Programme Area: Energy Storage and Distribution

Project: Offshore Connection 1

Title: Executive Summary

Abstract:

Large-scale offshore renewable energy farms, including wind, tidal stream and wave energy systems, are likely to play an increasingly significant role in enabling the UK to meet its long-term CO2 emissions reductions targets. However, the development and installation of large renewable energy farms off the coast of the UK provides a number of challenges in terms of: - the collection of electrical energy offshore from multiple renewable energy farms, - the transportation of electrical energy generated by these offshore farms to the UK shoreline, - the connection and integration into the onshore power system. This project, led by consultants Sinclair Knight Merz, has assessed new technology solutions to these issues, quantified their benefits, and provided guidance in respect of technology development opportunities. It has delivered: - a clear understanding of the key issues concerning the connection of multiple renewable energy farms off the UK coast - assessments of the likely technical limits concerning the integration of offshore renewable energy systems into the UK power system - recommendations for new, optimised solutions for the grid connection of multiple offshore renewable energy farms, including the provision of design concepts for offshore HVDC electrical systems - identification of technology development opportunities for the industry.

Context:

This project examined the specific challenges and opportunities arising from the connection of offshore energy to the UK grid system and considered the impact of large-scale offshore development. It also looked into the novel electrical system designs and control strategies that could be developed to collect, manage and transmit energy back to shore and identified and assessed innovative technology solutions to these issues and quantified their benefits. The research was delivered by Sinclair Knight Merz, a leading projects firm with global capability in strategic consulting, engineering and project delivery. The project was completed in 2010.

ETI Executive Summary

Programme: Energy Storage and Distribution

Project : Connection and Integration of Offshore Renewable Energy Farms into UK Power Systems

Introduction

Large-scale offshore renewable energy farms, including wind, tidal stream and wave energy systems, are likely to play an increasingly significant role in enabling the UK to meet its long-term CO_2 emissions reductions targets. However, the development and installation of large renewable energy farms off the coast of the UK provides a number of challenges in terms of:

- the collection of electrical energy offshore from individual and multiple renewable energy farms
- the transportation of bulk electrical energy generated by these offshore farms to the UK shoreline
- the connection and integration of these offshore farms into the onshore power system.

This project, led by consultants Sinclair Knight Merz (SKM), has assessed new technology solutions to these issues, quantified their benefits, and provided guidance in respect of technology development opportunities. It has delivered:

- a clear understanding of the key issues concerning the connection of individual and multiple renewable energy farms off the UK coast
- assessments of the likely technical limits concerning the integration of offshore renewable energy systems into the UK power system
- recommendations for new, optimised solutions for the grid connection of individual and multiple offshore renewable energy farms, including the provision of design concepts for offshore HVDC electrical systems
- identification of technology development opportunities for the industry, and specifically the ETI, and the preliminary identification of potential ETI development and demonstration activities in respect of the grid integration of offshore renewable energy farms.

Project Scope

The four main tasks of the project were as follows:

1. **Offshore Renewables Scenarios:** To define the expected volumes and characteristics of offshore renewable generation, and derive a number of specific scenarios ('Development Cases') for analysis in subsequent tasks.
2. **State of the Art of Offshore Network Technologies:** To establish the current state of the art and prospective development paths of technologies relevant to offshore networks.
3. **Connection of Individual Energy Farms:** To evaluate technologies and electrical connection architectures, to determine the optimum architectures for connection of individual farms, and to identify related technology development opportunities.
4. **Connection of Multiple Energy Farms:** To evaluate technologies and electrical connection architectures, to determine the optimum architectures for interconnection of multiple farms, and to identify related technology development opportunities.

