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Glossary

ANM - Active Network Management
BEV - Battery Electric Vehicles
CB - Circuit Breaker
CHP - Combined Heat and Power
CSC - Current Source Converter
DECC - Department Of Energy and Climate Change
DER - Distributed Energy Resources
DNI - Distributed Network Intelligence
DNO - Distribution Network Operator
DSM - Demand Side Management
DSO - Distribution System Operator
DSR - Demand Side Response
EHV - Extra High Voltage
ENW - Electricity North West
EV - Electric Vehicle
GSP - Grid Supply Point
GW - Gigawatt
GWh - Gigawatt Hour
HV - High Voltage
HVAC - High Voltage Alternating Current
HVDC - High Voltage Direct Current
kW - Kilowatt
kWh - Kilowatt Hour
LCNF - Low Carbon Network Fund
LV - Low Voltage
MTTE - Multi-Terminal Test Environment (also The National HVDC Centre)
MV - Medium Voltage
MVDC - Medium Voltage Direct Current
MW - Megawatt
MWh - Megawatt Hour
NPG - Northern Powergrid
PHEV - Plug-in Hybrid Electric Vehicles
PNDC - Power Networks Demonstration Centre
PPA - Power Purchase Agreement
PV - Photovoltaic
RAG - Red-Amber-Green Analysis

R&D	- Research & Development
RES	- Renewable Energy Sources
SCADA	- Supervisory Control and Data Acquisition
SGS	- Smarter Grid Solutions
SHEPD	- Scottish Hydro Electric Power Distribution
SHETL	- Scottish Hydro Electric Transmission Limited
SME	- Small Medium Enterprise
SO	- System Operator
SPEN	- Scottish Power Energy Networks
SPT	- Scottish Power Transmission
SSE	- Scottish and Southern Energy
SSEG	- Scottish and Southern Energy Distribution
SSEPD	- Scottish and Southern Energy Power Distribution
STOR	- Short-Term Operating Reserve
TCO	- Total Cost of Ownership
TNO	- Transmission Network Operator
ToU	- Time of Use
TRL	- Technology Readiness Level
TSO	- Transmission System Operator
TWh	- Terawatt Hour
UKPN	- UK Power Networks
VSC	- Voltage Source Converter
WPD	- Western Power Distribution

Executive Summary

TNEI Services, in partnership with Element Energy and Eunomia Research & Consulting, have been commissioned by Scottish Enterprise to undertake an assessment of energy system technology activity in Scotland and perform a benchmarking exercise. Energy system technologies are discrete services or technologies which exist to enable or facilitate the enhancement of energy networks. The study encompasses a review of the current technological and market position of selected energy system technologies, and expected growth out to 2025. Through these reviews, Scottish relative strengths and weaknesses in each sector can be identified with a view to providing recommendations to Scottish Enterprise on appropriate support mechanisms or targeted interventions.

Energy system technologies offer various methods of facilitating interconnection, interoperability and enhancement of existing energy networks and there is increasing activity in these sectors as a result. Scottish energy networks, in particular the electricity network where this work is focused, have many unique characteristics which have prompted an array of developments and innovations over the years, and energy system technologies have been no different. From domestic scale home energy control systems to HVDC transmission systems spanning hundreds of kilometres, Scotland has involvement across the supply chain.

The objectives of this study are to select and assess the energy system services and technologies that are understood not only to be particularly relevant to the development of Scottish electrical networks in the coming decade, but also those which present opportunities for Scottish companies to grow both in Scotland and in international markets. Nine energy system technologies in total were selected for this study. A review of these case studies encompasses both technical capability and market position assessments, as well as a benchmarking exercise where each sector is compared with the rest of the UK, and other developed and developing countries where appropriate.

The technical capability assessment includes an overview of the technology options and specifications, a description of developments and TRL, current deployment levels (in Scotland and elsewhere) and the capability of the energy system technology to deliver a lower cost of energy, reduced carbon emissions and improved user engagement.

The market assessment addresses how the energy system technology is relevant to Scotland, noting any niche requirements specific to the country, and details the evidence of existing strong capability and relative competitive advantage i.e. commercial presence in the market. Potential gaps and relative weakness in Scottish capabilities are also identified in the market assessment such that these could be developed if appropriate. An insight into international activity in the sectors is given and countries with particular strengths are identified.

A RAG analysis performed on each case study as part of the benchmarking exercise provides a high-level overview of Scotland's position in relation to the rest of the UK, and other developed and developing countries that are active in each sector. Recommendations are made to Scottish Enterprise based on the findings of each case study and include support for existing strengths as well as interventions for areas of weakness.

EV Charging, Dispatch Control and Grid Services

There are no significant technical barriers to the deployment of EVs for grid support and several trials have been successfully completed in Scotland. Rather, the main challenges lie with regulation and market structures which will require revision if a revenue stream is to be provided. Revenue per household is approximated at circa £100 per annum which will require efficient business models to ensure that enough of this can be passed on to customers to incentivise their engagement.

Home Energy Control Systems

Many smart home energy products are already or soon will be commercial however uptake is still in the early stages. There is significant potential for economic benefit from smart heating and smart microgeneration products however a number of commercial and regulatory challenges must be overcome before home energy controls contribute widely to demand-side response services. Scotland's high renewables deployment, grid constraints in isolated networks and high incidence of electric heating makes it a natural testbed for such technologies and regulations. However, export opportunities for Scotland must consider the strong advantage in market position of existing energy suppliers and appliance manufacturers in the export markets targeted.

Recommendations for Demand-Side Activity

In terms of the domestic scale technologies investigated i.e. EV charging and home energy controls, the key recommendation is the continued support of innovation and development of technologies and the associated regulatory requirements to address existing market barriers. There is considerable potential for Scottish households to contribute to the more efficient operation of the electricity network through increased demand side activity. Existing activity in the sector, from DNOs and vendors, should be maintained and increased and new technologies and businesses can be promoted further through various mechanisms e.g. competitive funding.

To improve the outlook for these demand side activities, targeted intervention could accelerate the deployment of technology and bring benefits sooner. Recommendations on how to achieve this include public-funded trials to create an evidence base on the benefits of domestic scale technologies. The development of a national roadmap would also be a very useful tool to involve and incentivise stakeholders to continue to support the area. Finally, it is also important to ensure that learnings and commercial opportunities created by the various innovation projects being conducted in this area within Scotland are fully exploited to maximise broader export opportunities for Scottish businesses.

Electricity Support from Battery Storage

Battery storage systems are fully proven in an operational environment and there are a small number of these systems in Scotland, including the first large scale installations in the UK. Many of these have been used to provide grid stability in island and rural communities. Although the cost of battery technologies is expected to decline in the coming decade, economic challenges remain due to high capital costs and relatively insecure and short contract lengths associated with the available revenue streams.

Battery storage has been shown to have great potential in overcoming a number of constraints and offering improved flexibility. The supply chain in Scotland presently however, is somewhat nascent and could benefit from a number of interventions. These include dissemination of learning from existing Scottish trials to promote and publicise the tangible benefits storage can provide, the provision of funding for R&D to improve storage technologies and associated control systems, and support for companies with existing links to the energy sector but limited resource and/or expertise specific to storage.

Active Network Management

ANM systems are fully proven in an operational environment with the majority of UK DNOs having implemented ANM. The relative costs of ANM are much cheaper than traditional network reinforcement whilst allowing more generation to connect.

Scotland has a very positive outlook for ANM and is home to the emerging market leader in the sector and expansion into North America is already underway. In order to maintain this position, and improve long term resilience, support to other Scottish businesses moving into commercial ANM product development could be provided to create competition and encourage growth. Additionally, over-arching support in regulatory areas and risk mitigating through consultations with national and international bodies would be beneficial.

Distributed Network Intelligence

DNI applications are a combination of innovative monitoring and control technology coupled with innovative algorithms for automated decision support. They are new and diverse. The relative costs of implementing a DNI application are much cheaper than network reinforcement with the added benefit of providing better visibility to management.

Aside from global players such as ABB and GE, Scotland has a number of small companies specialising in DNI applications for power systems. Since many of these companies are spin-outs from universities, the main recommendation is to foster these capabilities and expand the market are through seed funding and encouragement of cross-institute collaboration with universities and research organisations.

HVDC

HVDC systems are well established globally and proven in an operational environment. The main barrier to HVDC systems is the high capital cost of power electronic equipment and they become more cost effective as distances increase.

Market growth in HVDC systems in Scotland is expected to grow in the coming years with a number of projects ongoing, planned or proposed. Since the technologies themselves are considered to be mature, it is in other areas of the supply chain that Scotland can expand. Existing strengths in the R&D and test & demonstration areas can be supported for example, through research funding for universities or investment in the development of The National HVDC Centre. Relationships with foreign capabilities could also be fostered.

