Programme Area: Energy Storage and Distribution

Project: Network Capacity

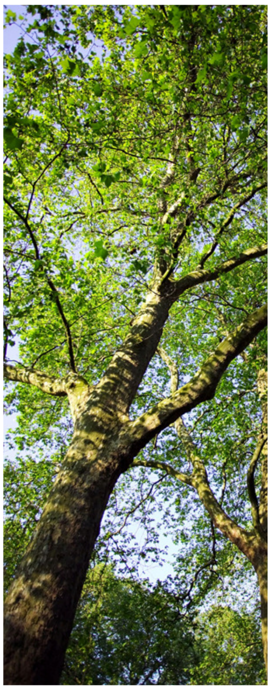
Title: Technology Options, Benefits & Barriers Workshop and Multi-Criteria Assessment

Abstract:

This report addresses the full range of technologies considered during the project, including both FACTS and HVDC technologies.

Context:

The Network Capacity research project identified and assessed new technology solutions that could enhance transmission and distribution capacity in the UK. It assessed the feasibility and quantified the benefits of using innovative approaches and novel technologies to provide improved management of power flows and increased capacity, enabling the deployment of low carbon energy sources in the UK. The project was undertaken by the management, engineering and development consultancy Mott MacDonald and completed in 2010.



The ETI Energy Storage and Distribution Programme - Network Capacity Project

Work Package 1 Task 6&7 Final Report
Technology Options, Benefits and Barriers Workshop, Multicriteria Assessment of Technologies

December 2010
The Energy Technologies Institute (ETI)

Mott MacDonald

The ETI Energy Storage and Distribution Programme

Work Package 1 Task 6&7 Final Report
Technology Options, Benefits and Barriers Workshop, Multicriteria Assessment of Technologies

December 2010

The Energy Technologies Institute (ETI)

Holywell Building, Holywell Park, Loughborough, LE11 3UZ

Mott MacDonald, 1 Atlantic Quay, Broomielaw, Glasgow G2 8JB, United Kingdom
T +44(0) 141 222 4500   F +44(0) 141 221 2048, www.mottmac.com

Issue and revision record

Revision	Date	Originator	Checker	Approver	Description
01	30th July 2010	R. Ball	M. Scutariu	R Ball	Original Issue
02	21 December 2010	R. Ball	M. Scutariu	R Ball	ETI Comments incorporated into Appendix B.

Mott MacDonald, 1 Atlantic Quay, Broomielaw, Glasgow G2 8JB, United Kingdom
T +44(0) 141 222 4500   F +44(0) 141 221 2048, www.mottmac.com

Content

Mott MacDonald

1. Summary

1.1 Background

Mott MacDonald has been commissioned by The Energy Technologies Institute (ETI) to carry out the ETI's Network Capacity Project. This project is aimed at supporting the ETI's overall goal of accelerating the deployment of technologies that will help reduce greenhouse gas emissions and thus help achieve climate change goals. Specifically the project will assess the feasibility of two potential areas of development to improve the operation and increase the capacity of the UK onshore T&D systems. The outcome will be a thorough, coherent and well presented analysis that will enable the ETI to make informed decisions as to where future work in the programme should be directed.

- The first area of the project is focussed on the feasibility of applying new and existing power electronic technologies to provide enhanced management of network power flows in order to release more capacity within the T&D system.

- The second area concentrates on the technical feasibility of multi-terminal HVDC in the context of operation within the existing UK T&D system.

The work associated with both areas comprises an assessment of the credible options from these technologies in the context of power flow management including the benefits and also associated impediments to their development and deployment, and will provide guidance in respect of technology development opportunities. The work has been structured into two packages;

- Work Package 1 concentrates on the novel technologies with the potential to release capacity in the UK T&D networks. The work in this package comprises a literature review and modelling of the various technologies integrated into the networks to determine their effectiveness and requirements for such integration. It will also include analysis of environmental and social impacts, and of the barriers to development and deployment.

- Work Package 2 concentrates on the use of multi-terminal HVDC transmission and its integration within the existing UK T&D networks. The work in this package will comprise a feasibility assessment and detailed modelling of multi-terminal HVDC to assess its performance, impact and potential interactions arising from its use. It will also include analysis of the requirements for such integration, the benefits case for conversion of existing AC lines, and of the barriers to development and deployment.

1.2 Work Package 1 Task 6 and 7 Final Reports

Mott MacDonald commissioned Smarter Grid Solutions (SGS) to organise and lead the Technology Options, Benefits and Barriers Workshop covered by the Work Package 1, Task 6 scope of work and then to use the output of the workshop and the other tasks to carry out a Multi-Criteria Assessment (MCA) of the candidate technologies. The reports received from SGS on the workshop and the MCA are included as Appendices A and B respectively. These reports incorporate amendments to the reports that have been made in response to ETI comments received on the draft report submitted in August 2010

This report is provided as a separate stand-alone document at this stage. The final report for the project consolidates and updates the outputs from each of the individual task reports, including that covered by this report, in order to provide a coherent output that represents the integrated output from all of the work carried out.

Appendices

Appendix A. Smarter Grid Solutions Report: Technology Options, Benefits and Barriers Workshop

ETI Network Capacity Project
Work Package 1 Task 6
Review of Workshop (Internal Project Use)

Issued to:	Mott MacDonald
	University of Strathclyde
	Manitoba Hydro HVDC
	TransGrid Solutions
By:	Smarter Grid Solutions Ltd.
Date:	18/06/2010
Reference:	1008-01-04B

Document Issue Control

Project Start Date: **20/01/2010**

Project Reference: **1008-01**

Document Number: **04**

Version	Date	Prepared by	Checked by	Description
A	19/05/2010	Andrea Michiorri Gareth McLorn David Wang	Colin Foote	Issued for comment and additions
B	18/06/2010	Gareth McLorn Joseph Awodola	Colin Foote	Final issue

Smarter Grid Solutions contact:

Colin Foote

Head of Power Systems

Telephone: +44 (0) 141 248 0063

Mobile: +44 (0) 7949 168 392

Email: colin.foote@smartergridsolutions.com

Smarter Grid Solutions Ltd.

113 West Regent Street,

Glasgow,

G2 2RU

Contents

Tables

1 Introduction

The Energy Technologies Institute (ETI) identified the need for important engineering studies to assess innovative approaches and technology solutions that could lead to either:

- the enhancement of the capacity of the *existing* onshore UK electricity transmission and distribution networks, or
- the *expansion* of these networks by means other than the construction of new overhead lines infrastructure,

and thereby enable the installation of substantially more renewable energy systems in the UK than the current transmission and distribution (T&D) systems can accommodate.

The project is aimed at supporting the ETI's overall goal of accelerating the deployment of technologies that will help reduce greenhouse gases emissions and thus help achieve climate change goals. The outcome is to be a thorough, coherent and well presented analysis that will enable the ETI to make informed decisions as to where future work in the programme should be directed.

1.1 Project Structure

Work Package 1 concentrates on the novel technologies with potentials to release capacity in the UK T&D networks. Work Package 2 concentrates on the feasibility of multi-terminal HVDC in the UK transmission network. The work comprises a literature review and modelling of the various technologies integrated into the networks to determine their performance, effectiveness and the requirements for such proposed integration. It also includes analysis of environmental and social impacts, and of the barriers to development and deployment.

Task 6 in Work Package 1 has delivered a workshop that allowed all project partners to meet with ETI members and others to discuss the technology options, benefits, barriers and solutions. The workshop collected information and opinions that were used to perform the overall assessment in Task 7 and the final project conclusions. The workshop encompassed the work being done in both work packages and so covered all aspects of the project scope.

This document provides comprehensive notes and a post-event summary. The purpose of this document is to fully capture the information shared at the workshop. All project partners were invited to make additions and comments to ensure that all useful information was recorded accurately. A separate, shorter document was produced and issued to workshop participants outside of the project team.

The outcomes of all other tasks were combined with the outcomes of the workshop to perform the Task 7multi-criteria assessment. Final reports for each of the work packages will consolidate the output from all tasks and provide clear recommendations to the ETI in respect of its Energy Storage and Distribution Programme scope, technology development opportunities and research and development priorities.

1.2 Task Methodology

The workshop was led by SGS with input from all partners. In collaboration with the ETI, the project partners agreed on a date and location for the workshop and identified and invited participants. Delivery of the workshop involves the following:

- A detailed workshop plan delivered to project partners only

- A briefing document issued to all participants to inform them of the workshop objectives and structure and provide essential background information
- Leading and directing the workshop with a mixture of sessions, including break-out groups and different methods of presentation and reporting, to ensure all participants have an opportunity to contribute and the required information and opinions are gathered effectively
- The outcome was a comprehensive set of workshop notes and a post-event summary (this document) delivered to project partners only
  - A separate document was produced as notes for dissemination to all workshop participants

The workshop was designed to elicit the views of stakeholders and discuss the technology options, benefits, barriers and solutions, in order to inform the multi-criteria assessment of technologies in Task 7, which will inform the final outcomes of the project.

2 Workshop Objectives

The main objectives of the workshop were to:

- Ensure all participants are informed about project activities and expected outcomes
- Consider the relative merits of the technologies under review
- Identify all issues that translate into benefits or barriers for the technologies under review
- Identify and prioritise assessment criteria
- Assess the range of opinions on uncertain, controversial and subjective issues
- Identify and assess technology development opportunities

The workshop satisfied all of these objectives, as detailed further below.

2.1 Multi-Criteria Assessment

The workshop has informed the multi-criteria assessment of technologies in, which also takes account of the outcomes of Tasks 1 to 5 in WP1 and Tasks 1 to 4 in WP2. The objective is to produce a multi-criteria assessment that:

- Uses the outcomes of the workshop and the other tasks to perform an objective assessment of the technologies identified and examined
  - Combines the results of quantitative and qualitative analysis with opinions gathered in the workshop
  - Identifies what is subjective and reflects the range of opinions expressed at the workshop
    - The assessment criteria agreed and used at the workshop have been revised according to project requirements
- Provides a systematic, clear and consistent appraisal of the multiplicity of benefits and risks that will support recommendations on further work
- Identifies the technology development options that address the most restrictive barriers and offer the optimal mix of benefits

3 Workshop Outcomes

The workshop was organised into a number of different sessions designed to share information and collect input from all participants. Participants were divided into groups as summarised in Table 7 and Table 8 in section 4.

3.1 Ideas Capture

The principal means of collecting people's ideas was a large wall-chart laid out as shown in Table 1 upon which people fixed post-it notes with their thoughts. The intention was that the participants would contribute ideas in each category across the different technology areas.

Table 1: Structure for ideas capture

	Power Electronics	FACTS	HVDC	Active Network Management
Benefits				
Impacts				
Barriers or Gaps				
Solutions and Opportunities				

The ideas captured are noted in the sections below. These ideas and observations reflect what was discussed and stated by participants at the workshop and therefore represent a broad set of views; they do not necessarily represent the views of the project partners.

3.1.1 Power Electronics

Benefits

Discussion focussed on the role of power electronics in facilitating the control of power flows through a network.

It was recognised that while existing thyristors (Silicon Controlled Rectifier) have a high current carrying capacity they switch off every half cycle when the input signal is reversed so a well designed control system is required for optimal performance.

IGBTs/GTOs (newer technology) are seen as offering better flexibility than thyristors as they can be better controlled and switched.

Power electronics devices are seen to bring benefits in improving the transient stability of a network, providing power factor correction, and providing a means to adjust power flow through the network.

Impacts

The harmonic distortion introduced by power electronic devices may cause problems.

IGBTs have higher losses compared to thyristors.

Losses in Silicon Carbide (SiC)/Diamond based devices are at the same level as existing IGBTs

The prices of Silicon Carbide (SiC) and diamond devices are high in comparison to existing substrate choices.

In manufacturing there is a relatively low yield for SiC devices, especially power MOSFETs.

Installation of power electronics devices can require large amounts of space due to their bulky structure.

Barriers or Gaps

Current operating limits for IGBTs and thyristors are 6.5 kV and 8 kV respectively. Devices are stacked in series to achieve higher voltage DC operation.

Although IGBTs/GTOs have better controllability than thyristors it is more difficult to increase the current capacity of IGBTs/GTOs than thyristors.

New network configurations may require power flows of 7200 MW on an HVDC link, which is equivalent to roughly 5000 A at a DC voltage of ±720 kV. Conventional IGBT is only capable of 1500 A maximum current at switching. This problem can be solved by sharing current in parallel across several IGBT branches.

Capacity can be increased with multiple circuits in parallel but this may necessitate the use of underground cables instead of overhead lines.

At the moment, power electronics are incapable of dealing with transient overloads.

There is a perception that there are limitations on the maximum voltage and current ratings of power electronics devices and that this restricts their applicability to extra high voltage networks. However, HVDC operates successfully at +/- 800 kV with a rating of 6400 MW so this perception is incorrect.

The material engineering of silicon carbide (SiC) or diamond, which could be used to improve the rating of power electronics devices, is not matured yet.

There are still not enough statistical data collected for reliability assessment of voltage source converters (VSC).

Solutions and Opportunities

SiC and diamond substrates envisaged for the future as they can tolerate much higher temperatures and faster switching speeds. Advancement of SiC and diamond related technologies will increase the power rating of IGBTs. However it is noted that SiC technology is much more mature than diamond.

There is need to increase IGBTs current capability beyond 1500 A. This requires better packaging techniques. Advances in this technology needs to be targeted towards the power systems industry instead of focussing towards smaller electronic applications and military uses.

It is possible to design composite circuits that do not force all the current through IGBTs but shares some of the power flow burden with thyristor schemes (which can have a higher current rating) and forcing switching, or other clever operations such as harmonic compensation, to occur within the IGBT branches. This would allow better harmonics compensation and fast switching at the same time.

Cascaded version of a thyristor using switching in series is being funded in the US.

There is potential to combine FACTS devices with energy storage to provide better active and reactive power support to a network. This may be applicable at distribution level using HVDC at lower voltages and thereby help to achieve distribution CO_2 reduction targets.

3.1.2 FACTS

Benefits

Flexible transmission AC systems (FACTS) are seen as providing real and reactive power control to improve transmission utilisation and release additional capacity. Transmission capacity is enhanced by controlling power flow and reducing stability margins. Consequently, proposed investment in load or generator driven reinforcements can be avoided.

Shunt connected FACTS control MVA flows by variation in voltage whereas series connected FACTS resolve power flows by adjusting system impedance via series connected capacitors or inductors. By so doing, FACTS support network voltages and improve the system voltage stability.

TCSC (Thyristor Controlled Series Capacitor) has better harmonics performance than other FACTS devices. TCSCs could be used in future as a replacement for quadrature boosters. TCSCs can also be used to control sub-synchronous resonance.

SVC has much better reactive power control than conventional switched capacitor banks.

FACTs devices have a reduced footprint compared to traditional mechanical switches. Existing applications are mainly driven by the lack of available space.

The greatest potential value for FACTS will be in constrained locations, e.g. the Scotland/England border bottleneck. Currently there are 4 × AC connections carrying 3 GW each.

Besides the benefits, most of the FACTS technologies are well matured and their advantageous could be achieved on networks today.

Impacts

FACTS are seen as expensive and so are expected to result in higher overall costs in building and maintaining networks.

With multiple circuits running in parallel the contingency requirements of SQSS means that what you do for one branch needs to be replicated across all parallel branches.

It was pointed out that power flow changes in the lifetime of a plant could make it obsolete. An example was the modification in power flows in consequence of increased integration with the European grid.

Installation of TCSC could complicate the deployment and setting of distance protection.

Barriers or Gaps

IGBT development is driven by the industrial drive industry (e.g. for moving trains or ships) and not specialised for FACTS deployment.

Slow adoption of STATCOM devices is a critical issue. It was estimated that SVC enquiries outnumber STATCOM enquiries by a ratio of 10:1.

It was observed that the current grid code and security of supply standards favour AC over DC, having been written with classical synchronous generators in mind. Thus, technical framework for the industry assumes the continuation of current practise rather than encouraging greater use of FACTS or HVDC.

Cost was highlighted as a barrier, given the existence of cheaper solutions that deliver the same capability.

A transmission system operator (TSO) may prefer to invest in new lines instead of FACTS due to their limited experience in operating with FACTS. There is very little accumulated knowledge regarding FACTS within the sector.

There is an absence of an industry wide standard across many of the separate FACTS technologies and this should be addressed so that the risks incurred by TSOs when buying FACTs are reduced. For example, there are many different types of static synchronous compensator (STATCOM). Similarly, other FACTS technologies are produced according to different standards by different manufacturers. There is therefore the lack of commonality between devices and this is currently making TSOs inclined towards negotiating maintenance contracts with the STATCOM manufacturer instead of training their own staff to do this job.

There are difficulties and complexities in coordinating the control actions between the FACTS connected at different locations and between FACTS and HVDC.

Solutions and Opportunities

In order to reduce costs, it is suggested that there should be development of standardised products. This would reduce both manufacturing and design cost.

There is a potential of enabling more advanced active network management (ANM) by integrating FACTS.

More advanced power electronics devices (UPFC, SSSC, IPFC, etc.) promise improved functionality but higher losses.

3.1.3 HVDC

Benefits

HVDC is seen as a solution for moving large amounts of power over large distances. HVDC overcomes problems with AC links such as those associated with capacitance and power losses at high voltage and removes the limit in length for electric cables.

HVDC links can be used as buffers between different areas of the network. This is useful both for asynchronous systems (e.g. in Japan[1]) and to isolate areas from faults (e.g. Hydro Quebec[2]).

---

[1] The northern island of the archipelago, Hokkaido, has a network working at 60 Hz, whilst the rest of Japan uses 50 Hz. The two systems are interconnected with a DC link.

[2] In the 2003 summer blackout across North East U.S.A and Ontario in Canada power was preserved in Quebec due to it being buffered from the affected area by HVDC links.

In the event of a trip it is possible to operate in HVDC islands – whereby one area has a different system frequency from another.

The possibility of converting an existing AC line to DC operation and increasing its power carrying capacity by a factor of three is recognised. Questions remain over the modifications required to the existing infrastructure.

For HVDC, line commutation converter (LCC) technology is much more mature than voltage source converter (VSC) technology.

VSCs produce both real and reactive power and have low or no filtering requirements.

New technologies, such as VSC, have a much smaller environmental footprint than their predecessors.

System damping on AC lines can be achieved by installing HVDC links either in parallel or series with the AC lines to share some of the power flows.

HVDC offers much higher power transferring capability than AC transmission lines, i.e. better utilisation of corridors. One DC bipole has the same capacity as 2 × 500 kV AC lines.

The advancement of the technology allows HVDC to be applied to different voltage levels.

The absence of reactive power flow in HVDC enhances the stability of the system and increase the independence of the two networks linked by the HVDC lines, therefore limiting the chance of faults cascading from one system to the other.

HVDC can switch from bipolar to monopole configuration to continue transferring power when there is a fault on one HVDC conductor.

Impacts

In multi-terminal networks, there are problems in handling faults because of the lack of suitable DC breakers for the VSC technology.

In faults it is not possible to discriminate and isolate the faulted section of the line so the whole DC line must be tripped.

If DC lines are carrying much more power than AC lines then a trip will have a bigger impact on the system. If the system cannot handle this impact then the trip of one DCline might result in cascade tripping and blackout.

In order to improve cross-channel HVDC security, a low voltage feedback connection would be required to facilitate bipole to monopole operation switching in the event of a fault.

Clearing a DC line fault using VSCs is very difficult as it requires a DC breaker or replacing the diode with an IGBT.

Line commutation introduces a lot of harmonics into the system and as such requires an expensive filter to get rid of them.

HVDC is seen as imposing higher maintenance costs than conventional AC solutions.

A concern was raised that there are different HVDC transformers based on different HVDC design philosophies and standards, but it was noted that this all applies to all large transformers whether for HVDC systems or not.

HVDC implemented with LCC technology has limited reactive power control for the power flowing into an AC system, which is still responsible for the transfer of most of the power generated. This problem has been overcome by the VSC technology which has full reactive control as it can both absorb and produce reactive power.

Barriers or Gaps

Significant network upgrades to the AC systems are required to prevent disastrous impacts if HVDC lines are tripped; one major concern will be the ability of the AC system to handle the additional power flow after the fault. As a result, the contingency criteria stated in SQSS and grid code at present favour an AC system over HVDC, therefore reducing the attractiveness of building a HVDC system. HVDC could overload an AC transmission line connected in parallel with it when there is a fault on the HVDC lines because large amounts of power typically flow through HVDC lines and as such significant security upgrades or a fast acting control system are needed to clear faults on the HVDC system when it fails.

Further development of multi-terminal HVDC with VSC, including the development of DC breakers for faster fault detection and protection, is necessary. The alternative, currently being developed by Areva, is to replace the diode with IGBT but this will come at higher cost.

It is believed that there are problems in using VSC based HVDC with overhead lines but the first system of this type is to be commissioned this year so these problems must have been resolved.

Solutions and Opportunities

HVDC breakers are needed, and are in development by ABB and Siemens. Areva is also working on the alternative of replacing the diode with IGBT, a control device.

The problem of DC faults can be solved temporarily with a low voltage feedback link that can trigger half power monopole operation.

Amendment of SQSS could initiate the construction of HVDC to replace part of the AC system within the main interconnected transmission system (MITS), which would allow the TSO to gain better understanding of the functional requirements for operating HVDC links in parallel with the AC transmission system.

3.1.4 Active Network Management

Benefits

Real-time network monitoring identifies available capacity, in real-time, which can be used allow access to the distribution network. It thereby facilitates more efficient use of the existing network and offers a less expensive alternative to grid reinforcement in areas where there are network constraint problems.

ANM allows a network to accommodate extra generation capacity without the need for reinforcements. Since it normally takes long time for the reinforcements to be granted, the process to connect generation is quicker with ANM. Transmission lines are better utilised and ANM provides the opportunities to improve the correlation between load demand and generation over time through generation curtailment and demand-side management.

Different priorities for generator access can be selected depending on what the system goal is, e.g. last-in first-off, ranking generators by net CO_2 contribution, etc.

ANM offers improved system visibility through additional monitoring.

Impacts

ANM requires additional monitoring and control equipment on the distribution network.

Increased generation at distribution level could mean new bottlenecks on the transmission network.

Real-time and reliable monitoring and control are required for ANM.

Better equipment utilisation implies that the equipment will age more quickly and require more frequent maintenance.

Network losses are increased due to heavier line loadings.

Barriers or Gaps

It may be necessary to measure power flow at very many constraint locations across the network.

DNOs may be uncomfortable with this type of control. They may lack the experience and skills to actively manage their networks. The incentives structure may not make it an attractive option. Network users must also be educated.

ANM solutions seem to work well with local constraints but there are doubts over scaling it to larger networks.

ANM requires better coordination between controlled equipment.

ANM can present problems with commercial access rights, generation curtailment and conflicts between network operators and generators.

Reliability of the network is undermined by ANM as the safety margin in operating the network is reduced.

A view was expressed that any ANM scheme will probably have to be replaced every 10 to 15 years.

Solutions and Opportunities

ANM is consistent with the incorporation of more information and communication technologies into electricity networks. It encourages the development of new control and monitoring systems.

ANM presents opportunities to develop more responsive demand, which will have an impact on load forecasting. ANM should improve the forecasting of demand and generation.

There is a potential to integrate power electronics devices into ANM to perform more advanced functions.

Energy storage could become an economically attractive option in ANM to minimise the amount of generation curtailed.

Coordination between ANM and HVDC is possible for improving system stability.

Different access right rules can be developed, offering the opportunity to change the priority scheme for generation curtailment to rules based on the environmental impact of generators.

The new low carbon network funding (LCNF) scheme could see more applications of ANM.

3.2 Framing the Assessment

This session pulled together the morning discussions and defined the detailed plans for the afternoon group discussions. The outcomes from circuit training and ideas capture were used to collate a set of technology development options and assessment criteria. The objective was to shift the focus from technologies to the technology development opportunities.

Technology development options were drawn from the ideas posted against the solutions and opportunities category. The opportunities / options identified and used in the remainder of the workshop were:

A. Support reviews of security and planning standards
B. Prompt changes in regulatory framework to change business drivers
C. Help to establish common standards and models
D. Support R&D in new devices for greater capability/performance, e.g. SiC / Diamond
E. Commission work on new HVDC systems/topologies
F. Develop effective DC Breaker / Blocking Capability
G. R&D on coordination of HVDC in the UK
H. Support trials or demonstrations
I. Investigate use of energy storage to help solve ANM constraints
J. Develop condition monitoring and asset management tools for a network with increased power flows
K. Training and education, e.g. courses, conferences (HVDC, FACTS, PE, ANM)

Assessment criteria were drawn from the benefits and impacts ideas but influenced by the project team to ensure certain issues were addressed. The assessment criteria identified and used in the remainder of the workshop were:

1. Potential to enhance UK industrial capacity and knowledge
2. Reduce through-life costs
3. Has a clear business case for all stakeholders
4. Overcome/bypass problems with consents
5. Potential to enhance Technologies Readiness Levels
6. Clear potential to reduce CO_2 emissions
7. More options and flexibility in network design and operation
8. Reduce (or don't increase) risks in system operation

The final objective of the session was to prioritise the assessment criteria. This was done with the whole group; all participants were invited to rank the criteria in order of importance using pre-prepared voting slips.

The cumulative results for this session are shown in Table 2. The rankings submitted by all participants were summed and the totals used to determine overall rankings, i.e. the criterion with the lowest total is assigned rank 1 and so on. The totals give some perspective on how closely some of the different criteria were ranked in comparison to others.

Table 2: Ranking of Assessment Criteria

Criterion	Description	Summed Rankings	Calculated Overall Rank
1	Potential to enhance UK industrial capacity and knowledge	110	5
2	Reduce through-life costs	118	7
3	Has a clear business case for all stakeholders	95	4
4	Overcome/bypass problems with consents	113	6
5	Potential to enhance Technologies Readiness Levels	126	8
6	Clear potential to reduce CO2 emissions	81	1
7	More options and flexibility in network design and operation	82	2
8	Reduce (or don't increase) risks in system operation	92	3

3.3 Place Your Bets

The morning session ended with an exercise designed to capture the collective views on which technology development options were favoured most. The options identified in the previous session were offered as "bets". Each participant had an amount of "money" that they could use to "back" an option. The placement of bets indicates which options were favoured.

Each participant was given 100 credits to divide as they see fit between the options. The credits assigned to each option were totalled and used to derive "prices" that are indicative of the expected likelihood of success. If an option is assigned a fraction X of all the credits and there are Y options then the likelihood of success can be calculated as X*Y. For example, if there are 5 options then an option assigned one tenth of the credits will have a price of 0.5 and an option assigned half the credits will have a price of 2.5. If all credits were assigned equally between all options then all would have a price of 1. These are equivalent to conventional bookmakers' odds of Z:1 where $Z = \frac{1}{X-1}$. For example, if X = 0.1 with Y = 5 then the price will be 0.5 and the bookmaker odds will be 9:1.

The initial round of betting yielded the set of results shown in Table 6. Each option is ranked according to the odds assigned to it, a value which was calculated from the option's relative popularity amongst the participants.

Table 3: Betting Results – Initial Round

Option	Description	Price	Calculated Odds (:1)	Ranking
A	Support reviews of security and planning standards	0.849	11.96	8
B	Prompt changes in regulatory framework to change business drivers	0.835	12.18	10
C	Help to establish common standards and models	0.628	16.50	11
D	Support R&D in new devices for greater capability/performance, e.g. SiC / Diamond	1.436	6.66	1
E	Commission work on new HVDC systems/topologies	0.862	11.76	7
F	Develop effective DC Breaker / Blocking Capability	1.202	8.15	3
G	R&D on coordination of HVDC in the UK	1.165	8.44	4
H	Support trials or demonstrations	1.284	7.56	2
I	Investigate use of energy storage to help solve ANM constraints	1.000	10.00	5
J	Develop condition monitoring and asset management tools for a network with increased power flows	0.849	11.96	8
K	Training and education, e.g. courses, conferences (HVDC, FACTS, PE, ANM)	0.890	11.36	6

3.4 Group Discussions

The main afternoon session saw the workshop split into three groups. The technology development options were assessed against the criteria with general supporting discussion. One objective was the identification of what is uncertain, controversial or subjective. Each group produced scores for each option against all the criteria, or otherwise specified what they thought were the best options.

The average scores of the 3 simultaneous group discussions combined are presented in Table 4 with the "best" option for satisfying each of the assessment criteria and the most fulfilled criterion for each option shown.

Table 4: Group Discussions Scores

Criterion \ Option	A	B	C	D	E	F	G	H	I	J	K	L	Best Option
1	0.33	1.67	2.67	7.33	4.67	5.00	5.33	5.67	5.67	3.00	9.00	7.00	K
2	3.67	2.67	2.00	3.33	4.33	1.67	1.33	3.33	3.33	6.00	2.67	0.00	J
3	4.33	4.67	3.00	3.00	5.67	8.67	6.33	5.00	6.00	3.00	9.00	7.00	K
4	7.67	5.67	3.00	0.67	0.33	5.00	0.00	5.33	4.67	1.00	2.33	0.00	A
5	0.33	3.67	4.33	4.33	2.67	7.33	5.00	9.00	6.67	2.67	6.67	7.00	H
6	6.67	6.67	0.67	4.33	2.67	5.00	2.67	3.67	9.00	0.67	3.33	0.00	I
7	5.00	6.00	5.00	5.00	6.00	6.67	8.00	6.00	9.00	5.33	5.33	0.00	I
8	4.00	4.33	5.00	2.33	1.67	4.67	8.33	7.33	7.33	1.67	6.67	7.00	G
Most fulfilled criterion	4	6	7, 8	1	7	3	8	5	6, 7	2	1,3	1, 3, 5, 8	

Notes: One group, rather than assign scores to each option against each criterion, identified the options they thought were "best" for each criterion. The calculation of average scores above has assumed a score of 7 for options identified as "best", assumed 5 where there was some qualification or hesitation associated with the option, and assumed 0 otherwise.

One group identified a 12th "opportunity", identified as option L in the table above: replace or increase generator inertia or otherwise improve system response, especially when it is windy and the output from wind farms is high; this would free capacity on the network and reduce security margins.

Notes were taken during the group discussions and these are summarised below.

Some comments from the discussion group led by Paul Fletcher:

- It is unclear which party would be the main beneficiary (National Grid, the DNOs or consumers) if the ETI were to support reviews of security and planning standards. Without clear cut merits being apparent it would be difficult to recommend this course of action for the ETI.
- Wholesale changes to existing security and planning standards could unnecessarily introduce extra risk into the system at a time when many changes are due to be deployed. Despite good intentions this could have serious implications for the grid.
- Changes in the regulatory framework ought to be focussed towards asset planning. One aspect of this would be to provide DNOs with incentives that would support their assets being put under the additional strain affected by the advent of smart grids. This is a basic driver towards influencing smart grid development.
- In some respects the current regulatory framework acts against the most logical commercial drivers for change in the system. From a business perspective it is rational for most new distributed wind generation to be connected in Scotland – however the greater potential

offered by Scottish sites, in comparison to elsewhere in Britain, is offset by the existence of higher transmission charges.