Results Summary

Selected key results are as follows:

- As a result of the work carried out during this project, the ETI now has a reference work describing the state of the art and likely development of technologies and architectures for offshore networks over the next 15 years and beyond.
- Along with High Voltage Direct Current (HVDC) systems, submarine cables and equipment marinisation have been identified as key areas for technology development to improve reliability.
- Interoperability and control issues were not judged to be significant (contrary to some initial expectations) since the requirements can be satisfied by routine project-specific tuning of energy farm control system designs, apart from two issues concerning the application of multi-terminal HVDC systems:
  - the need to standardise on voltage levels such that timely progress could be made in the development of the DC circuit breakers
  - the need to agree standards for exchange of control information between suppliers of different HVDC systems when operating multi-terminal HVDC systems
- The lack of any UK submarine cable manufacturing capability, together with the heavy booking of the European capability, is a serious supply chain constraint. This may lead to novel, more technically-superior designs being put aside in favour of standard designs that can be produced quickly.
- All of the optimised architectures which have been studied in detail comply with the requirements of the Grid Code in respect of those areas considered, i.e. Fault Ride Through and Harmonic Distortion. Therefore no modifications to the Grid Code in these respects seem necessary.
- Large scale offshore storage could drastically improve utilisation of electrical connections, but significant development of storage technologies would be required for them to be cost effective.

- The connection of generation farms to national or international interconnectors provides availability and potentially diversity benefits for relatively minor capex increases.

A summary of the detailed technical results is attached as Appendix 1.

The technology opportunities identified by SKM are tabulated in Appendix 2.

Key Findings

The project results will be studied carefully by the ETI and ESD SAG to determine whether any of the opportunities identified (or other related opportunities) should be pursued by the ETI.

Many of the recommendations will be discussed with the Carbon Trust who are assessing intra-array systems as well as turbine technologies, and this may result in work being incorporated into current or future projects.

In addition, many of the recommendations are likely to be taken up by the Original Equipment Manufacturers once the preconditions (such as industry voltage standardisation) have been resolved.

Appendix 1: Summary of Detailed Technical Results

1. Definition of Generation Scenarios

Representative scenarios for the type, quantities, locations and characteristics of offshore generation were defined. These were summarised into seven specific development cases, as follows, the key data for each being tabulated below:

- Distributed Smaller Windfarms
- Large Windfarms
- Very Large Windfarms
- Small Marine Case
- Medium Wave Case
- Large Tidal Case
- Combined Tidal and Wind Case

	Technology	Offshore Distance (Km)	Onshore Distance (km)	Energy Park Capacity (MW)	Distance Between Farms (km)	Onshore Network Strength	Water Depth (m)	Turbine Rated Output (MW)
Case 1	Wind	30-100	30-80	500	50-100	Weak	25-50	3.6
Case 2	Wind	>100	30-80	2000	50-100	Strong	25-50	5
Case 3	Wind	>100	>80	5000	>100	Strong	25-50	7.5
Case 4	Tidal/Wave	<30	<30	20	10-50	Weak	<40	0.5-1
Case 5	Wave	30-100	<30	200	10-50	Strong	>40	1
Case 6	Tidal	30-100	30-100	500	10-50	Strong	>40	1
Case 7	Tidal	30-100	30-80	500	10-50	Weak	>40	1
	Wind	30-100	30-80	500	10-50	Weak	>40	3.6

2. Review of State of the Art of Offshore Network Technology

2.1 Technology Review

The purpose of the State of the Art Technology review was to establish the current state of the art of offshore network technology and prospective development paths as indicated by manufacturers. Specific equipment types were selected on the basis that these would define the network technologies that required further investigation.

Definition of the current state of offshore network technologies was relatively straightforward and could be established as envisaged by interviews and discussions with the current suppliers of such technologies. What also became quickly apparent was that even for current technologies there exist alternatives which are already proven in non offshore applications, which could potentially deliver benefits in offshore applications. However, the drivers for offshore technology are not always clear and general uncertainty in the industry means that the adoption of these alternative technologies is also uncertain.

An example of this uncertainty is with power transformers where current state of the art is to use conventional mineral oil insulated technology which has been well proven in onshore applications. There are already alternative technologies which have been applied onshore which could bring benefits in offshore applications, e.g. synthetic ester insulating fluids or even SF_6 insulated transformers. The uncertainty as to whether such technologies are applied is not due to technical uncertainty but with the fundamental drivers for the offshore industry and in this case the relative importance of environmental assessments.

