables to larger ±60 kV transmission cables. However, it is likely that the greatest benefit of this topology would be realised if it could be implemented without offshore platforms, for example, with all connections being made in the base of a turbine.

The direct MVDC topology, with larger transmission cables and redundant rings between turbines, is shown in Figure 3-12.

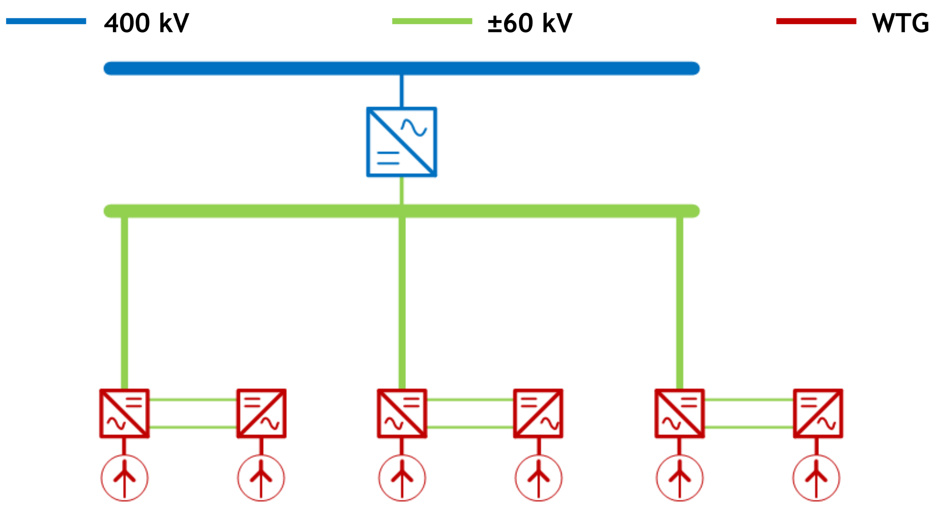


Figure 3-12: Direct MVDC Topology with Redundant Rings and Larger Cables

Applications for Wave and Tidal

Since the design philosophy for large marine energy arrays is very similar to that of offshore wind farms, direct MVDC arrays and transmission are also likely to be of interest to wave and tidal energy developers. Other components would be required for marine energy arrays, such as DC wet-mate connectors, which would not be used in an offshore wind farm.

The distances discussed in this case study would not initially appear be applicable for tidal energy connections, as the most energetic tidal resources are close to the shore. However, these resources are often in areas where the grid is very weak, and in these circumstances a direct MVDC connection could allow the project to connect to a stronger part of the transmission system over a much greater distance.

Benefits of Offshore MVDC Arrays

- Offshore wind developers
    - Low capital cost
    - Operational costs will fall as cost of energy from offshore wind falls
- Wave and tidal generators
    - Benefits are likely to be similar
- Manufacturers of DC converters and equipment
    - Potential large markets
- Investors
    - Lower capital cost reduces risk
- Distribution Network Operators and Transmission Owners
    - Proof of concept of several DC components
    - A step towards multi-terminal DC (both MV and HVDC)

Drivers for a Test & Demonstration Centre

- Accurate unavailability data can be gathered which can help to de-risk projects (unavailability costs are highly significant, therefore this is a key driver)
- The following novel DC components can be tested:
    - DC Circuit Breakers
    - DC/DC boost converters
    - Large CSA MVDC cables
    - DC wet-mate connectors (for marine energy applications)
- The use of AC disconnectors on DC circuits can be proven and explored
- T&D facility could be used to investigate the interaction of different converter technologies on a DC network

3.3 Distribution Network Reinforcement Cost Benefit Analysis

A second case study was undertaken to explore the suitability of MVDC for distribution network reinforcement. Rather than explore a generic example, as per the offshore wind case study, a specific section of SP Energy Networks' distribution network was explored for the second case study.

3.3.1 Anglesey Case Study

Following discussions with SPEN, Anglesey (in SPEN's Manweb distribution licence area) was selected as a case study for which an MVDC solution would be explored. The Anglesey network is symptomatic of a network under stress due to high levels of renewable generation connections and load growth. Several Investment Papers have been written by Scottish Power to suggest potential reinforcement options [24]. This is useful for the purposes of this case study, as the Investment Paper solution can be used as a base case against which the MVDC option can be compared.

Three scenarios in the Anglesey-Manweb network were identified where an MVDC application could be used to address future network issues. These are described in Table 3-3.

Table 3-3: Anglesey Network Scenarios

Scenario:	Conventional Reinforcement	MVDC Application
<u>1) Voltage Issues</u> Low volts at Bangor & Four Crosses at times of peak demand	2 x 15 MVA STATCOMs at Bangor and Four Crosses	Back to Back 40 MVA MVDC at Caernarfon
<u>2) Multiple System Issues</u> • Low Volts at Bangor at times of peak demand, • Thermal Overload of Llanfair PG – Bangor circuit at times of peak generation, • Requirement to accommodate expected generation on AngleseyVarious overloads during certain contingent cases	New Llanfair PG - Bangor 33kV circuits New 33kV circuit from Llangaffo -Llanfair PG New BSP at Llanfair PG	25MVA MVDC Link between Bangor & Llanfair PG 2x 90MVA Tx Upgrades on Anglesey 21.1km of OHL to be upgraded on Anglesey
<u>3) Future Generation</u> Requirement to accommodate expected 159 MW of generation on Anglesey by 2023.	Speculative reinforcement concept very difficult	Create 30kV DC Renewables Hub on at Caergeilliog.

It was determined early on in the study that MVDC is not an economic solution when it only mitigates against a single network issue, such as in scenario 1 in the table above. In this case it was shown that it is more cost effective to use conventional solutions to address the voltage issue[2]. However in scenario 2, the MVDC solution resolves a wide range of system issues, which would otherwise need to be addressed individually by a complex and costly conventional reinforcement scheme.

Scenario 2 thereby presents a promising economic case for MVDC, and this scenario is considered in the case study. The MVDC configuration proposed in this scenario is shown in Figure 3-13 below.

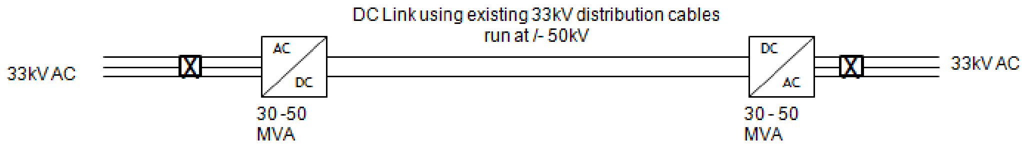


Figure 3-13 MVDC Configuration Considered in the Onshore Network Case Study

Scenario 3 is a novel idea: using a DC link to connect onshore renewable generation by creating a DC hub. However there are some significant challenges in scoping such a scenario and establishing a credible conventional reinforcement solution to compare against. Therefore this scenario was not considered for the case study.

A simplified single line diagram of the Anglesey network is shown in Figure 3-14. The island has two 132/33kV infeeds which are fed from the National Grid at Wylfa. In addition, there are two 33kV AC links from the mainland, which are fed at 132kV from Bangor and Caernarfon.

[2] The “conventional reinforcement” solution here would be to use STATCOMs which, as discussed in Section 2.1, may be classed as a type of MVDC technology

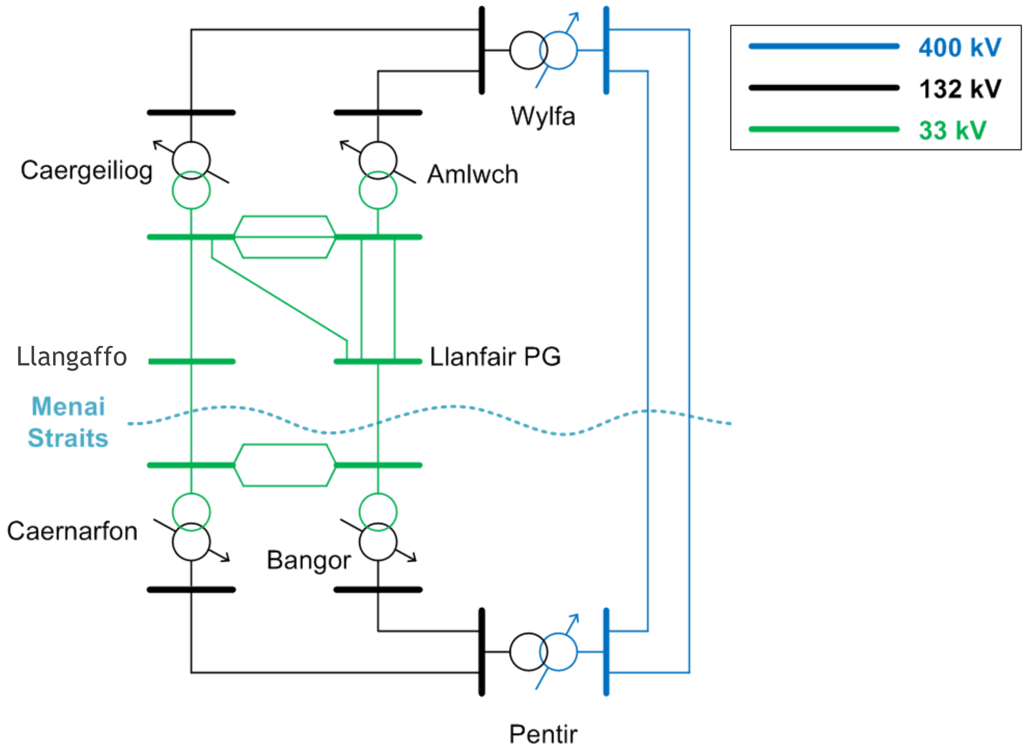


Figure 3-14: Existing Anglesey Network

There are a number of network issues on Anglesey and conventional reinforcement schemes which have been explored to date are extensive, in terms of both scope and cost. Issues which have been forecast include:

- By 2023, during winter peak demand certain outage conditions (e.g. transformer outages at Bangor) lead to unacceptably low network voltages on the 33kV network. Low voltages are problematic in terms of network security and also increase losses throughout the network.
- During summer minimum demand, with maximum forecast generation output, the circuit across the Menai Straits between Bangor and Llanfair PG would become thermally overloaded.
- In addition, networks need to be designed so that they operate safely during an N-1 outage, ie the loss of any one network component. On Anglesey, various overloads are observed during certain contingent cases, for example, on the 132/33kV transformers which supply the island.

Due to the extent of the network issues on Anglesey, conventional reinforcements which have been proposed to date have been quite extensive and costly. Most of these involve the establishment of a new 132kV infeed to the island.

SP Energy Networks provided a copy of their operational model for Anglesey for use in IPSA power systems analysis software. This model was updated with guidance from SP Energy Networks engineers to include all contracted generation on Anglesey.

Conventional Reinforcement

The conventional reinforcement scheme as proposed in SP Energy Networks' Investment Paper is shown in Figure 3-15.

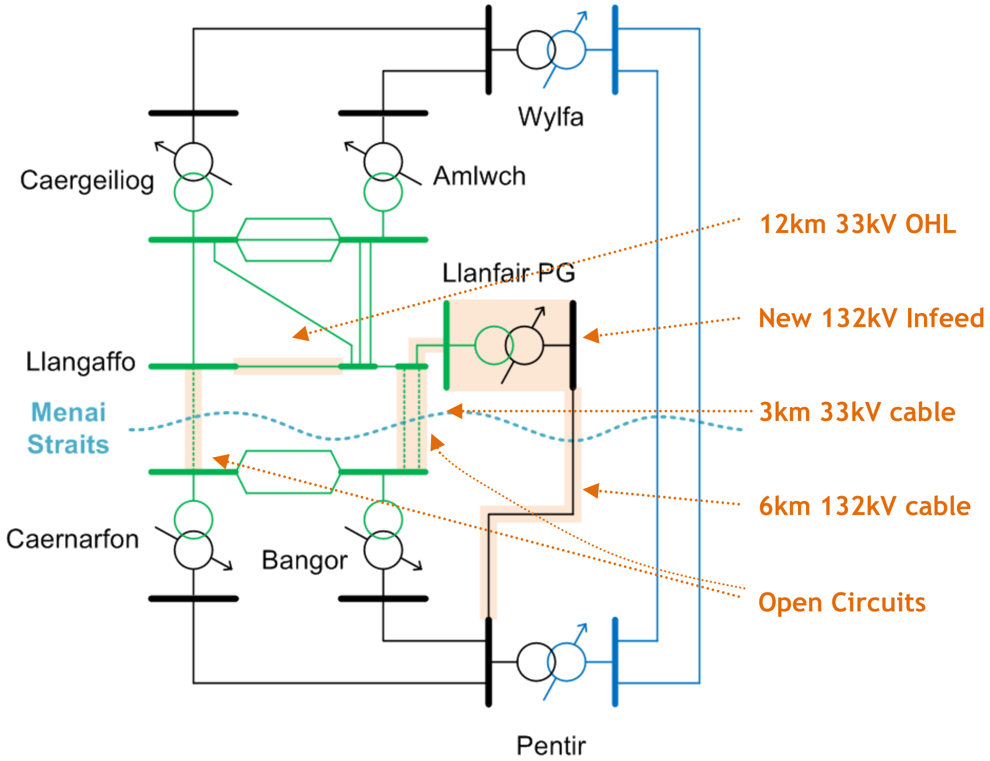


Figure 3-15: Proposed Conventional Reinforcements for Anglesey Network

This scheme consists of:

- Installing a new 132kV infeed at Llanfair PG, fed from Pentir via 6km of underground cable, including a subsea cable, under the Menai Straights;
- Installing 3km of 33kV underground cable between Bangor and Llanfair PG;
- Installing 12km of 33kV overhead line between Llangaffo and Llanfair PG.
- Opening the circuits between the mainland and the island so that Anglesey's 33kV network is separated from the mainland.

The estimated capital cost of this scheme is £15.8m, of which £4.3m is for 33kV reinforcements and £11.5m is for 132kV reinforcements.

The conventional reinforcements were modelled in IPSA using electrical parameters obtained from SP Energy Networks' operational model.

Proposed MVDC Reinforcement for Scenario 2

The proposed MVDC reinforcement solution is shown in Figure 3-16.

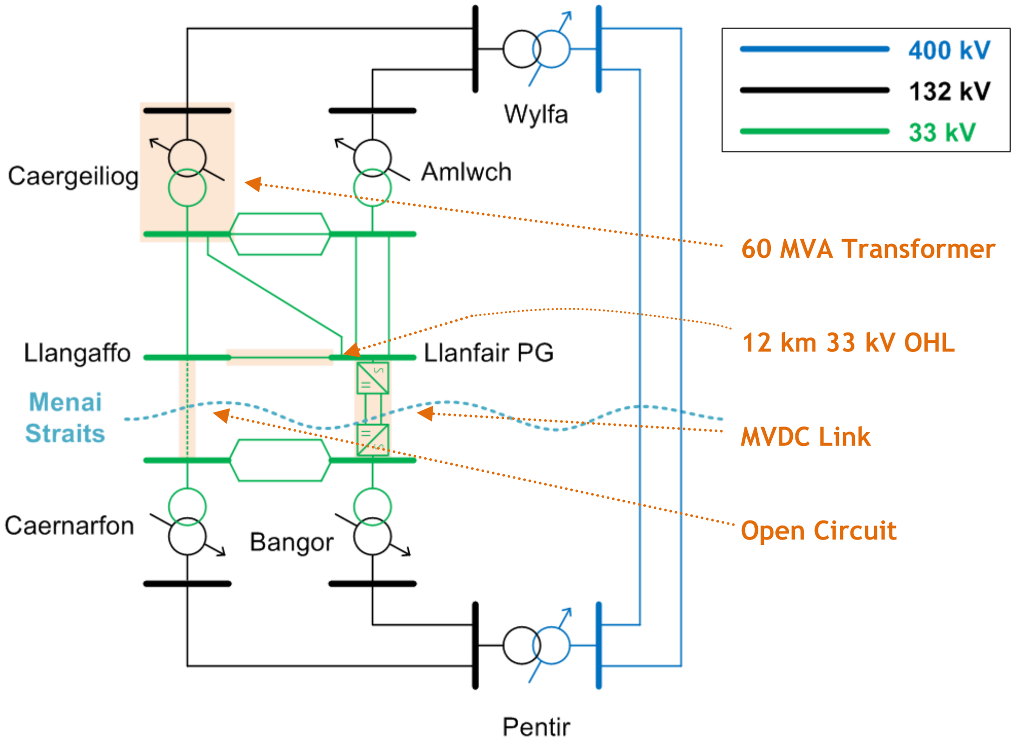


Figure 3-16: Proposed MVDC Reinforcements for Anglesey Network

This scheme consists of:

- Upgrading the transformer at Caergeiliog to 60MVA;
- Installing 12km of 33kV overhead line between Llangaffo and Llanfair PG;
- Installing an MVDC link between Llanfair PG and Bangor, using the existing 33kV conductor;
- Opening the circuit between Llangaffo and Caernarfon.

The technical feasibility of this scheme was examined by modelling an MVDC link in SPEN's Manweb operational model. It was not possible to undertake full network design studies; instead, key network outages were investigated for two extreme operating scenarios:

- Summer minimum demand with maximum generation export;
- Winter maximum demand with no generation export

The key network outages which were considered were

1. An outage of the 132/33kV transformer at Caergeiliog;
2. An outage of the 132/33kV transformer at Amlwch;
3. An outage of the MVDC link.

It was found that during certain outage conditions, the transformer at Caergeiliog is overloaded; this is why it is necessary to upgrade this transformer to 60MVA. There are also other branch overloads throughout the network, but these can be avoided by constraining some non-firm generators.

An added benefit of this reinforcement scheme is that the 33kV AC circuits on Anglesey can be separated from those on the mainland. This is also true of the conventional reinforcement scheme; however this conventional scheme requires a new GSP and a new 132kV system. Separating the island has positive implications in terms of short-circuit currents and fault levels, as generators on Anglesey will no longer contribute short-circuit current to faults on the mainland and vice-versa.

Losses, CIs and CMLs

The methodologies used to calculate the cost of electrical losses and unavailability for the onshore case study are not the same as those used in the offshore case study. Instead, electrical losses were determined using the IPSA model and unavailability was investigated in terms of Customer Interruptions (CIs) and Customer Minutes Lost (CMLs). To compare the two unavailability methodologies: CIs are analogous to MTTF and CMLs are analogous to MTTR.