MVDC

MVDC components are considered reasonably mature, however MVDC systems for distribution network reinforcement are considered less so due to lack of experience in the sector and risk-averse DNOs. Like HVDC, MVDC equipment has a high capital cost but can prove cost effective in network areas which suffer from multiple constraints.

In Scotland, the characteristics of MVDC as a reinforcement solution could be well suited to the network's niche requirements. Promotion and support for trials, demonstrations or deployments on Scottish networks by incentivising DNOs is a possible intervention pending the outcomes of ongoing trials in England and Wales which could determine the next steps for MVDC and its market in Scotland and elsewhere. Existing capabilities in R&D could be supported in the meantime through research funding opportunities e.g. help Scottish universities be successful in European funding bids.

Demand Forecasting and Power System Modelling

New, higher resolution, bottom-up, big data approaches to load forecasting and power system modelling are deployed commercially, though they are still undergoing innovation and wider deployment. Scottish grid challenges have meant that Scotland has led the way in some of these innovations. The expected cost benefits relative to network reinforcement are large and made possible through better planning and grid balancing through improved demand forecasting and system modelling.

There are already a number of innovation projects that have investigated the intricacies of demand forecast modelling and comprehensive systems have been set up to ensure alignment of learning outcomes such that synergies and opportunities can be fully exploited. A recommendation would be to provide support to ensure businesses are able to pursue broader commercial opportunities in the area. Given Scotland's high wind generation deployment, closely related work on wind generation forecasting could be promoted internationally, given the right commercial opportunities are available.

Ancillary Services (Grid Support) by Wind

The technology to provide ancillary services are available although not generally deployed in wind farms owing to a mix of technical and regulatory constraints. These constraints are limiting the adoption of ancillary services by wind although potential in Scotland is high owing to the large penetration of wind generation

Support of ongoing academic research and innovation projects with both National Grid and other European entities through seed funding or research grants as well as engagement between wind farm owners and consultancy/commercial expertise would be beneficial to explore opportunities further.

A high level overview of the findings, benchmarking and recommendations are provided in the summary table below.

Energy System Technology	TRL Range	Technological Capability, Development and Deployment in Scotland	Market Assessment	Benchmarking	Recommendations
Electric Vehicle Charging, Dispatch Control and Grid Services	EV components: TRL 9 For Grid Services: TRL 6 - 8	EVs are in mass production. The use of EVs for dispatch control and grid services is in the trial and development stage and results have been favourable so far. The significant challenge will be to demonstrate that EVs will be a reliable enough source of providing grid services to ensure widespread roll-out.	Scotland represents an excellent market for active demand technology with a range of Scottish companies and projects involved in demand side solutions incorporating EVs.	Scotland compare strongly against the rest of the UK and internationally in all areas, with the available skill set offering strong opportunities in the sector of demand side technologies.	Support for Scottish utilities and companies in this sector to advance EV charging mechanisms for grid support.
Home Energy Control Systems	Home systems: TRL 8 - 9 For Grid Services: TRL 6 - 8	Smart home energy controls are already technically well established, however the uptake of the technology remains very low (approx. 1.2% of households in Europe) owing to commercial and regulatory challenges.	Scotland has a strong base of commercial and research organisations that could play a role in the development of home energy controls, and several organisations are already active in the area.	Most countries, especially developed countries, are active in the sector. In certain aspects, such as the provision of tariffs to reward flexible demand in the home, countries including Germany and Switzerland can be seen to be ahead of Scotland and the UK. However, Scottish capabilities measure up strongly in most areas and perhaps exceed international levels of skills in the workforce.	Promotion of and investment in the sector to increase uptake of smart home energy controls and prompt the necessary commercial and regulatory changes.

Energy System Technology	TRL Range	Technological Capability, Development and Deployment in Scotland	Market Assessment	Benchmarking	Recommendations
Electricity Support from Battery Storage	TRL 8 - 9	Recent deployments in larger scale battery schemes have proven successful. Widespread roll-out is dependent on other emerging technologies such as intelligent control systems.	There are no battery storage developers located in Scotland presently; however the niche requirements of Scotland's many island communities means there is large potential for useful deployment.	The USA is dominant in the deployment of battery storage systems followed closely by several countries in Asia. Germany and the UK are the leading European countries in this sector. Scottish capabilities in the battery storage sector could be improved with relative weaknesses identified in the exportability and workforce areas.	Intervention to stimulate the commercialisation of large scale battery storage products. This could include dissemination of learning from existing projects, R&D funding and/or support for existing energy companies to expand into battery storage development.
Active Network Management	TRL 9	Several AMN product solutions addressing a number of network issues are commercially available and deployed throughout Scotland (and the UK).	Constrained Scottish networks prompted the development of ANM solutions and the market has grown, and continues to grow, in response to continued successful deployment.	Scottish market position in the ANM sector is considered world leading. Capabilities are strong in technological maturity, existing market and user engagement.	Support for businesses in Scotland emerging into the ANM sector to foster competition and innovation. Additionally, support and promotion of ANM on an international scale.

Energy System Technology	TRL Range	Technological Capability, Development and Deployment in Scotland	Market Assessment	Benchmarking	Recommendations
HVDC	CSC: TRL 9 VSC: TRL 8 Enhancement components e.g. DC boost, DC CB: TRL 1 - 6	HVDC transmission systems are commercially well established and deployed globally although only one is in operation in Scotland at present. Advances in VSC technology have improved the portfolio of technical benefits that HVDC systems can offer thus encouraging its consideration in more large scale projects. There are currently in excess of five HVDC projects either planned or proposed in Scotland.	The Scottish market for HVDC is limited but expected to grow over the next decade as more systems are commissioned.	Countries in South East Asia have a high uptake of HVDC systems, including CSC, VSC and more recently, multi-terminal systems. Despite the limited experience in deployment, Scotland has strong capabilities in pre-deployment areas of the supply chain such as R&D and test & demonstration.	Support to continue and maintain current trajectory of HVDC system development in Scotland, including multi-terminal R&D at The National HVDC Centre.
MVDC for Distribution Network Reinforcement	Components: TRL 8 – 9 MVDC for reinforcement: TRL 4 Enhancement components e.g. DC boost, DC CB: TRL 1 - 6	MVDC technology components are considered mature, however there is still de-risking required of MVDC systems (for control system integration for example) to be considered for use on electrical networks as a means of reinforcement. Network demonstrations are underway by two UK DNOs which will serve to de-risk this application, quantify the potential benefits and provide lessons learned.	There is no existing market in Scotland for MVDC systems as applicable to network reinforcement. The technology could prove useful on Scottish distribution networks in areas which experience multiple constraints however so there is potential for the market to grow if results from ongoing trials are favourable.	Scottish capabilities in MVDC could be improved in all areas and lag behind countries like England and Germany who have demonstration and limited deployment experience.	Capitalise on any favourable outcomes from the English MVDC network trials and support continued R&D in the meantime, perhaps collaboratively with the National HVDC Centre.

Energy System Technology	TRL Range	Technological Capability, Development and Deployment in Scotland	Market Assessment	Benchmarking	Recommendations
Distributed Network Intelligence	TRL 7 - 9	Large multi-national corporations have broad DNI capabilities however there are a multitude of smaller companies that are emerging with innovations and offerings in the sector, including automated distributed decision support, condition monitoring and asset management software platforms.	There is an active Scottish market for DNI and both of the utilities have investigated different capabilities for their networks. Emerging Scottish companies are helping to grow this local market while also developing internationally.	Scotland has strengths in DNI systems in all areas and measures up equally to other developed countries active in the sector. An expansion of the skills base (both in Scotland and globally) is required if large scale roll-out is to be achieved.	Provision of funding support through either seed money for promising start-up companies or research grants for universities or other institutions.
Demand Forecasting and Power System Modelling	Existing high-level approach: TRL 9 Big data approach: TRL 5 - 9	High-level forecasting and modelling techniques are well established and used extensively to date. It is the higher resolution, big data approaches that are currently at earlier stages of deployment. Several successful trials of such systems have been achieved and are available to facilitate network operator decision making.	High penetrations of intermittent generation sources in Scotland means there is significant potential for market growth in the country as network operators seek to improve both generation and demand forecasting capabilities.	Scotland measures up well internationally in all areas. There is potential for the Scottish market to leverage its forecasting and modelling capabilities around renewables deployment and constrained and/or islanded networks to develop export opportunities.	Support businesses in the sector to pursue broader commercial opportunities arising from the learning outcomes of the various system trials and projects.