Hence, in describing the current state of the art there is an element which also describes technologies which could be applied if the fundamental drivers for offshore technology demand certain characteristics.

The environmental challenge posed by the use of SF_6 onshore and offshore of course provide a substantial prize for an alternative environmentally friendly technology, which may become more relevant if Gas Insulated Transformers (GIT) and Gas Insulated Lines (GIL) were to be considered for offshore applications. However, due to the uncertainty of whether widespread application of SF_6 offshore will be needed and the difficulty in identifying an alternative gas, no specific alternative insulating gas projects are recommended at this time.

The task of identifying prospective technology development paths is more difficult as most individuals have some degree of vested interest. A number of measures were therefore taken, including the use of several views independent of the competing technologies.

Whilst it is concluded overall that the requirements for offshore networks are not driving fundamental technology development, with the possible exception of submarine cables, it is clear that technological developments can be adapted and optimised for offshore applications and it is this area which was the primary focus of analysis. Inevitably, it is in these areas of adaption and application that the most significant opportunities arise for support of individual technologies.

In addition, there is a complex interaction of technologies and system architectures.

2.2 General Technology Focus Areas

During Stage 1 of the Manufacturers Interviews process it quickly became apparent that there were two main areas of focus for offshore network technologies, these being Submarine cable systems and HVDC technologies.

- Submarine cable systems are critical to the development of networks because they contribute such a significant element in terms of project cost, risk and technology developments and also impact on the optimisation of system architectures.
- HVDC systems utilising technology which currently exists are able to be applied to support the development of offshore renewables for projects which are growing in size, complexity and connection distance.

Hence, a significant part of the focus of the State of the Art review was in these two areas of technology, together with the general area of equipment marinisation.

Most of the equipment currently being deployed for offshore networks applications is basically onshore equipment that has been adapted for offshore applications. There are of course examples where equipment exists for specific offshore applications such as submarine transformers, but these are the exception rather than the general case.

All suppliers recognise the need to adapt standard equipment for harsh marine environments but it also has to be recognised that experience with some equipment is very limited and it is not yet known whether general experience will be good or bad. Reliability and maintenance assumptions made are generally based on onshore data and the relevance of this data to offshore applications should be treated with some caution. In terms of potential risk to the rapid implementation of offshore renewables the issue of marinisation of equipment remains a very significant factor. Whilst considerable experience has been acquired in the Oil and Gas industries, the equipment now being deployed contains new elements (e.g. large power transformers, EHV switchgear, HVDC equipment) where experience is limited and an opportunity exists to mitigate some of these risks by undertaking appropriate studies / testing now rather than after a potentially negative incident or experience occurs.

2.3 Interoperability and Control Issues

Interoperability and control issues, and barriers to integration of technologies from different suppliers, were not seen as significant based on the input from those consulted, apart from the issues that were raised by several individuals concerning the application of multi-terminal HVDC systems. Here two specific areas were raised.

- Firstly, the need to standardise on voltage levels such that timely progress could be made in the development of the DC circuit breakers required for multi-terminal DC solutions.
- Secondly, the need to agree standards for exchange of control information between suppliers of different HVDC systems when operating multi-terminal HVDC systems.

In both areas, investment and thinking at an early stage was seen as being beneficial to the overall deployment of HVDC technologies in a potential HVDC offshore grid.

2.4 Supply Issues

Major bottlenecks in the supply chain over the next 30 years are well documented in the report ‘Quantification of Constraints on the Growth of UK Renewable Generating Capacity’ carried out by SKM on behalf of BERR. Excluding those linked to wind turbines, the major constraint identified was that of subsea cables, where there is no UK subsea cable manufacturing capability. There are three European suppliers – ABB, Nexans and Prysmian – who are fully booked for the next 5 years. Further, manufacturing time from order is around a year for HVAC cabling and over 2 years for HVDC mass impregnated cabling.