The following electrical loss and unavailability costs were provided by SP Energy Networks:

Table 3-4: Loss and Unavailability Costs for Onshore case study

Type	Cost	Unit
Electrical Loss	48.42	£ /MWh
Customer Interruptions	15.44	£ /Interruption
Customer Minute Lost	0.38	£ /minute

Losses need to be considered throughout the entire network rather than just considering losses in the components themselves. One of the proposed benefits of the MVDC link is that it will radically improve network voltages and this will reduce losses in circuits and transformers throughout Anglesey. To calculate losses, load flow studies were performed for the network in four operational configurations:

Table 3-5: Periods Used for Loss Calculation

	Demand	Export	Hours per Year
P1	Summer Minimum	Maximum Generation	2920

	Demand	Export	Hours per Year
P2	Summer Minimum	No Generation	4765
P3	Winter Maximum	Maximum Generation	817
P4	Winter Maximum	No Generation	258

After load flows had been performed, the total MW losses in the Bangor/Caernarfon and Caergeiliog/Amlwch groups were determined for the entire year, using the number of hours per year for each period in Table 3-5.

Losses in the MVDC link were not considered in the IPSA modelling. Instead, these were calculated separately using an efficiency of 98.3% which was provided by RXPE.

To calculate CIs and CMLs, the following methodology was used:

1. 2013/14 CIs and CMLs for the Bangor/Caernarfon and Caergeiliog/Amlwch groups were provided by SP Energy Networks;
2. SP Energy Networks also provided information about the number of customers in each group
3. For each group, the number of customers per MVA of firm group capacity was found by determining the total capability of all infeeds, minus one, into each group;
4. As per an Ofgem publication, it was assumed that 33kV and 132kV faults caused 10.6% of CIs and 4.6% of CMLs. For each group, CMLs/CIs was then determined;
5. The probability of an N-2 outage (i.e. loss of two EHV network components), P_{N-2}, was determined by dividing the number of customer interruptions by the number of customers, assuming that the network is designed for N-1 operation and that only an N-2 outage will cause interruptions;
6. The probability of an N-1 outage (loss of a single network component), P_{N-1}, was then found by taking the square root of P_{N-2};
7. By combining P_{N-1} with availability data for different types of components, the total number of customer interruptions associated with each reinforcement scheme was determined. The number of CMLs associated with each reinforcement scheme was calculated using the generic CMLs/CIs determined in Step 4;
8. MTTR for each component was not considered when determining CMLs. This assumes that minutes are only lost until the network is restored to an N-1 state. In essence, the MTTR of any single network component does not impact CMLs; it is the average MTTR (which is for the group, to bring

it from an N-2 to an N-1 state, that needs to be considered, and this is just CMLs/CIs.

3.3.2 Cost Benefit Results

The results of the cost benefit analysis are shown in Figure 3-17.

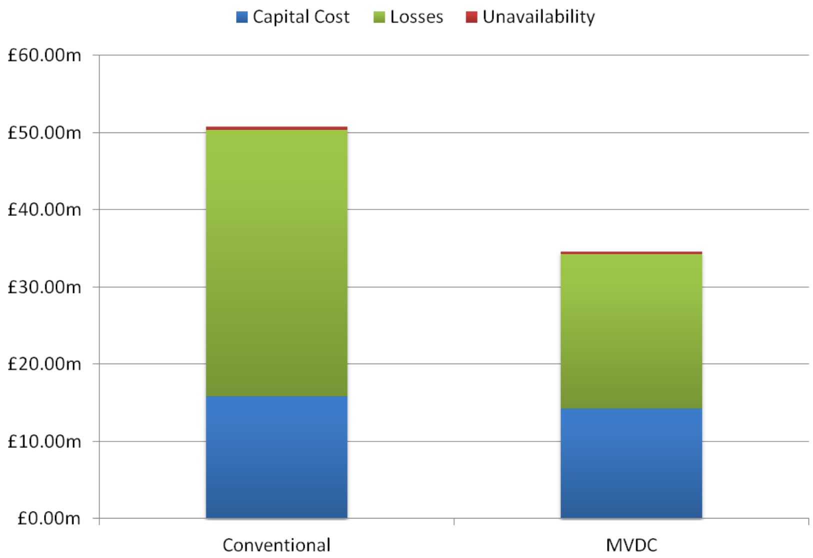


Figure 3-17: Total Cost of Conventional and MVDC Reinforcements

The results show that capital cost and network losses are significant factors in the cost benefit analysis, but that cost associated with unavailability (eg CIs and CMLs) are less likely to be significant.

Figure 3-18, Figure 3-19 and Figure 3-20 show detailed comparisons of capital costs and capitalised lifecycle costs (electrical losses and unavailability).

In terms of capital cost, the MVDC reinforcement scheme is approximately £2m less expensive than the conventional reinforcement scheme. The most significant element of the cost is the MVDC converter itself, assumed to be ~£9.7m (based on costs provided by a converter manufacturer). The attractiveness of this solution in terms of capital cost would therefore be sensitive to the cost of the converter.

The cost of electrical losses (over the asset's lifetime) is significantly lower when using the MVDC reinforcement than conventional reinforcements. This is because of the converter's ability to fully control power flow and power factors at either side of the link, allowing for significantly better voltage profiles throughout the entire Anglesey and wider Scottish Power Manweb networks. Electrical loss costs over the asset lifetimes are very significant when compared to the capital cost even though losses in the converter itself are relatively small.

Unavailability costs are insignificant when compared to the capital cost and costs of electrical losses. With the method used in this study, the MVDC reinforcement scheme is determined to have lower unavailability costs than the conventional reinforcement scheme.

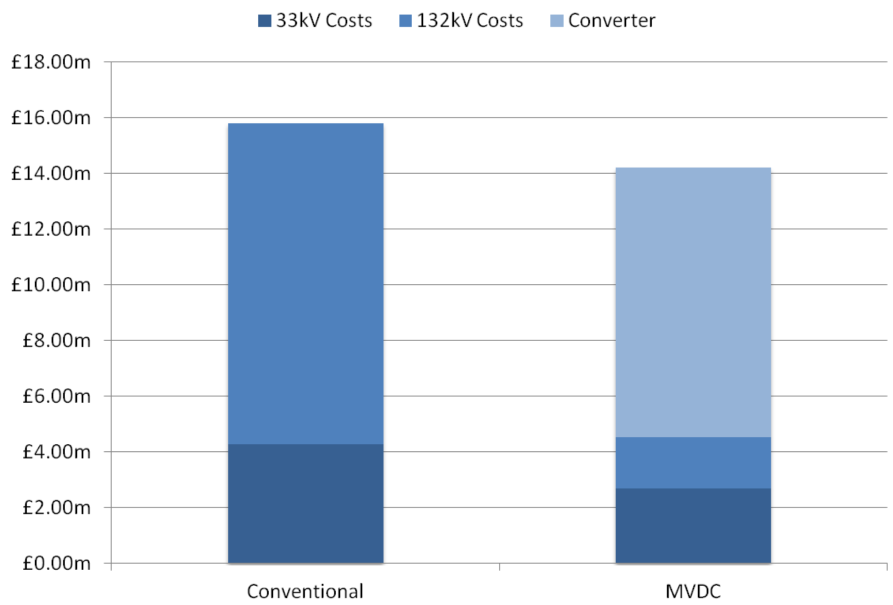


Figure 3-18: Capital Cost of Conventional and MVDC Reinforcements

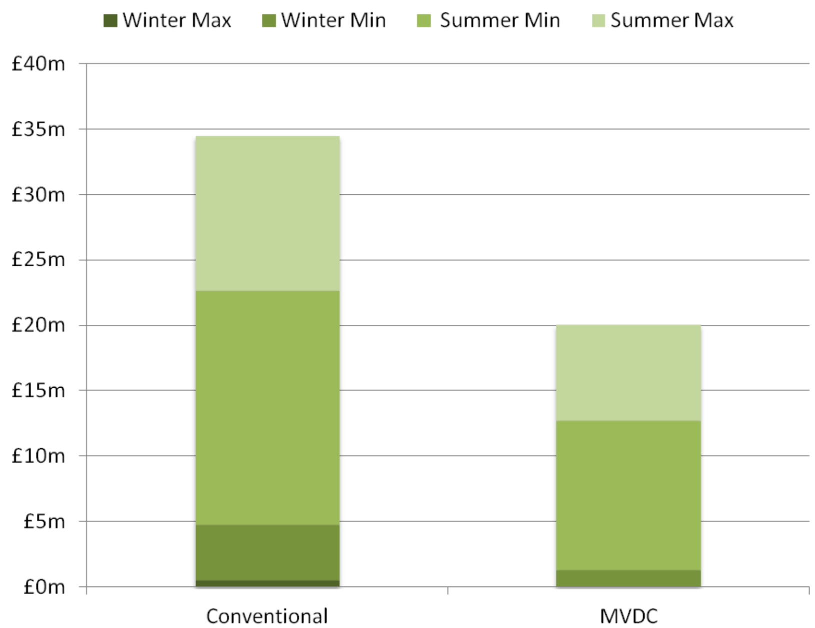


Figure 3-19: Electrical Loss Cost of Conventional and MVDC Reinforcements

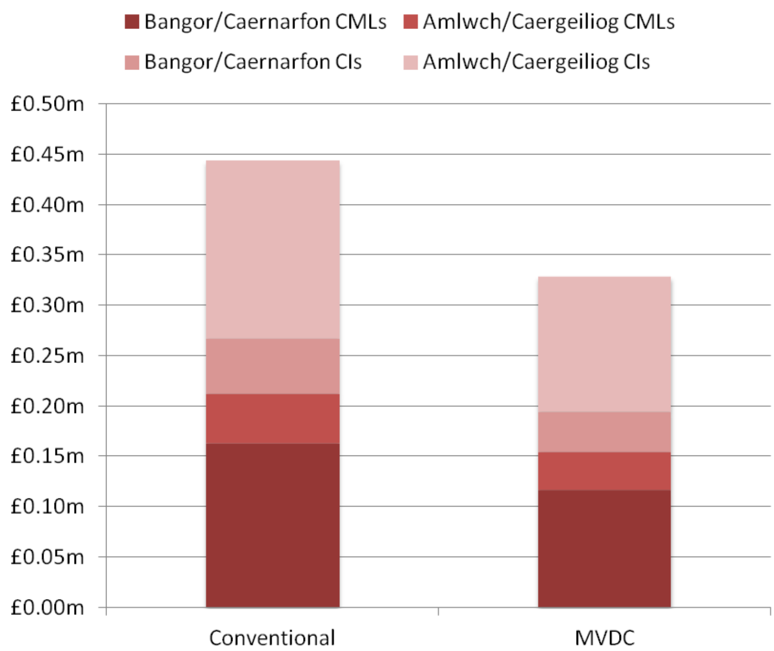


Figure 3-20: Unavailability Cost of Conventional and MVDC Reinforcements

3.3.3 Discussion

The results of the case study show that for Anglesey installing an MVDC link could be a cost effective way to simultaneously address several critical network issues. There are two key benefits which arise from the use of the MVDC link:

1. The power factors at either side of the link can be controlled independently, which allows for voltages throughout the network to be drastically improved;
2. The total flow of power through the link can be controlled. This flexibility means that the link can react to a variety of onerous operating conditions, eg various transformer outages, high demand on either side of the link or large volumes of export generation on the island;

However, there are additional benefits which would arise from the use of MVDC technology:

3. The MVDC technology allows for greater utilisation of the existing 33kV conductors across the Menai straits. Specifically, a 33kV AC conductor will be able to operate at a higher DC voltage level (eg around 50kV) and will be able to accommodate greater current, as there is no 50Hz "skin effect";
4. The Anglesey 33kV AC network can be separated from the mainland's 33kV AC network without the need for a new BSP and 132kV works. Separating the networks reduces fault levels on both sides of the MVDC link and could delay the requirement for switchgear upgrades.

To summarise, the case study results show that MVDC links can provide a host of benefits to an onshore distribution network if there are several significant problems which need to be solved. However, it is important to note that this also limits the scope of potential MVDC applications. For example, if a distribution network is only experiencing voltage problems, then it will undoubtedly be cheaper to install individual reactive compensation devices to improve voltage profiles (eg a STATCOM).

The MVDC reinforcement scheme works on Anglesey because the network is faced with several complicated problems with expensive conventional reinforcements. MVDC back-to-back links are not expected to be applied universally as a standard reinforcement tool; however they are likely to prove to be useful in other areas of the network with multiple issues. There are likely to be more areas such as this in the future, particularly as greater volumes of variable generation connect to GB's distribution networks. 33kV reinforcements are increasingly complex and costly as networks become saturated with generation, and more projects will require work to be carried out at 132kV. Therefore, in the minority of cases where MVDC could be an appropriate reinforcement solution, it is important that DNOs are aware of the costs and risks associated with the technology.

Islanded Networks

There may be potential for using MVDC links to connect the distribution networks of small islands over long distances. This would be especially attractive if these islands were likely to be locations for renewable developments, in which case a DC renewables hub could be possible. This would be along the lines of the direct MVDC offshore connections discussed in the previous case study.

Benefits of Onshore MVDC Reinforcement

- Distribution Network Operators
  - Cost effective solution for networks which require extensive reinforcement to address multiple issues
  - Can dramatically improve network voltages, thereby reducing losses in the network
- Customers
  - Reduction in losses will increase revenues by reducing loss factors
- Manufacturers of DC converters
  - Potential market for bespoke solutions, but likely to be relatively small volume [If each DNO had only 2 cases – that's not trivial volume]
- Transmission Owners
  - Proof of concept of DC links for reinforcement
  - Not clear whether the application would scale up to transmission voltages

Drivers for a Test & Demonstration Centre

- T&D facility would further de-risk the use of MVDC converters & MVDC cables
  - However, there are fewer drivers arising from this case study as the technology is already quite mature. DNOs are less likely to be interested in the items with greater requirements for test & demonstration, e.g. DC circuit breakers, DC/DC boost converters etc
- A T&D facility could be useful for investigating the potential of repurposing AC conductors for DC applications

3.4 Test & Demonstration Options

The results of the two case studies, the input from stakeholders, and the market analysis led to consideration of three potential test & demonstration options, these are:

- An MVDC hardware test & development facility.
- An onshore network reinforcement demonstration project;
- An offshore generation demonstration project;

Each of these options is described in more detail as follows:

1. An **MVDC hardware test & development facility** would see a purpose built "plug and play" hardware facility being built, for assisting in the research and development of DC components and technologies. The facility could be used to test novel DC components, integration of DC equipment at different voltage levels and produced by different manufacturers, and the technical & hardware aspects of multi-terminal DC configurations. There are no restrictions on where such a facility could be built. Anticipated timescales for the development of a facility are 2-3 years.
2. An **onshore network reinforcement demonstration project** would see an MVDC link (either back-to-back or using MVDC cables) installed on a real distribution network as a robust network reinforcement scheme. This link would likely be installed at 33kV and the case study results suggest that Anglesey would be an appropriate location for such a project. Other suitable parts of the distribution network could be identified (for example in Scotland) and other network voltages could be considered (eg 11kV or even 132kV transmission in Scotland). However, it would not be trivial to find a viable alternative location for the project. Development timescales for the Anglesey project would likely be in the region of 5-8 years.
3. An **offshore generation demonstration project** would see a generation project installed and connected to the transmission network using direct medium voltage DC transmission, as in Figure 3-2. Although the ultimate use of this topology is likely to be for connecting offshore wind and marine energy projects, it is suggested that the technology could be demonstrated using onshore wind. This would allow easier access for maintenance and repair in the event of any equipment failures. It is likely that such a demonstration project would be well suited to a relatively large and remote onshore wind farm in Scotland connecting to the 132kV transmission network. Such a demonstration project would require readily available DC disconnectors and a likely timescale would be 5-8 years;

3.4.1 Relative Benefits of Projects

The relative merits of each type of test & demonstration project are considered quantitatively in terms of the benefit to stakeholders and the learning benefits. These two metrics can be combined to determine the merit order of benefits for each type of project.

Stakeholder Benefit

The benefits of MVDC for each stakeholder were investigated by considering the different types of DC components and technologies, and then assigning these a high, medium, low, or N/A priority for each sector

Table 3-6: Stakeholder Sector Benefit - Component/Technology Priority

Components/ Technologies	Generation/ OFTOs	Distribution	Transmission
MVDC Back to Back Link	N/A	High	High
MVDC VSC Converter	High	High	High
HVDC VSC Converter	High	N/A	High
DC/DC Boost Technology	High	N/A	Low
Generator DC Integration	High	N/A	N/A
MVDC Cables	High	High	Low
HVDC Cables	High	N/A	High
DC Wet-mate Connectors	Medium	N/A	Low
DC Disconnectors	Medium	Medium	Medium
DC Breakers	Medium	Medium	Medium

To summarise:

- Generation developers and OFTOs are likely to be interested in all types of MVDC and HVDC technology with the exception of back-to-back links
- Fewer technologies and components will be of interest to Distribution Network Operators;
- Transmission Owners and Operators are likely to have interested in most technologies and components, with the exception of generator

integration, although some technologies will be of limited interest (eg there are likely to be limited applications for DC/DC Boost Technology, MVDC Cables and Wet-mate connectors for transmission networks).

Learning Benefit

The "Learning Benefit" of each project was quantified in terms of "Technology Readiness Levels" (TRLs). TRLs are used by industry to qualify the maturity of a given technology. A higher TRL indicates a technology which is further along the development path to business as usual deployment. There are 9 TRLs; the definitions of all nine are as:

TRL 1 Basic principles observed and reported

TRL 2 Technology concept and/or application formulated

TRL 3 Analytical and experimental critical function and/or characteristic proof-of-concept

TRL 4 Component/subsystem validation in laboratory environment

TRL 5 System/subsystem/component validation in relevant environment

TRL 6 System/subsystem model or prototyping demonstration in a relevant end-to-end environment (ground or space)

TRL 7 System prototyping demonstration in an operational environment (ground or space)

TRL 8 Actual system completed and "mission qualified" through test and demonstration in an operational environment (ground or space)

TRL 9 Actual system "mission proven" through successful mission operations (ground or space)

From what is known of MVDC technology, and from the stakeholder engagement activity carried out as part of this work (presented in Section 2.5), the existing TRL of the key MVDC technology components ranges from TRL1 to TRL4 (specific TRLs were subjective depending on the stakeholder). The majority of the stakeholders agreed that both a test & demonstration facility and demonstration projects would raise the TRL of MVDC technology thus improving its position for consideration in projects. Based on this, it has been assumed that a test & demonstration facility would raise the TRL of all HVDC/MVDC components to a 5, and that demonstration projects would raise the TRL or the relevant components to a 6 or a 7.

Existing TRLs, based on TNEI's best view and the stakeholder engagement responses, are given in Table 3-7 alongside expected increases in TRL from each type of project.

Table 3-7: Increase in TRL for Each Type of T&D Project

Components	Existing TRL*	T&D Facility	Network Reinforcement	Offshore Generation
MVDC Back to Back Link	4	+1	+3	
MVDC VSC Converter	4	+1	+3	+3
HVDC VSC Converter	8			
DC/DC Boost Technology	1	+4		
Generator DC Integration	3	+2		+3
MVDC Cables	4	+1	+2	+3
HVDC Cables	8			
DC Wet-mate Connectors	2	+3		
DC Disconnectors	4	+1		
DC Breakers	2	+3		

**Note that there is some disagreement amongst stakeholders as to the existing TRLs, for example, WPD consider that the TRL MVDC back to back to links could currently be as high as 6*

Merit Order of Benefits

The learning benefits and stakeholder priorities were combined so as to produce a "merit order of benefits" for each type of project. This is shown in Figure 3-21.