Energy System Technology	TRL Range	Technological Capability, Development and Deployment in Scotland	Market Assessment	Benchmarking	Recommendations
Ancillary Services (Grid Support) by Wind	TRL 7 - 9	Ancillary services provided by wind generation are being recognised as an approach that can be harnessed in a few countries, particularly those with high wind penetration. However, participation is limited to date due to the (Grid Code) requirements of the services required by TSOs. Targeted amendments to service requirements (i.e. service timescales) could open up the opportunity for wind generation to play a bigger role in the provision of grid support.	Although limited at present by regulatory conditions, the potential market for wind generation to provide ancillary services is significant in Scotland owing to its high penetration of wind farms both connected and contracted to connect.	The high availability of wind generation in Scotland and activities in the sector stand Scotland in good stead to take full advantage of any opportunities that arise for wind generation to provide ancillary services.	Encourage collaboration between existing Scottish expertise in grid support services (academic and private sector) and wind farm owners to map out potential opportunities and lobby for regulatory changes.

1 Introduction

There is growing interest in the commercial, economic and environmental benefits that can be realised by increasing the levels of interconnection, interoperability and enhancement of energy networks. Until now the focus has largely been on connecting large volumes of renewable generation in an effort to meet targets for renewable energy production and carbon emission reduction. Now that these large volumes have connected and various innovative technologies have emerged to manage networks and customers alike, there is a change in focus to energy system technologies which will both enable their operation and facilitate their interoperation.

Scotland has so far been faced with various challenges owing to the vast renewable resource in the country and correspondingly the high volumes of renewable generation connections. In response to this, many innovations and developments have been made by Scottish companies to improve integration and management of these connections on the grid. Most notable are the developments in HVDC research and development with the establishment of SHETL's Multi-Terminal Test Environment facility, and also advancements in ANM techniques being spearheaded by University of Strathclyde spin-out company Smarter Grid Solutions. Both HVDC and ANM can be considered as energy system technologies which facilitate the interconnection, interoperation and enhancement of electricity networks.

Scottish Enterprise, in their role as an economic development agency, is seeking to understand the various energy system technologies available for networks such that they can develop strategies to maximise economic benefits for Scotland out to 2025. In order for Scottish Enterprise to effectively inform on energy system technology strategy, they must gain a good understanding of not only the energy system technologies themselves, but also of how Scottish capabilities compare with other countries involved in the sector. Although there are a number of energy networks to be considered e.g. electricity, gas, transport and heat, this report focuses largely on the energy system technology subsectors relevant to the electricity network.

This report assesses on the technical aspects of these energy system technologies and how the capabilities of Scottish companies compare with the rest of the UK and globally. A shortlist of relevant energy system technologies have been selected for this study and areas where Scotland and/or Scottish companies have a competitive advantage which could be promoted and developed are identified and highlighted. Additionally, areas where there are gaps or relative weaknesses in Scottish capability are identified which could be developed and built through targeted interventions or bolstered with support from inward investment.

A benchmarking exercise highlights the capabilities of Scotland against the rest of the UK and other relevant developed and developing countries. This also serves to identify potential companies and/or regions where there may be opportunities for collaboration and growth.

Section 2 of the report provides an overall description of energy system technologies and what they are understood to be in the context of energy networks. Section 3 presents the case studies that were selected for study, and these provide a technical and market assessment as well as exploration of user engagement. Section 4 summarises the benchmarking exercise for each energy system technology and Section 5 presents the main recommendations of the study, both in terms of promoting areas where Scotland has a competitive advantage and also where interventions or inward investment could improve Scottish capability.

2 Energy System Technologies

Energy system technologies can be defined as discrete services or technologies which exist to enable or facilitate the enhancement of energy networks. Such systems include:

- Power Electronics, including DC transmission applications;
- Energy storage (Battery and Thermal);
- Heat Recovery and District Heating;
- Active Network Management; and
- Grid support services.

Energy system technologies offer a product or service which will benefit an energy network in some way, for instance, by increasing network capacity, allowing more low carbon customers/loads to connect or deferring reinforcement. Examples of this include: HVDC transmission, that enables improved interconnection between (relatively) isolated networks; energy storage which can provide a service to enhance the network by potentially levelling demand profiles and allowing more efficient operation; and ANM that facilitates improved interoperation of networks with customers through active (rather than passive) control.

Technologies have been developed over the years to ensure the continued improvement and enhancement of networks. Now that many of these are becoming commercially feasible, they are being utilised in the provision of useful energy system technologies as the benefits they can offer is being recognised more widely. The Energy Systems Catapult[1], a technology and innovation centre set up by InnovateUK, was established in 2015 to support both the UK Government and UK companies in developing products and opportunities related to energy systems and energy system technologies. The focus of the Energy System Catapult's research and innovation will be electricity, heat and combustible gas networks and the associated energy system technologies. This is an example of the support that is being provided in a UK context to accelerate local and international market benefits from commercialisation of local technology.

[1] https://es.catapult.org.uk/

3 Energy System Technology Case Studies

Following discussion with Scottish Enterprise, a shortlist of relevant energy system technologies was selected for assessment:

- Electric Vehicle Charging, Dispatch Control and Grid Services
- Home Energy Control Systems
- Electricity Support from Battery Storage
- Active Network Management
- Distributed Network Intelligence
- HVDC
- MVDC for Distribution Network Reinforcement
- Demand Forecasting and Power System Modelling
- Ancillary Services (Grid Support) by Wind
- Big Data Analytics (discussed within relevant case studies, not separately)

Each of the case studies presents the results of technology and market assessments which incorporate technical specifications and development, Scottish capabilities and international relevance. Following this, a benchmarking Red-Amber-Green analysis, is presented and the capabilities of Scotland are compared against the rest of the UK as well as relevant developed and developing countries where appropriate. Recommendations for Scottish Enterprise going forward are also provided to support further development of Scottish capabilities.

3.1 Case Study Definitions

3.1.1 Technology Readiness Level

As part of the technology assessment, there is reference to the TRL if relevant which refers to a scale by which a technology component or system is measured in terms of its readiness for use in real systems. The following definitions apply:

- TRL 1 – Basic principles observed
- TRL 2 – Technology concept formulated
- TRL 3 – Experimental proof of concept
- TRL 4 – Technology validated in lab
- TRL 5 – Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 6 – Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 7 – System prototype demonstration in operational environment

- TRL 8 – System complete and qualified
- TRL 9 – Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies)

3.1.2 Marketability

As part of the benchmarking exercise, where the marketability of energy system technologies is evaluated in a qualitative RAG analysis against relevant developing and developed countries, the following definitions apply:

3.1.2.1 Technological Maturity

The level of technical maturity of the local energy system technology that would enable this technology to be applied and deployed e.g. for some developing countries, there might not be the electrical infrastructure or technical experience to feasibly deploy.

- ❖ Green - High local technical maturity of energy system technologies and associated technical expertise
- ❖ Amber - Some local technical maturity of energy system technologies and associated technical expertise
- ❖ Red - Low local technical maturity of energy system technologies and associated technical expertise

3.1.2.2 Existing Market Capability

The capability of existing local market/companies in a country or region to develop and market the technology.

- ❖ Green - High existing local capability
- ❖ Amber - Some existing local capability
- ❖ Red - Low existing local capability

3.1.2.3 Exportability

The ease by which the energy system technology can be deployed outside the country of origin.

- ❖ Green – No difficulty in exporting the energy system technology
- ❖ Amber – Some difficulty exporting the energy system technology
- ❖ Red – High difficulties in exporting the energy system technology

3.1.2.4 Relative cost/economics

The relative cost of the energy system technology compared to either a relevant alternative solution or taking no action.

- Green – Lower cost than alternative solution
- Amber – Cost is about the same as an alternative solution
- Red – Higher cost than alternative solution

3.1.2.5 Carbon

The perceived carbon emission reduction (or conventional generation displacement) that the energy system technology can directly or indirectly achieve when compared to either a conventional solution or taking no action.

- Green – High level of carbon emission reduction
- Amber – Moderate level of carbon emission reduction
- Red – Low level of carbon emission reduction

3.1.2.6 User Engagement

The level of user engagement carried out in the development of the energy system technology to mitigate potential risks and maximise uptake.

- Green – High level of user engagement and input during product/service development
- Amber – Some user engagement and input during product/service development
- Red – Limited/No user engagement and input during product/service during development

3.1.2.7 Available Skillset

The availability of skills related to the energy system technology within a country or region.

- Green – Well dispersed expertise, skills market well established
- Amber – Skills market is developing but know-how is still within niche establishments
- Red – Limited/No expertise of the energy system technology

3.2 Electric Vehicle Charging, Dispatch Control and Grid Services

Electrified drivetrains - which include Battery Electric Vehicles and hybrid battery + internal combustion Plug-in Hybrid Electric Vehicles are recognised as a key technology to reducing CO_2 emissions from vehicle drivetrains and passenger cars in particular[2]. National decarbonisation strategies all rely heavily on the increasing market take-up of BEVs and PHEVs to decarbonise the passenger car fleet.