In order to justify manufacturers ramping up production to meet demand, a substantial amount of orders will need to be placed and novel designs may be put aside in favour of standard designs that can be produced quickly.

3 Connection of Individual Energy Farms

3.1 Main Conclusions from Development Cases Studied

Architectures were studied for each generation scenario (or 'case') identified in Section 1 of this Appendix. Optimum architectures and parameters were identified for each, and these are summarised in the table below.

In practice it is very unlikely that a 5000MW or even 2000MW wind farm would be constructed as a single design and would more likely be made up of modules of smaller developments of up to 1000MW each. The reasons for this would be to increase reliability, comply with grid code stipulations on maximum in-feed losses, and other technical considerations such as the maximum capacity of the export cabling, and design and economic considerations related to the funding of such large single developments.

Factor	**Case 1** **Now**	**Case 2** **Now**	**Case 3** **Near Future**	**Case 4** **Possible Future**	**Case 5** **Possible Future**
Farm Size	500MW	500MW	1000MW	1000MW	Up to 4000MW Single Connection
Array Voltage	33kV AC	33kV AC	Project Specific AC	DC	Project Specific AC
Export Distance	Up to 150km	>150km	All	All	All
Export Voltage	220kV	±150kV	±300kV	Up to ±300kV	Up to 550kV
Export Technologies	AC Cable	DC VSC Cable	DC VSC	DC Series Cable	AC GIL

3.1.1 132kV AC Export with 33kV Intra-array Arrangement

This is the current state of the art and is considered as the base case. Compliance with Grid Code requirements was confirmed.

3.1.2 132kV AC Export with Optimisation of AC Intra-array Voltage

For 500MW farms the optimal intra-array voltage is 33kV, irrespective of generator size. This conclusion applies to Development Cases 1, 6 and 7.

For larger farms of 2000 or 5000MW then the individual block size will likely increase to 1000MW. At these sizes the selection of optimal intra-array voltage is marginal, with lower platform and equipment costs being balanced by increased turbine switchgear costs. This sensitivity to turbine switchgear costs means that the optimal voltage will depend on project specific layouts of the generators and platform locations.

3.1.3 Assessment of 220kV, 400kV & GIL AC Export

Assuming the availability of suitable 220kV AC XLPE cables, it was concluded that for the base case of 500MW with offshore connection distances of up to 100kM, then 220kV is a preferred export voltage in comparison with the base case (present industry assumption) of 132kV export.

GIL is technically a very attractive proposition for larger power transfers and compared with HVDC does not require an expensive converter platform. However, with anticipated very high GIL installation costs it is also clear that potentially GIL would only be of benefit with a requirement for very large single circuit connections (up to 5000MW) with relatively small amounts of reactive compensation. Such connections would require significant changes to the present limits in the grid code for single circuit loss which are applied to offshore connections.

3.1.4 Impact of HVDC Export

Utilising 132kV AC export for 1000MW, it has been confirmed that the break point at which High Voltage Direct Current (HVDC) Voltage Source Converter (VSC) technology currently becomes the preferred choice is ≥ 70km.

By applying 220kV export for 1000MW, the 70km break point could be extended to around ≥100km.

3.1.5 HVDC Export with Intra-array Frequency Optimisation

A range of frequencies were evaluated, taking advantage of the isolation provided by an HVDC export link between the offshore collector system and the onshore grid. Losses and impacts on equipment design and cost were evaluated, (although the assumptions made on equipment costs should be further validated with manufacturers).

At 100Hz the initial analysis suggests that there could be economic advantages with such an approach.

At frequencies above 100Hz the losses become excessive and demonstrate that the combination of converter, skin effect and reactive power flow losses make such a system unattractive.

3.1.6 Medium Voltage DC Collection to a High Voltage Converter for Export

The use of intra-array DC collection, with turbine strings connected in parallel, has very little if any technical advantage over a common AC design and the costs required to design new converters for this are prohibitive to this architecture being economically feasible.