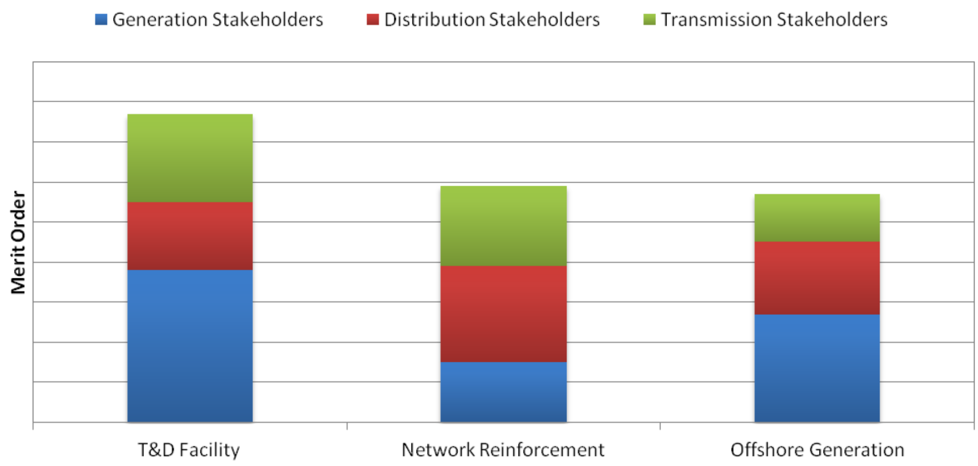


Figure 3-21: Merit Order of Benefits for Different Types of Project

To summarise, the T&D facility provides the greatest overall benefit, favouring generation stakeholders and transmission stakeholders. The demonstration projects provide less overall benefit, favouring those stakeholders which have greatest involvement in the project (eg distribution for the network reinforcement project and generation for the offshore generation project).

3.4.2 Conclusions

The potential opportunities and risks for each type of project are summarised in Table 3-8.

Table 3-8: Summary of Opportunities and Risks

Project	Opportunities	Risk
T&D Facility	• Component testing and availability data for all electrical components • Large advances in TRL for new/novel equipment, and relatively low risk	• Technology cost & procurement experience for a T&D centre is not representative of a commercial project • Risk duplication of existing Academic and Supplier test facilities • Less impact for more advanced technology (eg converters)

Network Reinforcement Demonstration Project	• A DNO backed project will test the commercial maturity of the technology, including:
	  ○ Contractual availability
	  ○ Losses
	  ○ O&M requirements
	• As a technology demonstrator, the MVDC project would show the wider network benefits of power flow control, voltage support and fault level reduction.
	• The long lifetime of a network project can be used to determine the true cost-benefit for MVDC network reinforcement, including running costs and the avoidance of future reinforcements
		• Wide range in current opinion on the Technology Readiness Level.
		• Demonstrator project assumes that technology is market ready. Immaturity could lead to difficulties over contractual assurances required for an asset that could affect public quality of supply.
		• No opportunity to down-scale the project for demonstration purposes, so high capital investment cost. Requires significant interest/investment from DNO

Offshore Generation Demonstration Project	• If successfully implemented, a full scale demonstration project would:
	  ○ Provide proof of concept for MVDC connections.
	  ○ Provide valuable failure rate & availability data for DC Cables & connectors
	• Could also integrate DC breakers/disconnectors, greater benefit although higher risk
		• High technology risk due to multiple as yet untested components:
		  ○ DC breakers
		  ○ WTG/Wave/Tidal generator DC integration
		• Onshore implementation does not robustly provide proof of concept for offshore implementation

A T&D Facility was selected as having the greatest benefit to the widest number of stakeholders. In Part C, a T&D facility has been scoped and the economic benefit case assessed.

4 Test and Demonstration Project (Part C)

An MVDC hardware test & development facility is proposed as the most effective route to de-risk and accelerate the deployment of MVDC technology. This is a result of the stakeholder engagement and technical case studies in parts A and B.

A test and development (T&D) facility is intended to be a purpose built "plug and play" hardware facility, accommodating DC component testing and certification as well as demonstrating whole system behaviours.

It was considered within Part C this study what the desired capabilities are for such a T&D facility are and scope a high level design to meet these requirements. Table 4-1 shows the requirements of individual stakeholders captured in Part A.

Table 4-1 Stakeholder Drivers for a T&D facility

Stakeholder	Desired learning outputs from a Test & Demonstration Facility
Repsol	• Availability of equipment, • power electronics (lifetime/cycle)
RES	• Tidal turbine connector technology
ABB	• DC breakers/switches, • converters, • different working combinations of the two
Herriot-Watt	• Intelligent asset management, • power electronics (reliability)
University of Aberdeen	• DC breakers, • DC/DC converters hardware demonstration
University of Strathclyde	• Realistic demonstration, • Choice of operating voltage, • DC/DC transformation (efficiency), • Bridging the gap between FAT and network operation conditions
GE	• DC protection & protection concept, • MVDC cables
MTTE	• Control of DC grids, DC breakers (hardware demonstration)
RXPE	• Independent verification of converter behaviour • DC cable jointing
SSE	• DC breakers, protection & control of large grids
WPD	Audible noise, reliability, protection & DC breakers, configuration of devices in environment (e.g. distribution network), response to network events, service record/lifetime/cycle

As a part of this scoping exercise, several key options were considered:

- **Point to point versus multi-terminal configurations -**

A multi-terminal test facility will enable aspects of HVDC multi-terminal systems to also be researched and tested, which is of use at transmission level in addition to distribution level. This is a strongly desired output from the

OEMs and DNOs consulted. However, multi-terminal configurations are likely to be significantly more expensive than point to point. And some of the desired outputs, particularly those from renewable generators/developers, could be addressed with a simpler, cheaper point to point solution.

For these reasons, both a point to point and a multi-terminal scheme are considered in the economic impact assessment.

- **Implementation of hardware versus software models –**

It was noted that some components such as DC breakers could be implemented in software rather than hardware which would lead to cost savings. However, responses from stakeholders clearly identified the need for hardware testing of DC circuit breakers and other protection in order to improve on existing test facilities and bridge the gap between the planned MTTE (Multi-Terminal Test Environment) and the a fully operational project.

In the economic impact assessment, it is assumed that all components in the Test Facility are implemented in hardware, as similar as possible to that which would be used on a full scale MVDC project.

- **DC voltage level –**

It was determined through the technical case studies in Part B that the DC voltage level is key to the benefit of MVDC technology, as the capacity of a MVDC system over conventional 33kV AC is dependent on operating at voltages above 50kV. The test facility should therefore be designed to enable component and cable testing at a range of DC voltages. Feedback from cable manufacturers in wider industry research has suggested that a sensible capability limit of MVDC cables would be approximately 80kV. On the AC side of the converter the AC voltage levels of interest are 11kV, 33kV and 66kV as these are the current AC standard for both offshore and onshore applications. There is a cost trade-off between designing a facility which could test components at all three voltage levels, resulting in a comprehensive but complex and expensive facility, versus a simpler single voltage level system which restricts the testing capability.

To investigate this further, both a single voltage (33kV) scheme, and a multiple voltage level scheme are considered in the economic impact assessment.

4.1 Specification for MVDC Test and Demonstration Options

The three proposed T&D configuration options at the end of the scoping exercise are described in Table 4-2. The cost and provisional layout of each configuration option are given in the following section.

Table 4-2 T&D Facility Configuration Options

Option	Configuration	DC Voltage & Scale	Hardware Demonstrated	Primary Benefits to:
1	Point to Point	Single DC voltage level Range: +/-30 - 50kV DC Converter size: 5 - 25MW	• 2 x VSC Converters • MVDC Cables • MVDC Breakers	• Converter Suppliers • Cable manufacturers • Supply chain • Offshore Developers • DNOs
2	Multi Terminal	Single DC voltage level Range: +/-30 - 50kV DC Converter size: 1 - 25MW	• Multiple VSC Converter models • MVDC Cables • MVDC Breakers • DC Generator Integration • Use of AC Disconnectors	• Converter Suppliers • Cable manufacturers • Supply chain • DNOs • TNOs • OFTOs • Offshore Developers • Multi-terminal DC projects • Generator Manufacturers
3	Multi Terminal	Multiple DC voltage levels +/-30 - 50kV DC And +/- 5 – 30kV DC Converter size: 1 - 25MW	• Multiple VSC Converter models • MVDC Cables • MVDC Breakers • DC Generator Integration • Use of AC Disconnectors • DC/DC Boost Technology • Different DC system voltages	• Converter Suppliers • Cable manufacturers • Supply chain • DNOs • TNOs • OFTOs • Offshore Developers • Multi-terminal DC projects • Generator Manufacturers

Proposed functionality of the test facility

The aim of the Test Facility is to enable the testing of both individual components and the whole MVDC system, in a realistic environment, and therefore a high degree of the monitoring and measurement functionality is required to provide detailed system behaviour data. Table 4-3 gives a short description of the monitoring equipment that may be required and the functionality that this adds to the test facility.

Table 4-3 Proposed Monitoring & Measurement Functionality

Monitoring & Measurement Equipment	Functionality
AC System measurement equipment	Collect 3 phase AC power data, including Voltage, Current and power factor, to determine system losses, converter efficiency and power capability.
DC System measurement equipment	Collect DC power, current and voltage measurements to determine cable losses, power capability and DC voltage control.
Power Quality measurements	Collect harmonic data, along with other power quality indicators, to determine the impact of VSC converters on the power quality of the AC grid.
Network Fault Identification	Monitor the health of the incoming AC grid supply to indicate network fault events, including transient events, to monitor fault withstand and ride through capability of MVDC converters.
Cable Temperature Monitoring	Collect temperature data for the DC cables on test, to help test cable ratings and power capability.
DC Generator Fault Simulation	Ability to simulate a windings fault or converter 'crowbar' fault on a DC generator. This will enable the testing of MVDC switchgear and converters in response to a DC fault.
DC Generator Converter System monitoring	Monitor voltage and current within the Generator Converter system, to test voltage control of the DC bus and DC generator control.

VSC Converter and other Equipment Sizing

In each of the proposed configuration options for the test facility, a range of converter sizes have been proposed, from 4 MW to 20 MW. The logic behind this design strategy is that it enables the testing of different scale components and assumes that the test company may only be able to provide a single prototype component for test. For example, if a small new entrant to the market wishes to test a prototype 12MW converter, a 20MW converter, supplied by the test facility can be used to form the other end of the point to point link. Similarly, if a company wished to test a standalone component such as a DC circuit breaker or

DC cable, then the test facility could still accommodate this with only a 4MW and a 20MW converter, if the power flow is restricted to 4MW.

Cable Testing

It will be noted that all the configuration options incorporate a *reference cable section*. This was identified as a requirement for testing the suitability of old AC cables for MVDC. The impact on system availability from the cable under test can be determined by comparison with the reference cable, which would likely be an oversized DC cable.

T&D Facility Configuration Option 1

Option 1 is a point to point system. The proposed configuration is shown in Figure 4-1. This configuration allows for the testing of MVDC Converters, DC Cables and DC circuit breakers or disconnectors. Because the system is point to point, the number of converters that can be tested simultaneously is limited to 2, and only one voltage level can be tested.

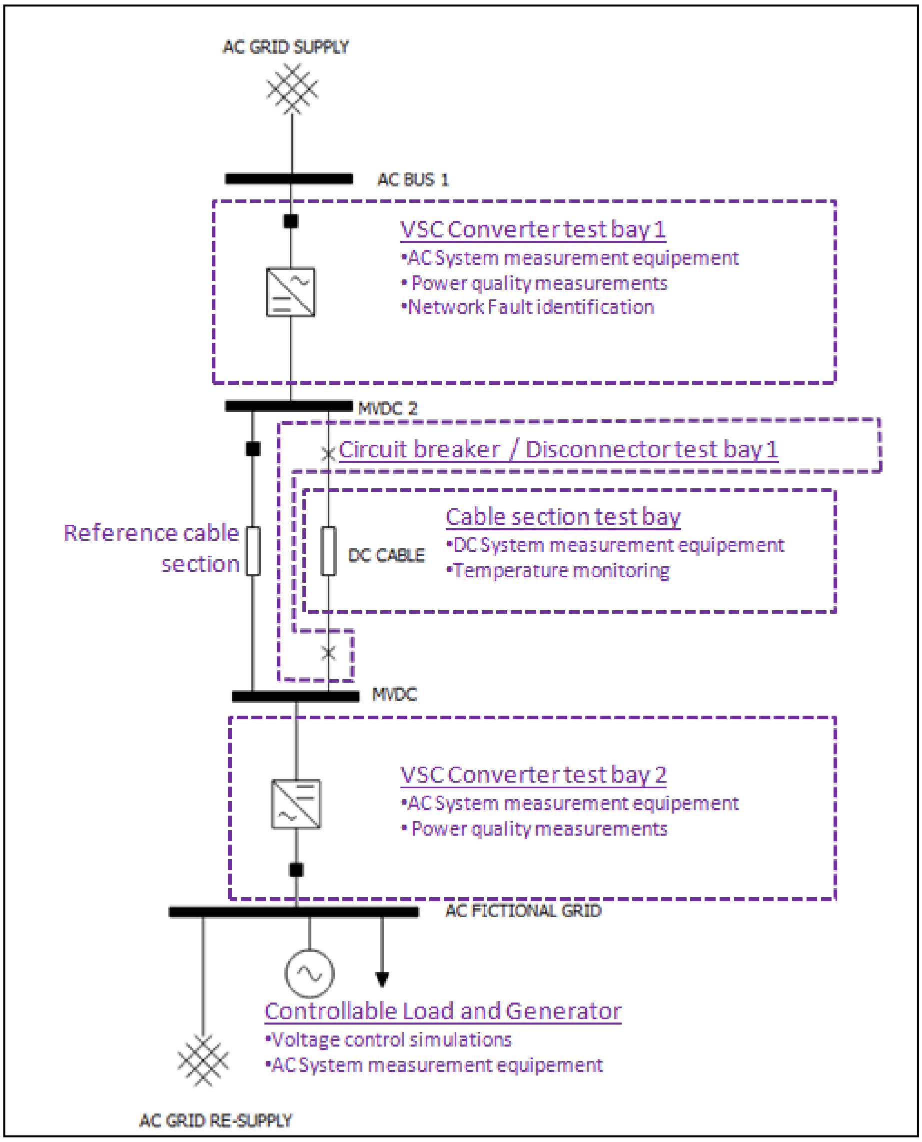


Figure 4-1 Test Facility Option 1 Schematic

This configuration offers the lowest capital build cost for the test facility, however because the configuration demonstrates only a point to point MVDC application, the stakeholder benefits from this option are limited. For example, there is very little benefit to transmission stakeholders from a facility with this configuration, as the crux of transmission DC applications is in the interactivity of DC components in multi-terminal systems.

Figure 4-2 gives the capital cost breakdown for this option. A significant element of the capital cost is in the converters themselves. For this reason it is recommended that a converter manufacturer is considered as an industrial partner in the test centre, who may be able provide converters free of charge. The capital cost of the test facility excluding converters is given as well.

	Electrical Infrastructure - main components				
	33kV Equipment	**Unit Cost**	**Units**	**Qty**	**Ex-Works Cost**
AC System	Cost of metered Incomer Panel	45000	each	2	£ 90,000.00
	33kV Circuit Breaker	45500	each	5	£ 227,500.00
Converters	VSC Converter (33kV) 20 MW	8100000	each	1	£ 8,100,000.00
	VSC Converter (33kV) 4 MW	2400000	each	1	£ 2,400,000.00
DC System	33kV 185mm2 Copper Cable	66.06	m	20000	£ 1,321,200.00
	33kV Cable Terminations	649.29	each	4	£ 2,597.16
	Outdoor Switchgear - Earthing	1625	each	4	£ 6,500.00
	Outdoor Switchgear - Disconnector, motoris	7410	each	4	£ 29,640.00
	Monitoring and logging equipement				
	33kV Equipment	**Unit Cost**	**Units**	**Qty**	**Ex-Works Cost**
AC System	Outdoor Switchgear - CTs, 3 phase	12636	each	2	£ 25,272.00
	33kV Control and Protection Panel	7800	each	2	£ 15,600.00
	AC Power Quality measurement equipment	30000	each	2	£ 60,000.00
DC System	DC System measurement equipment	20,000	each	2	£ 40,000.00
	Temperature Monitoring	15,000	each	2	£ 30,000.00
SCADA	Test Facility SCADA System	100,000	each	1	£ 100,000.00
	Total Ex-Works Cost				**£ 12,400,000.00**
	Contingency			5%	£ 95,000.00
	Design*			9%	£ 171,000.00
	Project Management*			4%	£ 76,000.00
	Transportation Costs			5%	£ 95,000.00
	Civil Works*			9%	£ 171,000.00
	Erection and Commissioning*			10%	£ 190,000.00
	Total Installed Cost				**£ 13,200,000.00**

Total Installed Cost excluding Converter Costs	**£ 2,700,000.00**

* Percentage Design, Project Management, Civil Works and Erection and Commisioning costs are taken from NAREC T&D project construction costs

Figure 4-2 Capital Cost Breakdown for Option 1

T&D Facility Configuration Option 2

Option 2 is a multi-terminal system, with 3 end points. The proposed configuration is shown in Figure 4-3. This configuration allows for the testing of the control and interaction of different MVDC components on a multi-terminal system as well as individual component testing of MVDC Converters, DC Generators, DC Cables and DC circuit breakers or disconnectors. Because the system is multi-terminal, a higher number of components can be tested simultaneously. This configuration has a total of 7 test bays, including 3 converter test bays and two cable test bays.