The main features of EVs (relative to the incumbent) are high capital cost, low operating costs, and lower driving range. BEV capital cost (which even with a grant could add £5-£15k to a C-D segment car typically costing £20k) acts as a significant disincentive to market uptake. Similarly, although typical daily mileage (40km in the UK) is significantly lower than BEV range (currently 150-200km) nevertheless concerns with vehicle capability as well as charging requirements have limited the market uptake. Limited make/model availability has also slowed deployment.

However, the market is developing very quickly. There have been recent and significant reductions in battery cost (40% in 5 years) and this drives reduced capital cost and increased range in a more affordable vehicle. Tesla has been early to the market, but next year, General Motors will launch the Bolt, the first mass market BEV with upwards of 200km range that should address the range issue.

Given recent evidence on reductions in battery prices[3], the expectation is that by 2025, total cost of ownership equivalence will be reached, supporting mass market take-up and the development of new ownership models[4].

The daily mileage of vehicles (typically 40km) is significantly lower than EV range (currently 150-200km, rising to 250km and more). For EVs charged at home (the majority at present) this means that they can be charged in c. 2 hours, significantly less than the 10-12 hours overnight they may be plugged in. This provides significant flexibility to move charging demand during each 24 hour period.

Without actively managing charging, EVs could double peak household electricity demand[5], increasing electricity prices (more generation, transmission and distribution investment required).

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[2] Excluded from consideration in this review are Hybrid Electric Vehicles, which do have electrified drivetrains, but where the battery is recharged from the IC engine, rather than the grid. These vehicles offer carbon savings but no smart grid benefits.

[3] http://www.hybridcars.com/gm-ev-battery-cells-down-to-145kwh-and-still-falling/

[4] TCO equivalence means that the (higher) capital cost (of a BEV) is offset against the (lower) recurring running costs – compared to a baseline IC vehicle. While the higher capex is still a barrier to purchase, new ownership models (such as mobility rentals) will be economic.

[5] For example, see the "Customer Led Network Revolution" and "My Electric Avenue Projects".

However, for most deployments envisaged, actively managed (smart) charging, could avoid new energy system technology investments. In addition, by actively managing charging, an EV fleet could provide useful grid balancing services to the System Operator (£200-400m UK market by 2020)[6], to reduce out-of-balance costs of suppliers, and increase RES penetration through demand turn-up, reducing losses, and smoothing out RES volatility at Distribution level[7]. These services could all be provided by changing the EV charging profile – which has no impact on EV battery life.

Further into the future, with Vehicle-to-Grid technology EVs could utilise their (spare) battery capacity via grid tied inverters to put energy back into the grid, offsetting local peak loads and reducing network constraints. There are many barriers to this currently: battery degradation, and the inverters that are infrequently utilised. However some manufacturers (Nissan) are actively trialling this technology in Europe.

The electrification of transport may pose challenges to the electricity system, particularly on LV distribution networks. If charging is unmanaged, EV charging will result in an increase in demand at peak times, leading to an increased requirement for network reinforcement (increased costs). However, due to the flexibility of EV charging, this can largely be mitigated by shifting EV charging away from peak times (into the night, or middle of the day). Since charging is simply delayed or staggered to suit network requirements under these kinds of scenarios, there is no additional cycling of the battery and hence battery lifetimes are not negatively affected. An example of a trial looking at these challenges with high concentrations of EVs on a single LV feeder is “My Electric Avenue” led by EA technology and SSEPD.

As well as Distribution (regional) level issues, EVs could support the national System Operator in stabilising the grid. The Future UK electricity grid will be characterised by:

- Lower inertia – fewer thermal generators and nuclear power, with zero inertia provided by high penetration of RES
- Lower generation predictability (higher penetration of non-predictable RES)

As a result, National Grid has identified in its Strategic System Operability Report (2025) a factor-four increase in requirements for Reserve (1 hour duration energy

[6] Frequency Sensitive Electric Vehicle and Heat Pump Power Consumption, Element Energy report for National Grid, July 2015. Link to report can be found on National Grid website, here: http://www2.nationalgrid.com/UK/Industry-information/Future-of-Energy/Technology-reports/

[7] For more on this, see the National Grid System Operability Framework: http://www2.nationalgrid.com/UK/Industry-information/Future-of-Energy/System-Operability-Framework/

service to balance out non-dispatchable RES). In addition frequency response (a much faster responding, shorter duration service to manage frequency, is projected to double from present levels. While most of these services are currently provided by generators, there is a recognition that in future the demand side can participate more actively[8]. Electrochemical devices such as batteries and chargers, can respond near instantaneously to control signals, and this characteristic is very valuable to the SO.

Scotland is unusual in terms of its abundant renewable energy resources (primarily wind) and also the requirement to export most of this energy to major markets (in Southern England). Distribution and Transmission level constraints are increasing the costs of RES deployment, and this provides an additional incentive to manage loads regionally/locally. As RES deployment grows internationally, these issues – and their potential solutions – will become more widespread[9].

3.2.1 Technology Assessment

3.2.1.1 Specifications

Vehicle drivetrains: The major drivetrain types are BEV and PHEV (as described above). While BEV will always have a larger battery capacity, the limited daily mileage means that, from a charging perspective, both vehicle types can be treated as similar in terms of daily kWh consumed and therefore the volume of grid services that can be provided by each vehicle. In the near term – to 2025 – PHEVs are expected to dominate sales of electric drivetrains. Thereafter, battery cost reductions should allow BEVs to gain more market share.

Chargers: Most residential chargers are in the 3-7kW range. During charging, this results in a c. doubling of residential electricity demand. It is unlikely that residential chargers will need to reach higher powers. Publicly available fast and superfast charging (c. 50kW or more) is currently being deployed by a range of organisations including Ecotricity and Tesla.

Charging profile: Passive charging means the vehicle begins charging as soon as it is plugged in. The correlation of vehicle arrival times and residential energy use means this will increase loads on the network. Smart charging means that charging relies on a separate signal to begin and terminate.

[8] **Duncan Burt, Head of Commercial Operations at National Grid:** On balancing services from demand side sources: “We’d like to be buying 30 to 50% by 2020. To put that in numbers, that would mean we would be spending £200 million to £400 million a year on demand side services in Great Britain. That’s an enormous amount. That’s a huge market.”

[9] Smart Grid initiatives are currently estimated at $44billion PA worldwide (SBC Energy Institute).

CO_2 Impact: Recent work by Element Energy shows that with strong policy support, by 2030 the EV fleet in Scotland could:

- Comprise 40% of new Passenger car sales (mainly PHEV)
- Save 2.5Mt CO_2 per annum
- Have a daily used battery capacity of c. 5kWh per vehicle[10]

For comparison (2030 figures)

- 5kWh x 0.5m EVs = 2.5GWh each night (compared to 80-100GWh electricity currently consumed per day in Scotland)

Charger costs: Smart charging capability can be provided by the charger or on board the vehicle. Analysis carried out for National Grid[11] on the incremental cost of putting *frequency response* capability on an EV charger found that, for the scheme shown below, the cost is £10/chargepoint for hardware (excluding engineering, design and testing costs). This scheme relies on frequency sensing at the charger, as this provides the fastest response. For other services, remote signals may need to be sent to the charger (this could be via GPRS[12] or via the customer's existing internet connection). There are also overhead and operational costs for managing service provision by many small assets. Overhead costs are estimated c. £10/customer per year in the National Grid study, while operational costs depend on communications method.

[10] The low carbon London Trial indicated an average daily use of 3.5kWh; higher figures are expected outside of London and as the vehicle range increases.

[11] http://www2.nationalgrid.com/UK/Industry-information/Future-of-Energy/Technology-reports/