3.1.7 Novel DC Design to Eliminate Requirement for Offshore Platform

In contrast to the parallel DC connection above, the use of a series-connected intra-array DC design could yield significant economic savings in platforms (which can be eliminated since the conversion is no longer required) and in HVAC & HVDC export equipment. However, the additional costs for DC switchgear and insulation requirements are not trivial and some significant cost assumptions have been made. Nevertheless it would appear that the elegant solution of the series architecture could provide some economic advantages compared to current HVDC Voltage Source Converter (VSC) systems.

3.1.8 Control System Implications

The main implications regarding control systems concern the interconnected HVDC systems. A generator or transmission facility controlled by fast responding power electronics can by itself be designed to operate with a stable response to power order changes and disturbances. When a second and different controller or transmission facility is located electrically close to the first, degraded overall system stability may result, notwithstanding that each facility on its own may be quite stable.

In terms of the individual connections architectures, the main interactions that need further review are those associated with the series DC intra-array architecture that has been identified. One challenge will be how to maintain a constant voltage across each string of generators given different outputs from each machine. The output voltage across each wind turbine depends on the ratio between the output power from each wind turbine, and the mean power production of the wind turbines in the string. Effectively this means that wind turbines that have an output power higher than the mean power in the stack, will have a higher output voltage and vice-versa.

Furthermore the rated output voltage of the wind turbine, i.e. the highest voltage the wind turbine generator is designed to operate with continuously, is of course limited. Therefore the power production would have to be reduced in order to limit the output voltage to the rated voltage. Due to this fact, the output power of the wind turbines in one stack will be limited by the wind turbine with the lowest production.

This would be especially severe if the production in one wind turbine goes down to zero, because then the production in the whole stack could be lost unless the remaining machines can withstand the voltage across the active machines. Practically, some voltage overrating must be done, in order to limit the energy production loss in the wind farm due to the uneven power production that naturally occurs.

In conclusion it would appear that not only would a DC collection system provide challenges for DC equipment and insulation technology but the control systems necessary would require significant development.

3.1.9 Grid Code and Security & Quality of Supply Standard (SQSS) Considerations

Studies have been undertaken to assess the impact of different connection architectures on Grid Code and SQSS issues. (The studies do not assess the issues of frequency and voltage control faced by generators which are beyond the scope of this connection architectures study).

All of the optimised architectures which have been studied in detail comply with the requirements of the Grid Code in respect of those areas considered, i.e. Fault Ride Through and Harmonic Distortion. Therefore no modifications to the Grid Code in these respects seem necessary.

The analysis considered the existing requirements within the National Electricity Transmission System Security and Quality of Supply Standard (NETS SQSS). This details the planning and operational design criteria applicable to both the onshore and offshore electricity transmission systems, including connections for offshore energy farms.

The SQSS details how for offshore energy farms:

- With HVDC connections, the allowable infeed loss risk is currently 1000MW (normal infeed loss risk) due to faults or outages of the HVDC converter, and 1320MW (infrequent infeed loss risk) due to faults or outages of HVDC cable transmission circuit.
- With AC connections, the allowable infeed loss risk due to a transformer fault or outage is currently 50% of the offshore grid entry capacity up to a maximum of the normal infeed loss risk (1000MW), and 1320MW (infrequent infeed loss risk) due to faults or outages of the HVAC cable transmission circuit.

In practice the first point will have the impact of limiting a single HVDC development (module) to 1000MW in size, irrespective of the fact that the HVDC cable transmission circuit could have a higher rating, unless two 660MW converters were used together. However, the use of two individual converters for each side of the HVDC cable circuit would add significantly to the cost of the scheme and hence it is not likely to be considered attractive. At present this is not likely to be a significant issue as the maximum theoretical HVDC (VSC) converter size is not significantly greater, at 1100MW. However, it is expected that VSC offshore converters will be available with maximum ratings up to and beyond 1320MW within the next ten years. Clearly to take advantage of these potential technology gains and improvements in HVDC converter ratings it will first be necessary to raise the loss risk associated with faults or outages of HVDC converters to a higher value if single developments greater than 1000MW are to be realised.