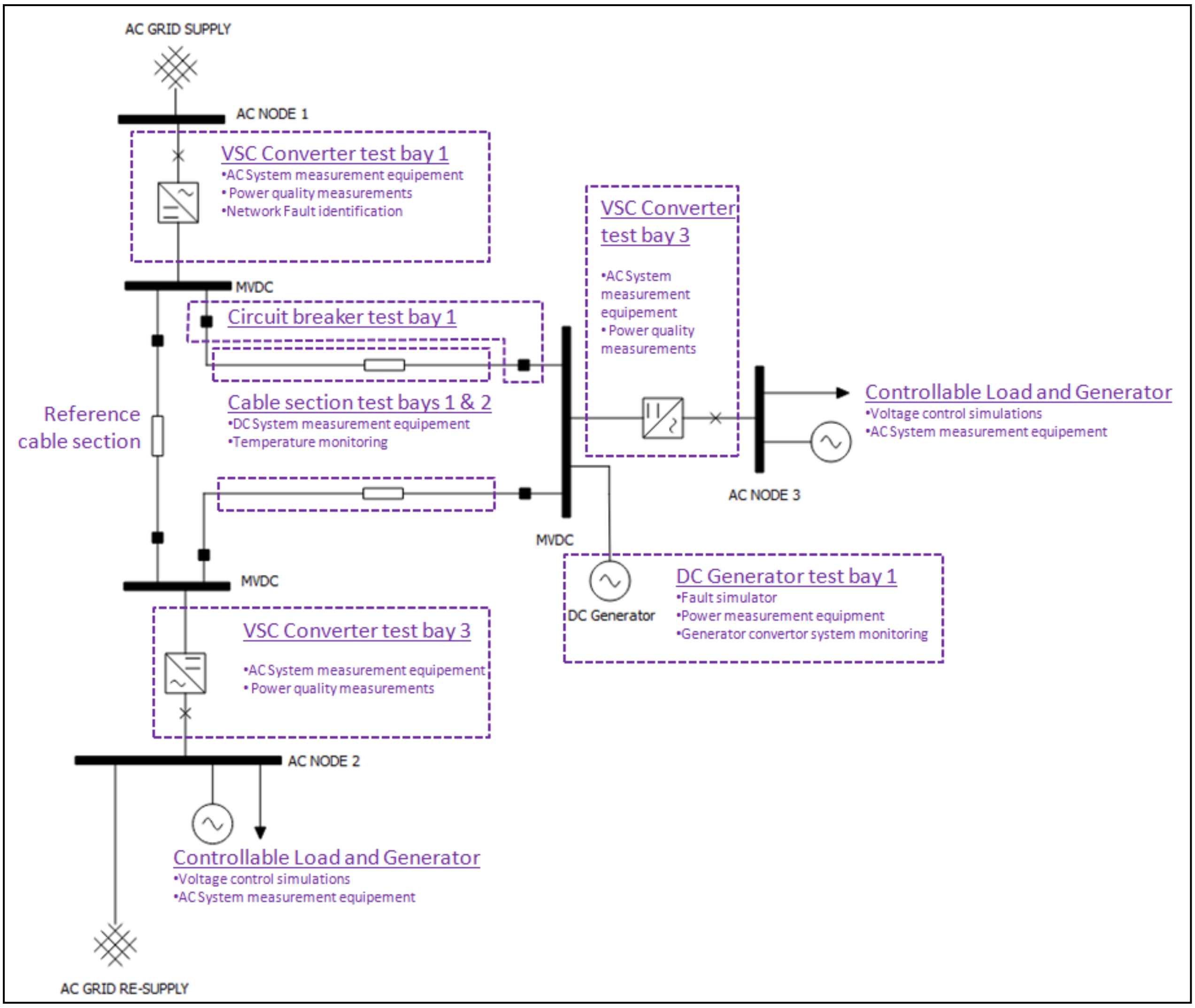


Figure 4-3 Test Facility Option 2 Schematic

This configuration has a much larger capital build cost for the test facility, partly due to the additional MVDC converter required, and partly in reflection of the additional complexity of a multi-terminal system. This additional functionality should provide a significant increase in the benefit to transmission stakeholders, as well as the better facilitating completion in the wider industry, as there are more test bays available and it would be possible for multiple suppliers to test their products simultaneously.

Figure 4-4 gives the capital cost breakdown for this option. The capital cost of the test facility excluding converters is given as well.

	Electrical Infrastructure - main components				
	33kV Equipment	**Unit Cost**	**Units**	**Qty**	**Ex-Works Cost**
AC System	Cost of metered Incomer Panel	45000	each	2	£ 90,000.00
	33kV Circuit Breaker	45500	each	8	£ 364,000.00
Converters	VSC Converter (33kV) 20 MW	8100000	each	2	£ 16,200,000.00
	VSC Converter (33kV) 4 MW	2400000	each	1	£ 2,400,000.00
DC System	33kV 185mm2 Copper Cable	66.06	m	30000	£ 1,981,800.00
	33kV Cable Terminations	649.29	each	6	£ 3,895.74
	Outdoor Switchgear - Earthing	1625	each	6	£ 9,750.00
	Outdoor Switchgear - Disconnector, motorised	7410	each	6	£ 44,460.00
	Monitoring and logging equipement				
	33kV Equipment	**Unit Cost**	**Units**	**Qty**	**Ex-Works Cost**
AC System	Outdoor Switchgear - CTs, 3 phase	12636	each	5	£ 63,180.00
	33kV Control and Protection Panel	7800	each	5	£ 39,000.00
	AC Power Quality measurement equipment	30000	each	3	£ 90,000.00
DC System	DC System measurement equipment	20,000	each	4	£ 80,000.00
	Temperature Monitoring	15,000	each	3	£ 45,000.00
SCADA	Test Facility SCADA System	150,000	each	1	£ 150,000.00
	Total Ex-Works Cost				**£ 21,600,000.00**
	Contingency			5%	£ 150,000.00
	Design*			9%	£ 270,000.00
	Project Management*			4%	£ 120,000.00
	Transportation Costs			5%	£ 150,000.00
	Civil Works*			9%	£ 270,000.00
	Erection and Commissioning*			10%	£ 300,000.00
	Total Installed Cost				**£ 22,860,000.00**

Total Installed Cost excluding Converter Costs	**£ 4,260,000.00**

* Percentage Design, Project Management, Civil Works and Erection and Commisioning costs are taken from NAREC T&D project construction costs

Figure 4-4: Capital Cost Breakdown for Option 2

T&D Facility Configuration Option 3

Option 3 is a multi-terminal system with 3 end points (same basic configuration as option 2). The key difference between options 2 and 3 is the introduction of different DC voltage levels, through the inclusion of DC boost technology. This technology is currently in very early stage R&D, but is a pre-requisite to the development of large scale DC grids.

The proposed configuration is shown in Figure 4-3. This configuration allows for the testing of the control and interaction of different MVDC components on a multi-terminal system as well as individual component testing of MVDC Converters including DC boost converters, DC Generators, DC Cables and DC circuit breakers or disconnectors. Because the system is multi-terminal, a higher number of components can be tested simultaneously. This configuration has a total of 8 test bays, including 3 converter test bays, two cable test bays, two DC generator test bays and the capability to test a DC Boost converter.

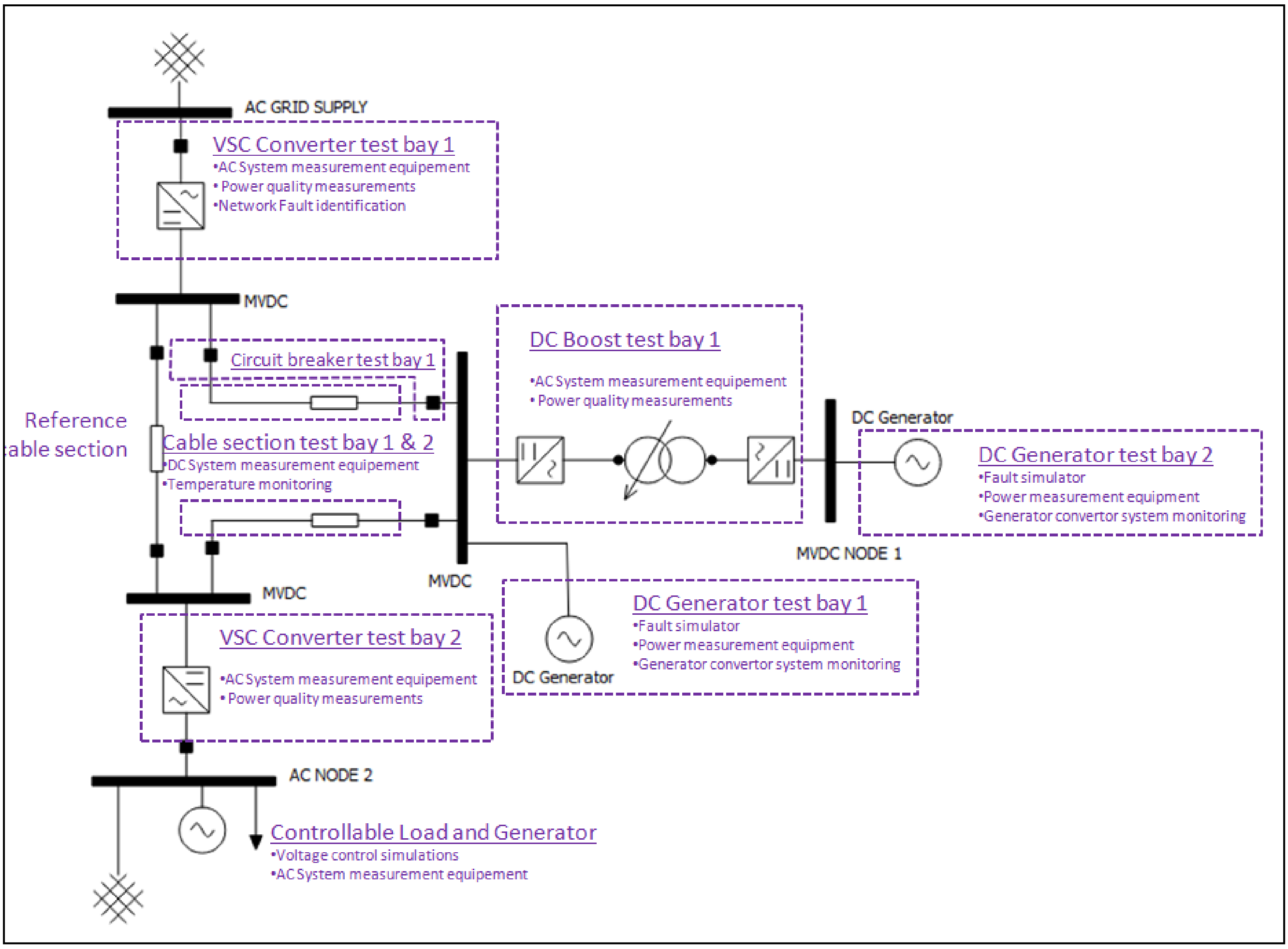


Figure 4-5: Test Facility Option 3 Schematic

This configuration has a similar capital build cost for the test facility as option 2. Again this is partly due to the additional MVDC converter required, and partly in reflection of the complexity of a multi-terminal system. This additional functionality should provide a significant increase in the benefit to transmission stakeholders, as well as the better facilitating completion in the wider industry, as there are more test bays available and it would be possible for multiple suppliers to test their products simultaneously.

Figure 4-6 gives the capital cost breakdown for this option. The capital cost of the test facility excluding converters is given as well.

	Electrical Infrastructure - main components				
	33kV Equipment	**Unit Cost**	**Units**	**Qty**	**Ex-Works Cost**
AC System	Cost of metered Incomer Panel	45000	each	2	£ 90,000.00
	33kV Circuit Breaker	45500	each	8	£ 364,000.00
Converters	VSC Converter (33kV) 20 MW	8100000	each	2	£ 16,200,000.00
	VSC Converter (33kV) 4 MW	2400000	each	2	£ 4,800,000.00
	33/11kV 7.5MVA Transformer	130000	each	1	£ 130,000.00
DC System	33kV 185mm2 Copper Cable	66.06	m	30000	£ 1,981,800.00
	33kV Cable Terminations	649.29	each	6	£ 3,895.74
	Outdoor Switchgear - Earthing	1625	each	8	£ 13,000.00
	Outdoor Switchgear - Disconnector, motorised	7410	each	8	£ 59,280.00
	Monitoring and logging equipement				
	33kV Equipment	**Unit Cost**	**Units**	**Qty**	**Ex-Works Cost**
AC System	Outdoor Switchgear - CTs, 3 phase	12636	each	4	£ 50,544.00
	33kV Control and Protection Panel	7800	each	4	£ 31,200.00
	AC Power Quality measurement equipment	30000	each	2	£ 60,000.00
DC System	DC System measurement equipment	20,000	each	10	£ 200,000.00
	Temperature Monitoring	15,000	each	4	£ 60,000.00
SCADA	Test Facility SCADA System	200,000	each	1	£ 200,000.00
	Total Ex-Works Cost				**£ 24,200,000.00**
	Contingency			5%	£ 153,500.00
	Design*			9%	£ 276,300.00
	Project Management*			4%	£ 122,800.00
	Transportation Costs			5%	£ 153,500.00
	Civil Works*			9%	£ 276,300.00
	Erection and Commissioning*			10%	£ 307,000.00
	Total Installed Cost				**£ 25,500,000.00**

Total Installed Cost excluding Converter Costs	**£ 4,400,000.00**

* Percentage Design, Project Management, Civil Works and Erection and Commisioning costs are taken from NAREC T&D project construction costs

Figure 4-6: Capital Cost Breakdown for Option3

4.2 Potential Locations and Geography

There are few geographic constraints to the development of an MVDC Test & Demonstration facility. A suitable site would require connection to the 33kV network and access to the road network to allow equipment to be delivered in shipping containers by Heavy Goods Vehicles.

Figure 4-7 below outlines the location of the National Electricity Transmission System in Scotland. It illustrates that the network is most extensive across the Glasgow and Edinburgh areas and across the Central Belt. Road access is not considered to present a constraint as it is unlikely that potentially suitable sites would be Greenfield sites which do not have suitable access for HGVs. As such, access requirements have not been considered in detail when determining suitable locations.

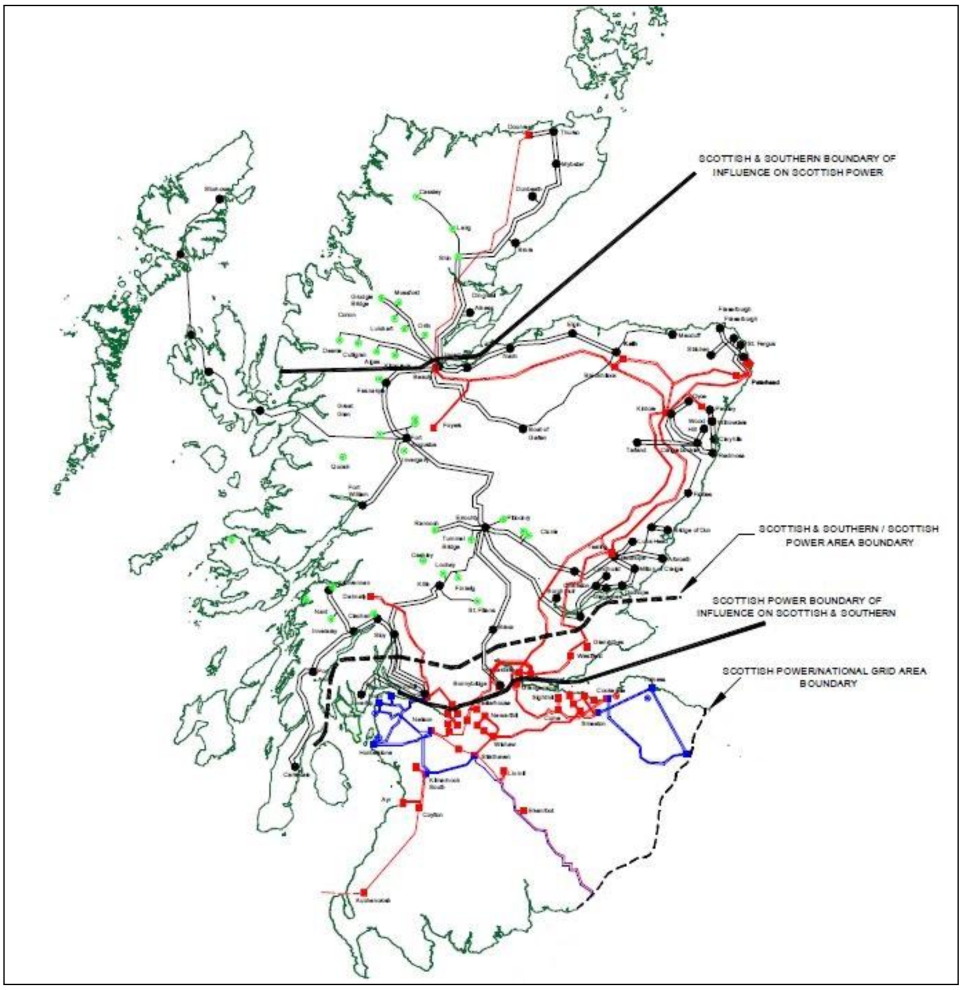


Figure 4-7 33kV Grid Network

The geographic strategy for the MVDC test facility has been considered as follows:

- Workforce capability (level of education);
- Employment level in relevant sectors;
- Proximity of MVDC stakeholders; and
- High level grid connectivity and road network access.

Data has been obtained from the Office of National Statistics (ONS), accessed via the NOMIS portal, for each Local Authority across Scotland with regard to NVQ qualifications and employment sectors. Each criterion has also been compared to the Scottish Average.

Areas that display a higher than national average number of residents qualified to NVQ Level Four and above are considered potentially suitable areas to locate the test facility as they are likely to have an employment base suitable for the test facility. However this is not considered to be a critical factor as, given the skills shortages in the power engineering sector and specialist nature of the facilities, it is considered that those fulfilling technical roles would be likely to re-locate.

In addition, data has been reviewed for employment sectors in each Local Authority in Scotland, particularly with regard to the Energy and Water Sector and Manufacturing Sector. Areas that display a higher than average employment level in these sectors are considered to be potentially more suitable areas to locate any test facility.

The Local Authorities around Aberdeen, Glasgow and Edinburgh display the highest level of NVQ Level 4 qualifications and the highest level of employment in the Manufacturing and Energy and Water Sectors.

This is supported by research undertaken by O'Herlihy and Co Ltd Management [28] consultants for Scottish Enterprise entitled 'Employment in Renewable Energy in Scotland'. This report confirms the onshore wind sector dominates employment in Glasgow and is the most significant employer in the South of Scotland and Lothian. Offshore wind is also a key employer in Glasgow and Lothian. Glasgow is also a key location for grid activities.

The above three broad areas of search also have the best road access via the main trunk roads and motorway network which radiates out of Glasgow and Edinburgh.

A review of the current locations of the key SME and Academic stakeholders has been undertaken. These are listed in Table 4-4. The case study based around the HVDC facility in Manitoba suggests that clustering such a facility around already established stakeholders has clear positive economic benefits.

Table 4-4: Location of Stakeholders

SME	Location
Source Low Carbon	Perth
Smarter Grid Solutions Ltd	Glasgow
Green Cat Renewables	South Lanarkshire
Aquamarine Power	Edinburgh
Sgurr Energy	Glasgow
Other Test Facilities	**Location**
SSE MTTE	TBC
EMEC	Orkney
Academia	**Location**
University of Strathclyde	Glasgow
University of Edinburgh	Edinburgh
University of Aberdeen	Aberdeen
Heriot-Watt	Edinburgh/ Orkney / Central Belt
The Energy Technologies Partnership	various
The Renewable Energy Skills Training Academy	Renfrew
PNDC test Centre	Glasgow

Of the SME stakeholders that were interviewed as part of the study: three are based in the Glasgow area, one is based in Perth, one in Edinburgh and one in Orkney.