[12] General Packet Radio Services i.e. the mobile phone network

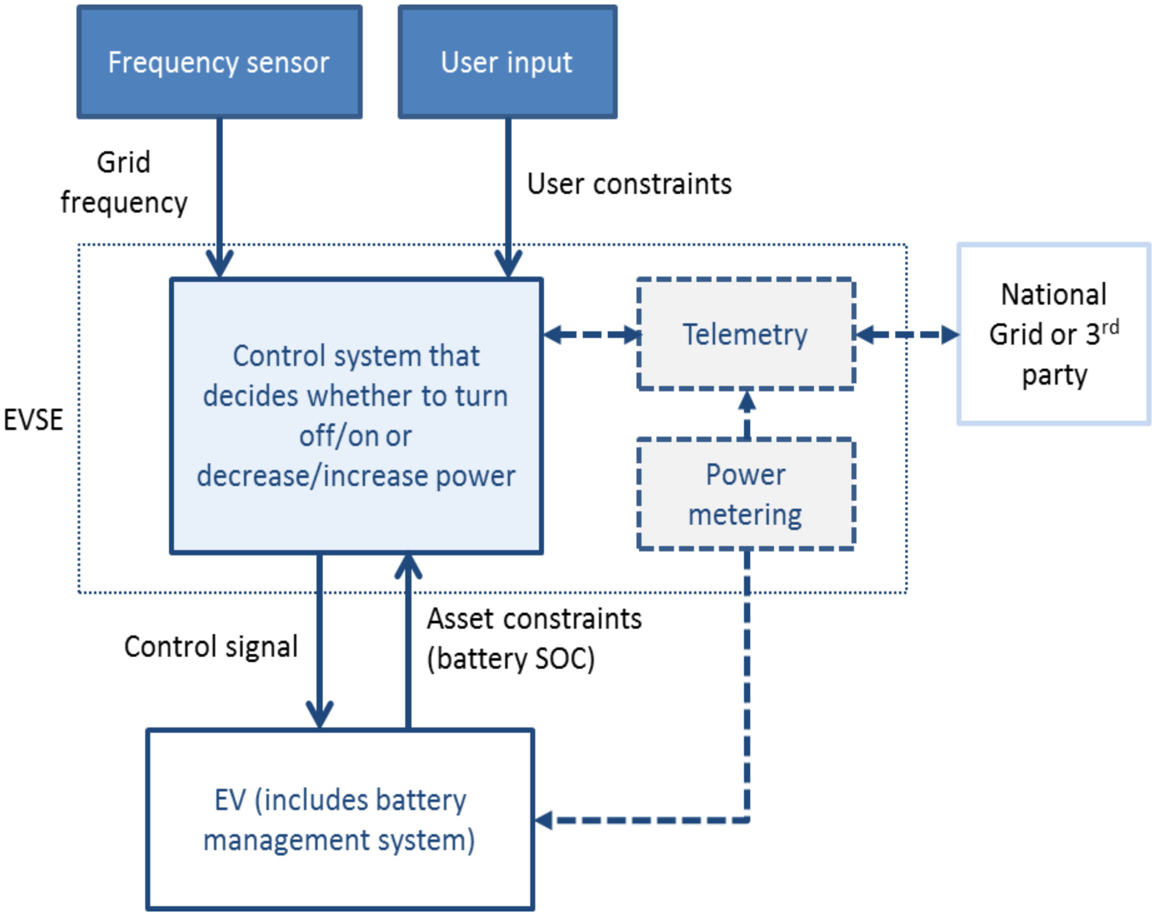

Figure 1: EV Charging for Frequency Response

Note however that the expected revenues from controlled charging are in the order of ca £100 per vehicle per annum (residential charging), relying mainly on frequency response. As the sector matures, additional revenues could arise (demand turn-up, reducing energy balancing costs of generators).

3.2.1.2 Development

Electric vehicles are now in mass production, with availability gradually extending across more makes and models. In 2017, the GM Bolt will be released in the US, a date for European release has not been provided. Environmental legislation is likely to support the PHEV growth to 2025 by which time BEV economics will look increasingly attractive[13].

[13] There is significant uncertainty associated with these estimates, primarily arising from battery cost forecasts, and from emerging consumer preferences for/against electric drivetrains

Active charging (providing aggregated SO benefits) is at a pre-commercial stage of deployment. Trials have been undertaken in a number of countries[14]

The following are EV chargers with scheduling and remote control capabilities:

- POD Point Solo - set charge scheduling manually, advanced version has 2 way GPRS communications[15]. Current price £650 excluding VAT
- Rolec Wallpod EV - has GPRS communications option[16]. Current price £395 excluding VAT

For charge points with remote control capability, a communications protocol is required to be able to send signals to vehicles to allow them to change their charging pattern in order to provide services. Open standards, such as the Open Charge Point Protocol[17], are under development. There are also challenges around communication between the charge point and the vehicle.

Network benefits arising from EV smart charging are limited mainly by EV deployment and by current lack of incentive for shifting EV charging to off peak times (requires ToU tariffs and/or half hourly settlement of domestic customers). EV provision of frequency response is similarly limited by EV deployment, and there is some final technology development required (incorporation of frequency response capability in charge points and testing/trial of solution).

Furthermore the energy sector is very conservative and risk averse. Even though the National Grid is procuring new demand side services, they refer to these as trials. It is likely to require many years of successful trials before the demand sector can be treated as being as reliable as the generator fleet.

There is limited systematic dependence and risk with other sectors. The main limitation, as mentioned above is the cautious approach of highly regulated energy utilities.

3.2.1.3 Capability

As shown above, by 2025, the TCO of EV and IC vehicles are expected to be equivalent. In addition, revenues of c. £50-100/annually per vehicle for grid services could be expected (note this excludes costs of additional hardware, overheads related to managing the aggregation service etc.). While there is the

[14] Examples include the Orkney Electric Futures Project; TENNET and The New Motion; My Electric Avenue)

[15] http://www.sourceeast.net/wp-content/uploads/2011/08/PP-DATASHEET-solo-charge-range-J1772-units.pdf

[16] http://evonestop.co.uk/wp-content/uploads/2015/01/EV-One-Stop-WallPod-EV-Economy-Boost.pdf

[17] http://www.openchargealliance.org/protocols/oscp/oscp-10/

potential to use a future EV fleet to avoid network investments, there are alternative demand side solutions which could provide similar services at lower costs.

Furthermore, the net revenue per EV is relatively diluted, and this presents a challenge to develop an efficient commercial and deployment model. A solution could be to bundle this up with vehicle upfront cost, or offer a lower electricity tariff to those providing smart charging.

There is significant potential for a large fleet of EVs to provide frequency response services to National Grid. The 2015 Element Energy study found that EVs could provide 50% of National Grid's projected frequency response requirement in 2030, subject to the fleet being large enough.

EVs providing frequency response would also reduce carbon emissions relative to Incumbent providers. Currently, frequency response is mainly provided by conventional thermal generators, coal and gas fired power plants, running at part load and then ramping up or down in response to frequency deviations. Replacing this with frequency response provision by EVs would reduce carbon emissions by c. 1.2 tonnes CO_2/year per EV.

In the future there will be a significant challenge to demonstrate that an aggregated EV fleet can be a *reliable source* of DSR and grid services. This comprises assembling reliable statistics on vehicle usage patterns (probably over a number of years and updated frequently as electric vehicles expand to more consumer segments); and the reliability of communication and control systems. This is an opportunity for Scotland given its high renewable energy deployment, its long distribution networks and the high reliance on electric heating in homes.

3.2.2 Market Assessment

3.2.2.1 Relevance to Scotland

Given the features mentioned above, Scotland represents an excellent market for active demand management technologies, including EV charging (as well as residential electric heating – the two sectors will share common solutions in providing grid services). Utilities in Scotland have been active in trialling ANM schemes (using load control to manage peak energy flows). The ACCESS project on the island of Mull is a good example of a home-grown demand for DSM solutions. While ACCESS is focussed on space heating, much of the sensing, communication and control technology, and the DNO experience, can support a nascent fleet of actively-charged EVs.

Smarter Grid Solutions is very active in innovative ways to manage loads on electricity networks, such as ANM schemes, and their technical solutions may be expected to become components of future actively charged EV fleets. SGS was part of the Low Carbon London project.

The University of Strathclyde is very active in researching the potential and benefits of Demand Side management through its Institute for Environment and Energy.

VCharge has a technology platform for managing and aggregating loads and providing these aggregates services to the System operator. VCharge has contracts in the US, Germany and with the UK National Grid. VCharge UK is based in Glasgow.

Johnson Matthey (formerly Axeon) is a leading provider of battery design, focussed on the automotive sector. For Vehicle to Grid applications (where the battery is discharged) their knowledge could be extremely useful in estimating and designing out impacts that are detrimental to battery life.

As mentioned above, Scotland can make a strong case as a relatively early adopter of actively managed demand technologies, given the high RES and relatively weak grid issues. Deployment of cost effective DSM technologies, including active EV charging, could reduce the cost of electricity to Scottish consumers.

3.2.2.2 International Relevance

Worldwide, the RES power sector is growing strongly. As a result, electricity supply is becoming less predictable. At the same time, rising demand and the extension of electricity grids to outlying areas is increasing losses and costs of electricity. Demand side management is expected to be an increasingly viable and vital component in managing costs of supply.

Managed charging of EVs is attractive because each EV load (c. 3-7kW) is relatively significant. However, as active charging will likely share a common communication and control platform as other DSM technologies, the relatively slow growth of the EV fleet could mean that other sectors capture the emerging market before aggregated EV services become significant.

3.2.2.3 User Engagement

Trials and surveys of EV users/owners have shown positive responses on attributes such as acceleration, response, and driving feel. The Tesla model S received the highest ever consumer rating[18]. However the Model S is not a mass market vehicle and alternatives such as the Nissan Leaf still have limited mileage which, along with recharging infrastructure, is still noted as a concern for drivers.