- Whilst being a welcome advancement in many areas of the industry the establishment of common standards and models will not necessarily lead to improved flexibility with regards to network design and operation – in fact they could inhibit flexibility.
- The ETI could support research and development into improving the capability of IGBT/thyristor devices.
- In general, the "Support for R&D" section scores very highly across all groups. How relevant therefore are the questions being asked? We would not normally assume that the major challenges in moving towards the facilitation of connecting more renewables to the grid lie in advancements in the power electronics industry. Does the topic encompass the development of new SCADA, new generation, new communications or just power electronic device development?
- As power electronic device performances are improved then this can facilitate greater power flows in the grid, with more efficiency – thus reducing CO_2 emissions.
- Upon considering the commissioning of work on new HVDC systems it should be noted that alternative topologies could be developed which would make better use of IGBTs and thyristors.
- It is thought that work on developing new HVDC systems would be beneficial, from a business perspective, to all stakeholders.
- It is felt that developing effective DC breaker / blocking capability is beneficial but should fall under the auspice of developing new HVDC systems criteria.
- A lot of HVDC contingency scenarios should be investigated as part of any research into the technology.
- National Grid should be encouraged/incentivised to invest in some trials which would enhance UK industrial capacity and knowledge. It is thought that trials in TCSC based FACTS systems or multi terminal HVDC links would be the most advantageous.
- It is easier to overcome or bypass consent issues if the vendor has already trialled a prototype and demonstrated its capability. Trialling therefore becomes a key component in encouraging the adoption of improved technologies in industry.
- Investigating the use of energy storage should not be confined to ANM schemes only. Thought should be given towards how batteries can be used to provide system balancing.
- Increased proliferation of batteries could be a key factor in overcoming the need to build new overhead lines and thus reduce the need to bypass consent problems.
- The reduction of through-life costs is a criterion which should be assessed with regards the use of energy storage. The life of the battery itself should be considered but also will the use of batteries have a negative impact on the lifespan of other network assets due to higher, more consistent power flows being envisaged in the system?
- Condition monitoring – presently there is a lot of work ongoing in this regard within academia. This would help to improve reliability for 40+ year old assets.

A. Support reviews of security and planning standards

- Interpreted mainly as review of SQSS criteria and other system planning standards
- Perceived to have the most impact on reducing through-life costs (Criterion 2) and adding flexibility to network design (7)
    - Example: Reviewing SQSS requirement can potentially reduce redundancy requirements as they apply to AC onshore networks; i.e. it is noted that offshore DC and offshore AC SQSS requirements have been made different primarily to help the economic cases of applying DC networks. A similar argument could be made for onshore DC (or FACTS) versus AC SQSS requirements.
- Strong point came across that risks in system operation are very likely to INCREASE if a case is made for 'relaxing' system security criteria – i.e. something has to give way! In reality this should mean a negative score (i.e. minus 10?) but a score of 0 was decided instead – THUS this should not be confused as meaning the criteria is irrelevant.

B. Prompt changes in regulatory framework to change business drivers

- Interpreted mainly as changes to regulation by OFGEM
- Key Example: support for innovation from OFGEM. Currently there is very little incentive for utilities with low rates of return on capital assets to invest in higher risk projects, which is a category all large-scale FACTS/HVDC projects being considered in this study (other than SVCs) would fall within (i.e. because there is minimal/no UK application). A change to solve this can include OFGEM allowing utilities to capitalise their investments in higher risk/technology development projects, basically underwriting the investment risks.
- Potential to enhance technology readiness (5) given very high score since a change in innovation funding from OFGEM would have serious impact.
- The type of OFGEM regulatory change discussed above is perceived as a KEY DRIVER to other options, e.g. (H) support trails or demonstrations – this would result since they could be underwritten by OFGEM, and also (K) training and education – more installations in the UK of newer technologies by utilities such as NG will naturally build capability/training.
- Regarding Criterion (6): a clear potential to reduce CO2 emissions was assigned after considering the example of changes to renewable energy tariff structures (i.e. currently there may be uneconomic tariff structures for some high renewable potential areas, e.g. Orkney, Shetland, etc.) – this could have high impact on increasing renewable generation directly.

C. Help to establish common standards and models

- Interpreted this as both utility (i.e. specification / functional requirement standardisation) and manufacturer (i.e. modularisation and reduce major differences between various manufacturer topologies, controls, etc.)
- Key benefits perceived across a number of criteria, particularly (1), (3), (7), and (8)
- Noted by manufacturers that standardisation would benefit utilities by letting them to better understand the operability, maintenance, etc. for complex technologies (e.g. VSCs) across manufacturer platforms – i.e. generally moving away from a 'black-box' mentality, reducing through-life costs, improving business case, reducing risks in system operation, increasing chance of adoption, reducing training requirements for maintenance and operation, etc.

D. Support R&D in new devices for greater capability/performance, e.g. SiC / Diamond

- Interpreted as applying to power electronics devices such as thyristors and IGBTs specifically, rather than R&D in general (i.e. on multi-terminal systems, DC breakers, etc. which are covered in other options).
- Benefits perceived across almost all options, which normally would translate to high scores across all criteria; however although successful R&D in devices could create many benefits the likelihood of success itself was perceived to be lower than for other options. Thus overall scores were lowered a bit as there was no method to 'weight' the success or importance of options relative to each other.
- The understanding is that next generation power electronic devices (i.e. SiC, diamond) are a significant step forward from current technologies so developments are in long-term horizons, and there is risk that gains across all criteria may not be significant compared to current devices (i.e. thyristor, IGBT).

E. Commission work on new HVDC systems/topologies

- Interpreted as a system innovation (i.e. point to point to multi-terminal, two level or three level to modular multi-level converters, etc.) rather than device based
- Strongly scoring across majority of criteria, unlike the device R&D option (D) the likelihood of success here is seen to be high.
- In areas such as multi-terminal development and study, significant gains in network design and flexibility, as well as business case for stakeholders is perceived.
- In areas such as new topologies, through life costs perceived to reduce if losses are reduced significantly.

F. Develop effective DC Breaker / Blocking Capability

- Scored identically to (E), as it is an integral step to developing secure multi-terminal networks.

G. R&D on coordination of HVDC in the UK

- Interpreted as research (simulations and demonstrations) on the embedding of HVDC into large scale AC systems, such as the UK transmission network, with complex security/operation requirements.
- Noted that HVDC applications to date have primarily been for long radial connections to remote generation, bulk power interchanges, back-to-back connections – as opposed to operation within complex AC networks with large-scale generation on either ends, potential for islanding, requirements for fast power reversal, transient stability support, etc. R&D is thus required in this area.

H. Support trials or demonstrations

- Interpreted as mainly technical trials/demonstrations, i.e. physical installations of devices/technologies, implementation of complex control systems, etc., non-technical aspects of option include regulatory changes, visualisation of environmental impacts (i.e. does it actually look horrible or not!), etc.
- Scored highly across everything (other than $C0_2$ emissions) as it was perceived that trials and demonstrations are key to resolving real and perceived barriers to adoption (Note: seems to be the key option being pursed as well in European Union funded studies)

- Particularly strong benefits in potential to increase UK industrial capacity (arguably better than direct investment in training and development), potential to increase technology readiness levels, as well as reducing risks in system operation
- Examples of past UK examples of this include NGT 225 MVAR STATCOM at East Claydon, as well as example of NG Kingsnorth – Beddington HVDC Link which was a key demonstration of valve technology and embedded system application, albeit in the 1970s

I. Investigate use of energy storage to help solve ANM constraints

- Interpreted as the overall use of energy storage devices in the power network (i.e. super-capacitors, batteries, etc.). Example applications include power storage for variable renewable generation, active power input for power electronics (i.e. STATCOMs), etc.
- Scored highly across all criteria. Wide range of benefits were perceived.

J. Develop condition monitoring and asset management tools for a network with increased power flows

- Interpreted as the use of condition monitoring technologies such as real time measurements of asset condition (i.e. enabling increased lifetimes), and tools such as real-time thermal monitoring to enable increased power flows
- Benefits perceived in most areas other than (4), (7), and (8) – for example regarding (4) the use of CM technologies, although enabling the extension of asset lives in many cases only DELAYS equipment replacement – thus consenting issues are still encountered but at a later date
- Clearest benefit (particularly with condition monitoring) of reducing through-life costs, as life of asset is increased.

K. Training and education, e.g. courses, conferences (HVDC, FACTS, PE, ANM)

- No interpretation needed, self-explanatory
- High scores across most criteria, generally considered a 'no-brainer' in terms of benefits. However, as noted previously it was felt strongly that some other areas such as trials and demonstrations may indirectly result in better training and development (e.g. if NG were to order a 1 GW HVDC-VSC from Areva then undoubtedly a new generation of UK power electronic engineers would rise)
- Only criteria where no impact was perceived were (4) bypassing consents, (6) potential to reduce C02 emissions, and (7) more flexibility in network design. Other options had much stronger impacts on these areas.

Some comments from the discussion group led by Keith Bell:

- Any improvement in the network can be claimed as a reduction of CO2 if enhanced network capacity is used for connecting renewables. Otherwise, only reductions in losses can account for CO2 reduction, since carbon intensive energy is also transferred on the network.
- Knowledge and education stand out among the main options. It was agreed that formation of workers and engineers in design and the new technologies available would facilitate their adoption and their correct management.
- The necessity of standards for the new technologies discussed in the meeting was mentioned several times. Standards would reduce manufacturing and design costs, as well as creating inter

operability in the current system, facilitating gradual improvement. However, standards may also have a detrimental impact if defined poorly.

- It was also pointed out that relaxing security standards for reducing CO_2 emissions (directly or indirectly) would be done at the expense of increased system risk.
- Some options are considered likely to increase system risk.
- It was suggested that the development of new devices (FACTS, power electronics) would have the greatest outcome for UK manufacturing industry.
- Network operators need to understand what is "inside the box"
- It was concluded that further development of SiC does not appear to offer great prospects

Some comments from the discussion group led by Ken Smith:

- Industry forums must be used to agree on common approaches and share knowledge
- There is a market pull for most developments but more proactive efforts are required at the device level
- Improvements in devices mean that manufacturers can offer more compact and more cost effective systems
- The UK has the technical lead in diamond but the US has the lead in SiC, driven largely by military investments
- A DC breaker is almost ready (from ABB) but has yet to be finally proven in operation; DC breakers were built in the 1970s but they are enormous and not suitable for use now. Market demand will prompt the final development of DC breakers. The opportunity seems to have passed for investing in the development of this technology.
- The SQSS is biased against DC transmission and other non-conventional approaches
- Standardised products or standardised characterisation is attractive to network operators but if the UK wants something specific to this (small) market then a premium price will have to be paid – reference made to the CEGB with very high technical standards but very high costs also
- The manufacturers want the network operators to accept "black box" functionality and invest in equipment with a long-term contract for maintenance and support; the large manufacturers have been around for more than 50 years already and there's no reason why they should not be around for another 50 years to service the equipment they deploy.
- Options E and G (Commission work on new HVDC systems/topologies and R&D on coordination of HVDC in the UK) were perceived by this group to be essentially the same
- Trials and demonstrations are useful but the score against each of the assessment criteria will depend on exactly what is being trialled

3.5 Wrap Up and Revise Bets

The day concluded with a single session with all participants. A participant from each group reported back on the highlights and conclusions from each of the discussions. Comments are summarised below.

- Why should National Grid build a STATCOM on trial given that the cheaper and trusted SVC technology can deliver similar performance?
- IGBTs with increased current carrying capacity could be very useful.
- National Grid is observed not to be geared towards funding much R&D work. R&D is followed by practical applications at a rate that is lower than other countries.
- There is a need to replace the inertia for reserve/response to fault events or frequency regulation.
- It is very important that training and education are improved.
- Any changes in standards must take into account guarantees for interoperability between systems.
- How is the desired reduction in CO_2 likely to be best met? Is it the networks' role to reduce emissions via improving the efficiency of the grid itself (and thus reducing transmission losses) or is it by facilitating the further growth of DG?
- The value of additional monitoring (including PMUs) depends on how it is used.
- The options that the group thought would definitely impose greater risks onto the system were B, C, E, G, I, J and K
- The discussion has highlighted the value of education and increasing knowledge of FACTS/HVDC within the industry itself and that they are not currently widely known.
- Storage does a lot of desirable things for the grid, e.g. smoothes out intermittent generation.
- Trials should be considered for ANM; there is no need for trials of FACTS/HVDC deployment as these are both relatively mature technologies.
- Funding into SiC development should be a target for the ETI. Otherwise there would be a possible 20 year wait until the industry got its hands on the power electronics devices that it needs.
- The need for DC breakers is well known and is currently the focus of several manufacturers.
- We cannot depend primarily on market drivers to get the advancements we require.
- ETI should think about supporting the UK manufacturing industry in particular. There is added merit in developing a knowledge base here.

The results from the earlier betting on options and ranking of criteria were presented. Participants were invited to place further bets, which reflect the outcomes from the group discussions. Table 5 shows, by way of the change in the betting patterns, how the consensus was influenced by the discussions. By contrasting with the original results from Table 3 many more participants seem to be convinced about the merits of Option K than were previously.

Table 5: Betting Results – Second Round

Option	Description	Price	Calculated Odds (:1)	Ranking
A	Support reviews of security and planning standards	0.935	10.76	6
B	Prompt changes in regulatory framework to change business drivers	1.082	9.17	4
C	Help to establish common standards and models	0.813	12.53	7
D	Support R&D in new devices for greater capability/performance, e.g. SiC / Diamond	0.794	12.85	8
E	Commission work on new HVDC systems/topologies	0.495	21.22	11
F	Develop effective DC Breaker / Blocking Capability	0.697	14.79	9
G	R&D on coordination of HVDC in the UK	0.996	10.04	5
H	Support trials or demonstrations	1.387	6.93	2
I	Investigate use of energy storage to help solve ANM constraints	1.357	7.11	3
J	Develop condition monitoring and asset management tools for a network with increased power flows	0.636	16.31	10
K	Training and education, e.g. courses, conferences (HVDC, FACTS, PE, ANM)	1.809	5.08	1

4 Participants

Participants were invited from the ETI Energy Storage and Distribution Programme Steering Group, which includes representatives from government, from major manufacturers of the technologies of interest, from network operators, from independent experts, from Ofgem and from the project team. The mix of participants meant that a wide range of issues were captured and there was a range of opinion to inform the discussions.

The invitations issued, indications of attendance and actual attendance are summarised in Table 6. There were 30 people in attendance with 19 from among the project partners.

Table 6: Workshop invitations and attendance

Invitee	Organisation	Reason / Recommended by	Email	Invited	Indicated Attendance	Actual Attendance
Graham Howes	BP	ESD SAG	graham.howes@uk.bp.com	Y	Y	N
Jean-Francois Faugeras	EDF Energy	ESD SAG	jean-francois.faugeras@edf.fr	Y	N	N
Martin Wilcox	EDF Energy	ESD SAG	Martin.Wilcox@edfenergy.com	Y	N	N
Pascal Girard	EDF Energy	ESD SAG	pascal.girard@edfenergy.com	Y	N	N
Claude Counan	EDF R&D	Pascal Girard	claude.counan@edf.fr		Y	Y

Invitee	Organisation	Reason / Recommended by	Email	Invited	Indicated Attendance	Actual Attendance
Philippe Egrot	EDF R&D	Pascal Girard	philippe.egrot@edf.fr		Y	Y
Richard Hair	Eon	ESD SAG	richard.hair@eon-engineering-uk.com	Y	Y	Y
Bob Ferris	Eon	ESD SAG	robert.ferris@central-networks.co.uk	Y	Y	Y
Roger Hey	Eon	ESD SAG	Roger.Hey@central-networks.co.uk	Y	N	N
Chris Bright	Rolls-Royce	ESD SAG	Chris.Bright@Rolls-Royce.com	Y	N	N
Nort Thijssen	Shell	ESD SAG	nort.thijssen@shell.com	Y	N	N
Andrew Perry	DECC	ESD SAG	andrew.perry@decc.gsi.gov.uk	Y	N	N
Samantha Riches	EPSRC	ESD SAG	Samantha.Riches@epsrc.ac.uk	Y	N	N
Filomena Laporta	TSB	ESD SAG	filomena.laporta@tsb.gov.uk	Y	N	N
Jenny Cooper	National Grid	ESD SAG	jennifer.cooper@uk.ngrid.com	Y	N	N
Nick Eraut	ETI	Programme Manager	nicholas.eraut@eti.co.uk	Y	Y	Y
Richard Knight	ETI		Richard.Knight@eti.co.uk	Y	Y	N
Ray Ball	Mott MacDonald	Project Team	ray.ball@mottmac.com	Y	Y	Y
Keithley Johnson	Mott MacDonald	Project Team	keithley.johnson@mottmac.com	Y	Y	Y
Ken Smith	Mott MacDonald	Project Team	kenneth.smith@mottmac.com	Y	Y	Y
Mircea Scutariu	Mott MacDonald	Project Team	mircea.scutariu@mottmac.com	Y	N	N
Sarajit Banerjee	Mott MacDonald	Project Team	sarajit.banerjee@mottmac.com	Y	Y	Y
Paloma.De Arizon	Mott MacDonald	Project Team	paloma.dearizon@mottmacinc.com	Y	N	N
Ruth Elder	Mott MacDonald	Project Team	ruth.elder@mottmac.com	Y	Y	Y
Paul Fletcher	Mott MacDonald	Project Team	Paul.Fletcher@mottmac.com	Y	Y	Y
Douglas Ramsay	Mott MacDonald	Project Team	douglas.ramsay@mottmac.com	Y	Y	Y
Zaneil Garnie	Mott MacDonald	Project Team	Zaneil.Garnie@mottmac.com	Y	N	N
Gergo Varhegyi	Mott MacDonald	Project Team	Gergo.Varhegyi@mottmac.com	Y	N	Y
Ken Webb	Mott MacDonald	Keithley	Ken.webb@mottmac.com		Y	Y
Keith Bell	University of Strathclyde	Project Team	keith.bell@eee.strath.ac.uk	Y	Y	Y
Steve Finney	University of Strathclyde	Project Team	s.finney@eee.strath.ac.uk	Y	Y	Y
Ivana Kocker	University of Strathclyde	Project Team	ivana.kockar@eee.strath.ac.uk	Y	Y	Y
Les Recksiedler	Manitoba Hydro HVDC	Project Team	LRecksiedler@hvdc.ca	Y	Y	Y
Alan Wang	Manitoba Hydro HVDC	Project Team	wang@hvdc.ca	Y	N	N
Paul Wilson	Manitoba Hydro HVDC	Project Team	plwilson@hvdc.ca	Y	N	N
Rebecca Brandt	Transgrid Solutions	Project Team	rbrandt@transgridsolutions.com	Y	N	N
Mojtaba Mohaddes	Transgrid Solutions	Project Team	mmohaddes@transgridsolutions.com	Y	N	N
Dan Kell	Transgrid Solutions	Project Team	dkell@transgridsolutions.com	Y	Y	Y
Bathiya Jayasekara	Transgrid Solutions	Project Team	bjayasekara@transgridsolutions.com	Y	N	N
Colin Foote	Smarter Grid Solutions	Project Team	colin.foote@smartergridsolutions.com	Y	Y	Y
Alan Gooding	Smarter Grid Solutions	Project Team	alan.gooding@smartergridsolutions.com	Y	Y	Y
Bob Currie	Smarter Grid Solutions	Project Team	robert.currie@smartergridsolutions.com	Y	Y	Y
Graham Ault	Smarter Grid Solutions	Project Team	graham.ault@smartergridsolutions.com	Y	N	N
Gareth McLorn	Smarter Grid Solutions	Project Team	Gareth.mclorn@smartergridsolutions.com	Y	Y	Y
Andrea Michiorri	Smarter Grid Solutions	Project Team	Andrea.michiorri@smartergridsolutions.com	Y	Y	Y
Andy Hiorns	National Grid	Keith Bell	andrew.hiorns@uk.ngrid.com	Y	N	N
Bee Hun Tan	National Grid	Keith Bell	Beehun.tan@uk.ngrid.com	Y	N	N
Mark Perry	National Grid	Keith Bell	mark.perry@uk.ngrid.com	Y	N	N
Ziming Song	National Grid	Keith Bell	ziming.song@uk.ngrid.com	Y	Y	Y
Alex Carter	National Grid	Keith Bell	alex.carter@uk.ngrid.com	Y	N	N
David Lenaghan	National Grid	Keith Bell	David.lenaghan@uk.ngrid.com	Y	N	N
Ian Plowright	National Grid	Les Recksiedler	ian.plowright@uk.ngrid.com	Y	N	N
David Monkhouse	National Grid	Les Recksiedler	david.monkhouse@uk.ngrid.com	Y	N	N

Invitee	Organisation	Reason / Recommended by	Email	Invited	Indicated Attendance	Actual Attendance
Steve Brett	National Grid	Jenny Cooper	Steve.brett@uk.ngrid.com	Y	N	N
Paul Coventry	National Grid	Jenny Cooper	Paul.coventry@uk.ngrid.com	Y	N	N
Damian Culley	National Grid	Jenny Cooper	Damien.Culley@uk.ngrid.com	Y	N	Y
Alan Michie	Scottish Power	Keith Bell	alan.michie@scottishpower.com	N	N	N
Colin Bayfield	Scottish Power	Keith Bell	Colin.Bayfield@SPPowerSystems.com	Y	N	N
Mike Barlow	Scottish & Southern Energy	Keith Bell	mike.barlow@scottish-southern.co.uk	N	N	N
Brian Punton	Scottish & Southern Energy	Keith Bell	brian.punton@scottish-southern.co.uk	Y	N	N
James Yu	Scottish & Southern Energy	Brian Punton	james.yu@scottish-southern.co.uk		N	N
Garry Staunton	The Carbon Trust	Nick Eraut	garry.staunton@carbontrust.co.uk	Y	Y	Y
Gareth Evans	Ofgem		Gareth.Evans@ofgem.gov.uk	Y	N	N
Richard Coates	Ofgem		Richard.Coates@ofgem.gov.uk		Y	Y
Bo Westman	ABB	Sarajit	Bo.Westman@se.abb.com	Y	N	N
Grant McKay	ABB	Sarajit	Grant.McKay@gb.abb.com	Y	Y	Y
Peter Jones	ABB	Sarajit	peter.r.jones@gb.abb.com	Y	N	N
Steve Aughton	Siemens	Sarajit	steve.aughton@siemens.com	Y	N	N
Michael G. Weinhold	Siemens	Dan Kell	michael.g.weinhold@siemens.com	Y	N	N
Dusko Nedic	Siemens	Ivana Kockar	dusko.nedic@siemens.com	Y	N	N
Dietmar Retzmann	Siemens	Michael Weinhold	dietmar.retzmann@siemens.com	Y	N	N
Norman Macleod	Areva	Sarajit	norman.macleod@areva-td.com	Y	Y	Y
Roger Critchley	Areva	Steve Finney	roger.critchley@areva-td.com	Y	N	N
Bjarne Andersen	Independent consultant	Keith Bell	Bjarne@AndersenPES.com	Y	Y	N
Graeme Bathurst	TNEI	Keith Bell	graeme.bathurst@tnei.co.uk	Y	Y	N

Table 7: Groups for the morning "circuit training" and ideas capture

Claude Counan	Philippe Egrot	Richard Hair
Bob Ferris	Damien Culley	Ziming Song
Grant McKay	Norman Macleod	Garry Staunton
Richard Coates	Nick Eraut	Ken Webb
Keithley Johnson	Ivana Kockar	Keith Bell
Ken Smith	Paul Fletcher	Andrea Michiorri
	Gareth McLorn	

Table 8: Groups for the afternoon group discussion

Keith Bell	Paul Fletcher	Ken Smith
Philippe Egrot	Claude Counan	Grant McKay
Bob Ferris	Richard Hair	Norman Macleod
Ziming Song	Damien Culley	Nick Eraut
Richard Coates	Bob Currie	Les Recksiedler
Steve Finney	Sarajit Banerjee	Douglas Ramsay
Dan Kell	Ruth Elder	Ivana Kocker
Ken Webb	Gareth McLorn	Colin Foote
Andrea Michiorri		

5 Appendix 1: Summary of Project Outcomes

Based on the description of work in the contract schedule, the expected outcomes from all tasks are summarised as shown in Table 9. This simplification and condensing of what is to be delivered will help to guide the workshop and multi-criteria assessment.

Table 9: Summary of project outcomes

WP1 T1	Hardware limitations / technology gaps and scope for technical advances in power electronics
WP1 T2	Quantified benefits of selected technologies at distribution level Barriers to deployment and proposed solutions Case studies, products, maturity, risk in bringing to market Impact on wider system of deployment at distribution level
WP1 T3	Models of the GB network to perform dynamic analysis Benefits and costs of different solutions Technology gaps and opportunities Technical requirements for integration including potential constraints and interactions
WP1 T4	Ability of industry to deliver; supply chain constraints Other barriers to development and deployment Possible solutions and investment requirements
WP1 T5	Quantify impact of more renewables Identify environmental and consenting risks and compare with conventional technologies Identify significant problems or opportunities in sectoral development or employment
WP1 T6	Elicit views from a range of stakeholders to inform the multi criteria assessment
WP1 T7	A systematic, clear and consistent appraisal to support recommendations Amongst other criteria, assess through-life costs and ease of implementation
WP1 T8	Identify the technologies that offer the most credible solutions Provide clear recommendations to ETI on opportunities and priorities
WP2 T1	Model of MT-HVDC components and integration into AC model of GB Assessment of power quality and comparison of options Discussion of DC cables and conversion of AC overhead lines to DC Control and operating regimes for MT-HVDC to assist the AC system Conclusions regarding the feasibility of onshore MT-HVDC
WP2 T2	Models of MT-HVDC control systems Assessment of behaviour, performance improvements and interactions
WP2 T3	Potential impact of MT-HVDC on renewables, thereby forming a benefits case
WP2 T4	Barriers and proposed solutions particularly in the supply chain Cost estimates
WP2 T5	Consolidate all findings on MT-HVDC Provide clear recommendations to the ETI on opportunities and priorities

6 Appendix 2: Full Results of Ranking and Scoring

			Participants Rankings																							
Criterion	**Description**	**Calculated Overall Rank**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
1	Potential to enhance UK industrial capacity and knowledge	5	7	4	7	5	6	5	1	3	8	7	1	6	3	3	6	1	4	8	4	3	3	3	8	4
2	Reduce through-life costs	7	4	5	6	2	5	2	6	7	6	8	5	8	5	2	2	3	3	6	2	4	5	7	7	
3	Has a clear business case for all stakeholders	4	2	2	4	6	2	1	2	8	3	6	8	4	4	1	4	4	7	3	2	1	6	8	6	1
4	Overcome/bypass problems with consents	6	8	1	8	7	4	4	3	2	2	3	2	7	8	8	5	4	5	5	2	8	4	6	4	3
5	Potential to enhance Technologies Readiness Levels	8	6	7	5	8	3	8	8	4	7	4	7	5	7	5	3	2	8	7	1	2	7	4	2	6
6	Clear potential to reduce CO2 emissions	1	5	6	1	1	1	3	7	6	4	1	3	2	6	4	2	1	6	1	4	5	8	1	1	2
7	More options and flexibility in network design and operation	2	3	3	2	3		6	4	1	1	2	6	1	2	6	1	2	2	2	3	7	2	5	3	7
8	Reduce (or don't increase) risks in system operation	3	1	8	3	4	1	7	5	5	5	5	4	3	1	7	1	2	1		3	6	1	1	5	5

					Participants "Bets"																								11	options in total
Option	**Description**	**Price**	**Odds (:1)**	**Ranking**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**Total**	**Fraction**
A	Support reviews of security and planning standards	0.849	11.96216216	8	9		20	8		5		5	10		15	15	25	15	5		5	15	5		15	5	8	0	185	0.077147623
B	Prompt changes in regulatory framework to change business drivers	0.835	12.17582418	10	5		10	9		5		10	10	5	15	15	5	10	10		15	30	5		10	5	8	0	182	0.07589658
C	Help to establish common standards and models	0.628	16.50364964	11	5		5	7		10		0	10		5	15	15	10	4		7	5	5		10	5	4	15	137	0.057130942
D	Support R&D in new devices for greater capability/performance, e.g. SiC / Diamond	1.436	6.661341853	1	7	40	3	10	10	5	40	0	15	20	10	5	5	0	20	20	15	0	10	30		20	3	25	313	0.130525438
E	Commission work on new HVDC systems/topologies	0.862	11.75531915	7	14		5	12		5	20	0			10	5	5	15	15	20	5	0	10			30	17	0	188	0.078398666
F	Develop effective DC Breaker / Blocking Capability	1.202	8.152671756	3	12		3	6	30	5		20	15	40	5	5	7	10	2	15	10	0	10	30	5	0	17	15	262	0.109257715
G	R&D on coordination of HVDC in the UK	1.165	8.440944882	4	12	20	5	12	30	5	20	10	10		10	5	15	10	20	15	8	20	5			0	17	5	254	0.105921601
H	Support trials or demonstrations	1.284	7.564285714	2	9	10	5	12	20	25		20	20		5	5	3	10	10	10	5	6	30	40	5	10	10	10	280	0.11676397
I	Investigate use of energy storage to help solve ANM constraints	1.000	10	5	9	10	20	9		5	10	25			5	15	1	0	8	5	10	20	5		40	5	11	5	218	0.090909091
J	Develop condition monitoring and asset management tools for a network with increased power flows	0.849	11.96216216	8	8	10	20	7		20	10	0		35	5	10	1	0	4		10	2	10			20	3	10	185	0.077147623
K	Training and education, e.g. courses, conferences (HVDC, FACTS, PE, ANM)	0.890	11.36082474	6	10	10	4	11	10	10		10	10		10	5	18	20	2	15	10	2	5		15	0	2	15	194	0.080900751
	Sum	11			100	100	100	103	100	100	100	100	100	100	95	100	100	100	100	100	100	100	100	100	100	100	100	100	2398	1
	Min	0.628440367																												
	Ave	1																												
	Max	1.435779817																												