A similar pattern applies to the location of relevant academic institutions, with three being located in and around Glasgow, two in Edinburgh, one in Aberdeen and one having facilities in various locations across the country.

Recommendations

Given the above, it is recommended that a suitable location for the proposed MVDC test & demonstration facility would be around Glasgow or around Edinburgh, as the facility is likely to benefit from strong relationships with academia and from clustering with other stakeholders. The location of this test facility should also take the final proposed location of the MTTE facility into account.

4.3 Identification of Potential Business Models

A number of potential business models exist, including:

4.3.1 Public Sector Research Establishment (PSRE)

A number of existing facilities, such as EMEC, are funded in this way. The need for EMEC was identified by the House of Commons Science and Technology Committee in 2001. Two years later the centre was established with funding provided by a range of public sector stakeholders ranging from the Orkney Islands Council through Scottish Enterprise to the European Union.

Benefits of this approach are the commercial independence of the test centre from any one industrial supplier as well as the potential for a future public revenue stream from testing activities in the future. This objective was raised by both manufacturers and DNOs during the stakeholder engagement, i.e. that it would be important to ensure the credulity and availability of test results and industry learning. However, without the inclusion of private sector finance, less investment may be available.

4.3.2 University Based Collaboration

Various test and research facilities are housed within universities, involving collaboration between them and public and private stakeholders. One example is the Power Networks Demonstration Centre (PNDC) which is part of the Department of Electrical and Electronic Engineering at Strathclyde University. Benefits of this business model include access to engineering talent (particularly individuals who might prefer to work within academia) and access to existing facilities. Disadvantages of this approach include the difficulty in ensuring that academic research activities are always clearly focused to address real industry needs, and that the scale and operation of the test centre is sufficient to allow practical use by industry. It is important to note that there are multiple existing academic HVDC labs around the UK, the majority of which are primarily concerned with early stage concept research and control system engineering, but which do not, for the most part, provide facilities for industrial hardware testing.

4.3.3 Private Enterprise

It is unlikely that a Test & Demonstration Facility would be entirely privately owned in the short term as stand-alone commercial viability is not anticipated. The benefit of a wholly private sector owned model is that there is no drain on public finances. However, the focus of research and testing is likely to be narrower and aligned to individual company objectives.

4.3.4 Public-Private Partnership

The inclusion of private sector investment can deliver a range of benefits allowing a broader scope of T&D activities. In this case, the obvious choice of industry partner would be a converter manufacturer or supplier, as these constitute the bulk cost of the test facility. In partnering with a supplier, or indeed a consortium of suppliers, the cost to the public would be significantly reduced while control over the policies and operation of the test centre could be retained by a public and commercially independent body. There may also be a quicker transition from the test phase into operation if the private sector partner(s) adopt the technology in the field, having first fully understood its evolution and capabilities. The MTTE facility is an example of this business model.

4.4 Benefit to Scotland

4.4.1 Potential Scottish MVDC Market Size

In order to give an indication of the size of the potential market for MVDC, the value of Scottish Offshore projects and interconnectors in 2014 was calculated. It can be seen from Figure 4-8 that there is a significant volume of Scottish offshore projects that will spend a total of £3.3bn on electrical infrastructure. If the same projects were to adopt direct to shore MVDC solutions, the reduction in capital costs, based on the offshore case study considered in section B of this report, could amount to £1.7bn, based on a future reduced cost of energy of £100/kWh.

Whilst most of these projects will go ahead with AC transmission solutions due to the timescales of the build, this figure does indicate the potential scale of the offshore market in Scotland for MVDC, if the technology is matured and de-risked sufficiently for developers to consider it as a transmission solution. Projects with transmission distances less than 50km, such as Neart Na Goithe have not been considered in this, as MVDC would not appear to be a commercially viable connection option at this distance.

Figure 4-8 Indicative Savings from MVDC applied to current Scottish Offshore Projects

Scottish Offshore Projects					
Project	Capacity (MW)	Transmission Distance	TEC Year	Estimated HVAC Capex	Estimated Direct MVDC Capex
Moray Firth Eastern Development Area Round 3 Wind Farm Zone	504	85	18/19	£293m	£139m
Moray Firth Eastern Development Area Round 3 Wind Farm Zone	612	85	18/19+	£356m	£169m
Firth of Forth Round 3 Wind Farm Zone Phase 1	1050	70	18/19	£559m	£260m
Firth of Forth Round 3 Wind Farm Zone Phase 2	1820	50	18/19+	£844m	£384m
Firth of Forth Round 3 Wind Farm Zone Phase 3	790	50	18/19+	£367m	£167m
Beatrice	664	85	18/19	£386m	£183m
Inch Cape	784	83	18/19	£452m	£214m
			Total:	£3257 m	£1516 m
			Reduction due to MVDC		£1741 m
					53%

4.4.2 Strategic Benefits to Scotland

The strategic aim of the project is to bring forward the economic opportunities for Scotland that would derive from establishment of an industry around MVDC, as well as the wider benefits that would be delivered as a result of the development of the technology.

By establishing a test centre specifically for MVDC hardware, the aim is to progress the technology while increasing the number of skilled employees in this sector (through PhDs, research contracts and training of existing staff in the industry). This has the potential to allow Scotland to accelerate and de-risk the integration of offshore wind and other renewable generation and to become a centre of excellence for MVDC technology. The inputs, activities, outputs, outcomes and impacts (in the form of a logic model as per the Scottish Enterprise Guidance) are summarised below in 4-8.

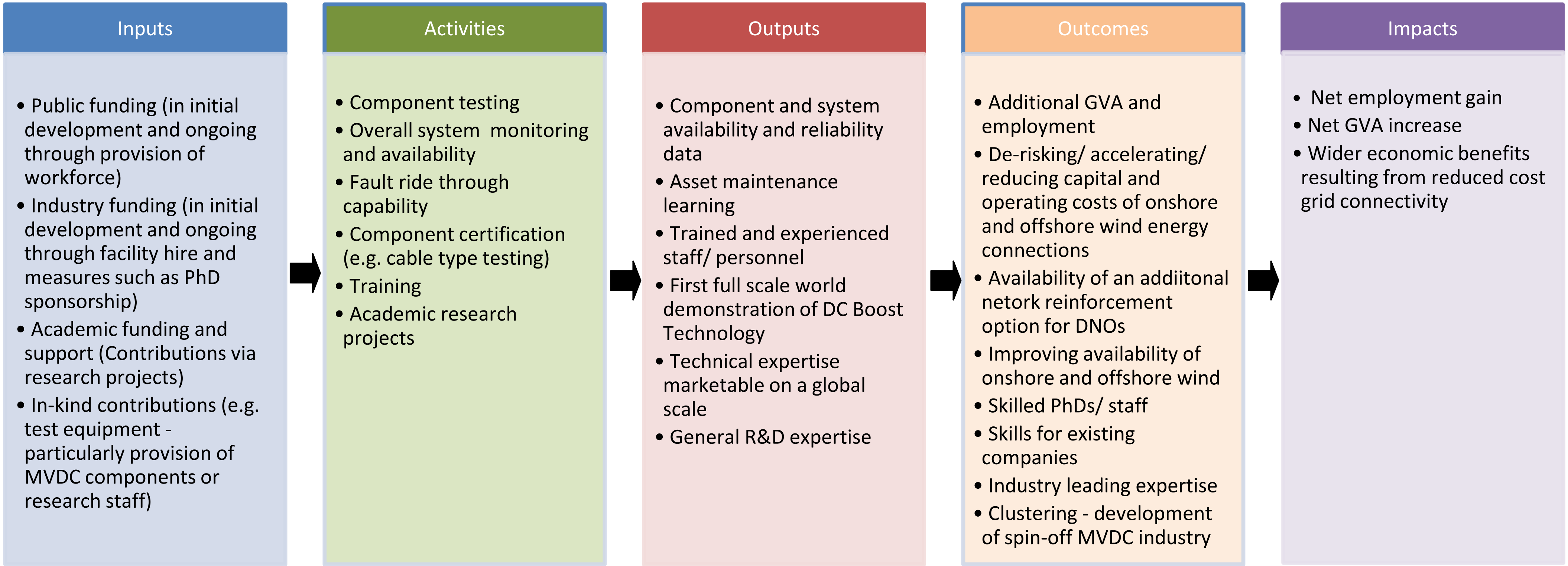


Figure 4-4-9: Inputs, Activities, Outputs, Outcomes and Impacts for the Proposed Options

The key strategic benefits for Scotland that could be generated by an MVDC T&D Project are as follows:

- Accelerate offshore wind generation by de-risking the MVDC connections required to connect wind farms to the electricity networks. In the medium term (5 to 10 years) this may bring forward additional generation that would not be viable utilising other technologies and may ultimately help to reduce consumer energy costs in line with the Scottish Electricity Generation Policy Statement. TNEI's predictions are that, based on the size of the offshore transmission and interconnector market today, if direct MVDC is adopted in the future as a transmission solution, there could be the potential to reduce Scottish Offshore capex by around £1,7bn and that the Test and Demonstration Centre could provide learning benefit for around £10bn worth of interconnector projects [30];
- Demonstrate the viability of MVDC network reinforcement, providing a cost savings where this is the most viable option, and ultimately helping to reduce consumer energy costs. This would also be in the short to medium term (2 to 5 years);
- Promote academic and industrial collaboration, leading to development of skilled workers (through PhDs and research positions) to assist in addressing the skills shortage in this sector. This could occur from the outset of operations at the site;
- Generation of spin-off R&D and consulting companies due to the uptake of MVDC technology and the associated engineering requirements and the development of skilled people. R&D activity, which is a key measure within the National Performance Framework [31] and within Scottish Enterprise's Economic Performance Indicators [32]. This may take longer to deliver based on the case study evidence; medium to long term (5 to 15 years);
- Reinforcement of Scotland as a hub for offshore renewable energy technologies and power systems expertise and development of a leading position within the global market. The benefits of this are through perception as well as project delivery and therefore would be delivered from the outset; and
- Help to raise the profile of electronic and electrical engineering and therefore encourage graduate engineers to develop careers in this field within Scotland. Again some benefit would be delivered from the outset with the announcement of the development of the Test and Demonstration Centre with further benefits delivered during its operation.

These wider benefits would be in line with the Scottish Government Economic Strategy [33] which aims to reaffirm the Scottish Governments commitment to delivering economic growth. One of the key objectives is to provide leadership to support Scotland's transformation to a low carbon economy.

The potential for MVDC technology to de-risk transmission costs for offshore wind, or for the T&D Project to prove or develop HVDC technology through scaling up research findings, is critical. This could lead to significant cost reduction for some offshore wind projects and may bring some within the threshold of commercial viability. It has been estimated in a study compiled by The Crown Estate in 2012 [34] that transmission capital costs in 2011 for wind farm sites 40km from shore were £0.5m/MW and total wind farm capital costs (including transmission) were in the range of £3.1m/MW to £3.4m/MW. Therefore, transmission costs represent 15-16% of total capital costs which is a significant proportion. In addition, the same report estimates that reducing the cost of capital (through reducing the perceived risks) by one percentage point is equivalent to a reduction in the levelised cost of energy of around 6%. This high reduction is due to the high capital intensity of offshore wind farms and is considered to also be likely for wave and tidal technologies. Therefore, de-risking offshore transmission and reducing the capital cost with the use of MVDC technology could have a significant positive impact on total costs. This may encourage investment into the offshore wind industry, which has recently experienced slower than anticipated growth.

4.4.2.1 Evidence of a Skills Shortage

In 2013, Scottish Renewables commissioned a report on Employment in Renewable Energy in Scotland [28]. While the findings are limited with regard to skills gaps specific to this study, the report found that the highest percentage of organisations citing skills gaps related to graduate level engineers, with a gap also identifiable relating to research and development roles at doctorate level.

The power industry in general is facing a skills shortage, driven by the need to renew ageing infrastructure, incorporate new generation (particularly renewables) and develop smarter networks. In addition, the privatisation of the electricity industry in the UK has led to a reduction in workforces within the sector, in particular within the Distribution Network Operators (DNOs). It is estimated that DNO workforces reduced by between 40% and 60% since the 1980s, partly due to outsourcing, and partly due to downsizing [35]. The Sector Skills Council for Gas, Power, Waste Management and Water summarised the main factors driving skills shortages in the transmission and distribution industries as follows:

- An ageing workforce in the industry and across the UK’s engineering workforce in general;
- Increased investment in the electricity network infrastructure to accommodate new generating capacity – from conventional, nuclear and renewable sources;
- Insufficient supply of STEM-related skills into the labour market from schools, colleges and universities; and
- Poor sector image amongst potential new entrants.

The Sector Skills Council identified a number of specific occupations within the industry that are facing skills shortages. Occupations relating to an MVDC T&D Project and potential associated activities include the category of "Electrical Engineers", which comprises "Power System Engineer", "Control Engineer" and "Protection Engineer". The report stated that this occupation passes 7 out of 12 shortage indicators, and that 39% of vacancies are skills shortage vacancies (SSVs). The definition of an SVV is a vacancy in which the cause is either a low number of applicants with the required skills, lack of required experience, lack of required qualifications or a combination of these causes.

"Design Engineers" were also identified as a category experiencing a skills shortage, passing 5 out of 12 shortage indicators according to Sector Skills Council analysis and with 38% of vacancies classified as SSVs. "Planning and Quality Control Engineers" which comprises "Planning/ Development Engineer" and "QHSE Engineer" passes 5 out of 12 shortage indicators and has 27% of vacancies classified as SSVs.

A skills shortage in power electronics engineering is commonly accepted as a key issue for development of the industry. Ofgem acknowledges this skills shortage within its RIIO framework. The Sector Skills Council also stated that "*over recent years the UK has built up a technological lead in off-shore wind farm connections to the grid and also in high voltage direct current (HVDC) undersea links. If this lead is unable to be maintained in the short-term due to continued skills shortages it could lead to serious economic consequences (not least EU fines for failing to meet 2020 renewable energy targets)*".

The Department for Business Innovation and Skills (BIS) published a report in 2011 that included an analysis of the skills required for the Power Electronics industry [36]. This report suggests a number of mitigating measures for increasing skills in Power Electronics, some of which have relevance for the MVDC T&D project and potential related activities. The relevant challenges and mitigating actions identified by BIS are summarised below:

Table 4-5: BIS Challenges and Actions for Power Semiconductor Activities

Challenge	Action
Ensuring the UK remains at the forefront of innovative Power Electronics design and manufacture.	Establishment of test beds.
	Participation of the wider Power Electronics community in promoting and improving research and development.
	Encouraging collaborative pre-competitive research opportunities.
To ensure a good supply of talented Power Electronics engineers for both industry and	Raise the profile of electrical and electronics engineering in general and Power Electronics in particular.
	Encouraging academics to spend time in industry.
	Encourage strategic deployment of Industrial CASE towards the training of Power Electronics engineers at

Challenge	Action
academia.	leading academic institutions.
	Industry and academia leading the way with well targeted Government support, where appropriate. Focused Research Council spending.
	Attraction of long-term funding by centres for excellence.

Challenge	Action
To improve access to leading technology and to competent engineers, notably bridging industry and universities.	Universities should be encouraged to develop simplified contractual arrangements for short-term projects.
	Provide incentives for long-term company-university strategic research partnerships, university-based company development teams (e.g. Newcastle University/Dyson) and long-term sponsored Chairs.
	Beneficial drafting of University contracts of employment.

4.4.3 Other Benefits of the Identified Options

4.4.3.1 Wider Benefit to Scotland

The Employment in Renewable Energy in Scotland Study [28] noted barriers to growth. Of those identified, notable numbers of respondents identified uncertainty over grid connections (139 out of 541 organisations) and prohibitive grid costs (84 out of 541 organisations) as barriers. The development of MVDC technologies as a network reinforcement tool has the potential to reduce these barriers and so support future market growth.

The global renewables market has experienced a shift of manufacturing from the West to the East, particularly China [40]. European and other western countries are more likely to retain the development and production of high tech elements including grid technology. Scotland is well positioned to lead on MVDC development and there are greater opportunities for Scotland to retain this piece and access the socio-economic benefits than in, for example, turbine component manufacturing.

4.4.3.2 Offshore Wind

Scottish Government and Scottish Renewables commissioned a study in 2010 to quantify the potential opportunity for offshore wind in Scotland. It was estimated that 28,377 jobs and a GVA of £7.1bn could be created for Scotland, if the full offshore wind capacity was reached and Scotland secured one third of the UK's offshore wind market. Further information can be found in Scotland's Offshore Wind Route Map [41]. Since the publication of this report, the industry has faced more challenging times which has been reflected in the stakeholder responses to this study. There is a less clear forecast as to the growth of this area, Many of the offshore wind farms currently planned will be connected via HVAC (see table below) due to the relative immaturity and cost of HVDC options. However, the offshore case study in Part B demonstrates potential cost savings from the adoption of MVDC given the development of a supply chain and demonstration of availability. HVDC technology is scalable relative to MVDCand an MVDC T&D Centre would therefore also enable critical risks and issues to be solved in terms of integration of offshore wind farms with HVDC links. The value of this technology learning in terms of jobs and GVA will be dependent on the direction and scale of the offshore wind market in 5 years time, but could potentially have a significant impact for Scotland.

The Scottish offshore wind projects are summarised in Table 4-63.

Table 4-6: Scottish Offshore Wind Projects

Project	Developer	Capacity (MW)	Distance to shore (km)	Connection
Moray Firth Eastern Development Area Round 3 Wind Farm Zone	Moray Offshore Renewables Ltd (EDPR and Repsol JV)	1116	105	HVAC
Firth of Forth Round 3 Wind Farm Zone	Seagreen Wind Energy Ltd (SSE and Fluor JV)	3500	36.8	HVAC or HVDC
Beatrice	SSE Renewables, Repsol	664	18.9	HVAC
Inch Cape	Inchcape Ltd (Repsol and EDPR JV)	784	22.4	HVAC or HVDC
Neart na Gaoithe	Mainstream Renewable Power Ltd	450	15.5	HVAC
Total		6,514		

4.4.3.3 Wave and Tidal

In addition to the Round 3 and Scottish Territorial Waters Offshore wind programmes, the Crown Estate has also invested in Wave and Tidal site in the Pentland Firth and Orkney Waters.

Between 2008 and 2010, The Crown Estate ran a leasing round in an area around the Pentland Firth and Orkney waters, off the north coast of the mainland Scotland and around the Orkney Islands. This led to the creation of eleven projects (six wave and five tidal) with a total potential capacity of 1,600 MW. The individual capacities of the projects range between 50 MW and 400 MW.

Each of the projects was planned to be developed and constructed in multiple phases, with each phase comprising a portion of the total potential capacity. Originally, the first phases of several projects were planned to be installed in 2014 to 2015, this is now likely to take longer than anticipated.