GB SQSS Review Request GSR007 – Review of Infeed Loss Limits (02/2009) details how a potential modification of the SQSS limits is to increase the normal infeed loss risk value to 1320MW and simultaneously increase the infrequent infeed loss risk value to 1800MW, this latter value being necessary to accommodate potential future new nuclear reactors with single shaft generators. However, even if this change is enacted it will still restrict the maximum size of a single HVDC converter to 1320MW, potentially much less than the technology would be capable of delivering. If this is the case, the only remaining option to allow larger single HVDC connections (with single converters on each side) would be to reclassify the infeed loss risk of HVDC converters due to a fault or outage as an infrequent infeed loss and consequently the proposed 1800MW rating would apply. For this change to be considered there would need to be sufficient evidence to support the claim that a fault outage of an offshore HVDC converter can be considered as “infrequent” and at the present time there is little if any operational data to support this assertion. It should also be noted that the maximum infeed loss risk for a single AC offshore transformer is also currently a maximum of 1000MW, and a transformer is likely to be more reliable offshore than an HVDC converter.

For AC connections the current SQSS rules have little impact, except to effectively rule out GIL connections which have been shown to not be cost effective until individual connections of around 2000MW or more are considered, far in excess of the present and even the future proposed SQSS rules. Currently, 400kV cable technology cannot support a circuit rating much beyond 700MW (assuming in any case that installation issues can be overcome) and consequently there is sufficient scope for further advances in 400kV cable ratings (or higher voltages) before the present SQSS limitations would be reached, and significant technological advancement will be necessary to come close to the possible future 1800MW infrequent infeed loss risk value proposed.

Longer term, increases in infrequent infeed loss limits might become possible with onshore network developments and possible increased levels of interconnection.

3.1.10 Offshore Storage

Further consideration of the impact of offshore storage on connection architectures would be justified, if it can be envisaged that large scale storage technologies could be cost effectively applied in an offshore environment.

4 Connection of Multiple Energy Farms

4.1 Assessment Summary

Based on the generation case studies originally identified in the Request for Proposals, four Study Groups were identified to facilitate consideration of multiple farm connections, each group encompassing a number of potential architectures:

- Study Group 1: 8.5GW of offshore wind farm at Dogger Bank
- Study Group 2: 3.5GW of offshore wind farm at Hornsea
- Study Group 3: 5GW of offshore wind farm in the Irish Sea
- Study Group 4: 500MW of tidal stream farm in the Irish Sea, plus 1GW of wave farm and a further 1GW of tidal stream and wave farm in the Pentland Firth

4.2 Study Groups 1 and 2

The designs investigated in Study Groups 1 and 2 indicate that where a single HVDC connection is possible it is the most financially attractive due to the significant capital cost saving over the installation of a second HVDC link. Switched DC arrangements show potential for savings, although this would hinge on the energy markets and development of VSC converters.

It is expected that a single HVDC connection is unlikely to increase beyond 2000MW due to both technical and SQSS limitations. However, interconnecting HVDC offshore nodes at either HVDC or AC provides revenue savings which outweigh the additional capital expenditure. The saving offered by interconnections increases with distance from shore. However, even at 90km (the minimum distance at which HVDC is likely to be financially attractive), interconnection can provide significant savings. The capacity of the interconnection only needs to be a proportion of the total installed capacity; around 20% has been shown to provide optimum results, although this will be dependent on the specific design of the interconnection, output characteristic of the development, and the capacity of the shore connection. AC interconnections provide the optimum saving due to significantly greater increase in availability compared to HVDC as the HVDC converters themselves have a significant unavailability.

4.3 Study Group 3

For high capacity AC connections such as those investigated in Study Group 3 there are inherently a high number of connection circuits providing a high availability. Interconnection or multi-terminal designs are therefore unattractive.