		Support reviews of security and planning standards	Prompt changes in regulatory framework to change business drivers	Help to establish common standards and models	Support R&D in new devices for greater capability/performance, e.g. SiC / Diamond	Commission work on new HVDC systems/topologies	Develop effective DC Breaker / Blocking Capability	R&D on coordination of HVDC in the UK	Support trials or demonstrations	Investigate use of energy storage to help solve ANM constraints	Develop condition monitoring and asset management tools for a network with increased power flows	Training and education, e.g. courses, conferences (HVDC, FACTS, PE, ANM)	Replace or increase generator inertia or otherwise improve system response	
	Paul Fletcher's Group													
		A	B	C	D	E	F	G	H	I	J	K		
Potential to enhance UK industrial capacity and knowledge	1	0	0	7	5	6	6	6	9	7	8	10		64
Reduce through-life costs	2	8	0	5	5	5	5	0	4	5	10	0		47
Has a clear business case for all stakeholders	3	3	4	8	4	9	9	6	7	10	8	10		78
Overcome/bypass problems with consents	4	6	2	1	1	0	8	0	6	9	2	0		35
Potential to enhance Technologies Readiness Levels	5	0	10	5	3	7	7	8	10	10	7	8		75
Clear potential to reduce CO2 emissions	6	7	10	1	6	7	7	0	1	10	1	1		51
More options and flexibility in network design and operation	7	8	1	7	6	10	10	7	8	10	8	1		76
Reduce (or don't increase) risks in system operation	8	0	1	7	2	4	4	10	10	10	1	8		57
		32	28	41	32	48	56	37	55	71	45	38		483
	Ken Smith's Group													
		A	B	C	D	E	F	G	H	I	J	K		
	1	1	5	1	10	1	2	10	8	10	1	10		59
	2	3	8	1	5	1	0	4	6	5	1	1		35
	3	10	10	1	5	1	10	6	8	8	1	10		70
	4	10	8	1	1	1	7	0	3	5	1	0		37
	5	1	1	1	10	1	10	7	10	10	1	5		57
	6	8	10	1	7	1	8	8	10	10	1	2		66
	7	7	10	1	9	1	10	10	10	10	1	8		77
	8	5	5	1	5	1	10	8	5	5	1	5		51
		45	57	8	52	8	57	53	60	63	8	41		452
	Keith Bell's Group	Assume a score of 7 for options identified as "Best" for each criteria, assume 5 where there is a qualifier, otherwise 0												
		A	B	C	D	E	F	G	H	I	J	K	L	
	1	0	0	0	7	7	7	0	0	0	0	7	7	35
	2	0	0	0	0	7	0	0	0	0	7	7	0	21
	3	0	0	0	0	7	7	7	0	0	0	7	7	35
	4	7	7	7	0	0	0	0	7	0	0	7	0	35
	5	0	0	7	0	0	5	0	7	0	0	7	7	33
	6	5	0	0	0	0	0	0	0	7	0	7	0	19
	7	0	7	7	0	7	0	7	0	7	7	7	0	49
	8	7	7	7	0	0	0	7	7	7	3	7	7	59
		19	21	28	7	28	19	21	21	21	17	56	28	286

					Participants "Bets"																								11	options in total
Option	**Description**	**Price**	**Odds (:1)**	**Ranking**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**Total in this Round**	**Fraction**
A	Support reviews of security and planning standards	0.935	10.76470588	6	10	5		12	10	10	15	10		15	5	10		6	15	10	20								153	0.085
B	Prompt changes in regulatory framework to change business drivers	1.082	9.169491525	4	5		10	6	10	20	15	10	10	15	5	15	5	6	15	10	20								177	0.098333333
C	Help to establish common standards and models	0.813	12.53383459	7	20	10		12	0	5	10	10	10	15	5	10		6	5	15	0								133	0.073888889
D	Support R&D in new devices for greater capability/performance, e.g. SiC / Diamond	0.794	12.84615385	8	2			15	10	5				0	15	5	15	8	15		10	30							130	0.072222222
E	Commission work on new HVDC systems/topologies	0.495	21.22222222	11	3		10	7	0	5				10	5	15		6	10	10	0								81	0.045
F	Develop effective DC Breaker / Blocking Capability	0.697	14.78947368	9	5		10	7	0	5				10		0	40	12	10	15	0								114	0.063333333
G	R&D on coordination of HVDC in the UK	0.996	10.04294479	5	10	20	20	5	15	5	5			15		10		8	0		20	30							163	0.090555556
H	Support trials or demonstrations	1.387	6.929515419	2	15	20	20	11	10	5	15	10	20	10	20	10	5	16	10	25	5								227	0.126111111
I	Investigate use of energy storage to help solve ANM constraints	1.357	7.108108108	3	5	10	15	5	20	20	15	30		0	15	5		12	10		20	40							222	0.123333333
J	Develop condition monitoring and asset management tools for a network with increased power flows	0.636	16.30769231	10	5	10	15	5	0	5	5	5		0	10	5	35	4	0		0								104	0.057777778
K	Training and education, e.g. courses, conferences (HVDC, FACTS, PE, ANM)	1.809	5.081081081	1	20	10		15	25	15	20	30	60	10	20	15		16	20	15	5								296	0.164444444
	Sum	11			100	85	100	100	100	100	100	105	100	100	100	100	100	100	110	100	100	100	0	0	0	0	0	0	1800	1
	Min	0.495																												
	Ave	1																												
	Max	1.808888889																												

Appendix B. Smarter Grid Solutions Report: Multi-Criteria Assessment of Technologies

ETI Network Capacity Project

Work Package 1 Task 7

Multi Criteria Assessment

Issued to: Mott MacDonald

By: Smarter Grid Solutions Ltd.

Date: 10/12/2010

Reference: 1008-01-07D

Document Issue Control

Project Start Date: **20/01/2010**

Project Reference: **1008-01**

Document Number: **07**

Version	Date	Prepared by	Checked by	Description
A	21/06/2010	Gareth McLorn	Colin Foote	Spreadsheets only issued for comment
B	26/07/2010	Gareth McLorn	Colin Foote	Report issued to partners for comment
C	30/07/2001	Gareth McLorn	Colin Foote	Issued to ETI for comment
D	10/12/2010	Colin Foote	Gareth McLorn	Incorporating comments

Smarter Grid Solutions contact:

Colin Foote

Head of Power Systems

Telephone: +44 (0) 141 248 0063

Mobile: +44 (0) 7949 168 392

Email: colin.foote@smartergridsolutions.com

Smarter Grid Solutions Ltd.

113 West Regent Street,

Glasgow,

G2 2RU

Table of Contents

Figures

Tables

1 Introduction

The Energy Technologies Institute (ETI) identified the need for important engineering studies to assess innovative approaches and technology solutions that could lead to either:

- the enhancement of the capacity of the *existing* onshore UK electricity transmission and distribution networks, or
- the *expansion* of these networks by means other than the construction of new overhead line infrastructure,

and thereby enable the installation of substantially more renewable energy systems in the UK than the current transmission and distribution (T&D) systems can accommodate.

The project is aimed at supporting the ETI's overall goal of accelerating the deployment of technologies that will help reduce greenhouse gases emissions and thus help achieve climate change goals. The outcome is to be a thorough, coherent and well presented analysis that will enable the ETI to make informed decisions as to where future work in the programme should be directed.

1.1 Project Structure

Work Package 1 concentrates on the novel technologies with the potential to release capacity in the UK T&D networks. Work Package 2 concentrates on the feasibility of multi-terminal HVDC in the UK transmission network. The work comprises a literature review and modelling of the various technologies integrated into the networks to determine their performance, effectiveness and the requirements for such proposed integration. It also includes analysis of environmental and social impacts, and of the barriers to development and deployment.

Task 6 in Work Package 1 has delivered a workshop that allowed all project partners to meet with ETI members and others to discuss the technology options, benefits, barriers and solutions. The workshop collected information and opinions that were used to perform a multi criteria assessment in Task 7 and inform the final project conclusions. The workshop and multi criteria assessment encompasses the work done in both work packages and so covers all aspects of the project scope. The final project report will consolidate the outputs from all tasks and provide clear recommendations to the ETI in respect of its Energy Storage and Distribution Programme scope, technology development opportunities and research and development priorities.

This document describes the Task 7 multi criteria assessment. The Task 6 workshop has been described in a separate document, 1008-01-04B T6 Workshop Review Internal.

1.2 Task Objectives

The multi-criteria assessment has been informed by the workshop but also takes account of the outcomes of Tasks 1 to 5 in WP1 and Tasks 1 to 4 in WP2. The objective was to produce a multi-criteria assessment that:

- Uses the outcomes of the workshop and the other tasks to perform an objective assessment of the technologies identified and examined
  - Combines the results of quantitative and qualitative analysis with opinions gathered in the workshop
  - Identifies what is subjective and reflects the range of opinions expressed at the workshop

  - The assessment criteria agreed and used at the workshop have been revised according to project requirements

- Provides a systematic, clear and consistent appraisal of the multiplicity of benefits and risks that will support recommendations on further work
- Identifies the technology development options that address the most restrictive barriers and offer the optimal mix of benefits

The Task 7 assessment is also to:

- Use the outcomes of the workshop and the other tasks to assess the ease of implementation (e.g. consenting and the practicalities of installation and ongoing maintenance)
- Use the outcomes of the workshop and the other tasks to assess through-life costs, with a comparison of the costs of the various technology solutions against conventional up-front reinforcement
- Explore the assignment of costs between multiple stakeholders in a heavily regulated environment

2 Development Options

The assessment has considered a set of development opportunities, or options. These represent options for further action by the ETI or others.

2.1 Workshop Options

The outcomes from the morning sessions of the workshop were used to collate a set of development opportunities. The options identified and used in the remainder of the workshop were:

A. Support reviews of security and planning standards

B. Prompt changes in regulatory framework to change business drivers

C. Help to establish common standards and models

D. Support R&D in new devices for greater capability/performance, e.g. SiC / Diamond

E. Commission work on new HVDC systems/topologies

F. Develop effective DC Breaker / Blocking Capability

G. R&D on coordination of HVDC in the UK

H. Support trials or demonstrations

I. Investigate use of energy storage to help solve ANM constraints

J. Develop condition monitoring and asset management tools for a network with increased power flows

K. Training and education, e.g. courses, conferences (HVDC, FACTS, PE, ANM)

During afternoon discussions, one group identified a 12th opportunity:

L. Replace or increase generator inertia or otherwise improve system response, especially when it is windy and the output from wind farms is high; this would free capacity on the network and reduce security margins.

2.2 Revised Options

The workshop options were reviewed and those used in the assessment are described below.

2.2.1 Support reviews of security and planning standards

This development option was interpreted as being a review of GB SQSS criteria and other system planning standards. The GB Security and Quality of Supply Standard (GB SQSS) sets out the transmission planning standards currently used by the GB transmission licensees. The standard was established for a power system predominately supplied by conventional generation and has provided the basis for the development of an economic and efficient transmission system over the years. As the levels of penetration for intermittent renewable generation into the GB grid system have increased, concerns have been raised over the suitability of the existing GB SQSS and its ability to continue to deliver an optimum level of transmission investment in the midst of such huge change.

2.2.2 Prompt changes in regulatory framework to change business drivers

This development option is concerned with changes to the regulatory framework as overseen by Ofgem. It is felt that it could be possible for the regulator to strike a better balance between technocratic economic theory and providing potential generators with incentives to connect to the system. For instance, the issue of Ofgem enforcing a localised transmission charging mechanism has been very controversial over the last number of years as it effectively acts to discourage generators from being situated in the areas where there is the most potential to be had from exploiting renewable energy resources.

2.2.3 Help to establish common standards and models

This development option is concerned with standards and models for both utilities (i.e. specification / functional requirement standardisation) and manufacturers (i.e. modularisation and reduce major differences between various manufacturer topologies, controls, etc.).

From a manufacturing perspective, as industries or products mature there is normally a period of consolidation where the “winning”, or dominant, application of the technology usually becomes the basis for an industry standard. This helps reduce costs on a number of levels for producers as the amount spent on actual R&D work will be reduced, there should be a quicker product turnaround time, and the pool of appropriately skilled engineers available to create or maintain these technologies should be much larger than for niche applications.

For example, in the case of STATCOMs, there are several competing topologies that are significantly different from one another although they provide the same overall functionality. From a customer perspective this could be seen as a deterrent to buying the products due to the risk involved of a customer being forced to “pick a winner”. Not choosing the “winner” could have financial implications for the network operators.

2.2.4 Support R&D in new devices for greater capability/performance

Many of the fundamental building blocks for each of the technologies under review are power electronics modules. Research in this area could thus have a wide reaching impact, from a bottom-up perspective, with regards to the effect it would have on each of the other technology areas. The assessment considers the benefits to be had from enhancing the performance of IGBT and thyristor devices specifically and exploring the potential gains to be had from introducing novel materials, such as Silicon Carbide (SiC) and diamond, as part of an improved semiconductor solution.

2.2.5 Commission work on new HVDC systems/topologies

HVDC is a relatively mature technology but, due to the compact nature of the UK grid, industrial experience in this country with regards to applying HVDC to our networks is fairly limited. The assessment of this option concentrates on the benefits to be gained from supporting projects that focus on proving the viability of new innovations within the scope of HVDC (e.g. multi-terminal applications) or projects which will result in experience levels of HVDC deployment within the UK being increased. It is important to consider which specific aspects of HVDC are likely to be deployed in the UK and whether any unique problems are likely to be encountered from trying to apply HVDC to the grid in this country. These issues have been addressed in this project, particularly in WP2 where studies highlighted the potential value of fast power controllability in improving system dynamic response but noted the limitations imposed by the security philosophy and the possibility of post-fault thermal overloads on parallel AC circuits.

2.2.6 Develop effective DC breaker or blocking capability

DC breakers and/or blocking capability are required to implement multi-terminal HVDC schemes and allow the application of VSC type HVDC to overhead lines. These devices have been applied to HVDC links in the past, but further research in this area would allow for further applications of HVDC.

Assessment of this option tries to quantify how crucial any advances in this field will be in terms of aiding the maturity of VSC-HVDC systems and thus multi-terminal HVDC topologies, where the possibility of being able to safely and reliably disconnect sections of HVDC networks has been identified as a major enabler for the technology subset. The investigation will also take account of the likely availability of DC breaker options, developed by established companies, over the coming years.

It should be noted that some potential alternatives to DC breaking technologies exist which will help to address fault management issues in HVDC networks. For example, one solution would use IGBTs in place of diodes to provide a breaking capability.

2.2.7 R&D on coordination of HVDC in the UK

This option is concerned with exploring the integration of HVDC within the existing network and the co-ordination of multiple HVDC installations, which may have terminals that are electrically close to one another or may form a part of separate parallel paths through the network. The focus is on the system level rather than on devices, HVDC topologies or individual components.

This area has started to be explored within this project. The outcomes are fully described in the project reports and the conclusions are described in the final project report.

2.2.8 Support trials or demonstrations

This option is concerned with demonstrating practical installations of devices or new technologies within the current UK transmission and distribution networks. With many technology solutions being proposed and significant problems starting to emerge on networks, there are opportunities to support trials and demonstrations of new technologies either as alternatives or in parallel with conventional solutions.

2.2.9 Investigate use of energy storage to help solve ANM constraints

Energy storage was highlighted in the workshop as being of interest because of its potential to further enable the greater adoption of ANM technology within the UK grid. Storage could help to address power flow constraints by, in effect, delaying the transfer of power to a time that it can be accommodated on a constrained network. Distributed storage devices, with suitable power electronic interfaces, would also provide a flexible means of controlling voltages on constrained networks. ANM technology would be required to exploit this type of resource most effectively; whereby the use of storage elements within a network could be managed to coincide with periods of high or low demand and high or low generation. If a highly efficient energy storage technology became widely available it would complement the connection of greater levels of intermittent renewable energy to the network.

2.2.10 Develop condition monitoring and asset management tools for a network with increased power flows

Many of the technologies and proposed changes in network operation will result in the existing assets being subjected to higher power flows. As a result, those assets may suffer additional degradation. Furthermore, as they are carrying more power than the lines they replace the consequence of their failure will become more severe. It was suggested at the workshop that new tools for condition monitoring and asset management would be important in supporting a network with higher power flows.

2.2.11 Training and education, e.g. courses, conferences

Assessment of this option seeks to quantify how much of an impact can be made in terms of enhancing existing levels of engineering expertise within the UK power systems sector by way of an increased emphasis on training and education. The assessment also takes into account how realistic it is for this option alone to act against the prevailing circumstances which the industry now finds itself in, namely that one of the major barriers identified from conducting the analysis thus far is that there is a major shortage in the supply of appropriately skilled engineers who will be able to execute the many changes envisaged to the UK grid over the coming years.

2.2.12 Replace or increase generator inertia or otherwise improve system response

Discussions during the workshop highlighted problems associated with reduced system inertia, which is expected when there is a higher proportion of power coming from wind farms or other renewable sources that do not use conventional generators and turbines. With lower inertia the system will be more prone to frequency deviations and there is a greater risk of instability and collapse. This would be especially true when it is windy and the output from wind farms is high and therefore places a limit on the maximum capacity of renewables that can be accommodated. There is an opportunity to develop solutions that will replace the inertia lost from switching off conventional large turbine generators or otherwise improve system response. This will help to ensure an acceptable response to fault events and maintain frequency regulation, which would thereby enable more renewables to connect.

3 Technologies

The project covers a range of technologies, which fit into different categories and are related to one another in different ways. The technologies used in the multi-criteria assessment are listed below.

- HVDC: LCC
- HVDC: CCC
- HVDC: VSC
- DC breakers

- Series compensation: TCSC
- Shunt compensation: SVC
- Shunt compensation: STATCOM
- Phase shifting transformers / quadrature boosters
- Active power flow management
- Dynamic thermal ratings
- Active voltage management
- Demand side management
- Energy storage

The list of technologies includes all those within the scope of the project and those additionally considered through the work in other Tasks. The technologies are all explained in detail in other Task reports. The list also includes DC breakers as they were identified as an important facilitating technology and energy storage as it was identified as being complementary to active power flow management and of high potential value in a system with a large penetration of intermittent renewable sources.

4 Barriers

The project has identified a range of barriers that restrict further use of the technologies. By reviewing the barriers faced by each technology a single set of barriers has been identified; some are specific to particular technologies but others are common to multiple technologies. The common barriers are listed below.

- High costs
- Limited deployment experience in the UK
- Lack of necessary technical skills in the UK
- Maturity level of the technologies
- Restrictions in the supply chain
- Lack of manufacturing standards or compatibility
- Footprint and other environmental constraints
- Regulatory constraints
- Technical performance in terms of losses/efficiency
- Technical limitations and operational constraints
- Negative impacts on quality of supply

The links between technologies and common barriers are summarised in Figure 1 where a shaded rectangle indicates that the technology is affected by the barrier and an empty block indicates that it is not.

The links between the common barriers and the development options are summarised in Figure 2 where a shaded rectangle indicates that the development option is expected to help address the barrier and an empty block indicates that it is not.

Figure 1: Links between technologies and common barriers

	High costs	Limited deployment experience in the UK	Lack of necessary technical skills in the UK	Maturity level of the technologies	Restrictions in the supply chain	Lack of manufacturing standards or compatibility	Footprint and other environmental constraints	Regulatory constraints	Technical performance in terms of losses/efficiency	Technical limitations and operational constraints	Negative impacts on quality of supply
HVDC: LCC	■				■	■	■			■	■
HVDC: CCC	■	■			■	■	■			■	■
HVDC: VSC	■	■	■		■	■	■		■		
DC Breakers	■	■		■	■	■					
Series compensation: TCSC	■	■	■			■	■			■	■
Shunt compensation: SVC						■				■	
Shunt compensation: STATCOM	■					■					
Phase shifting transformers / quadrature boosters					■	■				■	
Active power flow management				■		■		■			
Dynamic thermal ratings		■		■							
Active voltage management				■		■		■			
Demand side management	■	■						■		■	
Energy storage	■			■		■	■	■	■	■	■

Figure 2: Links between development options and common barriers

	High costs	Limited deployment experience in the UK	Lack of necessary technical skills in the UK	Maturity level of the technologies	Restrictions in the supply chain	Lack of manufacturing standards or compatibility	Footprint and other environmental constraints	Regulatory constraints	Technical performance in terms of losses/efficiency	Technical limitations and operational constraints	Negative impacts on quality of supply
Support reviews of security and planning standards			■			■		■			■
Prompt changes in regulatory framework to change business drivers	■						■	■			
Help to establish common standards and models	■		■	■	■	■					
Support R&D in new devices for greater capability/performance	■		■	■	■		■		■	■	■
Commission work on new HVDC systems/topologies		■	■	■	■	■	■	■	■	■	■
Develop effective DC breaker or blocking capability				■	■				■	■	■
R&D on coordination of HVDC in the UK		■	■	■		■		■	■	■	■
Support trials or demonstrations	■	■	■	■	■	■	■	■	■	■	■
Investigate use of energy storage to help solve ANM constraints				■					■	■	
Develop condition monitoring and asset management tools				■					■	■	■
Training and education, e.g. courses, conferences			■			■		■	■	■	
Increase generator inertia or otherwise improve system response									■	■	■

With the shaded rectangles assigned a value of one and the empty blocks assigned a value of zero, a simple sum of products is calculated to determine the strength of links between technologies and development options formed by the relationships to the common barriers. The results are shown in Figure 3. Zero values are entered where the development option has no link to a technology; for example, the development options concerned with HVDC only affect the HVDC technologies and the development of an effective DC breaking capability is assumed to affect only VSC and DC breakers.

Figure 3: Links between development options and technologies

	HVDC: LCC	HVDC: CCC	HVDC: VSC	DC Breakers	Series compensation: TCSC	Shunt compensation: SVC	Shunt compensation: STATCOM	Phase shifting transformers / quadrature boosters	Active power flow management	Dynamic thermal ratings	Active voltage management	Demand side management	Energy storage	Sum
Support reviews of security and planning standards	2	2	2	1	3	1	1	1	2	0	2	1	3	21
Prompt changes in regulatory framework to change business drivers	2	2	2	1	2	0	1	0	1	0	1	2	3	17
Help to establish common standards and models	3	3	4	4	3	1	2	2	2	1	2	1	3	31
Support R&D in new devices for greater capability/performance	5	5	5	3	5	1	1	2	0	0	0	0	0	27
Commission work on new HVDC systems/topologies	5	6	6	4	0	0	0	0	0	0	0	0	0	21
Develop effective DC breaker or blocking capability	0	0	2	2	0	0	0	0	0	0	0	0	0	4
R&D on coordination of HVDC in the UK	3	4	4	3	0	0	0	0	0	0	0	0	0	14
Support trials or demonstrations	6	7	7	5	7	2	2	3	3	2	3	4	8	59
Investigate use of energy storage to help solve ANM constraints	0	0	0	0	0	0	0	0	1	0	1	1	3	6
Develop condition monitoring and asset management tools	2	2	1	1	2	1	0	1	1	1	1	1	4	18
Training and education, e.g. courses, conferences	2	2	3	1	3	2	1	2	2	0	2	2	4	26
Increase generator inertia or otherwise improve system response	2	2	1	0	2	1	0	1	0	0	0	1	3	13
Sum	32	35	37	25	27	9	8	12	12	4	12	13	31	

The technologies with the highest and lowest sums are HVDC: VSC and dynamic thermal ratings respectively. Thus, the results suggest that the development options will together have the greatest impact on HVDC technologies, particularly VSC and the least impact on dynamic thermal ratings, which is as one would expect given the emphasis on HVDC in the development options.

Based on this simple analysis, the development option considered to have the greatest potential influence across all technologies is “support trials or demonstrations”. This option, and others with relatively high value sums, potentially have the widest ranging impact on the common barriers and therefore could do most to push forward the technologies.

However, it is important to highlight the limitations of this analysis. The links between technologies and development options, as defined, are not as direct as this simple calculation suggests. Development options like “support trials or demonstrations” will only influence the specific technologies that are involved in the trial or demonstration. Specific recommendations are made in the final project report.

Some of the development options score very lowly because of their limited applicability. For example, the “Develop effective DC breaker ...” option is considered relevant only to the HVDC: VSC and DC Breakers technology categories and so fails to score for the other technologies. Similarly, the “Investigate use of energy storage ...” option will affect only a subset of the technologies. This further highlights the limitations of the analysis in that options that are very general are being compared with options that are more specific.

Nevertheless, the analysis reveals something about the development options under consideration and their likely impact on the technologies. The emphasis is obviously on HVDC, which reflects the emphasis of the project as a whole. The development options expected to have the widest ranging impact, and so perhaps offering lower risk paths for investment, are:

- Support trials or demonstrations
- Help to establish common standards and models
- Support R&D in new devices for greater capability/performance
- Training and education, e.g. courses, conferences

5 Assessment Criteria

The multi criteria assessment compares and assesses technologies and development options against a set of criteria that represent the objectives and desired outcomes.

5.1 Workshop Criteria

The assessment criteria identified and used in the workshop are shown in Table 1.

The assessment criteria were drawn from the benefits and impacts ideas that arose during the workshop but were modified and added to by the project team to ensure certain issues were addressed. During the workshop the criteria were discussed and revised within the project team, with input from the ETI, to try and produce a coherent set of distinct topics.

The workshop included a session where participants ranked the assessment criteria in order of importance and the results from this session are shown in Table 1. The rankings submitted by all participants were summed and the totals used to determine overall rankings, i.e. the criterion with the lowest total is assigned rank 1 and so on. The totals give some perspective on how closely some of the different criteria were ranked in comparison to others.

Table 1: Workshop Assessment Criteria and Ranking

Description	Summed Rankings	Rank Calculated at Workshop
Potential to enhance UK industrial capacity and knowledge	110	5
Reduce through-life costs	118	7
Has a clear business case for all stakeholders	95	4
Overcome/bypass problems with consents	113	6
Potential to enhance Technologies Readiness Levels	126	8
Clear potential to reduce CO2 emissions	81	1
More options and flexibility in network design and operation	82	2
Reduce (or don't increase) risks in system operation	92	3

5.2 Revised Criteria

The assessment criteria, as defined and used during the workshop, have been revised and refined following discussion with the ETI and further consideration of the development options and assessment method. The revised assessment criteria are listed in Table 2.

Each of the assessment criteria is explained below in terms of what it means for assessing development options and for assessing technologies. There is a brief explanation of the basis for the assessment and details on how the assessment was performed. The ranking of criteria at the workshop is also noted.

Table 2: Revised Assessment Criteria

1	Potential to enhance UK industrial capability and knowledge
2	Potential to reduce through-life costs of technology use
3	Potential to reduce the cost of electricity for consumers
4	Has a clear business case for all stakeholders
5	Potential to overcome or bypass problems with consents
6	Potential to enhance or accelerate Technologies Readiness Levels
7	Potential to reduce CO2 emissions
8	More options and flexibility in network design and operation
9	Impact on system security and reliability
10	Potential to enhance capacity of the existing network
11	Links with other developments or technologies

5.2.1 Potential to enhance UK industrial capability and knowledge

For development options this is concerned with enhancing the skills, intellectual property and ability to deliver the required technologies and solutions within companies operating in the UK. Development options can be assessed in terms of the expectation that they will have a positive impact in the UK rather than elsewhere. The risk that development options will have a negative impact on UK capability is also considered.

The assessment is based on the workshop outcomes and the findings of WP1 T4, WP1 T5 and WP2 T4 in particular. Each development option is assessed as having a low, medium or high potential to enhance UK industrial capability and knowledge. If a risk of a negative impact is identified then this is included in the analysis too.

For technologies this is concerned either with building on an existing UK advantage or highlighting a specific opportunity for the UK to establish a lead in a particular area. Existing UK advantages are identified in terms of (1) technology design, (2) analysis, (3) manufacture, or (4) existing deployments. Specific opportunities in the UK may arise because the technology is (5) being neglected elsewhere or because (6) there is obvious scope for relatively widespread application in the UK.

The assessment is based on information collected at the workshop and the findings of Tasks 1 to 5 in WP1 and Tasks 1 to 4 in WP2. Each technology is assessed in terms of the six sub-criteria listed above. If a technology is considered to have a relatively strong UK advantage or opportunity then it is assigned one point for each sub-criterion. Thus, each technology has a score between zero and six.

5.2.2 Potential to reduce through-life costs of technology use

For development options this is concerned with the potential to reduce costs in the (1) analysis, (2) manufacture, (3) installation, (4) operation, (5) maintenance or (6) decommissioning of the technologies of interest. Cost reductions might be expected to come from advances in the methods and processes used or simply from wider use. Increases in cost might come from greater requirements or complexity in any of the cost areas.

The assessment is based on the workshop outcomes and the findings of WP1 T4, WP1 T5 and WP2 T4. Each development option is assessed against the six cost areas listed above. If a development option is expected to have a positive impact on reducing costs in an area then it is assigned one point. If it is expected to increase costs in an area then it is assigned one negative point. Thus, each development option has a score between negative six and six.

For technologies the potential to reduce through-life costs of technology use is assessed in terms of whether specific opportunities to reduce costs have been identified or whether there is scope for such wide deployment that economies of scale and batch ordering will produce savings.

Specific opportunities to reduce costs have already been identified in WP1 T1, WP1 T4 and WP2 T4. The potential scope for deployment has been discussed in WP1 T2, WP1 T3, WP2 T1 and WP2 T3. Technologies with no specific opportunities to reduce costs and no scope for wide deployment are assessed as having a low potential. Technologies with one or the other are assessed as having a medium potential. Technologies with both are assessed as having a high potential.

5.2.3 Potential to reduce the cost of electricity for consumers

It is impossible to accurately assess the impact of the development options or the technologies on the final cost of electricity for consumers. The price paid by consumers is affected by many factors, including being strongly influenced by international energy prices. The costs of building and running the network are reflected in the final price of electricity but the link is extremely loose.

This criterion is included in the overall assessment by simply identifying those development options and technologies that the workshop participants and the project team collectively perceive to be particularly expensive. Equally, if there is a widely held view that certain development options or technologies offer particularly good value for money or return on investment then this is highlighted. This simple identification is extremely subjective and must be recognised as such but provides a means of incorporating this criterion into an overall assessment.

Development options and technologies are all assessed as being either “excellent value”, “neutral” or “very expensive”.

The ETI consider cost to the consumer to be an important factor in the overall assessment of options.

5.2.4 Has a clear business case for all stakeholders

This has some overlap with other criteria in considering the impact on cost but is dealt with separately to explore the assignment of costs between multiple stakeholders in a heavily regulated environment. The assessment assumes that the existing regulatory environment in the UK is maintained.

The stakeholders considered are:

- Research Organisations
- Consultants
- Equipment Manufacturers
- Generators
- Network Owners and Operators
- Suppliers (Energy Retailers)
- End Customer
- Regulator
- Government

For each development option an assessment is made of the expected impact on costs and revenues for each stakeholder. This is based on project work and workshop discussions where appropriate but otherwise determined by the project team during the assessment. The net impact is assessed as positive, neutral or negative, where positive means revenues exceed costs and with a default of neutral if an assessment is not possible.

The technologies should all be similar in that they will be installed and operated by network owners and operators to enhance the service provided to network users. The assignment of costs between stakeholders can be expected to follow the same pattern according to the prevailing regulatory and commercial framework. If the project work or workshop has identified one of the technologies to be different in that it will require or make possible different assignments of costs then it is assessed in terms of whether it makes it easier or more difficult to agree a clear business case for all stakeholders.