At this stage it is understood that further work is required on the transmission capacity in order to connect the first stages of the projects.

4.4.3.4 Quantification of Wider Benefits

Whilst many projects are relatively close to shore, many of these are still far from suitable onshore connection points and therefore some of these connections are more likely to be via HVDC. Scottish Power Renewables is also developing 7.2 GW in the East Anglia zone, with the first project (EA ONE) being considered for HVAC or HVDC,and some of the subsequent projects forecast to connect via HVDC. SSE Renewables is developing Phase I and Phase II of Dogger Bank, and these will also be connected via HVDC.

However stakeholder engagement has indicated that developers may consider MVDC connections including for future schemes that are predicted to be at greater distances from the shore. The future development of wave and tidal generation may also utilise either MVDC or HVDC technologies and it is important to note that an MVDC test and demonstration centre could benefit both options as results would be scalable.

It is not possible to quantify wider benefits to Scotland that would be realised through the development of MVDC technology at this early stage in its development. Each of the 3 T&D Centre options would deliver additional benefits in terms of:

- spin-off business creation;
- increased technical expertise and skills that would directly benefit the energy sector in Scotland and also be exportable bringing additional income into Scotland;
- attracting engineering talent to Scotland;
- attracting talent into the power system industry, including through PhD opportunities, that will alleviate skills shortages that threaten to hamper growth of the renewable industry;
- enabling development of future onshore and offshore renewable generation that has potential to reduce consumer energy costs;
- providing a cost effective network reinforcement option in some cases that could enable renewable generation and potential to reduce consumer energy costs;
- assist development of HVDC technology through scaling up findings of MVDC testing; and
- attracting foreign investment into Scotland as an environment where technical solutions can be developed.

4.4.4 Test & Demonstration Case Studies

One of the primary benefits of an MVDC test & demonstration facility will be the establishment of Scotland as a hub for DC research and development activities. This agglomeration effect has been observed elsewhere within energy research activity. The Manitoba/ Winnipeg HVDC research cluster has been selected as a case study to investigate the level of additional benefit due to agglomeration, over and above direct, indirect and induced job creation.

The Manitoba/ Winnipeg HVDC cluster provides a good comparable example of where a successful power systems technology cluster has been created, in that case around development of leading software tools for analysis of HVDC technology. Scotland could benefit from a similar process relating to MVDC and associated technologies, potentially delivering increased employment and GVA as detailed below. This is a key driver for the development of a Test and Demonstration Project as proposed.

In addition, the European Marine Energy Centre has also been investigated to demonstrate the actual GVA , due to direct, indirect and induced jobs, for a contemporary test & demonstration facility in Scotland. EMEC provides a good example of a research facility which has not yet attracted other enterprise to locate nearby and has not yet formed a geographic cluster.

4.4.4.1 Winnipeg (Manitoba) Power Industry

The Manitoba/ Winnipeg cluster has developed over the last 20+ years, through the development of the Manitoba HVDC Research Centre, which was established to provide back-up support and research for the Nelson River HVDC transmission system. This transmission system was first established in 1966 and development of an HVDC simulations tool began in 1973. The HVDC research centre and its relationship with the Manitoba University have led to development of the region into the leading area of HVDC expertise.

In total, the five Winnipeg companies described below provide approximately 190 high value technical consultancy jobs and approximately 25 administrative jobs. These companies provide world leading services in the HVDC sector and are acknowledged global authorities. For example, PSCAD is the world leader in analysis software for HVDC, Teshmont Consultants have provided consultancy services to 50% of the world's HVDC projects and Electranix has provided consultancy services globally.

Manitoba HVDC Research Centre (PSCAD/EMTDC)

Manitoba HVDC Research Centre provides power system simulation tools, applied research and engineering services. It was established as a non-profit research company in 1981. In 1983 EMTDC was first used for commercial applications and in 1993 PSCAD became commercially available. The centre became a subsidiary of Manitoba Hydro in 2000.

The EMTDC programme was instigated in 1973 through a research project by employees of Manitoba Hydro and researchers at the University of Manitoba, who established the Manitoba HVDC Research Centre. PSCAD was the graphical user interface, which was developed from 1988. The Manitoba HVDC Research Centre has over 40 employees.

This example shows how collaborative research between a utility and academia can lead to ideas that in turn can generate spin-out companies. Many of the models in PSCAD have been developed by graduate students from the University of Manitoba. The Manitoba HVDC Research Centre provides funding for the Electrical Engineering department of the University, giving an example of a successful collaboration.

RTDS Technologies Inc.

The RTDS simulator was developed from research carried out at the Manitoba HVDC Research Centre in the 1980s and was the world's first real time digital power system simulator. RTDS Technologies Inc. was founded in 1994 to carry on the development, support and commercialisation of the RTDS simulator. RTDS was developed by four young engineers from the University of Manitoba who subsequently became principals of RTDS Technologies Inc.

In 2013 RTDS had 47 employees of which 38 are engineers or technical staff and 9 are administrative staff.

Teshmont Consultants

Teshmont Consultants began to develop their HVDC experience in 1966 due to their proximity to Manitoba Hydro and their involvement with the Nelson River Transmission Project. Teshmont has provided engineering services for projects representing approximately 50% of the world's installed capacity of HVDC with services including owner's engineer, power system studies, engineering design, project implementation, life extension and training. Their list of case studies includes:

- Multiterminal HVDC Transmission System Study for Statnett in Northern Norway;
- Sarawak to Peninsula Malaysia (SARPEN) HVDC Transmission Project;
- Atlantic Wind Connection;
- Manitoba Hydro Bipole I, II and III;
- Itaipu Transmission System;
- Nemo HVDC Project; and
- Malaysia-Thailand HVDC Interconnection Project.

Teshmont was established in 1966 from Templeton, Shawinigan and Montreal Engineering specifically to provide expertise for Bipole I of the Nelson River Transmission System. Development of this expertise has enabled the growth of a highly skilled company with the ability to sell this expertise worldwide.

Electranix Corporation

Electranix was established in 2000 by Dennis Woodford, Executive Director of the Manitoba HVDC Research Centre and Garth Irwin, a principal developer of PSCAD and also a long term employee of the Manitoba HVDC Research Centre. Electranix is a successful specialist transmission consulting company with highly skilled employees, operating in AC, HVDC, and difficult transmission for renewable energy projects around the world including Scotland, with the largest number of projects in the US.

Electranix has developed add-ons to PSCAD such as E-TRAN which translates and reduces power flow and transient stability data into PSCAD and allows PSCAD to run with transient stability programs under one simulation. This enables faster simulation times to be achieved by running the simulations on multiple processors.

TransGrid Solutions (TGS)

TransGrid Solutions is a specialist consultancy established in 2002 which had 11 engineering employees and 1 administrator in 2013. It is headed by Dr Mohamed Rashwan whose career started with Manitoba Hydro. The other company employees either have PhDs or degrees from the University of Manitoba or have been former employees of Manitoba Hydro.

TGS provides power systems consultancy, but has a particular specialism in developing in-house applications for small signal analysis including sub-synchronous resonance (SSR). TGS has analysed the following SSR phenomena and mitigation measures:

- Generator-turbine – Series capacitor sub-synchronous resonances;
- Generator-turbine – HVDC torsional interactions;
- Wind turbine – Series capacitor sub-synchronous resonances (SSCI);
- HVDC control interactions and DC resonance issues;
- Multi-in-feed HVDC interactions;
- All other sub-synchronous frequency interactions in power systems (Interactions of FACTS devices, Network resonances etc.);
- Controller tuning and sub-synchronous damping controller design; and
- Analysis of Eigen properties to determine the locations for damping controllers.

The ability to analyse these complicated interactions has clearly been developed from skills and expertise gained from the activities of Manitoba Hydro and Manitoba University, again giving an example of where expertise developed has lead to the foundation of a successful company.

4.4.4.2 European Marine Energy Centre (EMEC)

EMEC was established in 2003 and was the first and only kind of facility in the world which provides developers of both wave and tidal energy converters with purpose-built, accredited open-sea testing facilities. The facility is based in Orkney which is an ideal location as it has an excellent oceanic wave regime, strong tidal currents, grid connection, sheltered harbour facilities and the renewable, maritime and environmental expertise that exists within the local community.

EMEC has 14 full-scale test berths, which has attracted developers from around the world. These developers use the facilities to prove what is achievable in some of the harshest marine environments, while in close proximity to sheltered waters and harbours. It also operates two scale test sites where smaller scale devices, or those at an earlier stage in their development, can gain real sea experience in less challenging conditions than those experienced at the full-scale wave and tidal test sites.

EMEC currently employs 28 staff, broken down as follows.

Table 4-7: EMEC Staffing Numbers

Team	No. of Staff
Executive	4
Administration, Finance and Quality Team	6
Commercial and Market team	4
Operations Team	8
Research and Commercial Team	6

4.5 Economic Impact Assessment

An economic impact appraisal has been undertaken to inform any public sector intervention. The appraisal considers impacts during both the construction of a T&D Centre and its operation.

4.5.1 Methodology

The appraisal has been undertaken in line with the guidance provided by Scottish Enterprise [29].

The direct benefits of the test facility are considered to include:

- Job creation during the construction phase; and
- Full time equivalent jobs created by operation of the test facility.

The indirect benefits of the test facility are considered to include:

- Indirect job creation through consultancy activity and within companies using the test facility; and
- Gross Value Added in the supply chain and by the agglomeration of technical companies around the new MVDC test facility.

An appraisal of the likely benefits as a result of construction has been undertaken for each of the three identified options. This has been based on the forecast construction costs (excluding the cost of converters as this would skew results).

The number of full time equivalent jobs was calculated by considering the number of executive, administrative, support and technical staff required for each of the three test facility configuration options. In general, the more test bays in the configuration option, the larger the technical staff requirement and so the greater the direct benefit.

For each component tested in the facility, it is expected that there will be indirect jobs in terms of the testing company staff required to install and monitor the performance component. There will often also be consultancy support to perform design and electrical studies before the component under test can be connected to the facility. These jobs are accounted for in the discussion of indirect benefits of the MVDC facility.

To consider the indirect benefits caused by the agglomeration of similar enterprise, case studies have been undertaken to provide an insight into comparable projects elsewhere. These consisted of:

- The establishment of a specialist HVDC technology cluster in Winnipeg, Manitoba; and
- The European Marine Energy Centre (EMEC) test facilities for wave and tidal generators in Orkney.

Further details of these case studies are given in Section 4.4.4.

4.5.2 Construction Phase Benefits

Overall project costs for each option have been estimated as included in section 4.1 above.

Economic benefits associated with the construction of each of the three configuration options have been calculated based on both total installed costs (excluding converter costs as these would skew the results) and lower design and construction costs which also exclude other electrical equipment. The findings are detailed within Table 4-8 Table 4-9. Full Time Equivalent (FTE) jobs have been calculated assuming a 6 month construction period, an average turnover per employee of £181,000 and an average GVA per FTE per year of £65,000.

Table 4-8: Estimated Economic Benefits of the Construction Phase based on Total Installed Costs Excluding Converter Costs

Option	Total Installed Costs (Excluding Converter Costs) (£million)	Direct Jobs Supported	Direct, Indirect and Induced (Net) Jobs Supported	Direct GVA (£million)	Direct, Indirect and Induced (Net) GVA (£million)
Option 1 - Point to Point	2.7	7	16	0.48	1.02
Option 2 - Multi-Terminal	4.26	12	25	0.76	1.6
Option 3 - Multi-Terminal	4.4	12	26	0.79	1.66

Table 4-9: Estimated Economic Benefits of the Construction Phase based on Design and Construction Costs Excluding Converter Costs

Option	Total Installed Costs (Excluding Converter Costs) (£million)	Direct Jobs Supported	Direct, Indirect and Induced (Net) Jobs Supported	Direct GVA (£million)	Direct, Indirect and Induced (Net) GVA (£million)
Option 1 - Point to Point	0.7	2	4	0.13	0.26
Option 2 - Multi-Terminal	1.1	3	6	0.2	0.42
Option 3 - Multi-Terminal	1.1	3	6	0.2	0.42

4.5.3 Direct, Indirect and Induced Economic Benefit during Operation

4.5.3.1 Direct Employment

It is envisaged that the following jobs would be directly generated during the operation of each of the identified Test and Demonstration Centre options. These staff requirements have been built up per test bay for technical staff, assuming one technical job is required per test equipment category, with an additional head of testing. The administrative and executive staff numbers have then been scaled from the EMEC case study, according to the proportion of technical test staff required.

Table 4-10: Direct Job Creation during Operation

Option	Staff Type	FTE
Option 1 (Point to Point)	Administrative & Executive	10
	Technical	4
Option 2 (Multi-Terminal)	Administrative & Executive	12
	Technical	5

Option	Staff Type	FTE
Option 3 (Multi-Terminal)	Administrative & Executive	12
	Technical	5

4.5.3.2 Indirect Employment

In addition to employees of the Test and Demonstration Centre, further employment opportunities exist for consultants during periods of testing. It is assumed that these are additional jobs created on a Scottish scale rather than substitution of jobs elsewhere in the Scottish power systems industry.

It is envisaged that the following jobs would be indirectly generated during the operation of each of the identified Test and Demonstration Centre options. The indirect jobs would be created through use of the facility's test bays by industrial clients and by consultancy support throughout operation.

Table 4-11: Indirect Job Creation during Operation

Option	Indirect FTE	Induced FTE
Option 1 (Point to Point)	4.6	2.4
Option 2 (Multi-Terminal)	5.6	3.4
Option 3 (Multi-Terminal)	5.6	3.4

4.5.3.3 Economic Benefit

The per annum GVA benefit of the MVDC test & demonstration facility, for each of the three options, has been calculated in accordance with Scottish Enterprise's guidance. The results are shown in Table 4-12.

Table 4-12: Estimated Economic Benefits of the Operation of the MVDC Test Facility

Option	Direct Jobs Supported	Indirect and Induced Jobs Supported	Direct GVA (£million per annum)	Indirect and Induced GVA (£million per annum)	Total GVA (£million per annum)
Option 1	14	7	0.6	0.4	1
Option 2	17	9	0.7	0.5	1.2
Option 3	17	9	0.7	0.5	1.2

4.5.3.4 Revenue Generation

Direct revenue as a result of use of the facility may be as a result of charges for use. However, stakeholder engagement has suggested that various agreements may be put in place incorporating benefits in kind such as the donation of hardware after a period of testing or provision of staff during periods of testing.

Existing similar facilities are generally in initial stages and are incentivising users. It is not clear as to how long such incentives would need to be maintained and the transfer to income generation would be dependent on the speed of growth of the industry. Based on the example of HVDC in Manitoba, growth occurred relatively slowly with time between set-up of the facility and it becoming commercially available of 12 years. Stakeholder responses to this study broadly agree that it would be in excess of 5 years before MVDC technology was commercially adopted and given the increased strength of the renewable energy markets compared with when Manitoba HVDC as established it would be reasonable to assume that commercial viability of an MVDC Test and Demonstration Centre could occur more quickly than was the case in Manitoba.

However payment in kind may be received in the form of hardware that may be donated to the facility following a period of testing or staff time and expertise provided by the hardware manufacturers.

The three options being considered have differing functionality as set out in Section 3.4 above. As a result the range of applications increases with the scale and cost of the proposed facility. A key additional function of Option 3 is the ability to test DC boost technology which would be of particular interest to the offshore renewable energy industry.

4.5.4 GVA Benefit of Case Studies

In order to establish the economic impact of the companies in the case studies, the employee numbers in each company have been found from the company websites or through direct contact. In some cases the number of technical versus administrative staff was known, but elsewhere this had to be estimated. These employees are the direct or “gross” jobs.

4.5.4.1 Winnipeg (Manitoba) Power Industry

To estimate the direct, indirect and induced jobs as a result of those companies studied in Manitoba, the gross job numbers were multiplied by the relevant Type 2 Employment Multiplier (Scotland, 2011). No adjustment has been made to the standard multipliers for Scotland and deadweight, leakage and displacement were assumed to be zero given the nature of activities and early stage of development of the technology.

To estimate the GVA impacts from the number of jobs, the relevant GVA per head [37] was applied to the “gross” jobs. To find the “net” GVA, the relevant Type 2

GVA multiplier was applied to the "gross" GVA. This was then discounted in line with Scottish Enterprises guidance.

The multipliers taken from the input-output tables and GVA/head figures are as follows:

Table 4-13: Scottish Government Multipliers

IOC/SIC07	Industry Group	Type 2 Employment Multiplier*	GVA/ Employee (£)*	Type 2 GVA Multiplier
77/72	Scientific research and development services.	1.8	53,320	2.0
79/74	Other professional scientific and technical services.	1.8	46,420	1.5
86/82	Office administration, office support, and other business support services.	1.4	38,601	1.5

*Scottish Government Input-Output Statistics 2011 [36]

** Taking a 5 year average 2008 to 2012 from 2012 Scottish Business Statistics [38]

Table 4-14: Jobs for Manitoba Companies

Company	Company Type	IOC Mapping	Year Established	Gross (Direct) Jobs			Net Jobs
				Technical	Administrative	Total	Total
Teshmont Consultants	Consultancy	79	1966	90	10	100	150
Manitoba HVDC Research Centre	R&D	77	1981	40	4	44	82
RTDS Technologies Inc	R&D	77	1994	38	9	47	86
Electranix Corporation	Consultancy	79	2000	11	1	12	18
TransGrid Solutions	Consultancy	79	2002	11	1	12	18
Total (Upper)				***190***	***25***	***215***	***354***
Exc Teshmont (Lower)				***100***	***15***	***115***	***204***

Table 4-15: GVA for Manitoba Companies utilising Scottish Government Multipliers (£M)

Company	Company Type	IOC Mapping	Year Established	Gross (Direct) GVA (£million)			Net (Direct, Indirect and Induced) GVA (£million)			Discounted Net GVA*
				Technical	Admin	Total	Technical	Admin	Total	Total
Teshmont Consultants	Consultancy	79	1966	4.2	0.4	4.6	6.3	0.6	6.9	3.3
Manitoba HVDC Research Centre	R&D	77	1981	2.1	0.2	2.3	4.3	0.2	4.5	2.2
RTDS Technologies	R&D	77	1994	2.0	0.4	2.4	4.1	0.5	4.6	2.2
Electranix Corporation	Consultancy	79	2000	0.5	0.0	0.5	0.8	0.1	0.9	0.4
TransGrid Solutions	Consultancy	79	2002	0.5	0.0	0.5	0.8	0.1	0.9	0.4
Total (Upper)				***9.3***	***1.0***	***10.3***	***16.1***	***1.4***	***17.8***	***8.5***
Exc Teshmont (Lower)				***5.1***	***0.6***	***5.7***	***9.8***	***0.9***	***10.09***	***5.2***

*Discounted back to 1981 for all companies except Teshmont Consultants which is discounted back to 1966. All using a 3.5% discount rate.