In the UK, there have been a number of trials of EV use and impact on the electricity grid, including Low Carbon London, Customer-led Network Revolution, and My Electric Avenue. In general, the response to EVs is positive but owners need to see improvements in costs, and convenience (range).

[18] http://www.consumerreports.org/cro/cars/tesla-model-s-p85d-earns-top-road-test-score

3.2.2.4 Commercial or Regulatory Challenges or Barriers

Technical challenges: The major components (which together would comprise an actively managed EV fleet to provide useful network services) are all at commercial or late pre-commercial stage of deployment. The technical challenges are not fundamental. Recently, DSM techniques have been approved by the regulator to be included within Network Operators' Investment Plans. However the sector is inherently cautious and it is likely that some years of successful operation, generating reliable statistics on availability, will be required before the sector can be seen as a robust alternative to cables.

Regulatory barriers: Medium/Low. In the UK, the System Operator (National Grid) is pioneering the contracting of novel demand side services. In part this is because of the relatively small size of the UK synchronous region, requiring higher levels of frequency response. DNOs are currently cautious regarding deployment of EVs and smart charging, and slow EV deployment (compared with DECC government projections) means the sector is of secondary importance to DNOs. Also, the lack of vertically integrated utilities is a barrier in the UK, as revenues and burden sharing may be quite unbalanced (as compared with California).

Commercial: These issues represent a relatively high barrier. EV costs remain high, and until the early/mid 2020's, EV TCO costs are expected to be higher than the incumbent. Networked, actively managed charging may generate significant aggregated revenue, but per vehicle these may be quite low (circa £100/annum). Only very efficient business models will be able to pass enough of this revenue through to the consumer to make active charging attractive.

However there is significant investment into the smart grid and DSM sector, including the control, optimisation and dispatching architecture[19].

Arrangements where EV demand turn up reduces RES curtailment may be more efficient than curtailment payments, and would be relevant to Scotland. However the pathway of payments involves a number of stakeholders (RES owner, TNO/DNO, aggregator, EV owner) and such models are untested commercially.

3.2.3 Marketability

RAG ranking	Scotland	Rest of UK	Developed	Developing
Technological maturity	🟢	🟢	🟢	🔴
Existing market capability	🟡	🟡	🔴/🟡	🔴

[19] http://www.origamienergy.com/round2.html

RAG ranking	Scotland	Rest of UK	Developed	Developing
Exportability	Green	Green	Amber / Green	Red
Relative cost/economics	Amber / Red	Amber / Red	Amber / Red	Amber / Red
Carbon Abatement	Green	Green	Green	Green
User engagement	Amber	Amber	Amber	Amber
Available skillset	Green	Amber	Amber	Red

Further descriptions of the RAG analysis rankings are described in Chapter 4.

3.2.4 Recommendations

Actively managed charging of EVs sits within a wider transition towards controlling loads to support electricity utilities. It is likely that DSM infrastructures will first be constructed to manage “lower hanging fruit” such as electric space heating. Deployment of these techniques in Scotland would have significant benefits to Scotland in boosting RES deployment, reducing network investment, increasing the load factor on the existing infrastructure, and finally flowing towards the consumer in the form of lower energy bills.

Scotland is an excellent “test case” for the deployment of these technologies, and the “home market” is already supporting innovative service deployment (ANM systems by SGS) and bringing international companies to Scotland (VCharge setting up their UK office in Glasgow). Scotland also benefits from proactive DNOs (SSEPD and SHEPD). The international demand for innovative, DSM solutions will only grow over time. As long as Scotland continues to be clear about its need for DSM solutions, and Scottish Utilities are proactive about exploring solutions, innovation is expected to continue alongside opportunities for export.

Key Points for Scottish Enterprise

Benchmarking

- A number of smart EV charging and similar trials, linked to the provision of grid services, have been completed in Scotland
- Scottish companies, research organisations and utilities are active in this area
- There are no significant technical barriers to deployment, though regulations and market structures will need to be revised to provide revenue streams

Recommendations & Interventions

- Ensure development of technologies and regulatory requirements for provision of these services continues in Scotland which is well positioned given its high renewables deployment and islanded networks
- Support exploitation of learnings from existing innovation projects and application of these to broader export opportunities

3.3 Home Energy Control Systems

The drivers for the uptake of home energy control systems are varied, and include greater consumer convenience or comfort; enhanced user experience; the potential for energy and cost savings; remote diagnostics; and the potential to provide useful demand-side response services to the wider energy system.

While each of these benefits is desirable everywhere, the potential for home energy controls to enable demand-side response is of particular relevance to Scotland. The high current and planned deployment of intermittent renewables in Scotland, combined with the high rural and island population, is likely to place stress on the electricity distribution infrastructure and could result in significant curtailment of renewable generation. Demand-side flexibility can contribute to an improved matching of electricity generation and demand, potentially mitigating the cost of distribution grid upgrades, increasing the utilisation of renewable generation and increasing Scotland’s energy self-sufficiency.

The home energy controls sector is evolving rapidly, driven by recent developments in low cost communications, networking and data analysis. Increasingly, home appliances with the potential to connect to the Internet and to other products within the home are becoming available on the UK market. These products display a wide variety of functionality, typically giving the user a greater degree of control or monitoring of the system, often via a web-based application, and in some cases displaying enhanced or improved operation through some form of ‘intelligent’ algorithm or learning.

Many, though not all, of these products or systems can be termed ‘smart’; definitions of the term ‘smart’ vary, but refer broadly to systems whose operation makes use of digital information and communication technology to send signals between different components of the system. In this review, we focus on smart home energy controls, since they carry the greatest potential to enable demand-side response.

Smart home energy controls are already available for a wide range of end-uses within the home. In this case study, we include the following categories of controls as different ‘technology options’:

- Smart **heating** controls
- Smart **lighting** controls
- Smart **cold appliance** controls
- Smart **wet appliance** controls
- **Thermal/electrical storage** and smart **microgeneration management** systems

Smart electric vehicle charging controls could also be included within the scope; however, these are covered in the separate case study “*EV charging, dispatch control and grid services*”.

Furthermore, the operation of home energy controls is underpinned by a number of enabling technologies, including **sensors**, which gather information from the environment which may be used to influence the operation of the control system; the **communications technologies** defining the way information is transmitted between the components of the system; and **gateway devices** which may be used at the interface between parts of the system using different communications protocols or media (this could be between different devices within the home, or between the home and the wider system).

Deployment of advanced and smart home energy controls will lead to greater flexibility in energy demand, and thereby enhance the interoperability between the demand side (i.e. the household) and the supply side (i.e. electricity generation and distribution) of the energy system. Whereas in the traditional energy system, whereby energy demand is treated as inflexible and the supply side is designed to meet that demand in all foreseeable circumstances, the 'smart' energy system could enable the demand side to react and adapt to changes on the supply side.

This brings the potential to achieve greater efficiencies and/or lower costs in the energy system. For example, the ability to shift demand in time could enhance the utilisation of network assets including that of electricity distribution infrastructure, by reducing the variation in electricity demand over the day, and of renewable generation assets, by better matching in time of demand with generation.

Home energy controls could also provide a mechanism of interconnection between the heat and electricity networks. In the case where heating is supplied electrically, building-level thermal storage can be used effectively as a low-cost electricity storage asset. Home energy controls could then, in theory, be used to co-optimise the supply of heat and electricity. A similar co-optimisation of the heat and electricity networks could also be achieved in the case where heat is delivered to the home through heat networks, either where the heat is generated electrically (i.e. by a heat pump), or where combined heat and power (CHP) is used to provide both heat and electricity.

3.3.1 Technology Assessment

3.3.1.1 Specifications

In the above section, we set out the different technology options and/or components of a home energy control system. Here, we consider each of those technologies in turn and give a more detailed specification of the technology and, where available, an estimate of the current unit cost. We also describe the potential impact on carbon emissions qualitatively – in some cases, quantitative data on potential carbon savings is provided in the "**Capability**" section below.

First, we describe the enabling technologies underpinning the home energy control system. We then consider the technology options relevant for the control of heating, lighting, appliances and microgeneration.

Unless otherwise stated, all unit costs quoted are based on a review of the market by Element Energy in 2016.

Enabling technologies

Sensors

Sensors monitor the environment and provide information to the system to influence its operation. In the context of home energy control, relevant sensing technologies include temperature sensors, motion sensors, light intensity sensors, open door and window sensors, humidity sensors, weather compensators, powerline frequency sensors and others. All of these sensing technologies are currently used to assist the operation of home energy controls of one type of another – the functionalities this can provide are described further below. The current units costs of sensors vary from around £5[20] for a temperature sensor to £170[21] for a smart weather compensator, but these costs would be expected to fall as they are deployed more widely. Sensors are currently usually battery-powered, but it is expected that energy-harvesting sensors, where the power required for the sensor is provided by ambient light, heat or kinetic energy, will become increasingly widespread.