5.2.5 Potential to overcome or bypass problems with consents

For development options this is assessed in terms of whether or not its intent is to overcome or bypass problems with consents and its expected impact on the likely success in achieving consents. The assessment of intent is based on the definition of each option. The expected impact will be subjective based on comments made at the workshop and the project team's view, informed by the work done in WP1 T5. Each development option is assigned one point if its intent is to overcome consents and one point if it is expected to have a positive impact on the granting of consents. Thus, each development option has a score of 0, 1 or 2.

For the technologies the potential to overcome or bypass problems with consents is assessed by comparing the technology to conventional network technologies, i.e. existing overhead lines, cables, transformers and ancillary equipment. The assessment considers whether each of the technologies is likely to present easier or more difficult consent problems in terms of (1) footprint/size, (2) noise, (3) electromagnetic interference or (4) other issues. The assessment of the technologies is based on the information collected in WP1 T5 and in other tasks. Each technology is considered against the four issues listed above and assessed on whether it presents easier, the same or more difficult consent problems.

5.2.6 Potential to enhance or accelerate Technology Readiness Levels

The development options are assessed in terms of whether their purpose is to enhance or accelerate the readiness of the technologies of interest and the specific range of TRLs that will be affected.

This assessment is driven by the definition of the development options, which are in part based on the recommendations from project work, including the identification of gaps and barriers in the development activities currently underway in manufacturers. If a development option is not concerned directly with technology development then it is assigned a score of zero. If the development option is intended to support technology development then it is assigned one point. If the development option is expected to have an impact on technologies that are currently TRL 3-5 then it is assigned an additional point.

The technologies will simply be summarised in terms of their current TRL. This does not form part of the multi criteria assessment but helps to collate some useful information on all the technologies.

The importance of this criterion has been emphasised to the project partners by the ETI.

5.2.7 Potential to reduce CO2 emissions

The reduction of CO2 emissions is of great importance to the ETI but an accurate calculation of CO2 reductions is only possible within narrowly defined circumstances. In making changes to the electricity network, CO2 reductions will come from the connection of additional renewable sources but this may be offset by higher losses in the network equipment.

For development options the potential to reduce CO2 emissions is assessed in very simple terms and subjectively by the project team. Each development option is assessed as having either a positive, neutral or negative impact on reducing CO_2. Where there is reasonable justification to argue that a development option should be allotted anything other than a neutral score this will be indicated.

For each of the technologies the ultimate impact on the connection of renewables, and associated reduction in CO_2 emissions, will depend on the specific circumstances of its installation. However, where the work done in WP1 T2, WP1 T3 and WP2 T3 reached some conclusions, on the amount of additional generation that might be connected by deploying a technology, it is used to derive a score between 0 and 10, with 0 indicating no positive impact and 10 indicating an excellent performance. The technologies are also assessed in terms of the impact on network losses with the subjective assignment of a score between -10 and 0, with 0 indicating no adverse impact and -10 indicating a significant increase in losses. These scores must be considered as merely comparative assessments between the technologies.

The importance of this criterion has been emphasised to the project partners by the ETI.

5.2.8 More options and flexibility in network design and operation

For development options this is assessed in terms of whether or not its intent is to provide more options and flexibility in network design and operation and its expected success. The assessment of intent is based on the definition of each option. The expectation of success is subjective; being based on comments made at the workshop and the project team's view, informed by the work done in all project tasks. Each development option is assigned one point if its intent is to provide more options and flexibility in network design and operation and one point if it is expected to have a positive impact. Thus, each development option has a score of 0, 1 or 2.

For each of the technologies the impact on options and flexibility in network design and operation is assessed based on the work done in WP1 T1-3 and WP2 T1-3 and used to derive a score between 0 and 10, with 0 indicating no impact and 10 indicating a significant improvement in options and flexibility. These scores must be considered as comparative assessments between the technologies.

5.2.9 Impact on system security and reliability

This criterion is a revision of that identified at the workshop as "Reduce (or don't increase) risks in system operation".

For development options the impact on system security and reliability are assessed in very simple terms and subjectively by the project team. Each development option is assessed as having either a positive, neutral or negative impact on system security and reliability by comparison with the conventional approach.

The impact on system security and the reliability of each technology is assessed in terms of (1) severity of the impact of failure, (2) likelihood of failure, (3) capacity to prevent cascade tripping, and (4) ability to recover quickly from a fault condition. Each technology is assessed in terms of the four issues and assigned a score of low, medium or high according to its expected impact and performance. The first two issues are negative while the other two are positive and this is reflected in combining the scores across the four issues.

5.2.10 Potential to enhance capacity of the existing network

The overall purpose of the project is to explore how the technologies might enhance the capacity of the existing network and what development options are available to help overcome barriers to the use of these technologies. Enhancing the capacity of the existing network will allow the connection of additional renewable sources.

For development options the potential to enhance the capacity of the existing network is assessed in very simple terms and subjectively by the project team. Each development option is assessed as having either a positive, neutral or negative impact on enhancing capacity. Where there is reasonable justification to argue that a development option should be allotted anything other than a neutral score this will be indicated.

For each of the technologies the impact on network capacity will depend on the specific circumstances of its installation. However, where the work completed in WP1 T2, WP1 T3 and WP2 T3 reached some conclusions on improving capacity, by way of deploying a technology, it is used to derive a score between 0 and 10, with 0 indicating no impact and 10 indicating a significant enhancement in capacity. These scores must be considered as comparative assessments between the technologies.

5.2.11 Links with other developments or technologies

For development options this is concerned with whether the option is consistent and mutually supportive of other options. This assessment is driven by the definition of the development options, which are based on the recommendations from project work and the outcomes of the workshop. If a development option is independent of all the others then it is assigned a score of zero. It is assigned one positive point for each option with which it is complementary and one negative point for each option with which it is non-complementary.

For technologies this is concerned with whether they enable or enhance other technologies of interest, or whether they will compete with and hinder the use of other technologies of interest. The assessment also considers whether the technology will be enhanced by related applications in domains other than electricity networks. This assessment is based on the links between the technologies and the references to work in other domains already explored within the project. If a technology is considered to be an enabler for other technologies of interest it is assigned a positive point but if it is thought that broader use of the technology will hinder the use of others it is assigned a negative point. If the impact on other technologies of interest is mixed then the overall balance is assessed but the result is likely to be zero points. An additional positive point is assigned if the technology is linked to advances in other domains.

6 Methodology

The multi criteria assessment of development options and technologies has been performed using the assessment criteria as described above. The assessment takes account of the workshop outcomes, the project reports issued thus far, and input from project partners.

<u>Translation to Quantitative Values</u>

Two spreadsheets have been compiled to perform the assessments for development options and for technologies. Each spreadsheet has a worksheet for each criterion in which the development options or technologies are assessed, as described in Section 5. Where the assessment uses qualitative, and often subjective, scores these are translated into quantitative values according to a set of specified “Score Values”. Otherwise, where the assessment is based on assigning points or a numeric score these values are used directly. The scores are then converted to a normalised range such that the minimum score corresponds to a normalised value of zero and the maximum score corresponds to a normalised value of one. This allows the scores across all criteria to be combined fairly.

The normalised scores are combined with weightings for each of the criteria to produce the complete assessment. The weightings are set such that the total across all criteria is one. For example, if all eleven criteria are to be considered equal then all will be assigned a weighting of 1/11=0.09091. The overall score for each development option or technology is the sum of the product of the normalised score and weighting for each of the criteria. The assessment spreadsheets allow for easy variation of criteria weightings.

Weighting Sensitivity Analysis

For each assessment criterion a sensitivity analysis has been performed to show how the overall score changes as the weighting for that criterion (the "focal criterion") varies between zero and one. The analysis sets the weighting for the focal criterion and assumes that all other criteria are weighted equally, and such that the total weightings for all criteria sum to one. For example:

- When the focal criterion weighting is 0 the other ten criteria each have a weighting of 0.1
- When the focal criterion weighting is 0.3 the other ten criteria each have a weighting of 0.07
- When the focal criterion weighting is 1 the other ten criteria each have a weighting of 0

The sensitivity analysis for each assessment criterion gives an illustration of the extent to which that criterion can influence the overall score. If the relative positions of development options or technologies do not change very much across the full range of weightings for a criterion then this indicates that the criterion will not have a significant impact on the relative positions of development options or technologies in the overall assessment. This suggests that the weighting of the criterion might be reduced in the overall assessment so that the impact of criteria that are more discriminatory between the options can be accentuated. In contrast, if a large number of lines cross over one another it indicates that the criterion is influential in discriminating between the options.

Rankings and Weightings

For the overall assessment, criteria weightings have been set based on the workshop outcomes, project partner input and the findings of the sensitivity analysis. The criteria rankings derived from the workshop are shown in Table 1 above. These rankings have been modified to incorporate the new assessment criteria and produce interim values, as shown in Table 3.

- The workshop criterion of "reduce through-life costs" had rank 7. This rank has been assigned to the criterion concerned with reductions in through-life technology costs but the criterion concerned with the cost of electricity for consumers has been assigned a rank of 2 to reflect its importance to the ETI.
- The "potential to overcome or bypass problems with consents" has been increased in rank from 6 to 4 following comments from the ETI.
- The "potential to enhance or accelerate Technology Readiness Levels" has been increased in rank from 8 to 3 to reflect its importance to the ETI.
- The new criterion of "potential to enhance capacity of the existing network" has been assigned a rank of 2 to reflect the central purpose of this project.
- The new criterion of "links with other developments or technologies" has been assigned a rank of 8 to reflect its relative unimportance.

Table 3: Interim Assessment Criteria Rankings

<table>
<tr><th>Description</th><th>Workshop Ranking</th><th>Interim Ranking</th></tr>
<tr><td>Potential to enhance UK industrial capability and knowledge</td><td>5</td><td>5</td></tr>
<tr><td>Potential to reduce through-life costs of technology use</td><td rowspan="2">7</td><td>6</td></tr>
<tr><td>Potential to reduce the cost of electricity for consumers</td><td>=2</td></tr>
<tr><td>Has a clear business case for all stakeholders</td><td>4</td><td>=4</td></tr>
<tr><td>Potential to overcome or bypass problems with consents</td><td>6</td><td>=4</td></tr>
<tr><td>Potential to enhance or accelerate Technology Readiness Levels</td><td>8</td><td>=3</td></tr>
<tr><td>Potential to reduce CO2 emissions</td><td>1</td><td>1</td></tr>
<tr><td>More options and flexibility in network design and operation</td><td>2</td><td>=2</td></tr>
<tr><td>Impact on system security and reliability</td><td>3</td><td>=3</td></tr>
<tr><td>Potential to enhance capacity of the existing network</td><td></td><td>=2</td></tr>
<tr><td>Links with other developments or technologies</td><td></td><td>7</td></tr>
</table>

The interim rankings are further revised based on the sensitivity analysis and converted into weightings for use in the overall assessment in the appropriate results sections below.

7 Results

The assessment results are presented below, for the identified development options and for the technologies of interest. For each criterion there is:

- an appropriate extract from the assessment spreadsheet;
- a set of notes providing justification for, and explanation of, the scores; and
- a plot showing the results of the weighting sensitivity analysis.

The plots Figure 4show the overall weighted scores for each development option or technology as the weighting for the criterion of interest is varied and all others are equal to one another. The scores on the left hand side are those that would result if the criterion was of no importance and so had a zero weighting. The scores on the right hand side are those that would result if the criterion was the only one that mattered and so had a weighting of one. If the score lines cross over one another it indicates that this criterion is important in separating the development options.

For the development options and then for the technologies, the multiple criteria are combined by presenting the normalised scores, the final criteria weightings, and the resultant overall scores.

7.1 Development Options

The twelve identified development options are all assessed against each of the eleven criteria.

7.1.1 Potential to enhance UK industrial capability and knowledge

Table 4: Assessment of development options against criterion 1

Potential to enhance UK industrial capability and knowledge

No.	Development Option	Potential To Fulfil Criterion	Risk of Negative Impact	Score	Normalised
1	Support reviews of security and planning standards	Medium	None	1	0.67
2	Prompt changes in regulatory framework to change business drivers	Medium	None	1	0.67
3	Help to establish common standards and models	Low	Possible	-1	0.00
4	Support R&D in new devices for greater capability/performance	Medium	None	1	0.67
5	Commission work on new HVDC systems/topologies	High	None	2	1.00
6	Develop effective DC breaker or blocking capability	High	None	2	1.00
7	R&D on coordination of HVDC in the UK	High	None	2	1.00
8	Support trials or demonstrations	High	None	2	1.00
9	Investigate use of energy storage to help solve ANM constraints	High	None	2	1.00
10	Develop condition monitoring and asset management tools for a network with increased power flows	Medium	None	1	0.67
11	Training and education, e.g. courses, conferences	High	None	2	1.00
12	Replace or increase generator inertia or otherwise improve system response	Low	None	0	0.33
			Max Raw Score	2	
			Min Raw Score	-1	

Score Values	
High	2
Medium	1
Low	0
None	0
Possible	-1

Amendments to the GB SQSS could support the construction of HVDC as a means of replacing part of the AC system within the Main Interconnected Transmission System (MITS). Such a review would also allow Transmission System Operators (TSOs) to better understand the functional requirements for operating HVDC links in parallel with AC transmission system within MITS.

Ofgem could move to incentivise innovation more by underwriting some of the risks that utilities would take in pursuing the advancements of some key technology areas.

It may be possible that if common standards and models are pursued, as a means of further advancing the development of emerging target technologies, it could serve to act against the wider aim of enhancing capability and knowledge within the UK. This argument may be counter-balanced by incidences where industrial collaboration helps to promote the establishment of cross industry standards whilst simultaneously furthering the development of immature technologies. For example, it is known that IEC and CIGRE are seeking to develop a standard voltage level for VSC-HVDC.

Research into silicon carbide technology in particular has historically been funded by the defence and oil industries. It is difficult to quantify what effect power systems based research would have on the overall capability for this material within the UK.

The SiC market has been cornered by one company, Cree Research Inc. It is difficult to see how any research could compete with the experience of this giant in the sector.

There is a need for HVDC to be covered more deeply in the power electronics syllabus at universities. A major obstacle to wider HVDC adoption is a shortage of skilled labour. The fact that the industry is long established but has remained a niche concept might make it difficult to force the technologies into the mainstream in a very short time period.

Fast DC breaking technology does not currently exist as an off-the-shelf product but is in the latter stages of development. Targeted development in this area may present the UK with an opportunity to create highly skilled jobs in area that will be of great interest to other grid systems around the world.

At present there are only two HVDC links in operation within the UK. Both of these links (across the English Channel and the Moyle Interconnector between Northern Ireland and Scotland) are marine deployed LCC-HVDC installations. At the time of writing, two additional links are under construction, namely BritNed (between Britain and the Netherlands) and the East-West Interconnector (between the Republic of Ireland and Wales). Thus, there is currently very limited experience in the UK regarding HVDC – especially regarding onshore developments and links which incorporate VSC technology. Investment in co-ordinated R&D would help to improve knowledge within UK engineering circles.

Supporting trials or demonstrations would enhance UK industrial capability and knowledge. Trials should play a major role in moving a technology from conception to real-life practical use.

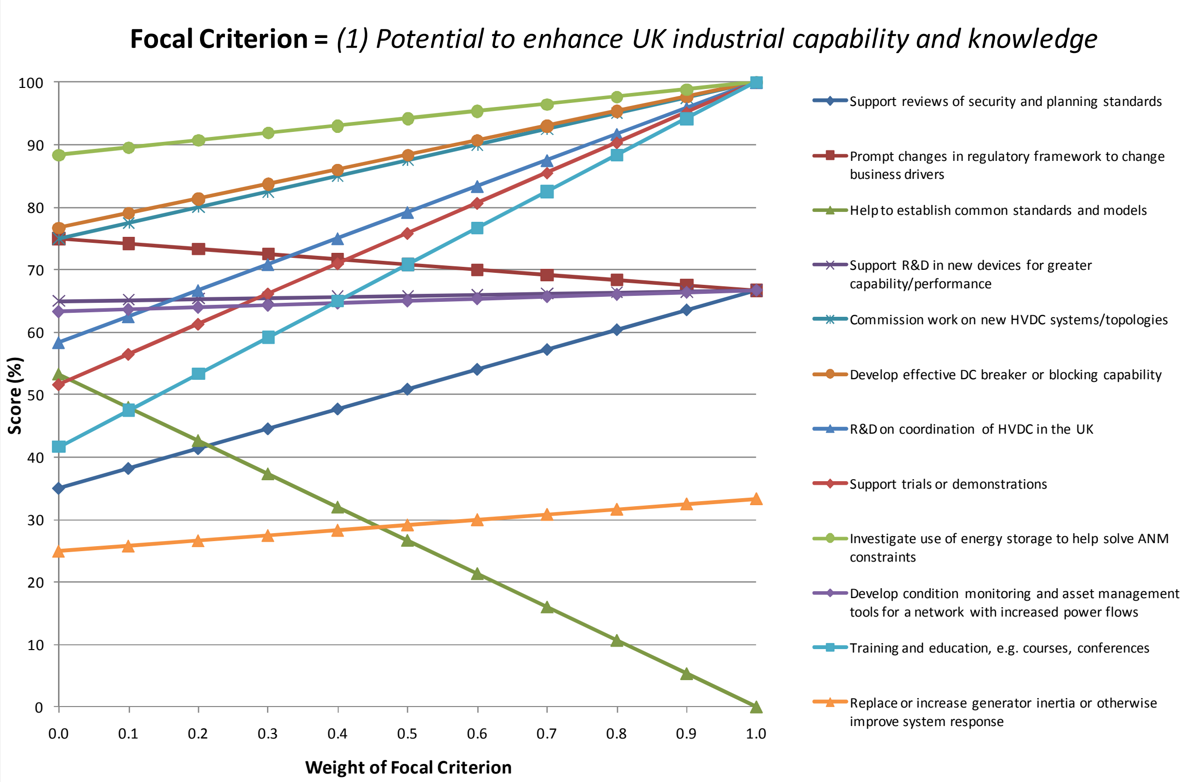
Energy storage is still a relatively immature technology. ANM schemes represent one of the many attractive potential uses for energy storage. Much could be learnt about energy storage applications and subsequently applied in other fields on interest.

The development of condition monitoring is well-established in the power sector and other industrial areas, such as oil exploration and nuclear. The development of new tools would represent a shift in the methodology but it would not be groundbreaking from a technology focussed perspective.

Training and education, including new courses and conferences, would directly address this criterion, i.e. using education to enhance knowledge within the UK.

Figure 4 has many lines crossing over one another so indicates that this criterion helps to separate the development options.

Figure 4: Weighting sensitivity analysis for criterion 1



7.1.2 Potential to reduce through-life costs of technology use

Table 5: Assessment of development options against criterion 2

Potential to reduce through-life costs of technology use									
		Potential for the technology option to reduce costs in ...							
No.	**Development Option**	***analysis***	***manufacture***	***installation***	***operation***	***maintenance***	***decommissioning***	**Score**	**Normalised**
1	Support reviews of security and planning standards	1	1	1	0	0	0	3	0.50
2	Prompt changes in regulatory framework to change business drivers	1	0	1	1	0	0	3	0.50
3	Help to establish common standards and models	1	1	1	1	1	1	6	1.00
4	Support R&D in new devices for greater capability/performance	0	1	1	0	1	-1	2	0.33
5	Commission work on new HVDC systems/topologies	0	1	1	1	1	0	4	0.67
6	Develop effective DC breaker or blocking capability	1	0	1	1	1	1	5	0.83
7	R&D on coordination of HVDC in the UK	0	0	1	1	0	1	3	0.50
8	Support trials or demonstrations	1	0	1	1	1	0	4	0.67
9	Investigate use of energy storage to help solve ANM constraints	1	1	1	1	1	0	5	0.83
10	Develop condition monitoring and asset management tools for a network with increased power flows	1	-1	0	1	1	1	3	0.50
11	Training and education, e.g. courses, conferences	1	0	0	1	1	0	3	0.50
12	Replace or increase generator inertia or otherwise improve system response	0	0	0	0	0	0	0	0.00
							Max Raw Score	6	
							Min Raw Score	0	

It is perceived that support for reviews of security and planning standards would impact significantly on the through life-costs of a project. It would be hoped that the outcome of any review process would be favourable in terms of allowing new renewable generation to be connected to the transmission network.

For example, reviewing SQSS requirements can potentially reduce redundancy requirements as they apply to AC onshore networks. It is noted that offshore DC and offshore AC SQSS requirements have been differentiated primarily to help the economic cases of applying DC networks. A similar argument could be made for onshore DC (or FACTS) versus AC SQSS requirements. Some potential has also been identified to reduce network operational costs and enhance the performance of the network via reviews of security and planning standards.

If the current transmission charging methodology was modified in favour of one that does not discriminate against plant sited in more remote areas then operating costs from the point of view of the generators could come down, depending on which region of Britain they are situated. However, from the system operator's perspective, the transmission charging policy currently in place acts to allocate operation costs amongst their customer base more fairly than costs recouped under any other scheme would.

If various forms, or brands, of the same technology adhere to the same set of guidelines and are composed of roughly the same components then the cost of replacement parts and of training maintenance teams to service the devices through their lifetimes should be lower than if each application of the same technology used bespoke methods. A standardised hierarchical analysis method, which is in keeping with the common standards and models used to develop the technology, would also be beneficial.

The initial cost of SiC and diamond based devices will be much higher than their typical silicon sourced counterparts. However, both substrate types are much more chemically inert and temperature resistant than silicon, making devices that are composed of such materials inherently more robust. Thus, they would not need to be replaced as often as their conventional counterparts.

Fabrication yields for power devices using SiC are poor due to the innate flaws of the SiC crystal structure (micropipes etc). This will have a big effect on device costing. Immature process flows, when compared to the long established silicon CMOS processes, will also act as a price barrier.

From a network perspective, performance and cost of new power electronic devices could also be improved. Lower parasitic impedances can be expected given SiC devices will be smaller in size. This should enable higher device switching speeds and enable better performance to be extracted from the network. The use of higher rated devices may mean that fewer elements will have to be installed per MW in comparison to topologies which use more established power electronics components.

Some research will be needed to assess the impact of decommissioning power electronic components comprised of new materials such as SiC and diamond. Will it cost more to recycle or dispose of old components if they contain any of these new materials?

Topologies have been identified whereby the introduction of VSCs would potentially eliminate the need for gearboxes to be installed in variable speed wind turbines. Benefits derived from this application of VSCs would be the emergence of more simple wind turbine designs, a reduction in the long term maintenance burden for a wind farm and a reduced onus for generators to employ as many specialised wind turbine maintenance engineers and/or have to provide staff with the appropriate advanced levels of maintenance training.

As the average distance from generation sources to load centres increases the viability of HVDC versus high voltage AC solutions improves. Transmission losses will be reduced by opting for HVDC over AC for transmitting power across long distances.

Further research into DC breakers would mean that VSC based multi-terminal HVDC would be easier to implement.

Due to the comparatively great expense of deploying new HVDC in preference to HVAC systems it makes sense to invest in some research and development prior to installing the systems so that efficiencies, benefits to the network and cost reducing measures in the long run can be identified and used to offset the initial cost of the deployment.

Any shared learning from the trialling of a product ought to be able to be used to reduce long term costs in areas such as day to day operation and maintenance.

The reduction of through-life costs is an important criterion to be assessed when considering the use of energy storage. Not only should the life of battery units themselves be considered but also the potential for externalities arising from their use. For instance, the installation of batteries could have a negative impact on the lifespan of other network assets due to higher averaged and more consistent power flows being present in the system. The network is likely to be exercised in a more optimal manner but this may lead to the increasing absence of natural "resting" periods from load flow profiles, meaning that over the course of several years the network will have been stressed significantly more than if energy storage had not been used.

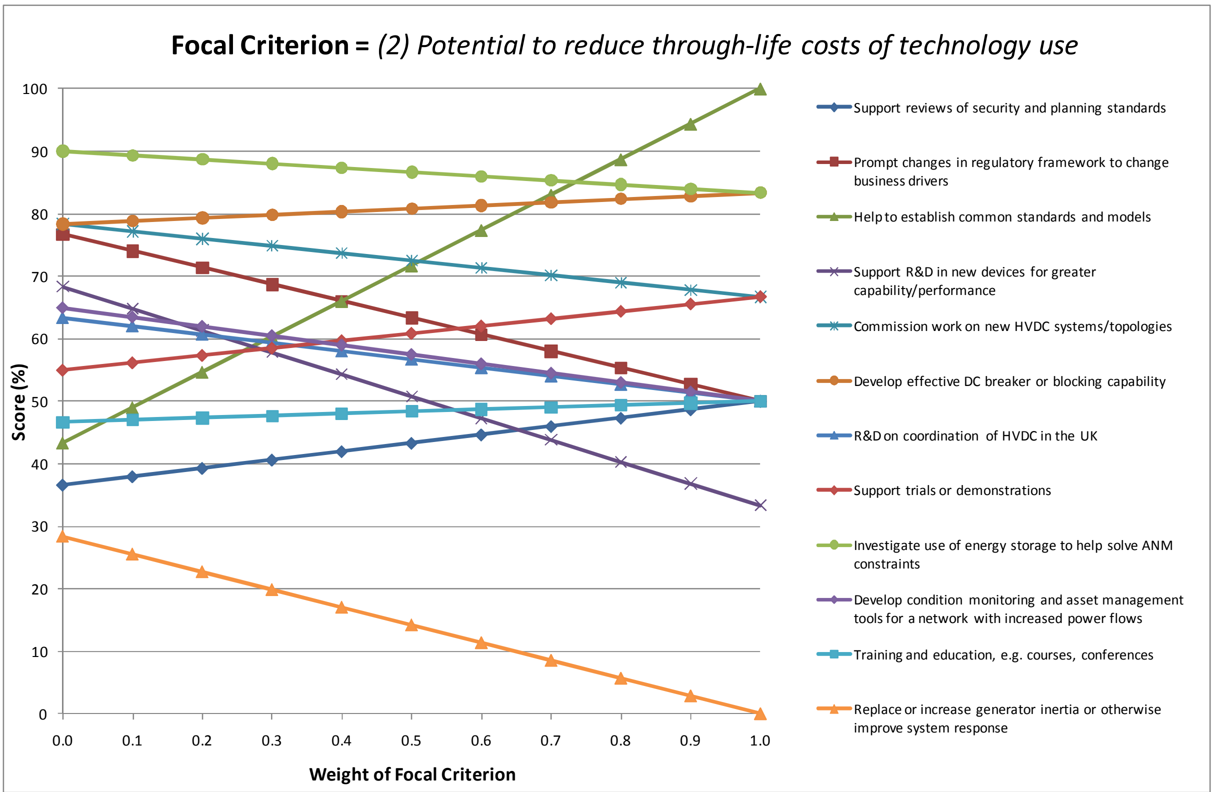
Another factor to consider regarding costs is the type of battery used in the system. Different materials will be subject to varying prices, some materials will be more energy efficient than others and some will be more environmentally hazardous.

The additional cost of condition monitoring would be offset by the long-term savings accrued throughout the life of the asset. Maintenance, for example, could be efficiently targeted and used as a method for prevention, rather than cure, which has the potential to significantly reduce costs for some of the more severe problems which an asset may experience over its life time.

Training and education could be targeted so that the operating costs of the technology deployment are reduced via improvements in the skill sets of the workforce.

Figure 5 has many lines crossing over one another so indicates that this criterion helps to separate the development options.

Figure 5: Weighting sensitivity analysis for criterion 2



7.1.3 Potential to reduce the cost of electricity for consumers

Table 6: Assessment of development options against criterion 3

Potential to reduce the cost of electricity for consumers

No.	Development Option	Potential To Fulfil Criterion	Score	Normalised
1	Support reviews of security and planning standards	Neutral	0	0.00
2	Prompt changes in regulatory framework to change business drivers	Excellent Value	1	1.00
3	Help to establish common standards and models	Excellent Value	1	1.00
4	Support R&D in new devices for greater capability/performance	Neutral	0	0.00
5	Commission work on new HVDC systems/topologies	Excellent Value	1	1.00
6	Develop effective DC breaker or blocking capability	Neutral	0	0.00
7	R&D on coordination of HVDC in the UK	Neutral	0	0.00
8	Support trials or demonstrations	Neutral	0	0.00
9	Investigate use of energy storage to help solve ANM constraints	Excellent Value	1	1.00
10	Develop condition monitoring and asset management tools for a network with increased power flows	Excellent Value	1	1.00
11	Training and education, e.g. courses, conferences	Excellent Value	1	1.00
12	Replace or increase generator inertia or otherwise improve system response	Excellent Value	1	1.00
		Max Raw Score	1	
		Min Raw Score	0	

Score Values	
Excellent Value	1
Neutral	0
Very Expensive	-1

Reducing the amount of spinning reserve required by the system ought to reduce prices. However, at what cost to the network? And will it cost National Grid more to balance the system if the spinning reserve is not there? Thus, it is unclear as to what the real net benefit, if any, would be to the consumer from reviews of security and planning standards.

It is assumed that any changes in the regulatory framework would encourage greater competition between DNOs and between generators. A more competitive electricity market should mean lower prices for consumers.

If the cost savings to be had from establishing common standards and models are realised then these should be passed on to the consumer in the form of reduced prices. However, the extent of this impact from the point of view of most technologies under examination is likely to be minimal.

Power electronic devices are seen as expensive and they will only be used where the costs, which would be passed on to the consumer in the form of higher prices, is matched by the benefits to be gained.

If R&D is funded from within utilities then they will most likely have to re-coup their costs from their customers, so in the short term electricity prices would probably rise. There are considerable up-front costs in R&D but this option has potential for savings in the long term and to also reduce the eventual up-front costs in future deployments.

In the long term, trials and demonstrations could possibly reduce costs to the consumer. However, in the short term prices might have to be increased to cover the cost of running trials. Barring these possible effects, the ETI's contributions might mean that prices would not have to be increased after all. Thus, the act of supporting trials could be regarded as positive in terms of the effect it would have on consumer pricing.