Further, an assessment comparing the potential capex saving from reducing the export capacity (to approximately 75%) with the resultant lost export revenue demonstrated that a reduction of export capacity significant enough to impact on capex is likely to result in an increase in lost revenue which outweighs the capex advantage, making this option unattractive.

4.4 Study Group 4

The application of multi-terminal architecture to marine developments as investigated in Study Group 4 will be dependent on specific details on a case by case basis. By its nature tidal generation is close to shore where it has been shown that multi-terminal is less attractive due to the short connection distance. Wave generation further from shore has been shown to be more attractive for multi-terminal application. There was a marked difference between small capacity developments close to shore and larger capacity developments further from shore. Close to shore multi-terminal is not financially attractive due to the very short connection distance; however, further from shore multi-terminal is clearly the preferred option due to significant capex savings. The revenue is not significant to the result in either option so the type of generation is not significant. An opportunity for further study may be to establish the “tipping point” distance between point to point and multi-terminal for such developments with project specific details at a later stage when such project details become available.

4.5 Gas Insulated Line (GIL)

GIL has been shown potentially to have a very low availability (approx. 93%) which would make it an unacceptable design option due to the high loss of revenue from a multi-GW export connection. Further, the very high capacity of the connection would cause significant impact to the onshore grid, and it may be necessary to split the connection onshore to spread the impact over a larger area at increased cost.

This issue is not expected to arise with AC or HVDC as the individual connections are of manageable capacities. HVDC is expected to have the least impact on the onshore grid given the potential for deep connections. However, AC connections may require network reinforcements close to shore.

4.6 National / International Interconnectors

Combined national or international interconnectors with offshore farm connections have been shown to be potentially attractive to both offshore developers and transmission grid operators, with a significant increase in availability resulting from a relatively small increase in capex, as well as the possibility to exploit increased diversity of generation (e.g. wind).

As previously identified for HVDC multi-terminal systems, HVDC switchgear and control solutions would be required for such national and international interconnector arrangements. Whilst the specific switchgear and circuit breaker devices are not presently available they could be developed within the next few years.

4.7 Offshore Transmission Operator (OFTO)

Penalties incurred as part of the OFTO regime are expected to be only a fraction of the cost related to lost energy and as such are not expected to be a leading factor considered in export architecture design.

Appendix 2: Technology Opportunities

Over the course of the project, SKM identified 19 areas in which they saw opportunities for the ETI or other organisations to address challenges, barriers and uncertainties, and to accelerate the development and deployment of optimised solutions for offshore networks.

From the outset, SKM were briefed not to filter this list by their own perceptions of ETI additionality (which were unlikely to be sufficiently accurate), but rather to list all such areas so that a more complete analysis and recommendations could be presented to other organisations which might be better placed to address many areas. In this way, the industry would gain the maximum learning, and the ETI could filter the opportunities itself.

It should therefore be no surprise that the majority of areas identified by SKM may be best addressed by organisations other than the ETI, and this is entirely consistent with the project objectives.

The full list of opportunity areas is tabulated overleaf (in the order in which they arose). These require proper consideration to determine which may be suitable for the ETI, and indeed whether there are opportunities which SKM have not identified.