Communications protocols

A communications protocol is the set of rules that defines how information is transmitted between the components of a communications network, typically including the semantics, synchronisation and error detection/correction methods. The protocol may be transmitted via a variety of media; in the home energy control sector, both wireless communication and communication over wires are common.

A wide range of communications protocols have been, and are being, developed for use in the context of home energy controls. These include 'open' protocols designed to facilitate communication between devices developed in general by different manufacturers, such as ZigBee, Z-Wave, Wi-Fi and Bluetooth, and 'closed' protocols, which may be specific to a certain product or manufacturer, and require a proprietary gateway device (see below) to communicate with other parts of the system.

[20] The Fibaro DS-001 (http://zwave-products.co.uk/epages/c52574ce-7814-4e39-8602-e19657ce0eaf.sf/?Locale=en_GB&ObjectPath=/Shops/c52574ce-7814-4e39-8602-e19657ce0eaf/Products/109&ViewAction=ViewProductViaPortal&gclid=CMmpu92S_MoCFQUFwwodt4AC1w)

[21] The Netatmo Weather Station (https://www.netatmo.com/en-GB/product)

Different communications protocols have a different characteristic range, latency[22] and data transfer rate, which determines their suitability for any given application. Communications protocols for home energy control typically do not require high data transfer rates, since the signals being sent are typically simple. However, range is an important consideration given the requirement, in general, to pass between different rooms, floors and furniture without loss of fidelity. The importance of latency is dependent upon the application; for many applications, such as manually changing the thermostat setting, or shifting a washing cycle from one time of day to another, a relatively high latency of a second is more than sufficient; for others, such as fast frequency response, a lower (e.g. milliseconds) latency would be required.

The cost of integrating a communications protocol varies between protocols and level of integration, but at present is typically on the order of a few pounds. Implementing ZigBee into a silicon chip currently costs on the order £1[23].

Gateway devices

The function of a gateway device is to provide interoperability between two or more networks. Typically, this is required when different parts of the system are operating using different communication protocols or transmission media. Example gateway devices in the context of home energy controls are the Vera Plus controller, which can interface between networks operating on Wi-Fi, Zigbee, Z-wave and Bluetooth, and the Samsung SmartThings Hub, which can interface between Zigbee, Z-wave, Wi-Fi, wired Ethernet and other protocols. Gateway devices for home energy controls currently cost in the region of £100[24].

Smart heating controls

There is already a wide range of smart home heating control products on the UK market. These products have a variety of functionalities, and key features include remote/external control of the thermostat and timer via a web-based app; learning algorithms and optimisation of heating system operation; wireless control of thermostatic radiator valves to enable independent control of different rooms or zones from the central device or web-based app; and others.

Furthermore, smart heating controls are available for a range of heating system types, including boilers, direct electric heating and heat pumps. Examples of these are given in Appendix 1.

Impact on carbon emissions

[22] Latency is the time delay between the signal being sent to the device, and the response being enacted.
[23] Discussion with industry stakeholders (2016).
[24] Samsung SmartThings Hub (http://www.cnet.com/uk/products/smartthings-hub-and-sensors)

The smart home energy control functionality described above carries the potential for energy and carbon savings. However, it is important to note that the same functionality brings the potential for 'rebound' effects; that is, an increase in energy demand. Whether the installation of smart heating controls leads to a decrease or an increase in energy demand will depend upon the interaction of the user with the original heating controls, and the smart heating controls. For example, a household where the heating was previously 'on' by default (i.e. even when the building is unoccupied) is likely to experience a reduction in heating demand on installation of smart controls. However, households where the heating system was previously 'off' for some periods when the building is occupied could experience an increase in their heating demand where the smart controls lead to heating being 'on' during all occupied hours. Element Energy modelling on this question is described in the "**Capability**" section.

Real-world data on the impact of smart heating controls on energy demand is likely to become available in the near future; for example, the UK Department of Energy and Climate Change and the Behavioural Insights Team are due to publish the results of a field trial of the *Nest* heating controls later in 2016.

Smart heating controls could lead to carbon savings via mechanisms other than direct energy savings. For example, such controls could enable the use of electric heating systems to provide frequency response or short-term operating reserve (STOR) services. To the extent that this displaces the use of fossil fuel capacity, carbon savings would result. Some figures on the potential carbon savings that could be achieved through this mechanism are given in the "**Capability**" section.

Furthermore, demand flexibility resulting from smart heating controls has the potential to reduce curtailment of intermittent renewable energy generation, enabling a greater fraction of electricity to be generated through those sources, leading to an overall reduction in carbon emissions.

Smart lighting controls

A number of smart lighting control products are also available on the UK market. Several example products, and approximate prices, are given in Appendix 1.

As compared with smart heating controls, smart lighting controls are expected to have a more limited impact on carbon emissions in the context of households. While energy and carbon savings could result in a reduction in unnecessary use of lighting, the lower energy intensity of lighting limits the potential carbon benefits of lighting controls. The main drivers for smart lighting controls are expected to be improved user experience, convenience and potentially security, rather than their energy saving potential.

Smart wet appliances

Smart wet appliances are at an earlier stage of deployment than smart heating and lighting controls, but there are nonetheless several commercial products available in the UK. Several example products, and approximate prices, are given in Appendix 1.

The impact of smart wet devices is expected to include the shifting in time of electricity demand, rather than any overall energy demand reduction (considering the counterfactual as an equally high efficiency but non-smart device). However, as for the smart heating devices above, carbon savings could result from a displacement of fossil-fuel plant for system services and from the ability to better match renewable generation with demand to increase the overall fraction of renewable electricity.

Smart cold appliances

Smart cold devices are at an even earlier stage of deployment than smart wet devices, with the first products expected to be available on the UK market later in 2016[25]. Several example products, and approximate prices, are given in Appendix 1.

Cold appliances are likely to be suitable for system services including frequency response, and could thus contribute some amount of carbon savings through the displacement of fossil fuel plant. There may be some potential for freezers to contribute other demand-side response services over longer timescales through pre-cooling, but this will be fairly limited due to the low thermal inertia of a domestic-scale freezer. Furthermore, cold devices have a relatively low energy demand overall in comparison to heating in the domestic context, and carbon savings associated with any demand-side response service will therefore be correspondingly lower.

Smart microgeneration management

Smart microgeneration management, combined with thermal or electrical storage, has the potential to increase on-site use of electricity generated from household solar PV. The primary driver for this is the large difference in electricity export and import price, which presents a strong incentive to maximise on-site consumption. In the case of thermal storage, solar PV electricity otherwise due for export is diverted to an immersion heater and hot water storage tank. In the case of electrical storage, the electricity is diverted to an electrical storage system.

Several example products, and approximate prices, are given in Appendix 1.

In theory, it could also be viable for consumers to use household electrical storage even in the absence of solar PV to provide demand-side response services; however, this is highly likely to be less economically attractive given the absence

[25] See for example: http://www.johnlewis.com/inspiration-and-advice/electricals/smart-home (Accessed April 2016)

of the driver to reduce low-value export of solar PV electricity. In the longer term, as battery prices fall, this option could become economically viable.

While the primary function of the smart microgeneration management is to increase the value of the generated electricity – and not to achieve energy savings – this could lead to higher overall utilisation of the renewable electricity produced by household solar PV, thus leading to overall carbon savings. Furthermore, to the extent that electrical storage could provide other demand-side response services, the carbon savings associated with those (as discussed above) could result.

3.3.1.2 Development

As described above, smart home energy controls are already commercial, and there are few technical barriers to their more widespread deployment. Smart heating and lighting controls have seen a rapid increase in take-up in recent years. However, smart home energy controls are not yet mainstream, and significant commercial and regulatory barriers remain to their wider deployment and particularly for their use in providing demand-side response services. These are described further in the later "**Commercial or regulatory challenges or barriers**" section.

There is limited data available on the current level of deployment of smart home energy controls, in Scotland and elsewhere. However, a 2015 report by Berg Insight estimated that at the end of 2014 there were a total of 3.3 million smart home systems in use in the EU28+2 countries, corresponding to an estimated 2.7 million homes (accounting for multifunction smart home systems), or 1.2% of all European households[26].

There are no critical dependencies on other nascent technologies. As described below, the major barriers to more widespread deployment and use of smart home energy controls, are commercial (i.e. business model-related), regulatory and consumer-related.

3.3.1.3 Capability

As described above, smart home energy control systems have the potential – among other drivers including greater consumer comfort, convenience and user experience – to provide value to the energy system through a variety of demand-side response services, thereby contributing to a lower cost of energy and, in some cases, reduced carbon emissions. Some smart controls could also, potentially, lead to overall reductions in energy demand, with an associated reduction in carbon emissions. Here, we highlight some of the evidence base available on the potential size of these impacts. On the whole, smart home energy controls would be

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[26] Berg Insight, *M2M Research Series: Smart Homes and Home Automation* (2015).

expected to lead to an increased user engagement in energy use, given the greater level of interaction these devices enable, and due to the awareness of the value of demand-side flexibility obtained through experience of different pricing structures and revenue streams. However, we also note that in some cases smart home energy controls could reduce the level of user interaction with energy use, to the extent that the home energy system technology becomes fully automated and optimised and the consumer chooses not to engage with that system.