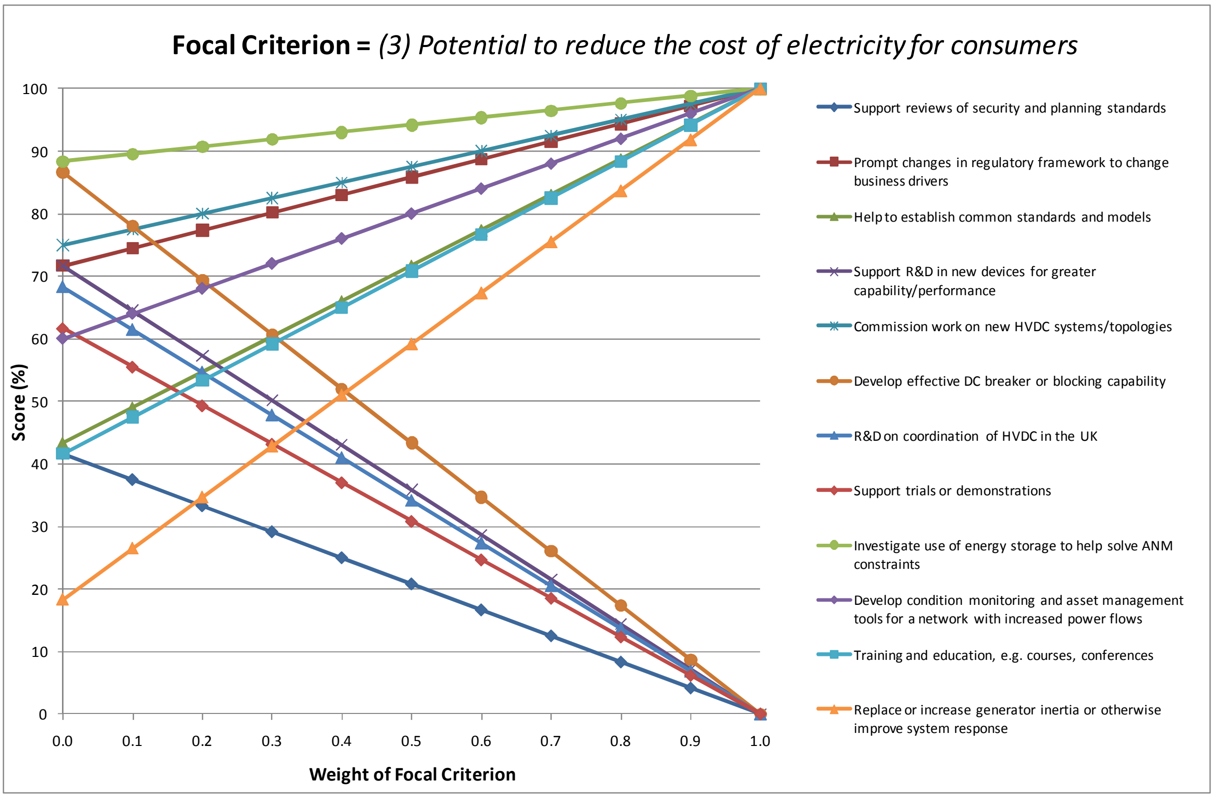
The use of energy storage means that irregular renewable generation profiles can be flattened out and there is less likely to be a need for marginal generation to be applied to balance the system. Discrepancies between peak and off-peak pricing are likely to fall if it becomes easier for utilities to provide power at any point in the day. Thus, investment in energy storage is deemed to be a positive move from the point of view of tying to reduce consumer prices.

The reduction of maintenance costs offered by this option would reduce the running costs of the electricity network, a benefit which could be passed on, in part, to customers. Continual monitoring of the system would hopefully mean that fault conditions could be fixed pre-emptively in many cases, thus reducing the likelihood that consumers will suffer blackouts, which is another benefit.

Some training could be delivered to households with regards to enabling greater demand side participation for the purposes of advancing Active Network Management solutions. From an industry perspective, training would be good value in terms of spreading knowledge of the newest technologies amongst engineers.

Figure 6 has many lines crossing over one another so indicates that this criterion helps to separate the development options.

Figure 6: Weighting sensitivity analysis for criterion 3



7.1.4 Has a clear business case for all stakeholders

Table 7: Assessment of development options against criterion 4

Has a clear business case for all stakeholders

No.	Development Option	Potential To Fulfil Criterion	Score	Normalised
1	Support reviews of security and planning standards	Neutral	0	0.00
2	Prompt changes in regulatory framework to change business drivers	Positive	1	1.00
3	Help to establish common standards and models	Positive	1	1.00
4	Support R&D in new devices for greater capability/performance	Positive	1	1.00
5	Commission work on new HVDC systems/topologies	Neutral	0	0.00
6	Develop effective DC breaker or blocking capability	Positive	1	1.00
7	R&D on coordination of HVDC in the UK	Positive	1	1.00
8	Support trials or demonstrations	Positive	1	1.00
9	Investigate use of energy storage to help solve ANM constraints	Positive	1	1.00
10	Develop condition monitoring and asset management tools for a network with increased power flows	Positive	1	1.00
11	Training and education, e.g. courses, conferences	Positive	1	1.00
12	Replace or increase generator inertia or otherwise improve system response	Neutral	0	0.00
		Max Raw Score	1	
		Min Raw Score	0	

Score Values	
Positive	1
Neutral	0
Negative	-1

It is unclear which party would be the main beneficiary (National Grid, the DNOs or consumers) if there were to be reviews of security and planning standards.

In some respects the current regulatory framework acts against the most logical commercial drivers for change in the system. From a business perspective it is rational for most new distributed wind generation to be connected in Scotland, however the greater potential offered by Scottish sites, in comparison to elsewhere in Britain, is offset by the existence of higher transmission charges.

There is only limited support for innovation from Ofgem, i.e. currently there is very little incentive for utilities with low rates of return on capital assets to invest in higher risk projects, which is a category all large-scale FACTS/HVDC projects being considered in this study (other than SVCs) would fall within (i.e. because there is minimal/no UK application). A change to solve this might include Ofgem allowing utilities to capitalise their investments in higher risk/technology development projects. This would allow the utilities to earn an agreed rate of return on that investment, irrespective of its success or failure; i.e. the investment risks would be underwritten by customers and not the utilities.

As common standards and models are developed devices should become cheaper to manufacture, easier to install and easier to maintain. There should be a fair division of benefits amongst stakeholders.

Support for R&D in new power electronic devices could offer a clear business case to most of the stakeholders involved through reduced losses, lower levels of maintenance required and improved component durability and longevity.

Any analysis should consider that there has been a huge ramp-up in demand for HVDC products in recent years. An observation has been that supply chain delays, not price or lack of demand; represent one of the main obstacles to wider proliferation of the technology. These factors imply that the classic behaviour of an oligopolistic market does not apply. The market should be able to easily absorb new suppliers without them being hindered to a great extent by the competitive barriers, such as price, that one would expect to be a strong feature in a market where only a few established competitors dominate.

There is a clear business case for multiple stakeholders for the development of DC breakers as this is one of the main barriers with regards to adopting VSC based HVDC on a much wider basis in the UK.

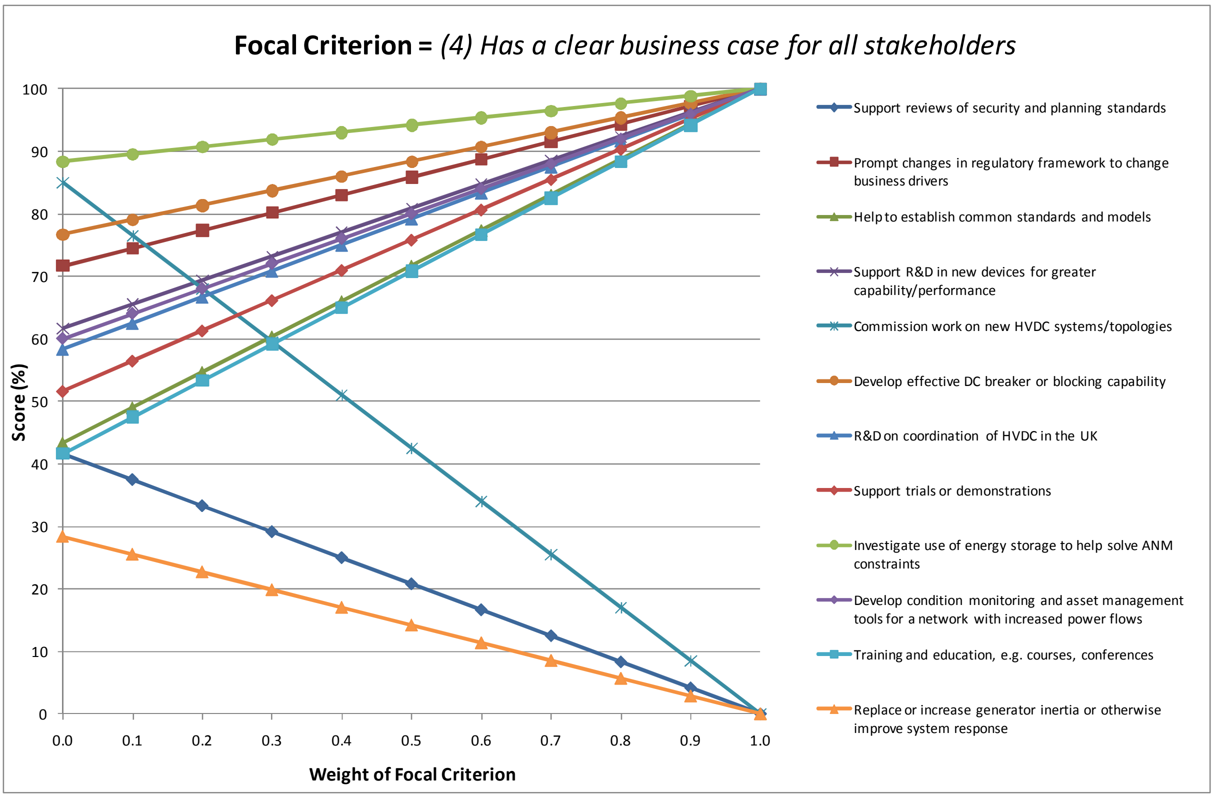
The long term benefits and the fact that greater volumes of power can be transmitted on the transmission system would mean that R&D on coordination of HVDC in the UK would have a clear business case for all. Huge savings could be realised in deploying HVDC should some background work be explored beforehand.

It would be hoped that trialling would sufficiently prove to DNOs and the system operator that an option can work successfully if connected permanently to the system. Successful trialling gives credibility to manufacturers and presents them with better opportunities to get consents for their projects. Much of the equipment on offer will be very expensive to procure, so from a buyer's perspective it is very important that the viability of the device is guaranteed before buying. Trialling therefore helps reassure potential buyers.

From an industry wide perspective there appears to be a very good case for most parties in terms of the benefits enjoyed by way of greater levels of education. The workforce would become better informed, acquire new skills and become more efficient in what they do.

Figure 7 has one line that crosses over several others so indicates that this criterion helps to separate the development options.

Figure 7: Weighting sensitivity analysis for criterion 4



7.1.5 Potential to overcome or bypass problems with consents

Table 8: Assessment of development options against criterion 5

Potential to overcome or bypass problems with consents					
No.	**Development Option**	**Intention to overcome consents?**	**Positively impacts granting of consents?**	**Score**	**Normalised**
1	Support reviews of security and planning standards	1	1	2	1.00
2	Prompt changes in regulatory framework to change business drivers	0	0	0	0.00
3	Help to establish common standards and models	1	1	2	1.00
4	Support R&D in new devices for greater capability/performance	0	1	1	0.50
5	Commission work on new HVDC systems/topologies	0	1	1	0.50
6	Develop effective DC breaker or blocking capability	0	1	1	0.50
7	R&D on coordination of HVDC in the UK	0	1	1	0.50
8	Support trials or demonstrations	0	1	1	0.50
9	Investigate use of energy storage to help solve ANM constraints	1	1	2	1.00
10	Develop condition monitoring and asset management tools for a network with increased power flows	0	1	1	0.50
11	Training and education, e.g. courses, conferences	0	0	0	0.00
12	Replace or increase generator inertia or otherwise improve system response	0	0	0	0.00
			Max Raw Score	2	
			Min Raw Score	0	

Common standards and models should allow key users, such as utilities, to better understand the operability and maintenance requirements for complex technologies as they are applied across different manufacturer platforms. As a result of additional commonality, through-life costs should reduce, business cases should improve, risks to system operation ought to reduce and the training requirements for maintenance and operation will decrease. These factors should help offer a better case for such technologies to be able to overcome consenting barriers.

SiC power devices can be made much smaller for the same voltage use when compared to similarly rated Si devices. Thus, highly rated FACTS or HVDC converter devices composed of SiC based components should cover a smaller area than conventional models with the same rating. SiC also has high temperature resistance, which should reduce the size and complexity of any cooling systems required for power devices. This would also act to reduce the potential footprint of the device.

If new topologies or co-ordinated R&D help to find practical solutions to the problems of converting existing AC lines to DC then this offers an opportunity to enhance transmission capacity within existing corridors.

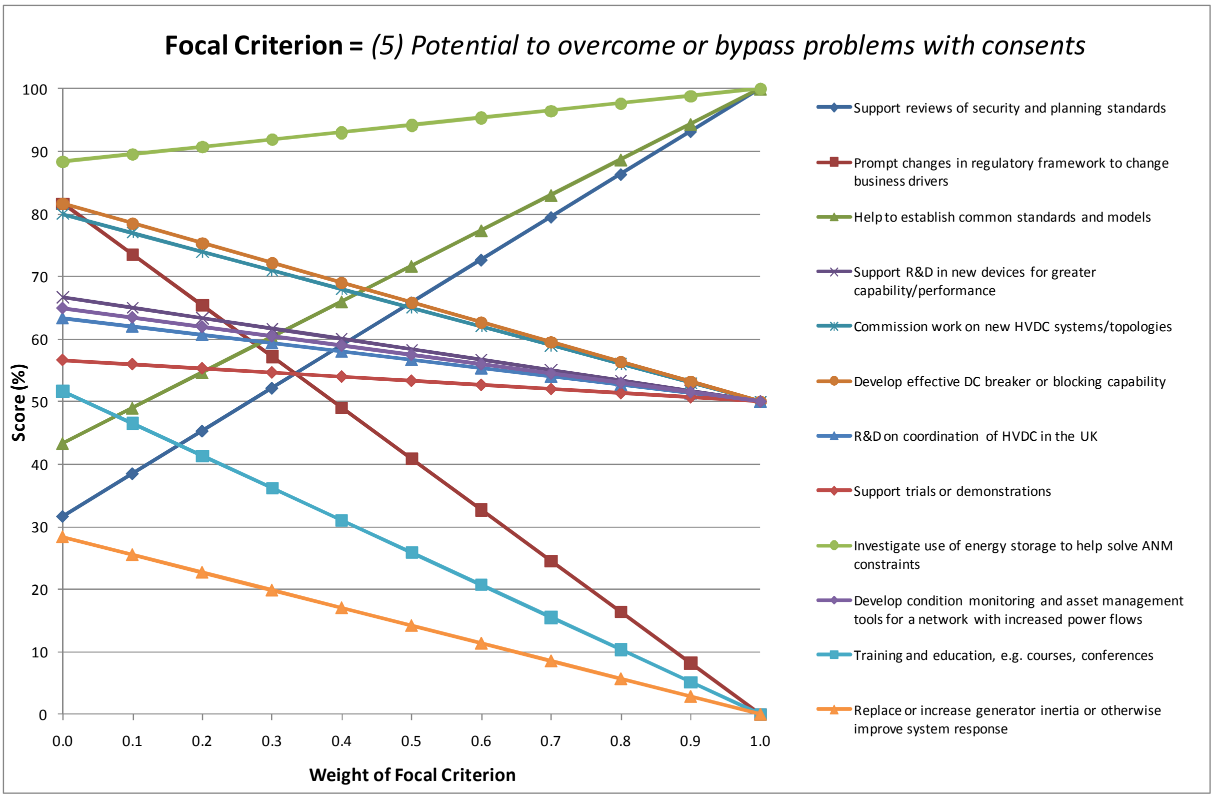
It is easier to overcome or bypass consent issues if the vendor has already trialled a prototype and demonstrated its capability. The granting of consents for that particular device is more likely if it has been shown to work effectively and some of the mystery can be removed regarding its impact.

Energy storage combined with ANM means power flows can be controlled more closely and the irregularity of flows from wind farms could be smoothed out, thereby achieving a better degree of asset utilisation with the existing infrastructure.

Condition monitoring may help to gain consents by ensuring that the potential for serious environmental impacts due to accidents would be reduced.

Figure 8 has many lines crossing over one another so indicates that this criterion helps to separate the development options.

Figure 8: Weighting sensitivity analysis for criterion 5



7.1.6 Potential to enhance or accelerate Technology Readiness Levels

Table 9: Assessment of development options against criterion 6

No.	Development Option	Intention to support technology development?	Impact on technologies at TRL 3-5?	Score	Normalised
	Potential to enhance or accelerate Technology Readiness Levels				
1	Support reviews of security and planning standards	0	0	0	0.00
2	Prompt changes in regulatory framework to change business drivers	1	1	2	1.00
3	Help to establish common standards and models	0	0	0	0.00
4	Support R&D in new devices for greater capability/performance	1	1	2	1.00
5	Commission work on new HVDC systems/topologies	1	0	1	0.50
6	Develop effective DC breaker or blocking capability	1	1	2	1.00
7	R&D on coordination of HVDC in the UK	1	0	1	0.50
8	Support trials or demonstrations	1	1	2	1.00
9	Investigate use of energy storage to help solve ANM constraints	1	0	1	0.50
10	Develop condition monitoring and asset management tools for a network with increased power flows	1	0	1	0.50
11	Training and education, e.g. courses, conferences	0	0	0	0.00
12	Replace or increase generator inertia or otherwise improve system response	0	0	0	0.00
			Max Raw Score	2	
			Min Raw Score	0	

Traditionally it has been perceived that the SQSS is biased against DC transmission and other non-conventional approaches. Thus reviews in SQSS, such that these issues are addressed, may lead to TRLs being improved as more non-conventional technologies are trialled on the system.

A change in the innovation funding provided by Ofgem might be enough to kick start many new projects. This would be a spur towards improving TRLs. This criterion was given a high score in the workgroup discussions for this reason.

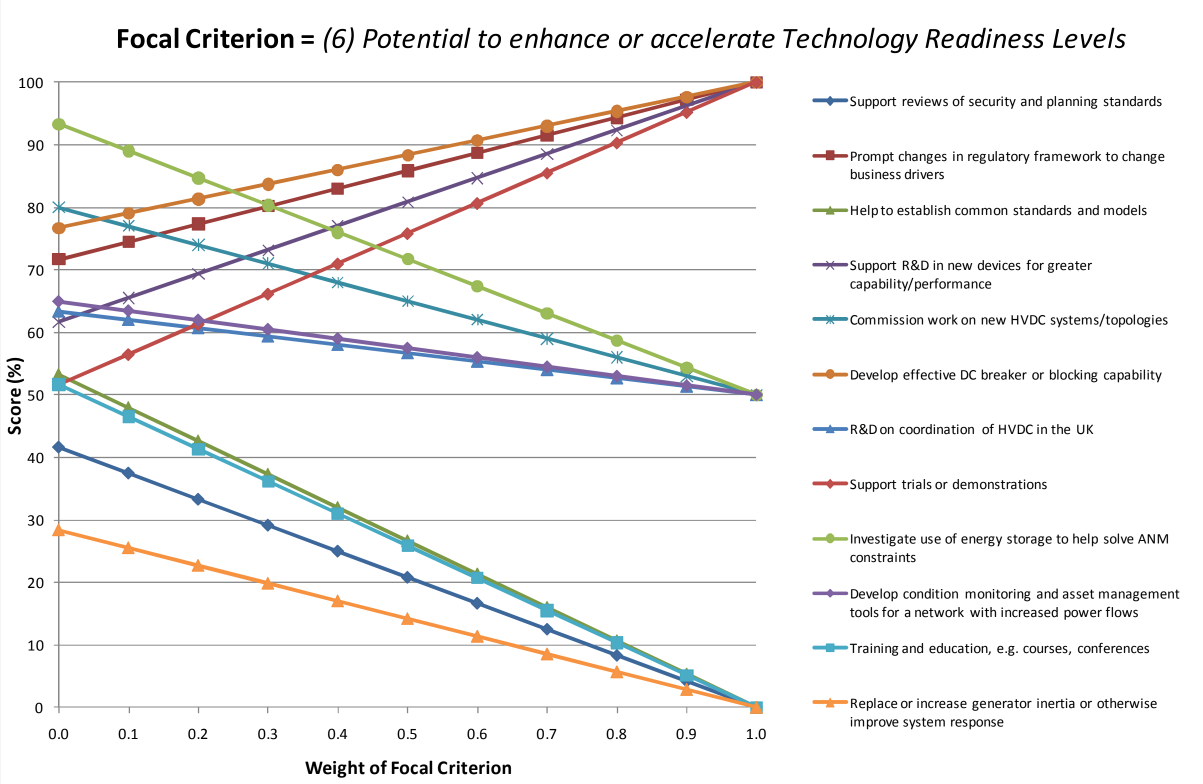
Common standards and models are only likely to come about as a consequence of a technology being judged to have already acquired a high TRL score. During the early stages of the development of a particular technology it is very likely that there will be a number of competing and divergent ideas and methods. Acting to constrict the creative process at this point by trying to apply a one-size-fits-all approach to development may be detrimental in the long-run.

Power electronics are the building blocks for a lot of different technologies and so this option could have a far reaching impact on developing TRLs for other products.

Commissioning work on new HVDC systems/topologies or R&D on coordination of HVDC in the UK would directly impact on the TRLs of the technologies concerned. Similarly, one of the main aims of trialling will be to accelerate the enhancement of TRLs.

Figure 9 has several lines crossing over one another so indicates that this criterion helps to separate the development options.

Figure 9: Weighting sensitivity analysis for criterion 6



7.1.7 Potential to reduce CO2 emissions

Table 10: Assessment of development options against criterion 7

Potential to reduce CO2 emissions

No.	Development Option	Potential To Fulfil Criterion	Score	Normalised
1	Support reviews of security and planning standards	Neutral	0	0.00
2	Prompt changes in regulatory framework to change business drivers	Positive	1	1.00
3	Help to establish common standards and models	Neutral	0	0.00
4	Support R&D in new devices for greater capability/performance	Positive	1	1.00
5	Commission work on new HVDC systems/topologies	Positive	1	1.00
6	Develop effective DC breaker or blocking capability	Positive	1	1.00
7	R&D on coordination of HVDC in the UK	Neutral	0	0.00
8	Support trials or demonstrations	Neutral	0	0.00
9	Investigate use of energy storage to help solve ANM constraints	Positive	1	1.00
10	Develop condition monitoring and asset management tools for a network with increased power flows	Neutral	0	0.00
11	Training and education, e.g. courses, conferences	Neutral	0	0.00
12	Replace or increase generator inertia or otherwise improve system response	Neutral	0	0.00
		Max Raw Score	1	
		Min Raw Score	0	

Score Values	
Positive	1
Neutral	0
Negative	-1

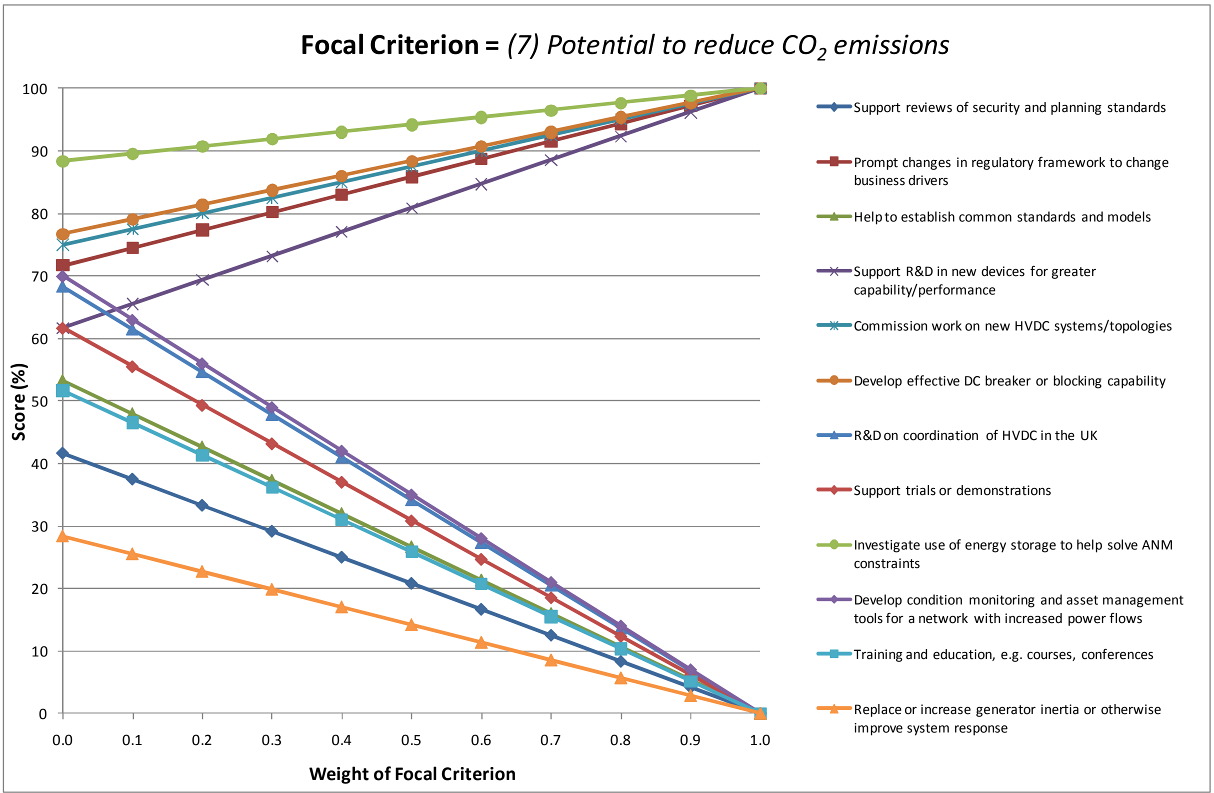
Renewable Obligation Certificates (ROCs) have been helpful in attracting greater numbers of renewable generators to connect to the network over the past few years. Evidence already exists therefore that changes to the regulatory structure can have the potential to reduce CO2 emissions. A clear potential to reduce CO2 emissions was assigned in the workshop after considering the example of changes to renewable energy tariff structures (i.e. currently there may be uneconomic tariff structures for some high renewable potential areas).

As the performance of power electronic devices improve then greater power flows can be facilitated within the grid at greater efficiencies, reducing CO_2 emissions.

DC Breakers are an enabler for VSC based multi-terminal HVDC. This could be an important step towards connecting more renewable energy onto the grid.

Figure 10 has only one line crossing over others so indicates that this criterion is not very helpful in separating the development options.

Figure 10: Weighting sensitivity analysis for criterion 7



7.1.8 More options and flexibility in network design and operation

Table 11: Assessment of development options against criterion 8

No.	Development Option	Positive intention?	Positive impact expected?	Score	Normalised
	More options and flexibility in network design and operation				
1	Support reviews of security and planning standards	1	1	2	1.00
2	Prompt changes in regulatory framework to change business drivers	1	1	2	1.00
3	Help to establish common standards and models	0	0	0	0.00
4	Support R&D in new devices for greater capability/performance	0	0	0	0.00
5	Commission work on new HVDC systems/topologies	1	1	2	1.00
6	Develop effective DC breaker or blocking capability	1	1	2	1.00
7	R&D on coordination of HVDC in the UK	1	1	2	1.00
8	Support trials or demonstrations	0	0	0	0.00
9	Investigate use of energy storage to help solve ANM constraints	1	1	2	1.00
10	Develop condition monitoring and asset management tools for a network with increased power flows	0	1	1	0.50
11	Training and education, e.g. courses, conferences	0	0	0	0.00
12	Replace or increase generator inertia or otherwise improve system response	0	1	1	0.50
			Max Raw Score	2	
			Min Raw Score	0	

It is hoped that any reviews of security and planning standards would lead to more flexible design constraints being applied, especially for the connection of new renewable generation.

The establishment of common standards and models will not necessarily lead to improved flexibility with regards to network design and operation. Standardisation could inhibit flexibility as the range of alternative designs could be limited.

New power electronic devices with greater capability/performance will offer better flexibility as they will offer a greater level of control and switching.

The availability of a DC breaking technology would increase the number of options which are available to planners regarding the incorporation of new transmission systems into the existing network.

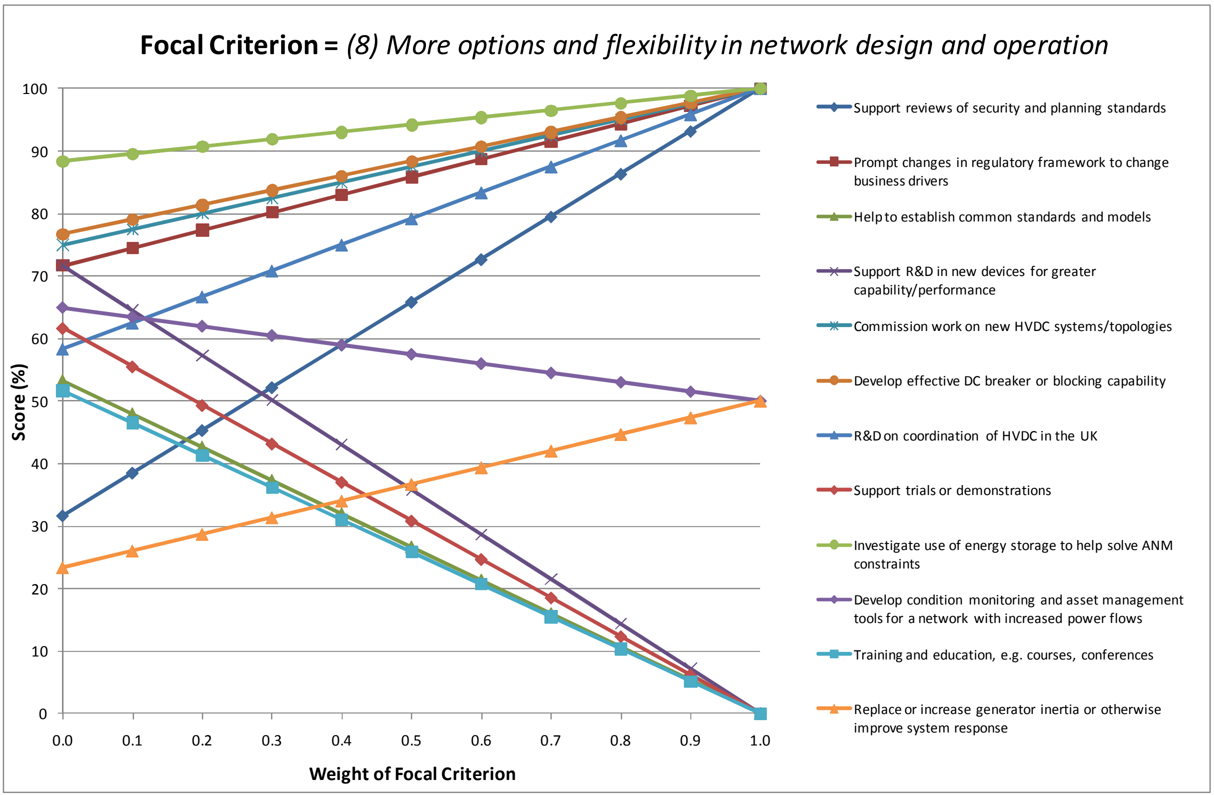
R&D into how HVDC would be implemented in highly meshed mixed AC/DC systems would offer a lot more flexibility to the design of the UK network. The work done in this project provides a strong foundation for further work.