Teshmont Consultants was established prior to the research facility, however it helped the facility to grow and develop the consulting business. Therefore, the totals with Teshmont included have been taken as an upper estimate and the totals without Teshmont included have been taken to be a lower estimate.

This leads to total gross jobs of 115-215 and net jobs of 201-377 at the end of a 32 year period (although all companies were established at the end of 21 years so it is reasonable to assume that this could be shorter). Related total Gross GVA has been calculated to be £6-10 million per annum, and total Net GVA has been calculated to be £13-£21 million per annum.

GVA has then been discounted to provide Net Present Values using a 3.5% discount rate in line with the Green Book [39]. A discount period of 21 years has been used for the Manitoba companies as the timescale in which they were all established. When discounted this gives a Net GVA of £5-8.5 million.

This simple quantitative estimation has been developed in discussion with the SE Appraisal & Evaluation team. It demonstrates the level of impact which has been achieved in Manitoba as the result of over 20 years of cluster development and the spinning out of five companies which have become global authorities in their niche markets. The impact method is simple – applying Scottish GVA per head and multipliers to Canadian jobs – but appropriate for giving a high level sense of the level of impact which could be achieved were a Scottish cluster to develop over 20 years with similar levels of success, driven primarily by demand from the global offshore renewables sector.

This cluster impact would be additional to the other benefits described in this report around: accelerating and reducing the cost of offshore wind generation through advances and greater competition in transmission technology; and increasing the flow of skilled engineers into the sector, meeting company skills needs, reducing skills shortages and improving company performance.

4.5.4.2 EMEC

Modelling of economic benefits has been undertaken in the same way for EMEC to provide an insight into an energy related R&D facility in Scotland. Findings are provided in Table 4-9 based on IOC Mapping category 79 and discounting net GVA back to 2003 when EMEC was established using a discount rate of 3.5%.

Table 4-16: GVA per Annum for EMEC utilising Scottish Government Multipliers

Gross (Direct) GVA (£million)			Net (Direct, Indirect and Induced) GVA (£million)			Discounted Net GVA*
Technical	Admin	Total	Technical	Admin	Total	Total
0.4	0.8	1.2	0.9	1.2	2.0	1.4

4.6 Examples of Successful Industry/ Academia Collaboration

Huge benefits can be achieved where industry collaborates with academia and there are a number of examples where skills shortages are being filled through collaboration or successful businesses have been developed. However, there are also some issues that should be identified. These include risks relating to IP if appropriate agreements are not put into place. Such agreements can ensure that the industrial partner retains ownership of the IP and the value derived from it but also that the academic institution receives recognition and can use this to attract future students and funding.

4.6.1 Newcastle University/ Dyson Collaboration

Newcastle University has a long-term collaboration with Dyson Ltd in which some of its research and development staff are permanently located at Newcastle University's Centre for Advanced Electric Drives. Dyson also sponsors a number of postgraduate and undergraduate students. The formal link was established in 2007 and will run until at least 2015. The research carried out by Newcastle University is used in real products which has a very positive impact for Dyson and therefore for the UK economy. A large proportion of Dyson's staff are graduates from Newcastle University and therefore there is a significant contribution to the development of skills.

4.6.2 Filtronic Comtek/ University of Leeds

Filtronic Comtek was a spin-out from the University of Leeds, established by Professor David Rhodes to manufacture microwave filters for mobile phone base stations. By 2000 Filtronic plc was a world leader in the supply of microwave frequency components for telecommunications and aerospace and a FTSE 250 company.

Filtronic retained its strong links with the University, sponsoring a number of PhD students each year and supporting undergraduate study and projects. Many Leeds students went on to have careers with Filtronic. Filtronic developed a part time MSc course with Leeds that contained microwave and filter design modules that provided their employees with specific knowledge.

Sir Christopher Snowden was a graduate and PhD graduate from the University of Leeds and was Head of the School of Electronic and Electrical Engineering from 1995-1998. He supervised 50 successful PhD candidates during his time at Leeds (many of which were sponsored by Filtronic) and in 1998 he joined Filtronic plc as Director of Technology before being promoted to CEO in 1999. Chris was knighted in 2012 for services to engineering and higher education [42].

Filtonic had a reasonably pragmatic approach to publications and in general were supportive and encouraging of students publishing papers and presenting at conferences. However, there were issues with publication in some instances. Chris Snowden himself has published 300 technical papers and 8 books and is now President and Vice-Chancellor of the University of Surrey.

Regarding IP, the situation was similar to that for the Dyson collaboration, in which Filtronic owned any IP generated in return for giving significant support to University of Leeds and its students.

These examples in addition to the evidence of collaboration between Manitoba University and Manitoba Hydro in Canada illustrate the potential mutual benefits of collaboration between industry and academia where a strong and long-term relationship can be established.

The power systems industry is experiencing skills shortages and therefore these types of relationships should be encouraged. Details relating to IP and confidentiality are likely to be dependent on the details of the agreement between the specific company and the university, but in general the company is likely to own the IP in return for supporting the university and its students. In turn, this generates a very valuable skills resource for the company and for the wider economy.

4.6.3 Further Recommendations to Maximise the Benefits to Scotland

Beyond the establishment of a T&D Centre there are a number of further intervention measures that might be considered to maximise benefits. These include:

- Encouraging the development of a technology cluster through start-up funding or innovation design competitions;
- Funding or part-funding training programmes;
- Funding future technology studies into specific applications of MVDC as these become more certain;
- Provision of business support activities and facilities, for example relocation grants or low rent office space for relevant small and medium enterprise.
- Provision in local development plans for conference or event facilities would also encourage visitors and delegations to come and see the test facility.

4.7 Summary and Conclusions

The construction of a T&D Centre would provide direct benefits calculated as being a Net GVA of between around £0.5 and £0.8 million based on total installed costs less converter costs or £0.25 to £0.4 million taking a more conservative figure based on design and construction costs alone.

There is evidence of a significant skills shortage in power electronics, and the activities of an MVDC T&D Centre and anticipated spin-off activities would help to attract and train new engineers to alleviate this. A lack of suitable skills could lead to a reduction in economic development in this industry within Scotland, with new companies and facilities being set up elsewhere.

HVDC activity in Manitoba, including Manitoba HVDC Research Centre, lead to the establishment of a number of R&D companies and consultancies. These have been analysed and the total discounted Net GVA, which includes direct and induced effects, was calculated to be between around £5 and £8.5 million per annum. This was achieved over approximately a 20 year period.

EMEC in Orkney has been operational since 2003. The establishment of a technology cluster around that facility has not been seen however that test centre has been analysed and the discounted Net GVA has been calculated as around £5 million.

Offshore wind is likely to lead to a huge number of jobs for Scotland, but to achieve this it is essential that offshore wind farms can be connected to the grid economically. De-risking MVDC technology would assist in this although the scale of the benefits as a result of MVDC and HVDC (which would also benefit from an MVDC T&D Centre) cannot be quantified. Specification Option 3 would provide the greatest potential benefits and particularly relating to DC Boost technology.

Development of a T&D Centre would help to put Scotland at the centre of the development of this technology and could develop world recognised expertise, as has been achieved for Manitoba with PSCAD.

Over a number of years (and it is considered that this could happen more quickly than was the case in Manitoba due to the current state of the industry and demand requirements), establishment of a T&D Centre could lead to significant specialised expertise being developed and the emergence of a number of consulting and R&D spin-off companies. By analogy with Manitoba and EMEC, this could ultimately have an impact equivalent to the discounted Net GVA in that case of around £5 - £8.5 million per annum although analyses has been limited to a very small sample and has not been able to account for differences in the potential uptake of future MVDC technology.

Wider benefits in terms of facilitating further development of renewable generation, energy self sufficiency (and exceeding it) and reductions in consumer energy bills cannot be quantified but have the potential to provide a real and significant benefit to the Scottish economy.

5 Conclusions & Recommendations

5.1 Summary of Benefits to the Industry

The technology case studies in Part B of this report have demonstrated the potential benefits of MVDC technology to the electricity supply industry, including offshore wind developers and distribution network operators. However, it is considered that there are likely to be benefits for other stakeholders including:

- Wave energy developers;
- Tidal energy developers;
- Offshore transmission network owners;
- Transmission network owners and operators;
- Investors in offshore projects;
- Developers of onshore projects on remote islands.

The key applications which have been explored in the case studies are MVDC arrays and the use of MVDC in onshore network reinforcement. However, it is likely that another benefit of MVDC will be proof-of-concept and de-risking for HVDC applications.

The benefits of MVDC technology to the electricity supply industry are summarised as follows:

- MVDC systems can be a cost-effective way to reinforce a network in which there are many problems which need to be addressed simultaneously. In particular, the key benefits of the DC link are:
    1. Power flow through the link can be controlled, which allows for flexibility under a number of operating conditions;
    2. Power factor can be controlled separately at each end of the link which can greatly improve network voltages
    3. It can be used to separate parts of an AC network which may be create problems when connected conventionally, e.g. due to fault level issues or phase angle issues.
- It could also be possible to convert existing AC circuits to DC so as to increase network capacity without installing new cables or overhead lines. AC circuit systems require three conductors, whereas DC systems only require two. Therefore it could feasibly be possible to convert existing double AC circuits (with a total of six conductors) into triple DC circuit systems;
- Using MVDC systems for arrays and transmission for offshore wind connections allows for the elimination of the offshore platform. This has significant implications for capital cost, as offshore platforms are a major

part of the capital cost of an offshore wind farm. A reduced capital cost should reduce project risk for investors, allowing for cheaper financing for developers;

- The advantages of MVDC arrays/transmission are likely to be applicable to developers of wave and tidal energy projects, as there are many similarities between offshore wind connections & marine energy connections. This could also be of interest to developers of onshore projects on remote islands, e.g. in the Scottish Isles, as it may allow them to circumvent local radial network constraints and connect to a stronger part of the transmission network on the mainland;
- MVDC technology can be used to demonstrate novel applications of DC technology and advanced DC components which may be used for HVDC applications. For example, multi-terminal HVDC could be used to create offshore DC grids which connect multiple offshore wind farms and interconnect many European transmission networks. The hardware concepts required for such a project could first be demonstrated at medium voltage to reduce risk.

5.2 Requirements for Successful Adoption of MVDC

The successful adoption of MVDC technology by the power system industry will be largely dependent on a range of technical and market-based challenges being addressed and overcome. There is a wealth of benefits to be reaped across the industry if the technology can be developed and deployed, and these benefits can be maximised if a number of critical issues are actively and collectively addressed.

It is anticipated that MVDC technology can be successfully adopted if the following list of criteria are met:

- Testing and associated de-risking of MVDC components in operation, both in an isolated environment and also alongside other network equipment e.g. components on the AC grid, DC generation;
- Validated proof and quantification of the benefits of MVDC technology for the various power system applications for which it has been recommended;
- The successful development of DC/DC voltage level transformation; and
- The successful development of DC protection devices and associated DC protection and control philosophies.

The result from these four achievements will be a demonstration track record which will improve the business case for MVDC technology, subsequently accelerating customer demand and the supply chain.

Through the research and stakeholder engagement activities carried out for this project, a strong case has been made for a test and demonstration facility as the most effective means of achieving the desired long-term benefits. A test and demonstration facility is considered to provide a means to test and develop the necessary equipment performance and track records required to give confidence to stakeholders.

Aside from the technical and market-related barriers being addressed, the widespread and successful adoption of MVDC technology will be dependent on industry acceptance of the technology, and the willingness of the key stakeholders to deploy MVDC in their projects in the early stages (when there is perhaps still a higher than desirable risk factor) to cultivate the confidence necessary for the market to grow.

5.3 Summary of Benefits to Scotland

An appraisal of the potential direct and wider economic benefits to Scotland has been undertaken for the proposed MVDC Test & Demonstration facility.

Direct benefits during the construction of a Test & Demonstration facility have been calculated based on predicted build costs and a range of assumptions. Net GVA, depending on the chosen Test & Demonstration facility option, has been calculated as between around £0.5 and £0.8 million based on total installed costs, or £0.25 to £0.4 million taking a more conservative approach based on design and construction costs alone.

It is predicted that direct benefits during operation will be derived from Full Time Equivalent (FTE) jobs created by operation of the test facility. Numbers of FTE jobs and GVA have been estimated as in **Table 0-1**.

Table 5-1: Estimated Economic Benefits of the Operation of the MVDC Test Facility

Option	Direct Jobs Supported	Indirect and Induced Jobs Supported	Direct GVA (£million per annum)	Indirect and Induced GVA (£million per annum)	Total GVA (£million per annum)
Option 1	14	7	0.6	0.4	1
Option 2	17	9	0.7	0.5	1.2
Option 3	17	9	0.7	0.5	1.2

One of the key benefits of the MVDC test & demonstration facility will be to encourage the development of a DC research cluster in Scotland. To quantify the impact of this agglomeration, the Manitoba HVDC research centre has been investigated as a case study.

In Manitoba, HVDC activity, including Manitoba HVDC Research Centre, lead to the establishment of a number of R&D companies and consultancies over approximately a 20 year period. This technology cluster has been analysed and the total discounted Net GVA, which includes direct and induced effects, has been calculated as being between around £5 and £8.5 million per annum.

Development of a T&D Centre would help to put Scotland at the centre of the development of this technology and could develop world recognised expertise, as has been achieved for Manitoba with PSCAD. It is considered that this could happen more quickly than was the case in Manitoba due to the current state of the industry and demand requirements. Establishment of a T&D Centre could lead to significant specialised expertise being developed and the emergence of a number of consulting and R&D spin-off companies. By analogy with Manitoba and EMEC, this could ultimately have an impact equivalent to the discounted Net GVA in that case of around £5 - £8.5 million per annum although analyses has been limited to a very small sample and has not been able to account for differences in the potential uptake of future MVDC technology.

The European Marine Energy Centre (EMEC) in Orkney, which has been operational since 2003, is a contemporary example of a test & demonstration facility in Scotland. The establishment of a technology cluster around that facility has not been seen however the test centre has been analysed and the discounted Net GVA has been calculated at around £1.4 million.

There is evidence of a significant skills shortage in power electronics and the activities of an MVDC T&D Centre, and anticipated spin-off activities helping to attract and train new engineers to alleviate this, is a potential wider benefit to the Scottish economy. A lack of suitable skills could lead to a reduction in economic development in this industry within Scotland, with new companies and facilities being set up elsewhere.

Offshore wind is likely to lead to a huge number of jobs for Scotland, but to achieve this it is essential that offshore wind farms can be connected to the grid economically. De-risking MVDC technology would assist in this although the scale of the benefits as a result of MVDC and HVDC (which would also benefit from an MVDC T&D Centre) cannot be quantified. Specification Option 3 would provide the greatest potential benefits and particularly relating to DC boost technology.

Wider benefits in terms of facilitating further development of renewable generation, energy self sufficiency (and exceeding it) and reductions in consumer energy bills cannot be quantified but have the potential to provide a real and significant benefit to the Scottish economy.

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8 Appendices

8.1 Appendix A.1 – Stakeholder Engagement Questions

The following sections detail questions posed to the different categories of stakeholder, in addition to the standard questions given in Section 2.5.3.

8.1.1 Renewable Developers (Onshore and Offshore)

The following questions were asked of Renewables Developers in addition to those detailed in Section 2.5.3:

- How far offshore do you envisage your projects being located in the next 10 years (2015-2025)? (Offshore only)
- In what timeline do you consider MVDC collector systems feasible for offshore projects? (Offshore only)
- What is of greater concern to your business: the cost of offshore transmission or the availability of network capacity? (Offshore only)
- MVDC collector systems have been pitched for offshore projects, do you think MVDC collector systems would ever be feasible for onshore projects? (Onshore only)
- Are or would you consider alternative technologies alongside MVDC e.g. LFAC (low frequency AC) for collector arrays? (Both)

8.1.2 Equipment Suppliers

The following questions were asked of Equipment Suppliers in addition to those detailed in Section 2.5.3:

- Do you supply any MVDC technologies at present?
- What is the current market position for MVDC technologies in Scotland, the UK and globally?
- Do you think that there is the need for a demonstration facility to grow this business?
- Would you invest time and/or technology to it, assuming part of the risks/costs?
- How easy or hard (in terms of skills/capabilities) would it be for your supply chain to follow you into MVDC technology development?
- What do you see as being the most ‘important’ piece/principal facilitator of MVDC equipment that the market will demand?
- Do you have ballpark cost information that you would be prepared to share (anonymously) for MVDC technologies?

8.1.3 Turbine Manufacturers

The following questions were asked of Turbine Manufacturers in addition to those detailed in Section 2.5.3:

- Does your turbine set up allow for connection to a DC array?
- If not, what would be the challenges of enabling this and the incentives have to be?
- Would you say small or larger turbines are more likely to be transformed to a DC output?
- Which turbine output voltage would you consider necessary to make DC parks (involving MVDC collection and an HVDC link to shore) competitive against AC/DC existing solutions?

8.1.4 Distribution Network Operators

The following questions were asked of DNOs in addition to those detailed in Section 2.5.3:

- Would you consider using MVDC technology as an alternative to traditional reinforcement?
- What would you consider to be the main challenges in implementing MVDC at distribution level in this context?
- What would be required to assure you of its reliability?
- What would have to be the benefit margin or saving for it to be chosen?
- Do you think that there is the need for a demonstration facility to grow this business?
- Would you collaborate/invest time and/or technology to it assuming part of the risks/costs?

8.1.5 Academic Institutions

The following questions were asked of Academia in addition to those detailed in Section 2.5.3:

- Do you have/know of any research or projects underway on the subject of MVDC?
- What do you consider to be the key challenges in implementing MVDC?
- Do your projects make use of the existing facilities (e.g. PNDC, University of Nottingham DC lab, MTTE)?
- If so, how does this mechanism work? Do you pay for the use of it?
- Are there any identifiable gaps in the existing facilities such that there would be benefit gained from an MVDC facility?

- What sort of project set up would be preferable for testing/demonstration purposes?

8.1.6 Existing Test & Demonstration Facilities and Other Facilitators

The following questions were asked of Existing Test & Demonstration Facilities in addition to those detailed in Section 2.5.3:

- What sort of projects and research do you cater for in your facility?
- Are there any gaps in your facility that could potentially be met with an additional MVDC demonstration capability?
- How is your test/demonstration facility set up?
- What stakeholders use your facility and to what extent and benefit?
- Are there any lessons learned at this stage with respect to setting up a facility such as this?
- Would a potential MVDC facility form a cluster with existing ones (e.g. PNDC and MTTE) or would there be a greater benefit in locating it elsewhere?

How have you achieved/intend to achieve a sustainable business model?