Technology Area	Potential Benefit of Technology	Development Need	Potential ETI Input
HVDC circuit breakers and switchgear	DC circuit breakers and switchgear required for multi-terminal DC systems	DC circuit breaker and switchgear devices	Specific projects to support development of DC circuit breakers and switchgear
HVDC voltage standardisation	DC circuit breakers and other switchgear items required for multi-terminal DC systems. Voltage standardisation would allow more rapid development of these devices	International cooperation between HVDC suppliers. Ensure clarity of offshore renewable requirements	1 - Promote international bodies such as CIGRE to initiate such work 2 - Fund studies to ensure that the needs of offshore renewable are clearly identified and can be fed into the standards process
HVDC multi-terminal control standardisation	To allow interoperability between different suppliers HVDC systems in multi-terminal configurations without IPR concerns	International standard activity to develop requirements	Promote international bodies to initiate such work
HVAC collector voltage optimisation studies	In the short term benefits in terms of system efficiency and cost optimisation likely if collector voltages are optimised	Fundamental studies to investigate benefits of voltage optimisation and select optimised voltages	Task 7.2 optimal design of electrical infrastructure addresses this point
Offshore cable reliability and repair improvements	Reduce the significant costs involved in repair / loss of offshore cabling	1 - Opportunity to use fibre optics to measure / monitor mechanical strain during cable laying and when in service 2 – Cable system physical protection systems 3 – Development of techniques to assess condition of extruded cable cores during manufacture and in service	Identify whether there are cost effective mechanisms to support these developments or whether to leave to market forces
Pilot projects to connect small generation sized units using direct DC connections	DC collection and DC export schemes potentially offer benefits of simpler overall architectures and reduced losses	Project to highlight what can be achieved and to ensure that all issues are understood and have been addressed	Support to identify, scope and deliver a suitable project
Alternative technologies for production of higher voltage power electronic devices	System losses and converter footprints / weights can be reduced through use of alternative power electronic based materials technologies	Integration of new devices into offshore applications	Identify whether there are cost effective mechanisms to support the deployment of new devices or whether to leave to market forces
Alternatives to replace HVAC export cables	May provide the ability to utilise AC export systems for large offshore projects and potential offshore grid	Application development of specific technologies, particularly Gas Insulated Line (GIL) and superconducting cables	1 – Participation / support of existing projects 2 - Set up new specific projects

Technology Area	Potential Benefit of Technology	Development Need	Potential ETI Input
Equipment marinisation	Ensure that operation and reliability of offshore connections are not compromised through equipment marinisation issues	Up-front studies and environmental tests on current marinisation methods to determine accelerated long term performance	Support for a specific project with objective focused on offshore connection equipment and system
Platform design	Reduced costs for offshore collector and converter platforms	Up front design work to further implement standardisation and modularisation concepts	Support specific projects including standardisation of fire protection
Condition Monitoring	Optimise connection availability	More widespread application of condition monitoring systems	Promotion of benefits of application of condition monitoring philosophy
Series DC intra-array systems	DC/DC system eliminating offshore converter platform	High Voltage insulation connections on turbine strings Control systems	More detailed feasibility studies to investigate challenges and potential benefits
Alternative frequency systems for intra-array systems	Reduced overall system costs and reduced losses	Equipment design and system implications	More detailed feasibility studies and verification of concepts
Offshore storage	Improved utilisation of electrical connections	Establish potential benefits linked to likely storage developments	Detailed study to optimise connection ratings and architectures based on storage technology data and actual farm outputs
Intra-array AC equipment	Reduced costs to facilitate use of higher collector voltages	Equipment specifications and designs to meet application need	System studies to establish new specifications that could enable lower equipment costs compared to conventional equipment
Offshore equipment reliability	Improvement in availability figures	Establishing and improvement of equipment availability figures	Initiate studies to establish reliability figures as experience is built up and identify improvement areas
Offshore connection availability	Improvement in availability figures	Improve offshore repair and maintenance procedures and access to equipment	Study proposed repair and maintenance procedures, including offshore access issues, and optimise
Single loss of infeed limits	To allow increased capacity single connections and promote multi-terminal approach	Studies to determine options to enable increase of SQSS limits and potential implications	Sponsor studies
Interconnectors	Can realise financial and other benefits for stakeholders	Detailed studies of particular interconnectors in conjunction with specific generation developments, potentially at both ends of interconnector	Discuss within SAG to assess whether project could be viable and with real information

Technology Area	Potential Benefit of Technology	Development Need	Potential ETI Input
VSC multi-terminal control	To facilitate potential VSC multi-terminal applications	Establish whether VSC multi-terminal control is a potential technology implementation constraint	Verify findings of this study that VSC control will NOT constrain implementation of technology