The workshop noted that HVDC applications, to date, have primarily been used for long radial connections to remote generation, bulk power interchanges and back-to-back connections. This collective industry experience differs from many of the various proposed installations of HVDC in future, e.g. HVDC operation within complex AC networks with large-scale generation at either end.

Energy storage in combination with ANM would offer much more flexibility in network operation. This flexibility will be very useful as the UK generation mix becomes more reliant on intermittent technologies.

Figure 11 has several lines crossing over one another so indicates that this criterion helps to separate the development options.

Figure 11: Weighting sensitivity analysis for criterion 8



7.1.9 Impact on system security and reliability

Table 12: Assessment of development options against criterion 9

Impact on system security and reliability

No.	Development Option	Potential Impact	Score	Normalised
1	Support reviews of security and planning standards	Negative	-1	0.00
2	Prompt changes in regulatory framework to change business drivers	Neutral	0	0.50
3	Help to establish common standards and models	Positive	1	1.00
4	Support R&D in new devices for greater capability/performance	Positive	1	1.00
5	Commission work on new HVDC systems/topologies	Positive	1	1.00
6	Develop effective DC breaker or blocking capability	Positive	1	1.00
7	R&D on coordination of HVDC in the UK	Neutral	0	0.50
8	Support trials or demonstrations	Positive	1	1.00
9	Investigate use of energy storage to help solve ANM constraints	Positive	1	1.00
10	Develop condition monitoring and asset management tools for a network with increased power flows	Positive	1	1.00
11	Training and education, e.g. courses, conferences	Positive	1	1.00
12	Replace or increase generator inertia or otherwise improve system response	Positive	1	1.00
		Max Raw Score	1	
		Min Raw Score	-1	

Score Values	
Positive	1
Neutral	0
Negative	-1

Wholesale changes to existing security and planning standards could unnecessarily introduce extra risk into the system at a time when many changes are due to be deployed. Despite good intentions this could have serious implications for the grid.

Standardisation across power system components should make it easier to predict the performance of the system and improve security.

The availability of DC breaking technology will help to improve the security of VSC based HVDC systems. This could prove to be very important as HVDC lines are likely to carry greater amounts of power than their AC counterparts.

Replacing AC links with HVDC alternatives has only been demonstrated once in reality. The lack of industrial experience in this area will bring an inherent amount of risk with regards to applying this idea within the UK.

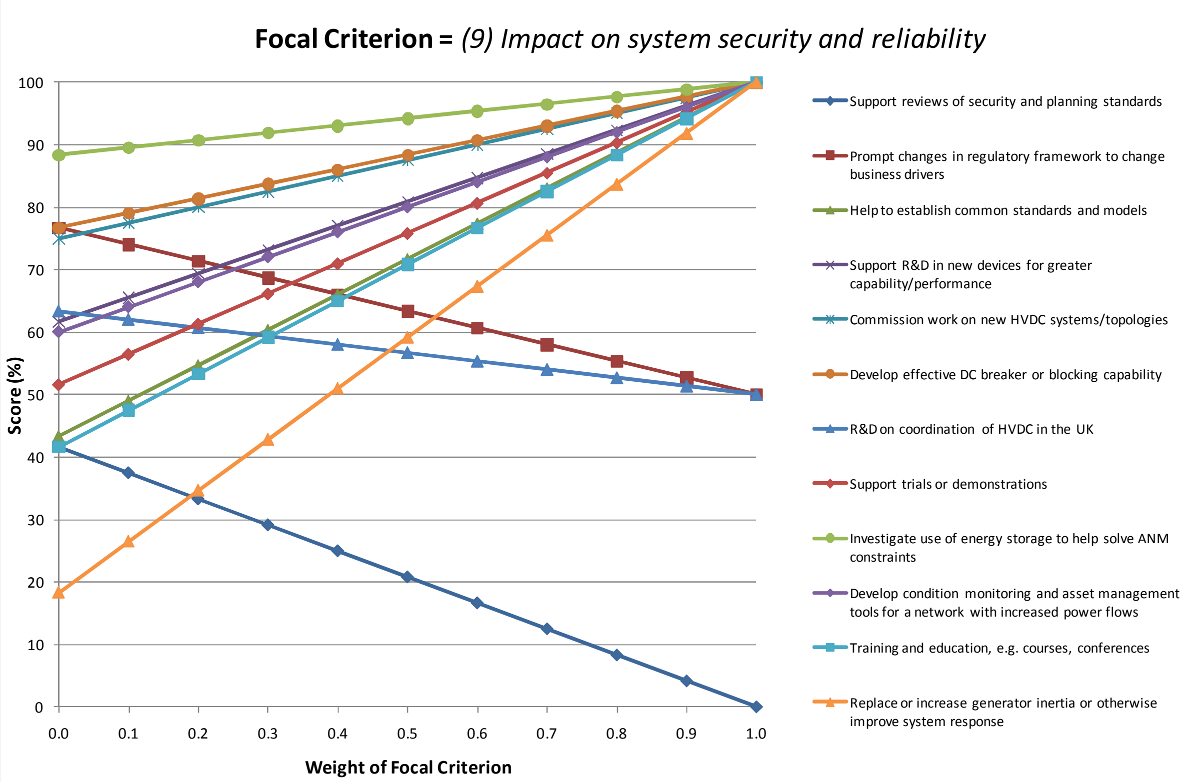
Embedding an HVDC link within an AC network may bring some added benefits regarding system control. HVDC power flows can be controlled much better than the power flows on an AC line. This attribute can be used to stabilize parts of the surrounding AC system.

The ability to use energy storage to adjust power flows at critical nodes on a network could become a helpful tool in controlling the system and ensuring the security of supply.

Condition monitoring would act to provide better system security as faults could be recognised earlier or perhaps even be avoided in some cases via failure prediction analysis.

Figure 12 has several lines crossing over one another so indicates that this criterion helps to separate the development options.

Figure 12: Weighting sensitivity analysis for criterion 9



7.1.10 Potential to enhance capacity of the existing network

Table 13: Assessment of development options against criterion 10

Potential to enhance capacity of the existing network

No.	Development Option	Potential To Fulfil Criterion	Score	Normalised
1	Support reviews of security and planning standards	Neutral	0	0.00
2	Prompt changes in regulatory framework to change business drivers	Positive	1	1.00
3	Help to establish common standards and models	Neutral	0	0.00
4	Support R&D in new devices for greater capability/performance	Positive	1	1.00
5	Commission work on new HVDC systems/topologies	Positive	1	1.00
6	Develop effective DC breaker or blocking capability	Positive	1	1.00
7	R&D on coordination of HVDC in the UK	Positive	1	1.00
8	Support trials or demonstrations	Neutral	0	0.00
9	Investigate use of energy storage to help solve ANM constraints	Positive	1	1.00
10	Develop condition monitoring and asset management tools for a network with increased power flows	Positive	1	1.00
11	Training and education, e.g. courses, conferences	Neutral	0	0.00
12	Replace or increase generator inertia or otherwise improve system response	Neutral	0	0.00

Max Raw Score	1
Min Raw Score	0

Score Values	
Positive	1
Neutral	0
Negative	-1

The evolution of security and planning standards is driven by competing objectives, to enhance the quality and security of supply but also to make fullest use of the installed assets. A review of standards may not enhance the capacity of the existing network and could result in a lower overall capacity to provide higher security of supply. This option is therefore scored as neutral in this assessment.

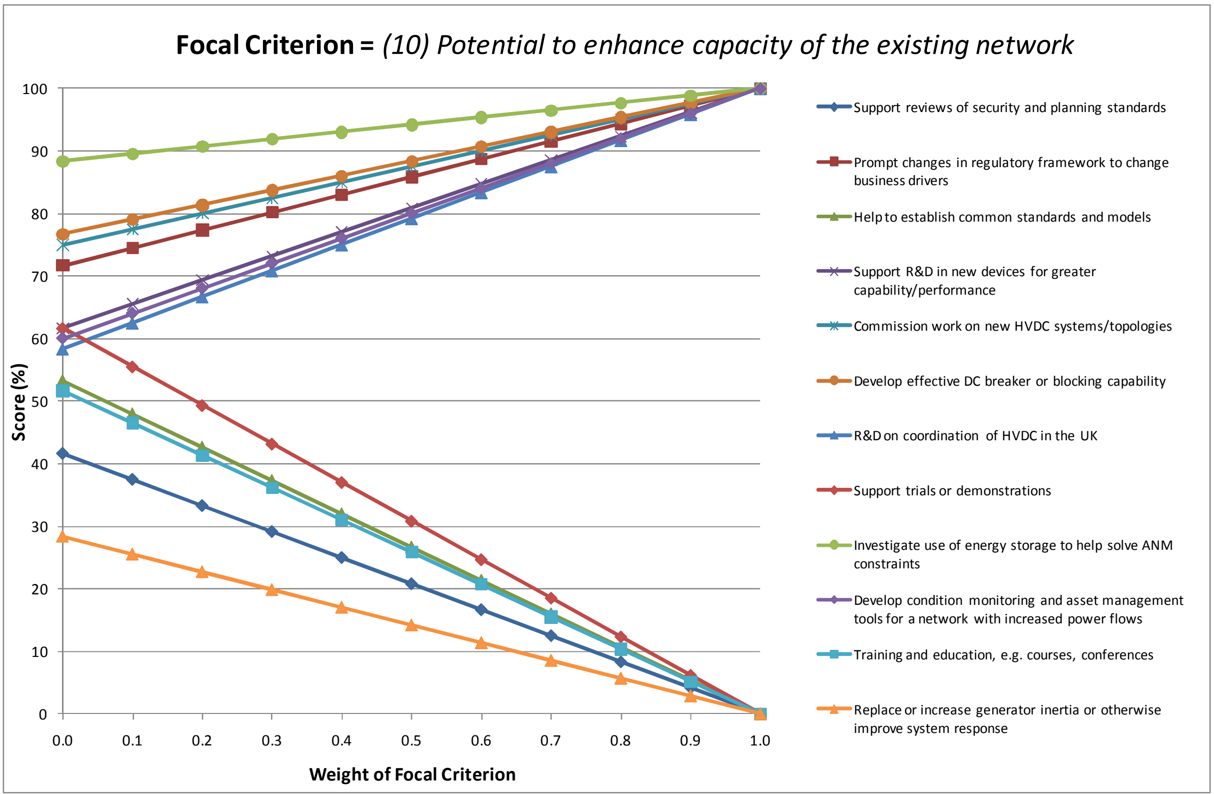
If regulatory changes can help to make the adoption and management of new methods and technologies less restrained then this should have a positive impact on enhancing capacity.

The capacity of the network can be enhanced by using higher power rated materials so that more power can flow over existing routes.

The introduction of energy storage would serve to increase the utilisation of the existing network.

Figure 13 has only one line crossing over others so indicates that this criterion is not very helpful in separating the development options.

Figure 13: Weighting sensitivity analysis for criterion 10



7.1.11 Links with other developments or technologies

Table 14: Assessment of development options against criterion 11

Links with other developments or technologies		Inter-dependence with other options													
No.	**Development Option**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Score**	**Normalised**
1	Support reviews of security and planning standards		1	1	0	0	1	1	1	0	1	0	1	7	1.00
2	Prompt changes in regulatory framework to change business drivers	1		0	0	1	0	0	1	1	0	0	0	4	0.50
3	Help to establish common standards and models	1	0		0	0	0	1	0	0	0	1	0	3	0.33
4	Support R&D in new devices for greater capability/performance	0	0	0		1	0	0	1	1	1	1	0	5	0.67
5	Commission work on new HVDC systems/topologies	0	1	0	1		1	1	1	0	0	1	0	6	0.83
6	Develop effective DC breaker or blocking capability	1	0	0	0	1		1	0	0	0	0	0	3	0.33
7	R&D on coordination of HVDC in the UK	1	0	1	0	1	1		1	0	0	1	0	6	0.83
8	Support trials or demonstrations	1	1	0	1	1	0	1		1	0	1	0	7	1.00
9	Investigate use of energy storage to help solve ANM constraints	0	1	0	1	0	0	0	1		1	0	0	4	0.50
10	Develop condition monitoring and asset management tools for a network with increased power flows	1	0	0	1	0	0	0	0	1		0	0	3	0.33
11	Training and education, e.g. courses, conferences	0	0	1	1	1	0	1	1	0	0		0	5	0.67
12	Replace or increase generator inertia or otherwise improve system response	1	0	0	0	0	0	0	0	0	0	0		1	0.00
													Max Raw Score	7	
													Min Raw Score	1	

Supporting reviews of security and planning standards links well with helping to establish common standards and models as it would be easier to change planning standards when everything fits into a common model.

Prompting changes in the regulatory framework to change business drivers is compatible with commissioning work on new HVDC systems/topologies as utilities could be persuaded to invest in new HVDC topologies. Similarly, energy storage is not consistent with the existing regulatory framework. Therefore changes in regulation might improve the case for energy storage.

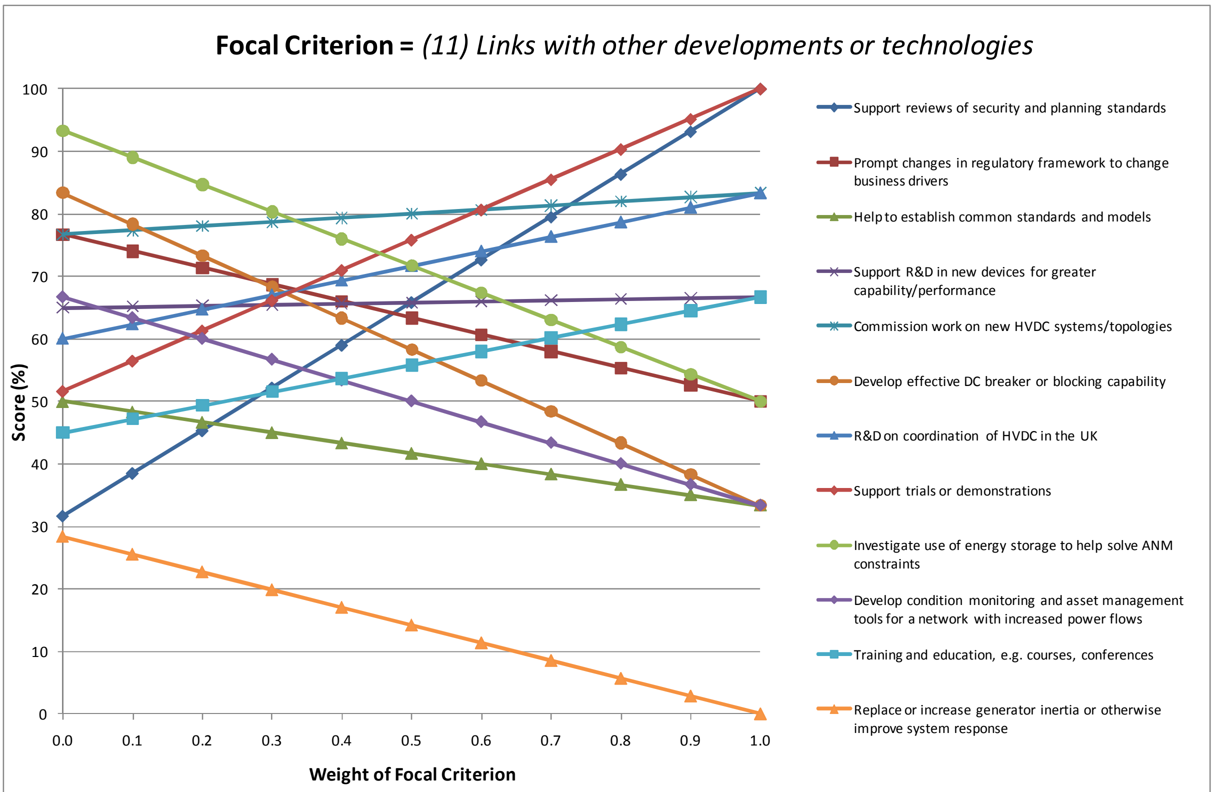
There may be additional merit in establishing common standards and models in conjunction with the development of condition monitoring techniques. Condition monitoring could be aided if common models were agreed for the system at large, so that it became composed of well-defined, quasi-homogenous components.

Battery use implies that existing network assets will be put under more stresses than under prior conditions. The development option of "condition monitoring" is therefore a complementary option with respect to helping the system operator manage those additional strains placed on the system.

It is thought that by providing extra training the progression of several other development options could also be enhanced. Education and research and development in HVDC in the UK will both help to reinforce each other. In the workshop discussions it was felt strongly that some other areas such as trials and demonstrations may indirectly result in better training and education.

Figure 14 has several lines crossing over one another so indicates that this criterion helps to separate the development options.

Figure 14: Weighting sensitivity analysis for criterion 11



7.1.12 Combining Multiple Criteria

The normalised scores for all development options across all criteria are shown in Table 15.

Table 15: Normalised scores for development options across all assessment criteria

Development Options		1 Potential to enhance UK industrial capability and knowledge	2 Potential to reduce through-life costs of technology use	3 Potential to reduce the cost of electricity for consumers	4 Has a clear business case for all stakeholders	5 Potential to overcome or bypass problems with consents	6 Potential to enhance or accelerate Technology Readiness Levels	7 Potential to reduce CO2 emissions	8 More options and flexibility in network design and operation	9 Impact on system security and reliability	10 Potential to enhance capacity of the existing network	11 Links with other developments or technologies
Support reviews of security and planning standards	1	0.67	0.50	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00
Prompt changes in regulatory framework to change business drivers	2	0.67	0.50	1.00	1.00	0.00	1.00	1.00	1.00	0.50	1.00	0.50
Help to establish common standards and models	3	0.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	1.00	0.00	0.33
Support R&D in new devices for greater capability/performance	4	0.67	0.33	0.00	1.00	0.50	1.00	1.00	0.00	1.00	1.00	0.67
Commission work on new HVDC systems/topologies	5	1.00	0.67	1.00	0.00	0.50	0.50	1.00	1.00	1.00	1.00	0.83
Develop effective DC breaker or blocking capability	6	1.00	0.83	0.00	1.00	0.50	1.00	1.00	1.00	1.00	1.00	0.33
R&D on coordination of HVDC in the UK	7	1.00	0.50	0.00	1.00	0.50	0.50	0.00	1.00	0.50	1.00	0.83
Support trials or demonstrations	8	1.00	0.67	0.00	1.00	0.50	1.00	0.00	0.00	1.00	0.00	1.00
Investigate use of energy storage to help solve ANM constraints	9	1.00	0.83	1.00	1.00	1.00	0.50	1.00	1.00	1.00	1.00	0.50
Develop condition monitoring and asset management tools for a network with increased power flows	10	0.67	0.50	1.00	1.00	0.50	0.50	0.00	0.50	1.00	1.00	0.33
Training and education, e.g. courses, conferences	11	1.00	0.50	1.00	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.67
Replace or increase generator inertia or otherwise improve system response	12	0.33	0.00	1.00	0.00	0.00	0.00	0.00	0.50	1.00	0.00	0.00

The sensitivity analyses for each of the criteria (shown in Figure 4 to Figure 14) suggest that the following criteria have little influence in differentiating the development options:

- Criterion 7: Potential to reduce CO2 emissions
- Criterion 10: Potential to enhance capacity of the existing networks

The relative ranking of the options are the same irrespective of the weightings assigned to theses two criteria. Both of these criteria have high interim rankings, as shown in Table 3 above, but for the overall assessment of development options their ranking has been reduced, as shown in Table 16, to accentuate the influence of other criteria that serve to better differentiate between the development options. These two criteria remain very important to the ETI so this approach represents a compromise between the analytical method used to score the development options and the strategic aims of the ETI.

Table 16: Final Criteria Rankings for Assessing Development Options

Description	Interim Ranking	Final Ranking
Potential to enhance UK industrial capability and knowledge	5	5
Potential to reduce through-life costs of technology use	6	6
Potential to reduce the cost of electricity for consumers	=2	=2
Has a clear business case for all stakeholders	=4	=4
Potential to overcome or bypass problems with consents	=4	=4
Potential to enhance or accelerate Technology Readiness Levels	=3	=3
Potential to reduce CO2 emissions	1	=3
More options and flexibility in network design and operation	=2	=2
Impact on system security and reliability	=3	=3
Potential to enhance capacity of the existing network	=2	=4
Links with other developments or technologies	7	7

The final criteria rankings are converted into weightings for the overall assessment of development options by calculating the reciprocal of the rating, summing the reciprocals, and calculating what fraction of the sum is assigned to each criteria. This calculation is shown in Table 17.

Table 17: Calculation of Criteria Weightings for Assessing Development Options

Description	Final Ranking	Reciprocal	Weighting
Potential to enhance UK industrial capability and knowledge	5	0.200	0.061
Potential to reduce through-life costs of technology use	6	0.167	0.051
Potential to reduce the cost of electricity for consumers	2	0.500	0.153
Has a clear business case for all stakeholders	4	0.250	0.077
Potential to overcome or bypass problems with consents	4	0.250	0.077
Potential to enhance or accelerate Technology Readiness Levels	3	0.333	0.102
Potential to reduce CO2 emissions	3	0.333	0.102
More options and flexibility in network design and operation	2	0.500	0.153
Impact on system security and reliability	3	0.333	0.102
Potential to enhance capacity of the existing network	4	0.250	0.077
Links with other developments or technologies	7	0.143	0.045
	Sum	3.259	1.000

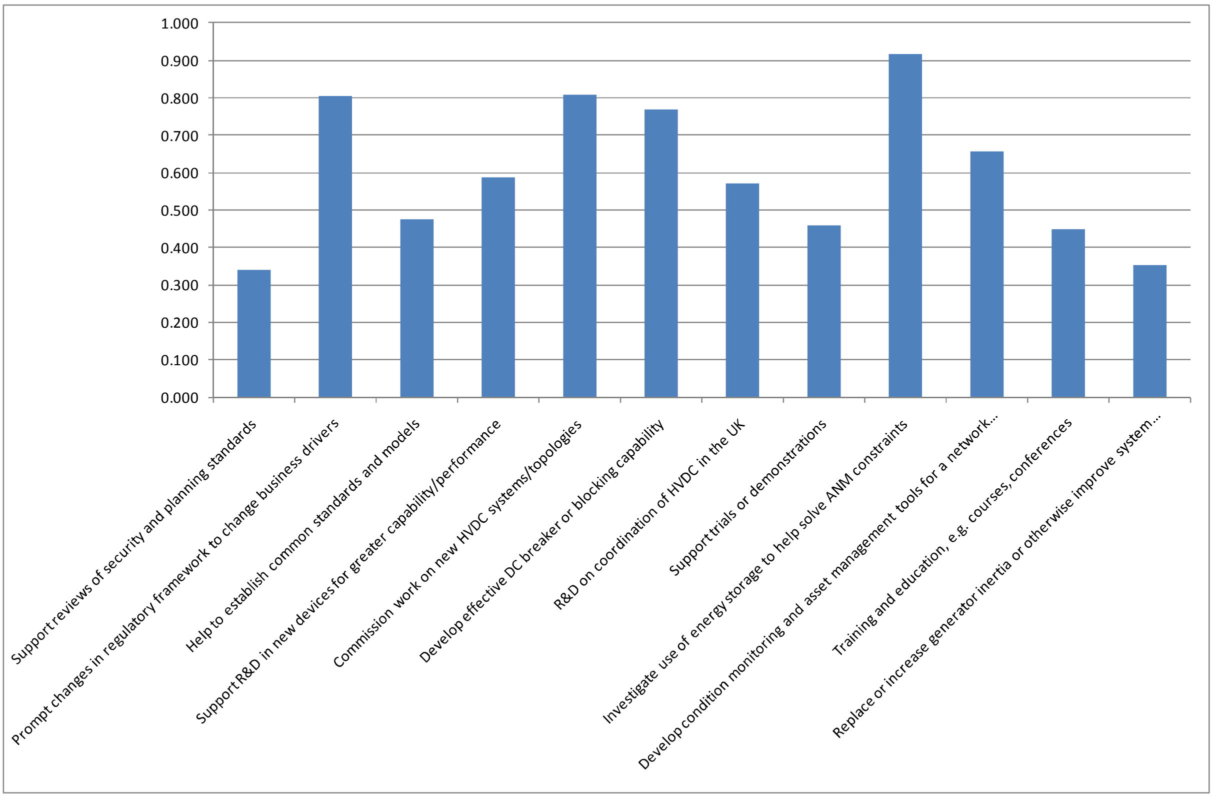
Note: The reciprocals and then the weightings are each rounded to three decimal places. The weighting for “Links with other developments or technologies” is increased by 0.001 so that the sum is 1.000.

From the normalised scores in Table 15 and the criteria weightings in Table 17 it is possible to calculate the overall score for each of the development options. The results, and their conversion into an overall ranking, are shown in Table 18 and the overall scores are plotted in Figure 15.

Table 18: Overall Scores and Ranking for Development Options

Development Options	Overall Score	Rank
Support reviews of security and planning standards	0.341	12
Prompt changes in regulatory framework to change business drivers	0.804	3
Help to establish common standards and models	0.475	8
Support R&D in new devices for greater capability/performance	0.586	6
Commission work on new HVDC systems/topologies	0.809	2
Develop effective DC breaker or blocking capability	0.770	4
R&D on coordination of HVDC in the UK	0.572	7
Support trials or demonstrations	0.460	9
Investigate use of energy storage to help solve ANM constraints	0.918	1
Develop condition monitoring and asset management tools for a network with increased power flows	0.656	5
Training and education, e.g. courses, conferences	0.449	10
Replace or increase generator inertia or otherwise improve system response	0.352	11

Figure 15: Overall Scores for Development Options



7.2 Technologies

The thirteen technologies of interest are all assessed against ten of the criteria; technology readiness level is presented for information but is not used in the assessment.

7.2.1 Potential to enhance UK industrial capability and knowledge

Table 19: Assessment of technologies against criterion 1

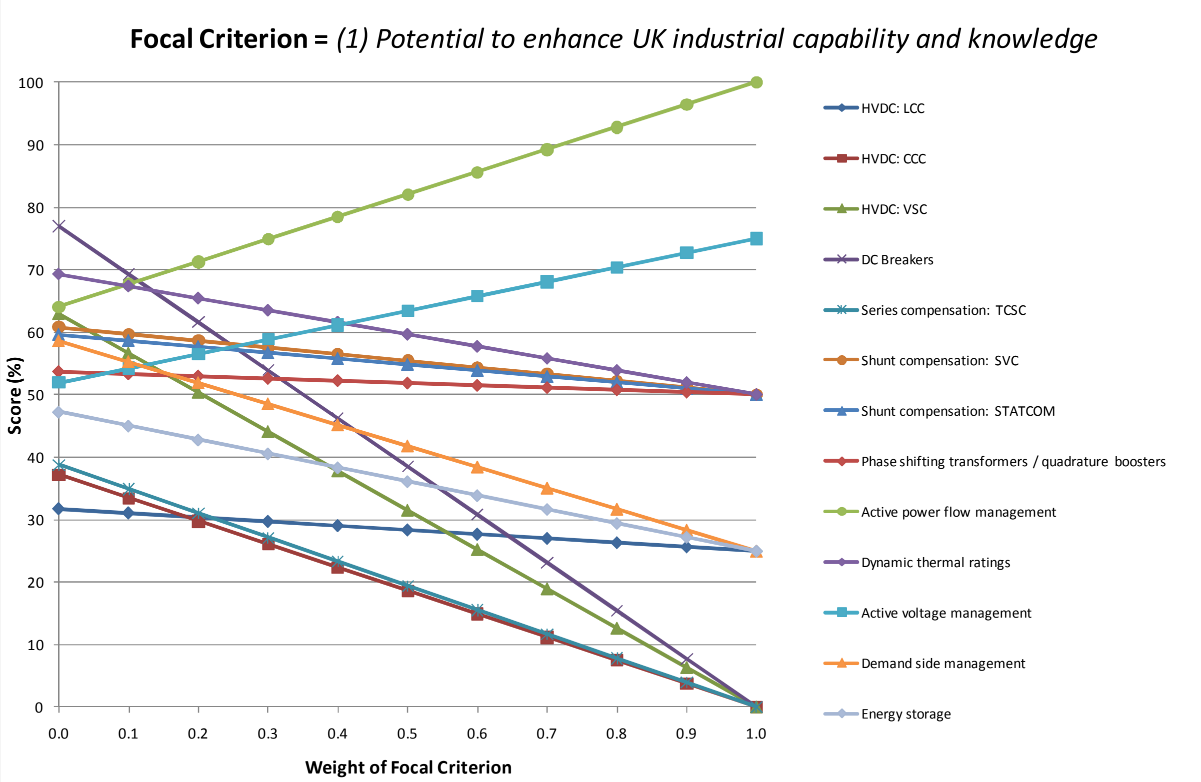
Potential to enhance UK industrial capability and knowledge									
		Existing UK Advantages (of each technology) in ...				*Specific opportunities in the UK because ...*			
No.	**Technology**	*technology design*	*analysis*	*manufacture*	*existing deployments*	*the technology is being neglected elsewhere*	*there is obvious scope for relatively widespread application in the UK*	**Score**	**Normalised**
1	HVDC: LCC	0	0	0	1	0	0	1	0.25
2	HVDC: CCC	0	0	0	0	0	0	0	0.00
3	HVDC: VSC	0	0	0	0	0	0	0	0.00
4	DC Breakers	0	0	0	0	0	0	0	0.00
5	Series compensation: TCSC	0	0	0	0	0	0	0	0.00
6	Shunt compensation: SVC	0	1	0	1	0	0	2	0.50
7	Shunt compensation: STATCOM	0	1	0	1	0	0	2	0.50
8	Phase shifting transformers / quadrature boosters	0	1	0	1	0	0	2	0.50
9	Active power flow management	1	1	0	1	0	1	4	1.00
10	Dynamic thermal ratings	0	0	0	1	0	1	2	0.50
11	Active voltage management	1	1	0	1	0	0	3	0.75
12	Demand side management	0	0	0	0	0	1	1	0.25
13	Energy storage	0	0	0	0	0	1	1	0.25
							Max Raw Score	4	
							Min Raw Score	0	

The UK can claim advantages in the design and analysis of active network management solutions and the analysis of shunt compensation and phase shifting transformers, although this perhaps understates the strength of analysis and consultancy resources. There are no particular advantages in manufacturing but existing deployments do provide some experience and background on particular technologies.