8.2 Appendix A.2 – Stakeholder Engagement Responses

Repsol

Repsol are a global integrated energy company that undertake energy projects across a wide range of sectors (refining, LPG (liquefied petroleum gas), chemicals and 'new energy'). Their involvement in 'new energy' has led them to develop three large offshore wind farms in Scotland; Inch Cape, Moray Firth and Beatrice. They are seen as a key stakeholder in MVDC technology owing to its potential applications in offshore array collector systems.

Interestingly and encouragingly, Repsol have previously considered MVDC, as well as LFAC (low frequency alternating current) and HFAC (high frequency alternating current), for their offshore projects. The option was research at the early concept stage but it was ruled out mainly due to the technology not being well enough established, with a TRL (Technology Readiness Level) between 2 and 4 (see Section 3.4.1 for the TRL scale and definitions), and there being limited information on costs (and not enough information on technology or previous projects to even estimate). There is the general assumption that onshore applications will precede offshore applications such that reliability can be improved before it is taken offshore, where the costs of failure are much higher.

From their perspective, the main things that still have to happen for MVDC to become an effective solution are a demonstration and a comprehensive cost benefit analysis. Regulation and specifications are also challenges, as is the future proofing of power electronic equipment, which is known to have a short shelf-life, and buy-in from turbine manufacturers to offer turbines suitable for connection to a DC network.

In terms of timescales, 3 to 5 years is seen as reasonable to get a demonstration operational with a view to taking the technology offshore within 6 or 7 years.

Repsol's three offshore projects in Scotland are only roughly 20km offshore however they need to go an additional 60km south to get a connection point with enough network capacity. In the future, they expect their offshore platforms to be between 100 and 200km offshore.

RES

RES (Renewable Energy Systems) is one of the world's most prominent renewable energy companies. They provide services across the spectrum of a project, from development through engineering, construction and operation. They work on onshore and offshore projects encompassing wind, solar, wave, tidal, thermal and storage technology.

From a tidal perspective, RES believe the main challenges are technical and lie in connector technology associated with the tidal turbines, where problems (and the effort required to solve them) increase disproportionately with voltage. Additionally, most of the equipment in tidal schemes is subsea which increases the challenges and problems faced and results in higher costs of failure.

In future, a surface approach will be taken and the use of a DC collector array would remove the need for some of the power electronics which will in turn remove some of the failure cost risk. However, some problems may be encountered with DC voltage level in that, each of the turbines within an array will inherently require a different voltage level to operate optimally and avoid power back-feed into the turbines thus causing high transient loading. There is a lot of technical development to understand these problems of the turbines operating connected to a DC line, and it is felt that tidal developments already have a number of barriers to overcome without involving subsidiary technologies that are also in their infancy.

The use of MVDC as tidal collector arrays has not been ruled out however, and if the technology can be suitably de-risked and the TRL raised most likely in an onshore application) and is proven to be cost effective and bankable then RES would definitely consider it for their tidal applications as it is an attractive option. This would also be dependent on whether understanding of how to integrate DC generation with DC systems at the collector level, rather than network level (to overcome the problems outlined above), can be achieved to an acceptable degree.

RES estimate 5 to 10 years for MVDC technology to be established with feasibility of offshore applications coming in the latter few years dependent on tidal turbine technology and how it evolves.

ABB

ABB are a global company spanning five distinct business units, each dedicated to a different area of the energy industry (Power Products, Power Systems, Discrete Automation and Motion, Low Voltage Products and Process Automation). MVDC technology could be of interest to more than one of these business units.

ABB work on MVDC projects, in the context of the power system, has involved some research carried out in the area. The research revealed that the most important application for MVDC is seen as the collection of renewable generation where DC arrays will have reduced losses. Two other potential applications are seen as support for distribution networks, and also for use in microgrid systems which have a lot of renewable generation and where there would be a desire to minimise fault levels. This reflects the applications for MVDC that are being considered in this study. In the UK, back to back MVDC systems as network reinforcement solutions are considered to have potential, and ABB have already been approached by three DNOs regarding this.

There is little worry about technology being a barrier with high confidence that the technical know-how exists to implement MVDC; ABB have significant experience in supplying MVDC products to the rail industry [19] and so their AC/DC converter technology is considered to be in a mature state; they also have the HVDC Light product (mentioned previously in Section 2.3.7) which has been deployed for a number of projects and applications throughout the world (assumed TRL of 8-9 for both). The products ABB would offer in any back to back power system application would be very similar to those already developed for the rail network, where arrangements are typically run at ±6 kV.

There is much more concern over technical issues relating to regulations and specifications, and the market case for the technology. The market is the key for ABB and this is easier built upon a demonstration which showcases and de-risks the technology. Incentivising of MVDC schemes could be another way to help the market and create the necessary demand.

As stated, ABB believes that a demonstration project is necessary to accelerate the MVDC market, suggesting a demonstration in the range of 5-10 kV. This is similar to Nottingham University's set up however ABB have specified an industrial demonstration is preferable to an academic one to create a more realistic operational environment. In terms of ABB supporting an MVDC venture, they would be happy to contribute to research and investigations but providing equipment would be a business decision that would have to be made at a later stage with more information.

A timeline of 5 years has been suggested for the market to grow, with R&D and pilot schemes being set up in the meantime. From a technology development point of view, they believe the biggest demand will come from Europe, the USA and China.

DC/DC converters and DC circuit breakers are believed to be the principal technology for MVDC and this will be what the market demands first and foremost.

RXPE

RXPE have already deployed a number of MVDC projects, two of which were retrofitting existing AC links between oil platforms, and one which was a demonstration project for MVDC use to supply a central city where fault levels were a concern.

The main barriers to the technology at this stage are considered to be;

- From a technology perspective, industry acceptance in terms of specifications e.g. ENA, IEC; and
- From a market perspective, the lack of an industrial demonstration to encourage the market adoption of the technology.

An industrial demonstration is preferable, as opposed to a test centre demonstration, to showcase operation, however it is acknowledged that a test centre may be an initial step in this process. RXPE would be happy to provide MVDC technology for demonstration but only on the understanding that it was a route to actual network demonstration/operation, rather than it being confined to a test centre. This is especially true as RXPE have their own test and demonstration facilities in China which they can use, so in fact, a demonstration facility is not necessary for RXPE to test their products however there may be some cost savings to be gained from using a facility in the UK rather than transporting equipment and personnel to China.

RXPE expect that it will take 5-10 years to get a couple of projects deployed and, beyond that, progression would be dependent on the merits seen from these projects. For back to back applications for urban networks, there could be some interesting projects that come out of the LCNF (see Section 2.3.9).

RXPE, in line with ABB, are of the opinion that DC/DC converters and DC circuit breakers will be the most urgent technology for MVDC in that these will be what the market demands initially. Converting existing technology, such as cable jointing, from AC to DC will also present an interesting challenge.

GE Power Conversion

Because of the way GE Power Conversion approach demonstration projects, they would happily consider getting involved in a joint venture with SP Energy Networks if they were to find out more about the project specifics going forward. As stated, they are looking to close gaps so they are very interested in demonstrations where MVDC could provide a better solution than conventional options.

Siemens

Siemens also have an MVDC product which is used mainly by the oil and gas industry and currently implemented at 11 kV.

The main issues highlighted by Siemens were:

- MVDC is unlikely to be attractive to developers if it is seen to tie them to a single turbine supplier choice; and
- Therefore, connecting to the DC side of a turbine will require some kind of standardisation of DC voltage/DC interface across turbine suppliers.

Gamesa

Gamesa are aware of MVDC and its potential as a future connection technology for offshore wind collection systems. The main application here would be for direct MVDC connection to shore, with no offshore substation included in the topology.

From a business perspective, Gamesa is not actively pursuing MVDC technology in present turbine R&D. Both the drivers and the timescales for the adoption of MVDC as an offshore collector system technology will be largely dependent on the overall behaviour of the offshore wind market (which has not picked up as quickly as expected). Future directions for R&D will depend on the business focus of the new Areva-Gamesa Joint Venture.

Responses from Turbine Manufacturers in PNDC Stakeholder Engagement Activity

Three turbine manufacturers were contacted in the course of the PNDC investigation into MVDC technology; Alstom Wind, Andritz Hydro and Gamesa. The full transcript can be found in Section 5 of [4], however to summarise:

- Minimal activity in the area presently, and minimal activity anticipated for the next 5 years
- Between 10 and 20 years from now is when we could potentially expect to see the first commercial wind farm developments using the technology (once it has been validated)
- Testing and validation of MVDC technology is expensive and as such the market based challenges must be overcome to drive technical advancements
- DC/DC converters, bi-directional converters, DC circuit breakers, control systems, subsea connectors and MVDC cables are the agreed technologies that are relevant to MVDC viability for turbine manufacturers
- The feasibility of DC collection systems for offshore renewable in the next 10-20 years will be dependent on investments in demonstration projects, a sufficient amount of development projects and whether existing technical and economic challenges can be solved
- Opinion on the size of turbines that will be likely to be converted for DC output is divided between small (<100 kW) and large (>5 MW)
- Opinion on the preferred voltage level of the MVDC collector arrays is also varied

All three manufacturers believe that it would be somewhat difficult for their habitual supply chain to follow them into DC output turbine design and that partners would have to be chosen carefully.

SSE Power Distribution

MVDC is seen as an interesting idea for a distribution network reinforcement solution at around 10 kV DC, however the high cost of such a scheme is preventing its use presently, and it is perhaps a few years off being considered. There are two exceptions:

- An industrial area with a side DC network; and
- A renewable generation area or hub where all generation is DC.

The main barriers are the high cost of power electronic equipment, as well as the lack of control schemes for integral operations.

In order for an MVDC scheme to be considered as a distribution network reinforcement solution for SSEPD, a business case would have to be proven. If the technology is established and the overall solution is cost effective then there is no reason why it would not be chosen. In terms of the future, as and when there is more of a DC grid presence, DC circuit breakers will be an issue, and the control and protection of large grids gets complicated.

The internal engineering policy department at SSE performs type testing, and decides which technologies need type testing. Any technology utilised must meet these performance requirements.

In terms of a demonstration, SSEPD can understand the need however, if a supplier can provide evidence of appropriate tests and standards then it may be that a separate MVDC demonstration would not be required for their acceptance to use the technology.

With regards to supporting an MVDC demonstration venture, SSEPD would possibly be interested however it is not known to what extent as the specifics of the project remain unclear. SSEPD would be keen to ensure that the project focuses on both the technical and economic feasibility of MVDC solutions.

Western Power Distribution

WPD believe the use of MVDC schemes as distribution network reinforcement solutions is most applicable at 132, 66 and 33 kV (there is not sufficient cost benefit analysis evidence to use this at 11 kV or below). WPD already have high interest in the technology and they already have a project whereby a STATCOM makes up one half of a DC link. As described in Section 2.3.9 above, they have also just been awarded Ofgem funding for the Network Equilibrium project which will be looking at MVDC applications for distribution networks.

It is unlikely that MVDC will ever be cheaper than conventional solutions however it can be useful in areas where high fault level or circulating current are a problem. WPD can foresee the use of MVDC in tens of deployments (rather than hundreds).

In terms of barriers, WPD see a mix of technical and market issues, with cost and reliability being the main challenges. A major technology challenge to overcome is audible noise from all of the fans necessary at converter stations. Additionally, reliability has to be demonstrated, as does protection in a network scenario. In terms of operational barriers, the case has to be proven that this technology will not adversely affect the existing equipment on a network and it is felt that the testing of these things is worthy of a demonstration.

WPD estimate a TRL of 6 [20] at the moment for MVDC technology, with the objective to reach TRL8. There are examples of these systems working already so de-risking would perhaps not be the primary function of a test and demonstration centre, rather the configuration of these devices in the environment (distribution network) is more in need of de-risking.

From a demonstration, whether in a dedicated centre or a network project, WPD would seek the following assurances of reliability:

- Tests of equipment response to networks conditions/events e.g. lightning strikes and transients;
- Better understanding of power electronic units and how the technology is coupled and used; and
- Extrapolated learning from different sources i.e. learning from other uses of power electronic equipment in terms of its function, lifecycle and reliability.

As a timeline, WPD don't expect any deployments (for network reinforcement) before 2020, and deployments post-2020 will depend on the success of any trials carried out between now and then.

As WPD are actively trying to demonstrate MVDC technology, they would be happy to collaborate on any work that comes out of this project.

University of Aberdeen

As described in Section 2.3.2, the Power Systems Research Group at the University of Aberdeen has already undertaken a number of research projects relating to MVDC, which is considered as being DC voltages between 4 kV and 60 kV. Their work has encompassed both technical models and cost analysis.

Their work focuses on MVDC as a facilitator to HVDC grids so grid or collector system applications are seen as the most feasible. They have four current projects on HVDC and the outcomes of these could potentially be scaled down to MVDC. The key components for MVDC adoption are considered to be DC/DC converters and DC circuit breakers, both of which the research group are prototyping in their laboratory facility albeit at LV (up to 1 kV and 200 A DC).

The main barrier to DC is understood to be the market. It is necessary to provide an incentive to investors to spend their money and at the moment, the market and regulation are the biggest challenges to this.

As a timeline, it is believed that within the next 5-10 years, the first HVDC offshore grids will be in operation, implemented and proven, and MVDC will follow on from this with offshore generation developments taking advantage of the DC collection grids.

An MVDC demonstration centre is required to demonstrate hardware which will be key to MVDC, such as DC/DC converters, DC substations and DC hubs which will not be used extensively at HVDC level so there will not necessarily be scalable equivalents to provide an additional incentive for MVDC R&D.

Heriot-Watt University

Remote offshore integration of generation to the grid, i.e. platforms and near shore renewables, is believed to be the main application of MVDC technology, within a preferred voltage range of 5 kV and 50 kV.

The criticality of offshore operation (in terms of time and cost) requires technology to be reliable. Better in-situ monitoring and informed intelligent asset management capability is needed to de-risk investment [21]. These, in addition to power electronic equipment's susceptibility to failure, are seen as the main barriers to MVDC adoption.

Requirements for any demonstration facility include the capability for electrical dynamic testing alongside environmental/physical testing and smart monitoring.

University of Strathclyde

The two principal applications for MVDC technology are understood to be offshore collector systems and network reinforcement. For the network reinforcement application, there are two potential options:

- Use of point to point MVDC to bypass congestion points on the main AC grid; and
- Use of back to back MVDC to control power flows and regulate fault levels.

The voltage level can be variable and will depend on the application. For offshore collector systems, the voltage would be between 20 kV and 50 kV to obtain conduction efficiency. In order to address any issues of HV electronics, the voltage would have to be greater than 10 kV.

The Power Electronics, Drives and Energy Conversion research group at the University of Strathclyde are active in HVDC research, and studies have been carried out previously which show MVDC can be useful but it has not received the same market interest as HVDC. At 6 kV and below, MVDC can use high capacity drives such as those used on oil platforms. At higher voltages the technology is similar to HVDC technology so some components could be scaled down if the desired size reduction could also be achieved.

Multi-terminal MVDC is an area that requires more work and development. Additionally, the control of these complicated systems in terms of the number of nodes and converters is also a challenge that must be addressed. Other technical issues include the choice of operating voltage, the efficiency of any step up/down transformation and the protection of DC networks. From a market perspective, the main challenge is getting power electronics at an acceptable cost, footprint and efficiency. It must be demonstrated that using DC is justifiable in terms of cost.

Until there is a track record for demonstration of product operation, reliability etc., there will be reluctance to adopt the technology. There needs to be a realistic demonstration or some form of demonstration centre (such as is being proposed here). There is an identifiable gap of a technology demonstration that is realistic, so a hardware combined with real-time simulation could provide the means to fabricate real time conditions which could bridge the gap between factory testing carried out by manufacturers and network operation conditions. A reasonably quick timeline is anticipated for the adoption of MVDC, with meaningful results being achieved roughly 3-4 years from any demonstration of this nature.

The ability of any MVDC facility to cluster with existing facilities such as PNDC and/or MTTE would depend on the level of overlap between ambitions. There could perhaps be the opportunity to twin demonstrations with R&D programs.

University of Nottingham

The MVDC laboratory at the University of Nottingham was described in Section 2.3.3. As described, the facility is a 3.3 kV AC/5 kV DC/3 MW grid which has a flexible topology inclusive of six converters, three of which are programmable. Real-time simulation is achieved using Opal-RT processors and allows for hardware-in-the-loop functionality.

The lab is funded primarily by the EPSRC with additional funding provided by the university itself. The facility is intended purely as a research environment where individuals and companies can perform tests and demonstrations. As a result, there is no business model at this stage.

RWTH Aachen University/ FEN-Consortium

The MVDC laboratory at the RWTH Aachen University was described in Section 2.3.4. As described, the facility is an MVDC research grid intended to connect up to power existing DC nodes (test benches) in a campus DC grid. The final specifications of the research grid have not yet been finalised, however a minimum voltage of 5 kV DC is being considered. The topology of the MVDC grid will be flexible such that different configurations can be studied in terms of equipment set up as well as protection and control philosophies.

The RWTH Aachen University started the FEN-Consortium (Flexible Electrical Networks) in October of 2014 along with 12 industry partners forming a consortium encompassing utilities and manufacturers. The work they will do will span low, medium and high voltage DC technology but the main focus will be MVDC. The consortium has a Steering Committee and a Scientific Advisory Board who make decisions about new research projects, patents and new memberships. The industry partners also vote to decide which research is taken forward. Members of the consortium can attend meetings and network, they can also make use of the facility e.g. manufacturers can test their equipment. Aside from partners and members, it is not yet defined who can use the facility and how the service should be charged.

In terms of funding, the German government supports this work through the Federal Ministry of Research as they are keen to accelerate innovation, and they provide €2m annually to the facility. This funding is secured for 5 years with a potential additional 5 years following this (and again) so they have a sustainable business model in the short term. The consortium is also applying for EU funding on top of this.

The FEN-Consortium believes it is a good idea to cluster. They have good links with the Top and Tail project in the UK which is looking at LVDC and HVDC and this is useful to keep track of what is happening in related projects.

Multi-Terminal Test Environment

The Multi-Terminal Test Environment is described in Section 2.3.5. As described, the Centre will be used to perform real-time simulations on HVDC projects, to support the planning, development, commissioning and operation of HVDC systems in Great Britain.

The site for the facility has been identified and the construction design is being finalised, with the Centre planning to open in 2017. Following on from this, the facility is funded through Ofgem's NIC until 2021 for use by Transmission Licensees. Restricted access may also be granted to academic partners in this period. Post-2021, a business model is required to dictate how the continuation of the facility will be achieved. The MTTE project team will develop a number of potential business plans some of which may include the options to be funded through RIIO-T2 or become a commercial facility.

There are potential synergies between MTTE and any MVDC demonstration that may be set up, provided the MVDC demonstration accommodates MVDC hardware based. More formalised plans would have to be offered to MTTE for it to take a MVDC collaboration into consideration, as would interest in MVDC from the TO stakeholders, SPT and NGET. Clustering of expertise would also be a good idea, where co-location would enable sharing of capabilities and resources which would be mutually beneficial.