None of the technologies can be identified as being neglected elsewhere. The scope for application in the UK is obviously a contentious issue but a number of the technologies have been identified as having more obvious scope than others. The technologies applicable to distribution networks, in the broad domain of active distribution networks, have relatively broad scope for application because of their direct link with the connection of new generation and the much greater extent of distribution networks. In contrast, while the transmission network covers the whole country and transports large amounts of energy, there are relatively few nodes and circuits and correspondingly few opportunities for installations.

Figure 16 has several lines crossing over one another so indicates that this criterion helps to separate the technologies.

Figure 16: Weighting sensitivity analysis for criterion 1



7.2.2 Potential to reduce through-life costs of technology use

Table 20: Assessment of technologies against criterion 2

Potential to reduce through-life costs of technology use						
No.	**Technology**	**Specific opportunities to reduce costs and/or scope for wide deployment**	**Score**	**Normalised**	**Score Values**	
1	HVDC: LCC	Low	0	0.00	High	2
2	HVDC: CCC	Low	0	0.00	Medium	1
3	HVDC: VSC	High	2	1.00	Low	0
4	DC Breakers	High	2	1.00		
5	Series compensation: TCSC	Medium	1	0.50		
6	Shunt compensation: SVC	Medium	1	0.50		
7	Shunt compensation: STATCOM	Medium	1	0.50		
8	Phase shifting transformers / quadrature boosters	Medium	1	0.50		
9	Active power flow management	High	2	1.00		
10	Dynamic thermal ratings	High	2	1.00		
11	Active voltage management	High	2	1.00		
12	Demand side management	High	2	1.00		
13	Energy storage	High	2	1.00		
		Max Raw Score	2			
		Min Raw Score	0			

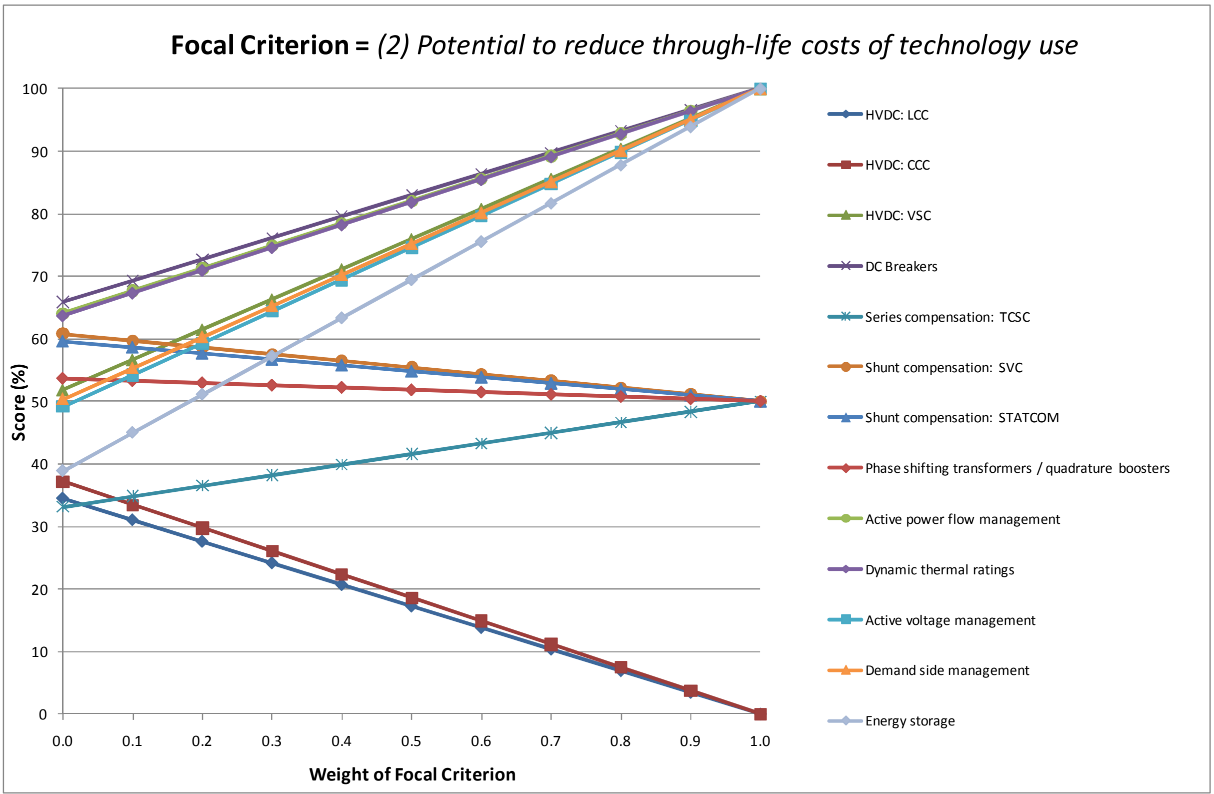
For the LCC and CCC versions of HVDC there are no specific opportunities to reduce costs and the scope for deployment is small enough that there are unlikely to be savings from economies of scale or batch ordering. In contrast it is judged that the through-life costs of VSC and DC breakers might be reduced both from specific technology or manufacturing developments and from an expansion in the overall market size.

For series compensation, shunt compensation and phase shifting transformers there are no specific opportunities to reduce costs identified but an expansion in the numbers ordered and installed in the UK would be expected to lead to cost savings.

Active network management technologies and energy storage are relatively young with few deployments and there are various ways in which through-life costs might be reduced by development or refinement of the technologies and the way they are used or by the economies of scale achieved with a much wider roll-out.

Figure 17 has several lines crossing over one another so indicates that this criterion helps to separate the technologies.

Figure 17: Weighting sensitivity analysis for criterion 2



7.2.3 Potential to reduce the cost of electricity for consumers

Table 21: Assessment of technologies against criterion 3

Potential to reduce the cost of electricity for consumers

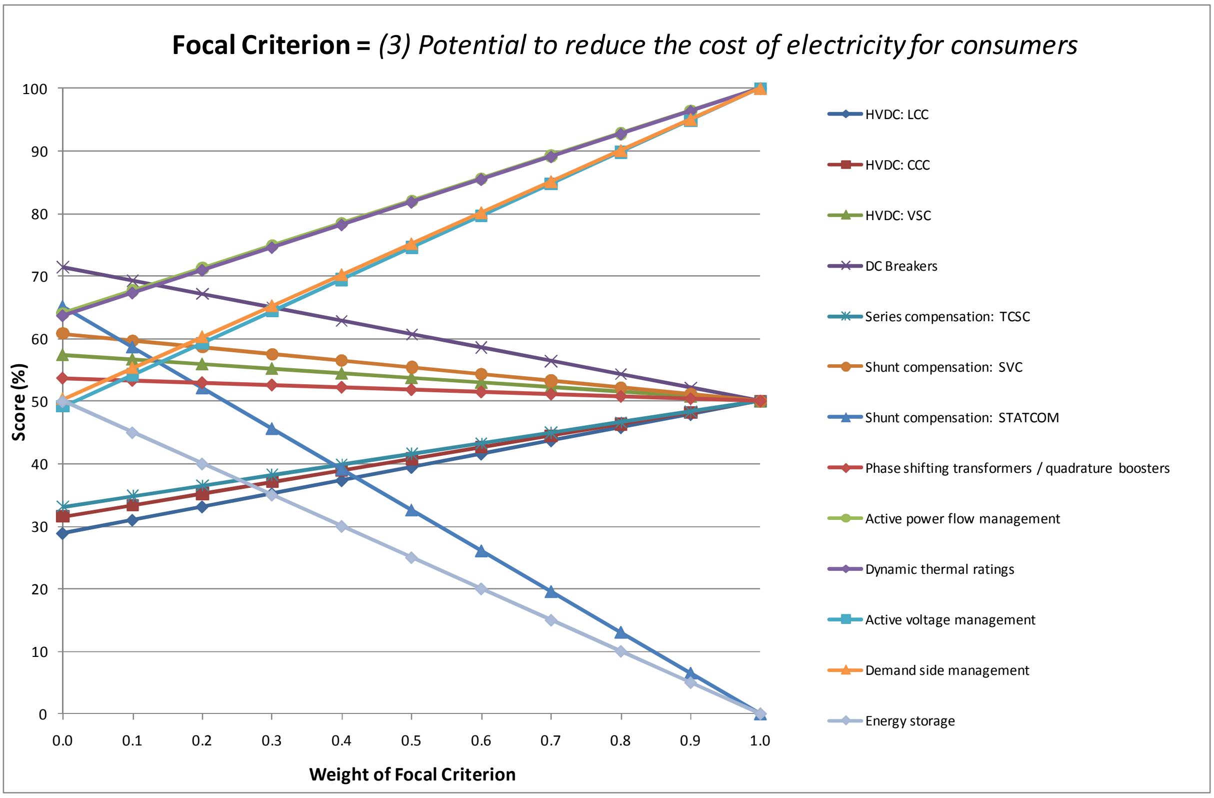
No.	Technology	Potential To Fulfil Criterion	Score	Normalised
1	HVDC: LCC	Neutral	0	0.50
2	HVDC: CCC	Neutral	0	0.50
3	HVDC: VSC	Neutral	0	0.50
4	DC Breakers	Neutral	0	0.50
5	Series compensation: TCSC	Neutral	0	0.50
6	Shunt compensation: SVC	Neutral	0	0.50
7	Shunt compensation: STATCOM	Very Expensive	-1	0.00
8	Phase shifting transformers / quadrature boosters	Neutral	0	0.50
9	Active power flow management	Excellent Value	1	1.00
10	Dynamic thermal ratings	Excellent Value	1	1.00
11	Active voltage management	Excellent Value	1	1.00
12	Demand side management	Excellent Value	1	1.00
13	Energy storage	Very Expensive	-1	0.00
		Max Raw Score	1	
		Min Raw Score	-1	

Score Values	
Excellent Value	1
Neutral	0
Very Expensive	-1

Based on the project findings, and applying the very simple and subjective assessment of cost, STATCOMs and energy storage are identified as being relatively more expensive than other technologies, the four active network management technologies are identified as being cheaper, and the other technologies are assessed as being roughly equivalent to conventional solutions.

Figure 18 has several lines crossing over one another so indicates that this criterion helps to separate the technologies.

Figure 18: Weighting sensitivity analysis for criterion 3



7.2.4 Has a clear business case for all stakeholders

Table 22: Assessment of technologies against criterion 4

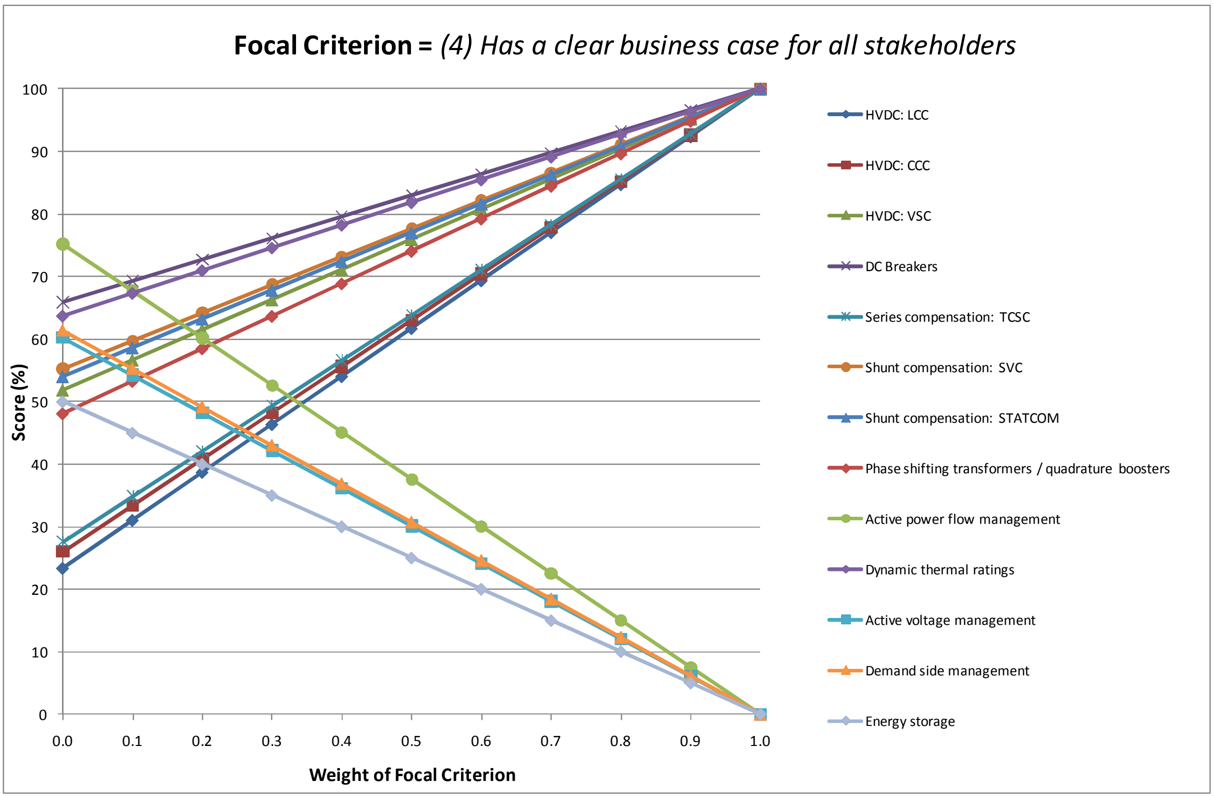
No.	Technology	Potential To Fulfil Criterion	Score	Normalised
	Has a clear business case for all stakeholders			
1	HVDC: LCC	Neutral	0	1.00
2	HVDC: CCC	Neutral	0	1.00
3	HVDC: VSC	Neutral	0	1.00
4	DC Breakers	Neutral	0	1.00
5	Series compensation: TCSC	Neutral	0	1.00
6	Shunt compensation: SVC	Neutral	0	1.00
7	Shunt compensation: STATCOM	Neutral	0	1.00
8	Phase shifting transformers / quadrature boosters	Neutral	0	1.00
9	Active power flow management	Harder	-1	0.00
10	Dynamic thermal ratings	Neutral	0	1.00
11	Active voltage management	Harder	-1	0.00
12	Demand side management	Harder	-1	0.00
13	Energy storage	Harder	-1	0.00
		Max Raw Score	0	
		Min Raw Score	-1	

Score Values	
Easier	1
Neutral	0
Harder	-1

Most of the technologies would be implemented in the same way as conventional solutions as far as the business case for different stakeholders is concerned. Active power flow management and active voltage management present new challenges in the commercial agreements as loads or generators are offered "non firm" connections or are otherwise constrained in their operation. For demand side management it is probably the complexities of the business case and the lack of clear incentives for all stakeholders that has prevented adoption rather than any technical barriers. Energy storage presents a range of new challenges relating to its ownership, the roles it might play in energy markets and network operation, and the assignment of costs for losses.

Figure 19 has several lines crossing over one another so indicates that this criterion helps to separate the technologies.

Figure 19: Weighting sensitivity analysis for criterion 4



7.2.5 Potential to overcome or bypass problems with consents

Table 23: Assessment of technologies against criterion 5

Potential to overcome or bypass problems with consents								
		Compared with consent problems for conventional						
No.	**Technology**	***footprint/size***	***noise***	***EMI***	***other issues***	**Score**	**Normalised**
1	HVDC: LCC	More Difficult	The Same	More Difficult	More Difficult	-3	0.00
2	HVDC: CCC	More Difficult	The Same	More Difficult	More Difficult	-3	0.00
3	HVDC: VSC	More Difficult	The Same	More Difficult	More Difficult	-3	0.00
4	DC Breakers	The Same	The Same	The Same	The Same	0	0.75
5	Series compensation: TCSC	More Difficult	The Same	More Difficult	More Difficult	-3	0.00
6	Shunt compensation: SVC	The Same	The Same	The Same	The Same	0	0.75
7	Shunt compensation: STATCOM	Easier	The Same	More Difficult	The Same	0	0.75
8	Phase shifting transformers / quadrature boosters	The Same	The Same	The Same	The Same	0	0.75
9	Active power flow management	Easier	The Same	The Same	The Same	1	1.00
10	Dynamic thermal ratings	Easier	The Same	The Same	The Same	1	1.00
11	Active voltage management	Easier	The Same	The Same	The Same	1	1.00
12	Demand side management	Easier	The Same	The Same	The Same	1	1.00
13	Energy storage	More Difficult	The Same	The Same	More Difficult	-2	0.25
					Max Raw Score	1	
					Min Raw Score	-3	

Score Values	
Easier	1
The Same	0
More Difficult	-1

HVDC technologies and series compensation require significant installations with a large footprint, although their installation should then enable greater power flow on transmission corridors and therefore deliver some benefit in a reduced wirescape. STATCOMs are an alternative to the more widely used SVC or other options and deliver similar functionality within a smaller footprint. STATCOMs have an additional advantage over SVCs of being able to offer the same amount of reactive power support with a depressed voltage, whereas the MVArs produced from an SVC are voltage dependent. Active network management methods rely on new communications and control, which have a very small footprint compared with the primary plant required for conventional reinforcement. Energy storage installations must have various ancillary systems that mean the footprint can become quite large.

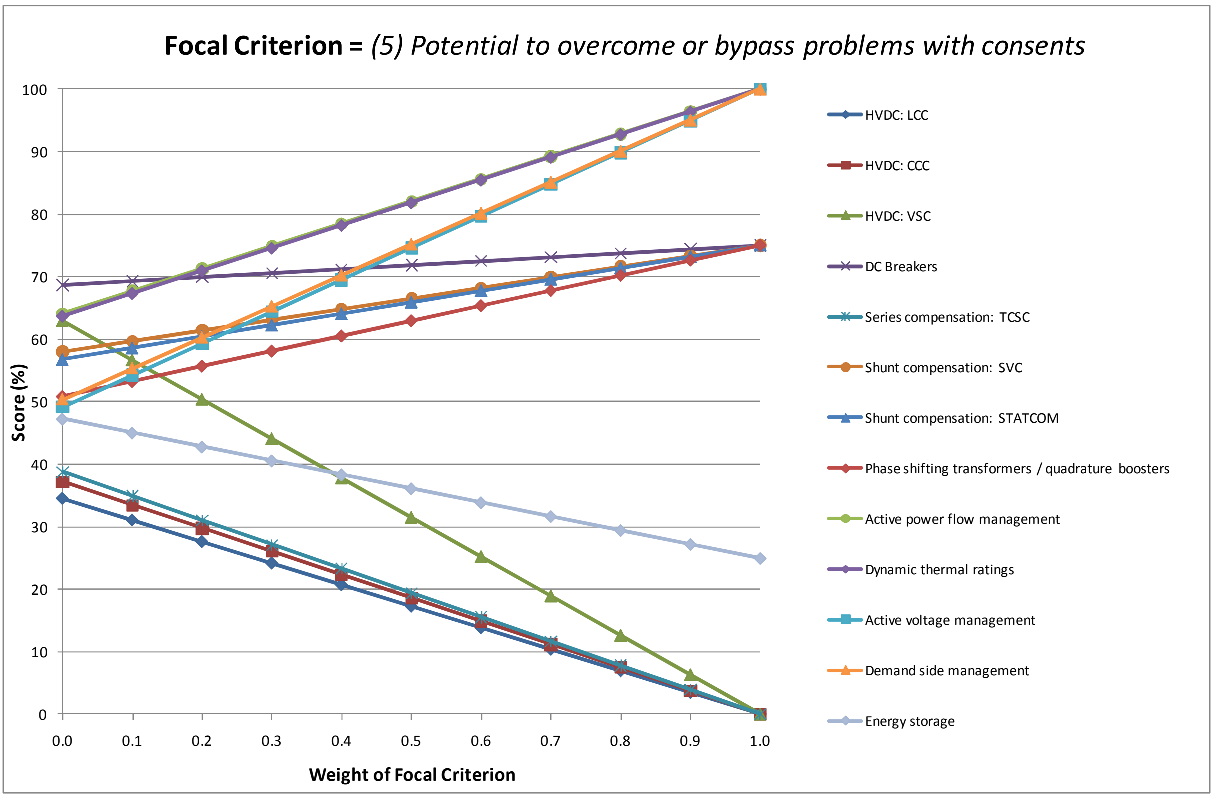
None of the technologies are expected to result in noise problems any worse than conventional solutions.

The significant size of HVDC installations and the fast switching associated with TCSC and STATCOM are considered to represent a slightly higher risk of problems as far as electromagnetic interference is concerned. Practical evidence suggests that the risk is minimal given an absence of EMI related complaints in previous installations, however, future installations may be much closer to population centres and other infrastructure and present new challenges.

The size of HVDC installations and the novelty of TCSC in the UK, where new equipment may be required part way along existing transmission lines, are considered to present additional risks to achieving consents. Energy storage is also thought to present a more difficult set of problems including environmental concerns relating to heavy and corrosive metals.

Figure 20 has several lines crossing over one another so indicates that this criterion helps to separate the technologies.

Figure 20: Weighting sensitivity analysis for criterion 5



7.2.6 Potential to enhance or accelerate Technology Readiness Levels

The TRLs for each of the technologies are shown in Table 24 but were not included as part of the multi criteria assessment.

Table 24: Technology Readiness Levels of selected technologies

Technology Readiness Levels		
No.	**Technology**	**Current TRL**
1	HVDC: LCC	9
2	HVDC: CCC	8
3	HVDC: VSC	8
4	DC Breakers	6
5	Series compensation: TCSC	9
6	Shunt compensation: SVC	9
7	Shunt compensation: STATCOM	9
8	Phase shifting transformers / quadrature boosters	9
9	Active power flow management	8
10	Dynamic thermal ratings	8
11	Active voltage management	7
12	Demand side management	6
13	Energy storage	6

Technology Readiness Levels (TRLs) have been discussed throughout the project and these values reflect those presented in other project reports. Likewise, the TRL enhancement potential of each is discussed elsewhere. The final project report makes recommendations on which technologies offer the best opportunities for TRL enhancement.

HVDC is listed as TRL 8-9 but use in the UK in the manner which is the subject of this project represents a different application and suggests a lower TRL might be more appropriate. DC breakers of the characteristics required have yet to be commercially demonstrated but manufacturers claim to have developed the technology, which places some uncertainty on the listed TRL 6.

It has been noted that ANM technologies would benefit from further investment so while some products are TRL 8, others are of lower readiness. Some ANM technologies and energy storage take many different forms so, although the average TRL may be as listed, there will be a range depending on the specific technology. For energy storage the range is quite wide from university research on different forms of hydrogen storage, through developing technologies that exploit super-capacitors or superconductivity, early stage products based on flow batteries or compressed air, proven applications with flywheels or sodium-sulphur batteries, to established battery technologies like lead acid and the large scale solution of pumped hydro.

7.2.7 Potential to reduce CO_2 emissions

Table 25: Assessment of technologies against criterion 7

Potential to reduce CO2 emissions

No.	Technology	Aids connection of new renewable generation	Adverse impact on network losses	Score	Normalised
1	HVDC: LCC	3	-2	1	0.60
2	HVDC: CCC	4	-2	2	0.70
3	HVDC: VSC	5	-3	2	0.70
4	DC Breakers	5	0	5	1.00
5	Series compensation: TCSC	3	-1	2	0.70
6	Shunt compensation: SVC	5	-1	4	0.90
7	Shunt compensation: STATCOM	6	-2	4	0.90
8	Phase shifting transformers / quadrature boosters	4	0	4	0.90
9	Active power flow management	4	-1	3	0.80
10	Dynamic thermal ratings	3	-1	2	0.70
11	Active voltage management	2	-1	1	0.60
12	Demand side management	2	-1	1	0.60
13	Energy storage	5	-10	-5	0.00
			Max Raw Score	5	
			Min Raw Score	-5	

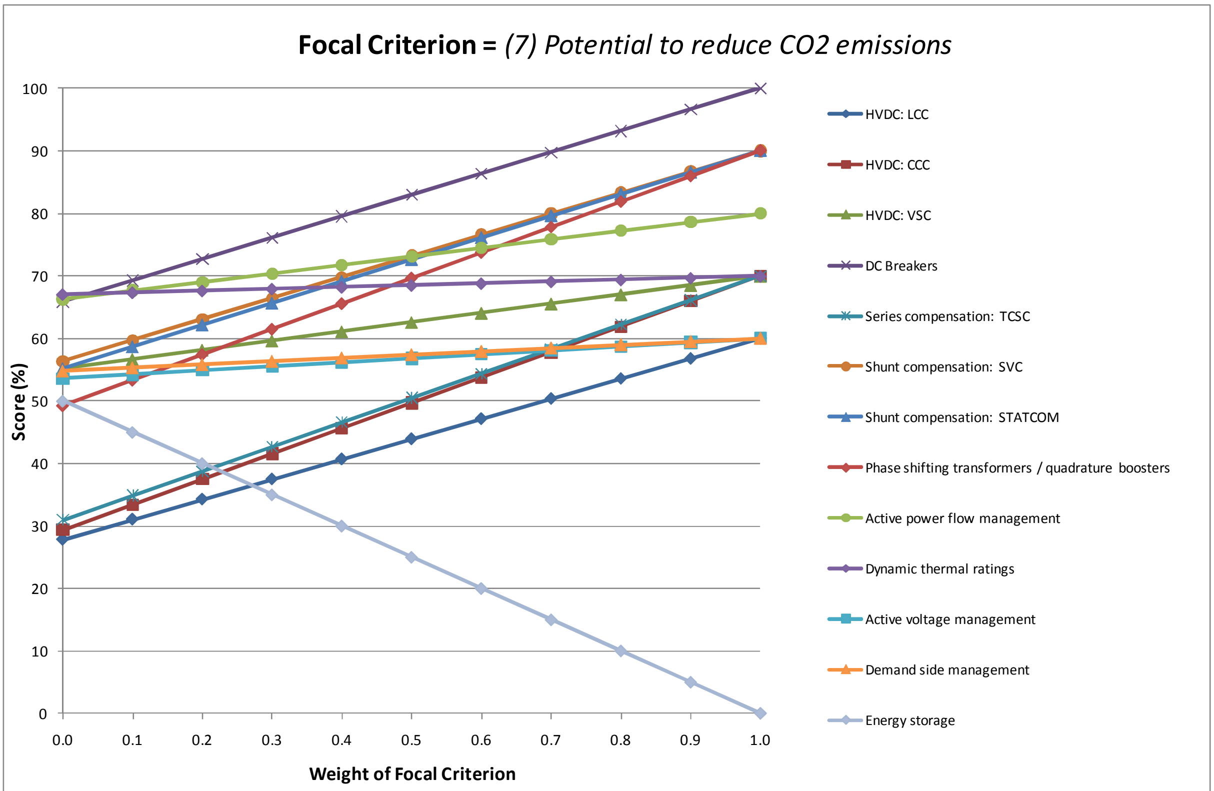
In terms of aiding the connection of new renewables the comparative assessment of the technologies has determined that LCC is slightly less effective than CCC, which is slightly less effective than VSC. DC breakers are assigned the same score as VSC as their deployment is likely to go together. Series compensation is expected to be less useful than shunt compensation with STATCOMs expected to offer better gains than SVCs. Phase shifting transformers are placed between series and shunt compensation with a similar impact to active power flow management. Dynamic thermal ratings are judged to deliver slightly less and active voltage management and demand side management are expected to have a relatively small impact on the connection of new renewables. Energy storage is scored reasonably high because it should address problems with both network capacity and intermittency from renewable sources.

The HVDC and compensation technologies all cause losses in the devices themselves, which are unlikely to be made up for by a reduction in losses on lines in the UK where distances are relatively short. VSC based technologies are assigned larger negative scores to reflect their higher losses, although it must be recognised that if reactive compensation is provided by the VSC-based equipment then this may avoid the need for additional compensation and thereby avoid losses associated with that additional equipment. The active network management technologies will result in higher power flows more often on the existing lines and so will cause a marginal increase in losses.

Energy storage will introduce substantial new losses given that the round-trip efficiency of typical batteries is less than 80%.

Figure 21 has several lines crossing over one another so indicates that this criterion helps to separate the technologies.

Figure 21: Weighting sensitivity analysis for criterion 7



7.2.8 More options and flexibility in network design and operation

Table 26: Assessment of technologies against criterion 8

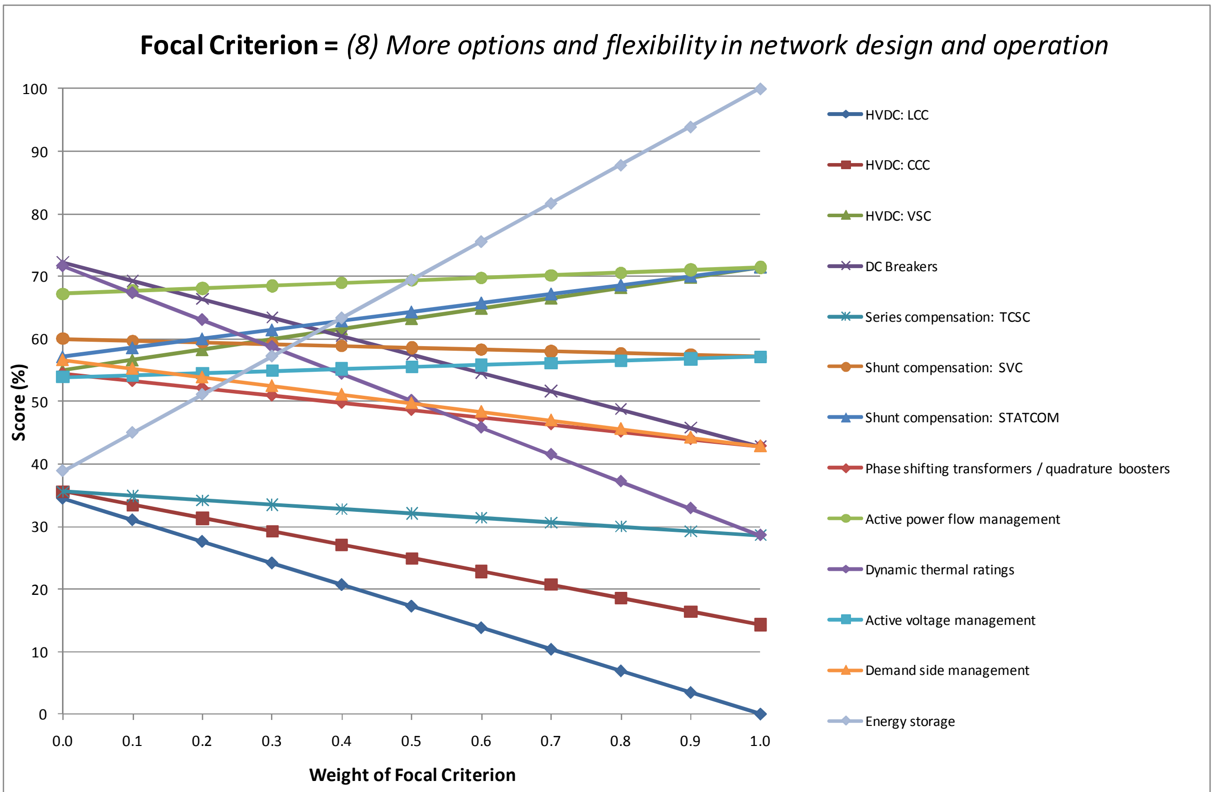
More options and flexibility in network design and operation			
No.	**Technology**	**Impact on network design flexibility**	**Normalised**
1	HVDC: LCC	2	0.00
2	HVDC: CCC	3	0.14
3	HVDC: VSC	7	0.71
4	DC Breakers	5	0.43
5	Series compensation: TCSC	4	0.29
6	Shunt compensation: SVC	6	0.57
7	Shunt compensation: STATCOM	7	0.71
8	Phase shifting transformers / quadrature boosters	5	0.43
9	Active power flow management	7	0.71
10	Dynamic thermal ratings	4	0.29
11	Active voltage management	6	0.57
12	Demand side management	5	0.43
13	Energy storage	9	1.00
	Max Raw Score	9	
	Min Raw Score	2	

For each of the technologies the impact on options and flexibility in network design and operation is assessed based on the work done in WP1 T1-3 and WP2 T1-3 and used to derive a score between 0 and 10, with 0 indicating no impact and 10 indicating a significant improvement in options and flexibility. These scores must be considered as comparative assessments between the technologies.

LCC is deemed to be the least attractive in terms of options and flexibility, followed closely by CCC. Series compensation and dynamic thermal ratings are considered to be equivalent, delivering slightly less than DC breakers, phase shifting transformers and demand side management. SVCs and active voltage management are seen as offering more flexibility but not as much as VSC, STATCOMs or active power flow management. The best performing technology is energy storage, which is assessed as presenting considerable new options and flexibility in network design and operation.

Figure 22 has several lines crossing over one another so indicates that this criterion helps to separate the technologies.

Figure 22: Weighting sensitivity analysis for criterion 8



7.2.9 Impact on system security and reliability

Table 27: Assessment of technologies against criterion 9

Impact on system security and reliability		Impact on system security and reliability according to ...								
No.	**Technology**	*Severity of the impact of failure*	*Likelihood of failure*	*Capacity to prevent cascade tripping*	*Ability to recover quickly from a fault condition*	**Score**	**Normalised**	**Score Values**		
1	HVDC: LCC	High	Low	High	Medium	1	0.50	Negative		
2	HVDC: CCC	High	Low	High	Medium	1	0.50	High	-2	
3	HVDC: VSC	High	Low	High	Medium	1	0.50	Medium	-1	
4	DC Breakers	Medium	Low	High	High	3	1.00	Low	0	
5	Series compensation: TCSC	Medium	Low	Low	Medium	0	0.25	Positive		
6	Shunt compensation: SVC	Medium	Low	Medium	Medium	1	0.50	High	2	
7	Shunt compensation: STATCOM	Medium	Low	Medium	Medium	1	0.50	Medium	1	
8	Phase shifting transformers / quadrature boosters	Medium	Low	Low	Medium	0	0.25	Low	0	
9	Active power flow management	Medium	Low	Low	Medium	0	0.25			
10	Dynamic thermal ratings	Low	Low	Low	Medium	1	0.50			
11	Active voltage management	Medium	Medium	Low	Medium	-1	0.00			
12	Demand side management	Medium	Medium	Medium	Medium	0	0.25			
13	Energy storage	Medium	Medium	Medium	Medium	0	0.25			
					Max Raw Score	3				
					Min Raw Score	-1				

If HVDC is to be used to enhance the capacity of existing transmission corridors then it means that a single failure event, which may mean the loss of a corridor, will have a more severe impact on the system. Other technologies are assessed as having a medium impact except dynamic thermal ratings, which is assessed as having a low impact because of its marginal impact on power flows and its inherently fail safe nature.

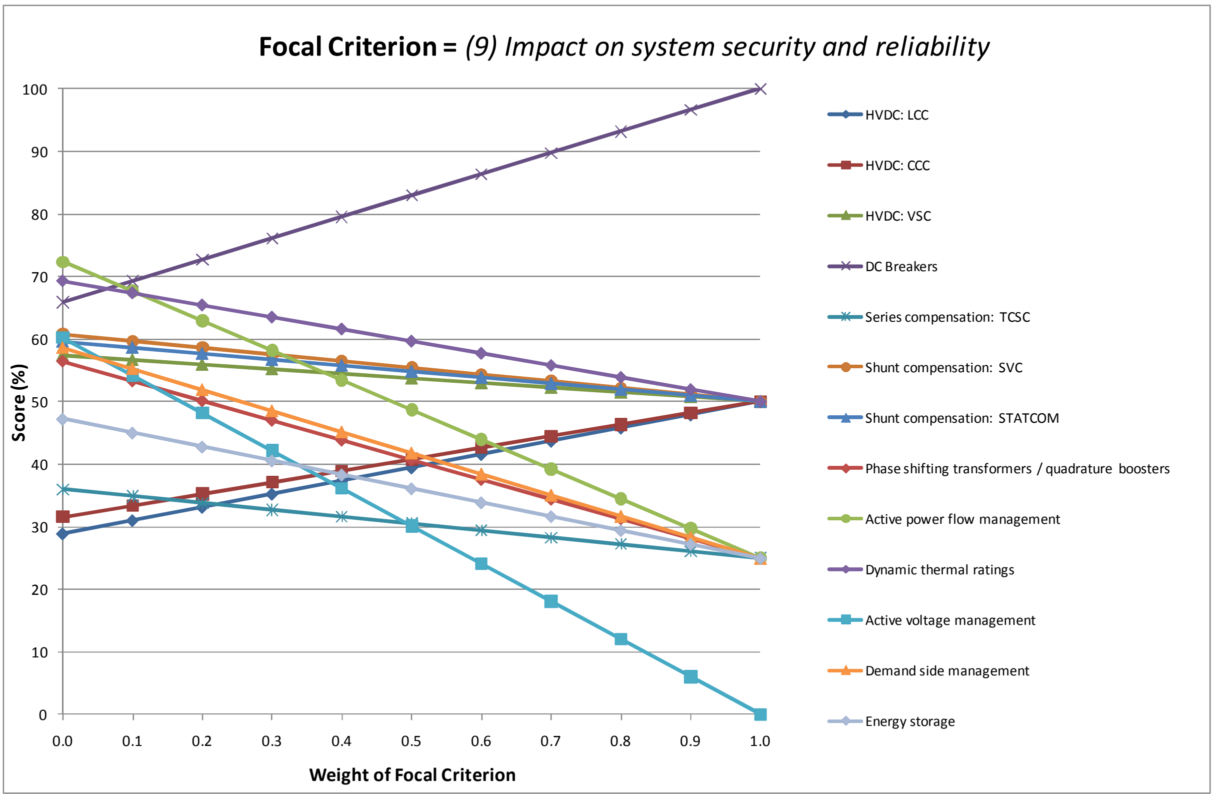
All technologies are deemed to have a low likelihood of failure except active voltage management, demand side management and energy storage because the novelty and new complexities introduced with these technologies, and exposure to factors outside the control of the network operator (particularly in the case of DSM), are thought to make them a little more risky.

The ability to prevent cascade tripping is an important attribute for HVDC and DC breakers are an important component in delivering that functionality, especially for multi-terminal systems. It is thought that shunt compensation can play an important role in limiting the extent of network collapse and that demand side management and energy storage may play useful roles in modifying the load under disturbance conditions.

Only DC breakers are considered to have any special capability as far as an ability to recover quickly from a fault condition because that is their primary purpose within the scope of VSC based HVDC.

Figure 23 has several lines crossing over one another so indicates that this criterion helps to separate the technologies.

Figure 23: Weighting sensitivity analysis for criterion 9



7.2.10 Potential to enhance capacity of the existing network

Table 28: Assessment of technologies against criterion 10

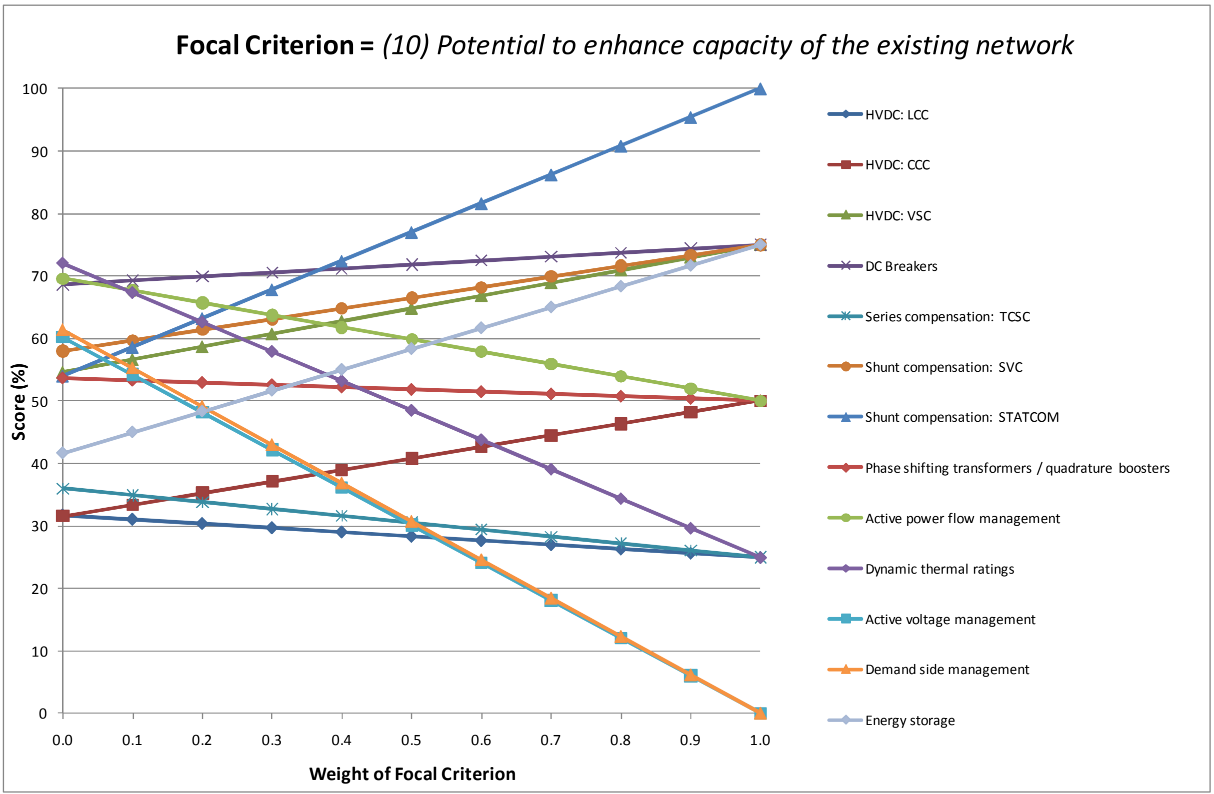
Potential to enhance capacity of the existing network			
No.	**Technology**	**Capacity improvement envisaged**	**Normalised**
1	HVDC: LCC	3	0.25
2	HVDC: CCC	4	0.50
3	HVDC: VSC	5	0.75
4	DC Breakers	5	0.75
5	Series compensation: TCSC	3	0.25
6	Shunt compensation: SVC	5	0.75
7	Shunt compensation: STATCOM	6	1.00
8	Phase shifting transformers / quadrature boosters	4	0.50
9	Active power flow management	4	0.50
10	Dynamic thermal ratings	3	0.25
11	Active voltage management	2	0.00
12	Demand side management	2	0.00
13	Energy storage	5	0.75
	Max Raw Score	6	
	Min Raw Score	2	

For each of the technologies the impact on network capacity will depend on the specific circumstances of its installation. However, where the work completed in WP1 T2, WP1 T3 and WP2 T3 reached some conclusions on improving capacity, by way of deploying a technology, it is used to derive a score between 0 and 10, with 0 indicating no impact and 10 indicating a significant enhancement in capacity. These scores must be considered as comparative assessments between the technologies.

The potential to enhance capacity of the existing network is really the same as the potential to aid the connection of new renewables and so the scores are the same as the assessment against criterion 7. The comparative assessment of the technologies has determined that LCC is slightly less effective than CCC, which is slightly less effective than VSC. DC breakers are assigned the same score as VSC as their deployment is likely to go together. Series compensation is expected to be less useful than shunt compensation with STATCOMs expected to offer better gains than SVCs. Phase shifting transformers are placed between series and shunt compensation with a similar impact to active power flow management. Dynamic thermal ratings are judged to deliver slightly less and active voltage management and demand side management are expected to have a relatively small impact on network capacity. Energy storage is scored reasonably high because it should address problems with both network capacity and intermittency from renewable sources.

Figure 24 has several lines crossing over one another so indicates that this criterion helps to separate the technologies.

Figure 24: Weighting sensitivity analysis for criterion 10



7.2.11 Links with other developments or technologies

Table 29: Assessment of technologies against criterion 11

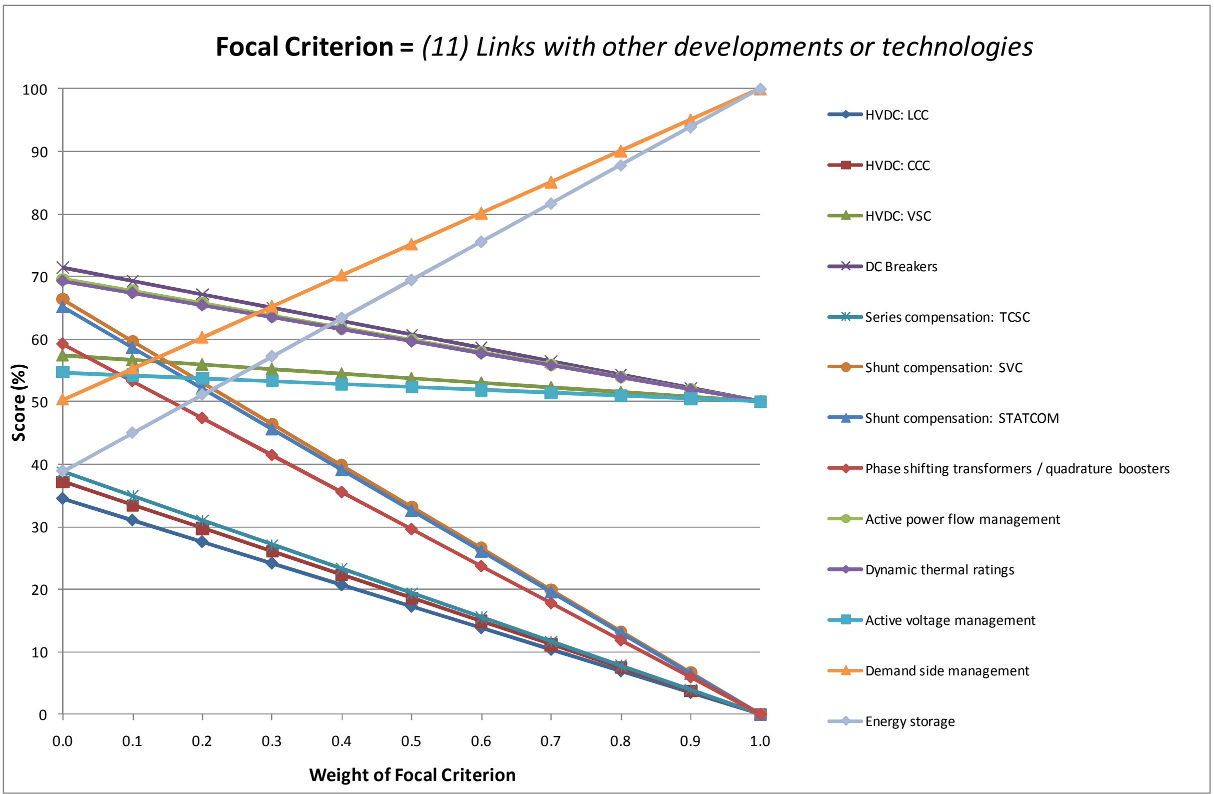
Links with other developments or technologies					
No.	Technology	Enabler for other technologies	Technology is linked to advancements in other domains	Score	Normalised
1	HVDC: LCC	0	0	0	0.00
2	HVDC: CCC	0	0	0	0.00
3	HVDC: VSC	0	1	1	0.50
4	DC Breakers	1	0	1	0.50
5	Series compensation: TCSC	0	0	0	0.00
6	Shunt compensation: SVC	0	0	0	0.00
7	Shunt compensation: STATCOM	0	0	0	0.00
8	Phase shifting transformers / quadrature boosters	0	0	0	0.00
9	Active power flow management	0	1	1	0.50
10	Dynamic thermal ratings	1	0	1	0.50
11	Active voltage management	0	1	1	0.50
12	Demand side management	1	1	2	1.00
13	Energy storage	1	1	2	1.00
			Max Raw Score	2	
			Min Raw Score	0	

DC breakers clearly stand out as an enabler for multi-terminal HVDC. Dynamic thermal ratings, demand side management and energy storage are also identified as enablers because they might be used to enhance the performance of an active network management scheme, which might otherwise rely on fixed line ratings and control of generators only.

Active network management is linked to developments in telecommunications, which make it cheaper and more feasible to implement the type of control systems required. Likewise, HVDC relies on very fast co-ordinated control. In particular, multi-terminal systems will require communications links between terminals to ensure co-ordinated control is achieved. Energy storage for utility network applications is closely linked to developments in transport and other fields.

Figure 25 has several lines crossing over one another so indicates that this criterion helps to separate the technologies.

Figure 25: Weighting sensitivity analysis for criterion 11



7.2.12 Combining Multiple Criteria

The normalised scores for all technologies across the ten assessed criteria are shown in Table 30.

Table 30: Normalised scores for technologies across all assessment criteria

Technologies		1 Potential to enhance UK industrial capability and knowledge	2 Potential to reduce through-life costs of technology use	3 Potential to reduce the cost of electricity for consumers	4 Has a clear business case for all stakeholders	5 Potential to overcome or bypass problems with consents	7 Potential to reduce CO2 emissions	8 More options and flexibility in network design and operation	9 Impact on system security and reliability	10 Potential to enhance capacity of the existing network	11 Links with other developments or technologies
HVDC: LCC	1	0.25	0.00	0.50	1.00	0.00	0.60	0.00	0.50	0.25	0.00
HVDC: CCC	2	0.00	0.00	0.50	1.00	0.00	0.70	0.14	0.50	0.50	0.00
HVDC: VSC	3	0.00	1.00	0.50	1.00	0.00	0.70	0.71	0.50	0.75	0.50
DC Breakers	4	0.00	1.00	0.50	1.00	0.75	1.00	0.43	1.00	0.75	0.50
Series compensation: TCSC	5	0.00	0.50	0.50	1.00	0.00	0.70	0.29	0.25	0.25	0.00
Shunt compensation: SVC	6	0.50	0.50	0.50	1.00	0.75	0.90	0.57	0.50	0.75	0.00
Shunt compensation: STATCOM	7	0.50	0.50	0.00	1.00	0.75	0.90	0.71	0.50	1.00	0.00
Phase shifting transformers / quadrature boosters	8	0.50	0.50	0.50	1.00	0.75	0.90	0.43	0.25	0.50	0.00
Active power flow management	9	1.00	1.00	1.00	0.00	1.00	0.80	0.71	0.25	0.50	0.50
Dynamic thermal ratings	10	0.50	1.00	1.00	1.00	1.00	0.70	0.29	0.50	0.25	0.50
Active voltage management	11	0.75	1.00	1.00	0.00	1.00	0.60	0.57	0.00	0.00	0.50
Demand side management	12	0.25	1.00	1.00	0.00	1.00	0.60	0.43	0.25	0.00	1.00
Energy storage	13	0.25	1.00	0.00	0.00	0.25	0.00	1.00	0.25	0.75	1.00

The sensitivity analyses for each of the criteria suggest that all of the criteria have an important influence in differentiating the technologies. For the assessment of technologies the final ranking of criteria is the same as interim rankings discussed above, as shown in Table 31. Note that the potential to enhance or accelerate TRLs does not appear as a criterion for the assessment of technologies.

Table 31: Final Criteria Rankings for Assessing Technologies

Description	Interim Ranking	Final Ranking
Potential to enhance UK industrial capability and knowledge	5	5
Potential to reduce through-life costs of technology use	6	6
Potential to reduce the cost of electricity for consumers	=2	=2
Has a clear business case for all stakeholders	=4	=4
Potential to overcome or bypass problems with consents	=4	=4
Potential to reduce CO2 emissions	1	1
More options and flexibility in network design and operation	=2	=2
Impact on system security and reliability	=3	=3
Potential to enhance capacity of the existing network	=2	=2
Links with other developments or technologies	7	7

The final criteria rankings are converted into weightings for the overall assessment of technologies by calculating the reciprocal of the rating, summing the reciprocals, and calculating what fraction of the sum is assigned to each criteria. This calculation is shown in Table 32.

Table 32: Calculation of Criteria Weightings for Assessing Technologies

Description	Final Ranking	Reciprocal	Weighting
Potential to enhance UK industrial capability and knowledge	5	0.200	0.052
Potential to reduce through-life costs of technology use	6	0.167	0.043
Potential to reduce the cost of electricity for consumers	2	0.500	0.130
Has a clear business case for all stakeholders	4	0.250	0.065
Potential to overcome or bypass problems with consents	4	0.250	0.065
Potential to reduce CO2 emissions	1	1.000	0.260
More options and flexibility in network design and operation	2	0.500	0.130
Impact on system security and reliability	3	0.333	0.087
Potential to enhance capacity of the existing network	2	0.500	0.130
Links with other developments or technologies	7	0.143	0.038
	Sum	3.843	1.000

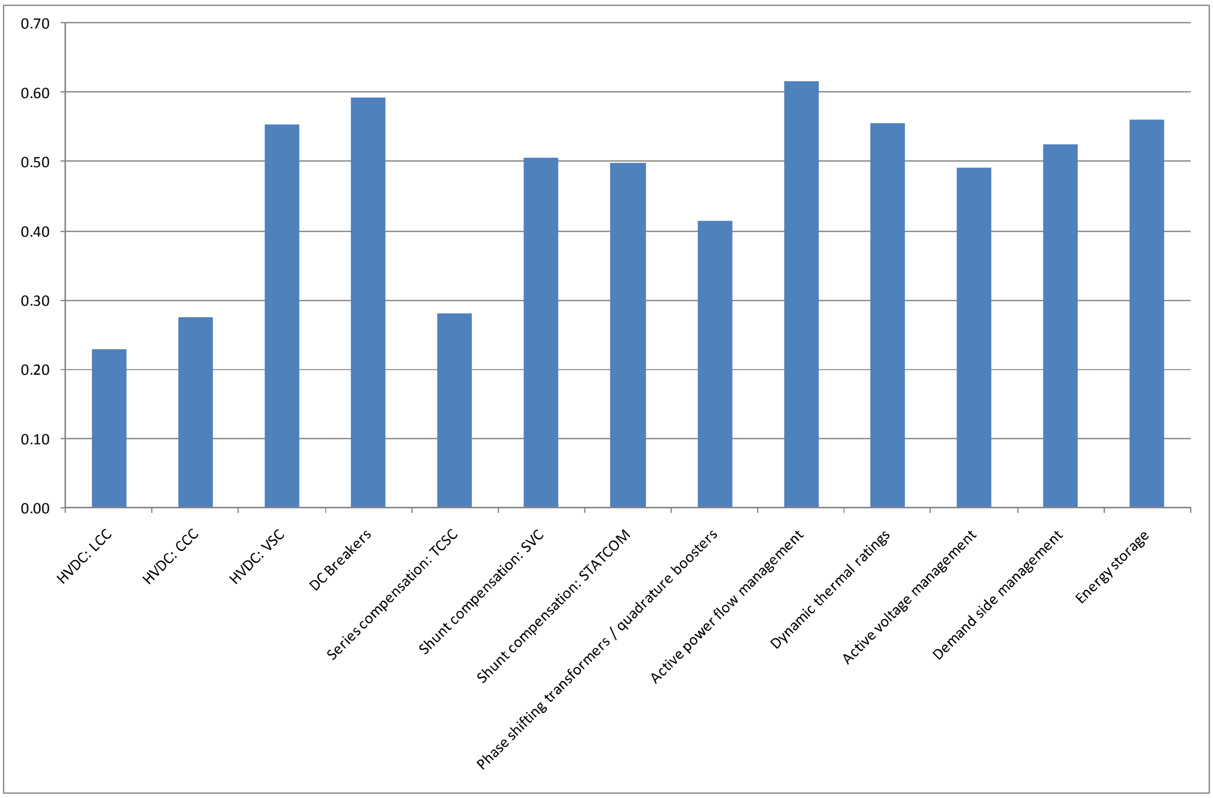
Note: The reciprocals and then the weightings are each rounded to three decimal places. The weighting for "Links with other developments or technologies" is increased by 0.001 so that the sum is 1.000.

From the normalised scores in Table 30 and the criteria weightings in Table 32 it is possible to calculate the overall score for each of the technologies. The results, and their conversion into an overall ranking, are shown in Table 33 and the overall scores are plotted in Figure 26.

Table 33: Overall Scores and Ranking for Technologies

Technologies	Overall Score	Rank
HVDC: LCC	0.23	13
HVDC: CCC	0.28	12
HVDC: VSC	0.55	5
DC Breakers	0.59	2
Series compensation: TCSC	0.28	11
Shunt compensation: SVC	0.51	7
Shunt compensation: STATCOM	0.50	8
Phase shifting transformers / quadrature boosters	0.41	10
Active power flow management	0.62	1
Dynamic thermal ratings	0.56	4
Active voltage management	0.49	9
Demand side management	0.52	6
Energy storage	0.56	3

Figure 26: Overall Scores for Technologies



8 Discussion and Summary

The multi-criteria assessment presented in this report has explored the technologies of interest to the project and the development options associated with those technologies and their application. The assessment criteria reflect the objectives of the ETI but also reflect the aims and preferences of the electricity supply sector more broadly. The assessment presented here feeds into the overall project and the analysis of technologies and development options but must be considered alongside other work and does not represent the final conclusions or recommendations of the project.

A workshop was organised to discuss the project activities and collect input from a wide range of stakeholders including researchers, manufacturers, network operators and the regulator. The outcomes of the workshop defined the framework for this multi-criteria assessment. In particular, the workshop produced a list of development options and assessment criteria. These were subsequently revised but are still representative of the discussions and suggestions that arose during the workshop.

The assessment has proved quite difficult because of the multitude of options of different types. It was often not possible to directly compare one option with another because their purpose and characteristics were quite different. Nevertheless, an assessment has been performed and the results do reveal something of the priorities of the workshop participants, the impacts and difficulties associated with different technologies, and the courses of action that are seen as most likely to meet the objectives relating to network capacity, the connection of renewables and the reduction in carbon emissions.

For the technologies of interest a common set of barriers was identified and the development options considered in terms of the barriers they might help to overcome. This revealed that the suggested development options will together have the greatest impact on HVDC technologies, which is consistent with the emphasis on HVDC in the overall project. It must be recognised that development options like "support trials or demonstrations" will only influence the specific technologies that are involved in the trial or demonstration. However, the analysis reveals that the development options expected to have the widest ranging impact, and so perhaps offering lower risk paths for investment, are:

- Support trials or demonstrations
- Help to establish common standards and models
- Support R&D in new devices for greater capability/performance
- Training and education, e.g. courses, conferences

The multi-criteria assessment was conducted using two spreadsheets, for development options and for technologies. Scores were assigned against each of the criteria and then these were combined with criteria weightings to produce overall scores. The spreadsheets allow for the easy modification of scores and weightings. The scores were based on the findings of the project and the workshop discussions. The criteria weightings were based on the preferences expressed by the workshop participants and then adjusted to reflect the sensitivity of the overall score to the weighting of different criteria.

The assessment results indicated that the assessment criteria would be fulfilled most effectively by pursuing the following development options:

1. Investigate use of energy storage to help solve ANM constraints
2. Commission work on new HVDC systems/topologies
3. Prompt changes in regulatory framework to change business drivers
4. Develop effective DC breaker or blocking capability

Notably, these top four best-performing options are all different from the top four identified as tackling common barriers. This shows that trying to satisfy the general objective of tackling barriers will not necessarily meet specific objectives, as reflected in the assessment criteria.

The assessment results indicated that the assessment criteria are best satisfied by the following technologies:

1. Active power flow management
2. DC breakers
3. Energy storage
4. Dynamic thermal ratings

An alternative interpretation of the analysis is to focus on the one criterion that was ranked most highly, which was the potential to reduce CO_2 emissions. The development options that were considered to perform best for this single criterion were:

- Prompt changes in regulatory framework to change business drivers
- Support R&D in new devices for greater capability/performance
- Commission work on new HVDC systems/topologies
- Develop effective DC breaker or blocking capability
- Investigate use of energy storage to help solve ANM constraints

The technologies that performed best for this single criterion were:

- DC Breakers
- Shunt compensation: SVC
- Shunt compensation: STATCOM
- Phase shifting transformers / quadrature boosters

The high score for the development option of investigating energy storage and for energy storage as a technology reflects the discussions at the workshop, where energy storage was highlighted as being of particular interest and very relevant to the challenges faced in connecting more renewables to the existing system. It is an important outcome of this work that energy storage did not feature amongst the technologies identified for consideration but when industry stakeholders discussed the objectives and context for the assessment energy storage was highlighted as being of value.

For HVDC the development options that scored most highly were those concerned with new systems/topologies and the development of an effective DC breaker. DC breakers were one of the highest scoring technologies and the assessment results suggest that VSC is favoured over the older HVDC technologies. This reflects the view that the fundamental power electronic building blocks are available and there is little pressing need for new devices. VSC promises to deliver much in terms of flexibility, control and the potential to operate multi-terminal systems. The challenge is at the systems level where all components must be made to work together and operate effectively within the existing AC network. DC breakers are seen as crucial for the deployment of multi-terminal HVDC and an essential element of the new systems/topologies that must be defined.

The regulatory framework is under constant review but the multitude of stakeholders in the electricity sector means it is difficult for everyone to be satisfied. The high score for this option reflects the sense of frustration, perhaps most notable amongst engineers, that network companies are unable to be bold and take risks with new technologies and methods that might address some of the problems faced. Few think that network companies should be given free rein to try whatever they want, and incur large costs in so doing, but arguments persist about the balance of regulatory incentives and the need for constant fine-tuning according to the prevailing priorities.

Active power flow management and associated technologies, like dynamic thermal ratings, are a prime example of where the technology is mature but the barriers to its use lie mainly in the regulatory and commercial framework, and what this means for the business drivers of different stakeholders. The problems associated with constraint payments and the principles to be applied in sharing network access are mainly commercial. It is perceived that the technology could be effective in meeting the assessment criteria, including enhancing network capacity and allowing more renewables to connect, but some changes to the regulatory environment may be necessary for this solution to be used widely.