As an indication of the cost savings that smart home energy controls could provide, we can consider the current value attached to some of the services in question. For example, frequency response typically carries a value in the range 10-20 £/MW/hr [27], where the payment applies to every hour the load is available to provide the required response. In relation to the avoided cost of grid reinforcement, we can consider the 'yardstick' values currently used in DNOs' network investment planning. NPG attaches a value of 57-64 £/kW/yr for reinforcement to the low voltage network[28].

An Element Energy study for National Grid[29], focusing on the potential for providing frequency response using residential heat pumps and electric vehicles, found that a revenue of up to approximately £72 per heat pump per year could be accessed, assuming a typical availability payment for frequency response of £10/MW/hr. That report also estimated the carbon savings attributable to the use of heat pumps for frequency response as around 2 tonnes of CO_2 per heat pump per year, due to the displacement of coal and gas-fired plants to provide the same service.

Element Energy has recently carried out modelling analysis for DECC to quantify the potential costs and benefits of smart home energy controls[30]. The analysis considered the initial capital cost for the home energy control equipment; the potential savings or increases in annual heating demand due to smart heating controls; and the potential savings or additional revenue that could be accessed through frequency response and peak demand flexibility. On the impact of smart heating controls on the annual heating demand, Element Energy found, by studying a range of consumer behaviour use-cases, that there is the potential for annual energy consumption either to increase by up to 50% or to decrease by up to 50%,

[27] National Grid Monthly Balancing Services Summary data and Fast Frequency Response post-assessment tender reports 2014

[28] Element Energy, *Customer-Led Network Revolution Commercial Arrangements Study - Phase 2 (CLNR-L145)* (2015)

[29] Element Energy, *Frequency Sensitive Electric Vehicle and Heat Pump Power Consumption*, Report for National Grid (2015)

[30] Element Energy, *Barriers and benefits of home energy controllers*, Report for DECC (to be published in 2016)

depending on the householder heating behaviour before and after installation of the smart heating controls.

The same report found, in a similar result to that in the National Grid study, potential revenue of around £40 per year for a heat pump in a typical dwelling. By comparison, the potential revenue for frequency response from other appliances – limited to cold appliances – is significantly smaller, at around £5 per year, as a result of the lower average power consumption of those appliances. To estimate the potential energy bill savings due to peak demand flexibility, a static time-of-use tariff scenario was considered. An illustrative tariff schedule taken from the Customer-Led Network Revolution studies[31], had a large price differential of 11 p/kWh for off-peak electricity and 32 p/kWh for peak electricity. Under these tariffs, Element Energy found that annual cost savings of up to approximately £20 could be available for heat pumps, with a further £12 from other appliances, in the case of no electrical storage. In the case of solar PV and electrical storage, potential annual cost savings of up to £200-300 were identified.

The LCNF-funded Low Carbon London project, led by UKPN, trialled the application of dynamic time-of-use tariffs to incentivise flexibility in the timing of energy demand among residential consumers. In one Low Carbon London trial[32], customers were provided with day-ahead notifications of the tariffs through an in-home display and by text message. The peak/off-peak price differentials studied were very high, ranging from 4 p/kWh for 'Low price' electricity to 67 p/kWh for 'High price' electricity. Among a sample of 922 households, the trial found mean annual energy bill savings - relative to a flat tariff structure – of £21, amounting to 4% of the average energy bill. The household with the largest savings achieved a reduction of £148. It is important to note that no home energy control technologies were installed in this trial, and as such any response was in general achieved by 'manual' consumer shifting of energy use. Nonetheless, the trials indicate the level of flexibility some consumers are willing to provide. Smart home energy controls could assist a greater proportion of consumers to provide a similar level of flexibility, and even to unlock greater flexibility through control of a wider range of appliances. It should be noted, however, that as a greater number of households offer increased demand flexibility, the value to each household could reduce according to the balance of supply and demand.

[31] Frontier Economics, *CLNR Closedown report: SMEs Test cells 2b, 9b, 10b* (2014); Jiang et al., *CLNR Post Trial Analysis: Residential DSR for Powerflow Management (CLNR-L223)* (2015)

[32] Imperial College London, *Residential consumer responsiveness to time-varying pricing, Low Carbon London Learning Lab Report A3* (2014)

3.3.2 Market Assessment

3.3.2.1 Relevance to Scotland

Scotland has a strong base of commercial and research organisations with the potential to play a key role in the future development of the smart home energy control sector. Previous work by Scottish Enterprise[33] has highlighted a very wide range of organisations that could form part of the value chain in the smart grid, including home energy control. Here we highlight a number of organisations with particular relevance to home energy controls.

Scotland's largest utilities are already active in the smart home energy control sector. SSE has released the Tado smart thermostat, and Scottish Power the *Connect* smart thermostat. In addition, the Dimplex Quantum electric storage heating system was developed in collaboration between Dimplex and SSE. Furthermore, SSE is involved in a number of demonstration projects trialling smart home energy control. For example, the ACCESS project[34] is trialling the use of the Quantum electric storage heaters on the Isle of Mull to better balance the renewable electricity generated on the island with the local electricity demand. Indeed, the additional smart hardware and software developed for that project was provided by VCharge; though VCharge is a US firm, VCharge UK is based in Glasgow.

Several Scottish SMEs are developing technology for application in smart home energy controls. These include NetThings[35], based in Edinburgh, who are developing a low-cost wireless energy management platform. Their products include *Click*, an energy management system for businesses which can monitor and control building energy use, and the Home Energy Manager, which provides real-time monitoring (although not control) of energy use in the home. INSPIRO by d3[36], a company based in Perth, is developing smart home technology incorporating control of multiple home systems including lighting, heating, security and audiovisual devices. As described above, Sunamp, based in East Lothian, is developing high density thermal storage based on phase-change materials. One of their products, the Sunamp PV, allows excess solar PV generation to be stored as heat, to be released on-demand.

A number of other Scottish SMEs are working in the area of energy management and the smart grid more generally; whose expertise could potentially add value to Scotland's capability in the smart home energy control sector. These include

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33 Scottish Enterprise, *Scottish Smart Grid Sector Strategy: Enabling the Low-Carbon Economy, Creating Wealth* (2012)

34 http://www.accessproject.org.uk/ (Accessed April 2016)

35 http://www.netthings.co.uk/ (Accessed April 2016)

36 http://www.inspiro.house/ (Accessed April 2016)

Smarter Grid Solutions; a spin-out of the University of Strathclyde which develops software for ANM, whose data analytics and network optimisation expertise could potentially be applied in the context of aggregated household energy demand management. Flexitricity, based in Edinburgh, is an energy service company that works with a range of commercial and public organisations to provide demand-side response services including frequency response, STOR[37] and Footroom, as well as peak management and building-level optimisation solutions.

As regards Scotland's University research base, the Universities of Strathclyde, Edinburgh, Glasgow, Heriot Watt, St. Andrews and West of Scotland are all active in the areas of smart grid, smart metering, energy monitoring, energy management, energy storage and communications. The University of Strathclyde is also a partner in the PNDC, a venture aiming to accelerate research into innovative technologies in the electricity sector, along with Scottish Enterprise, Scottish Power, SSE and the Scottish Funding Council. The PNDC was the location for the testing of the smart control system being used in the ACCESS project described above.

The potential benefits of smart home energy controls are by no means unique to Scotland, but a number of factors mean that those benefits are of high relevance to the Scottish case. One such factor is the large current and planned deployment of intermittent renewables, and in particular wind power, which will present significant challenges for the electricity distribution system. This is especially relevant to Scotland's many rural and island communities, where grid constraints are typically greatest. This offers an excellent opportunity for smart home energy controls to access value through demand-side response. Furthermore, the relatively high fraction of off-gas grid households means that electric heating is prevalent and a highly relevant alternative to other heating options (i.e. oil and solid fuel). As described above, electric heating and heat pumps provide the best opportunity among domestic appliances to access value for demand-side response, given the high energy intensity of heating as compared with other end-uses.

As described above, Scotland has a strong skills base in all areas relevant to smart home energy controls, including energy management, communications, data analytics, energy storage and smart metering. However, our review of smart home energy control technology developers identified relatively few companies working specifically in the area of smart home energy controls (notwithstanding the examples given above). Given the expertise in the relevant disciplines, it would appear that this gap could be addressed relatively straightforwardly by promotion of and investment in the smart home energy control sector.

[37] Short Term Operating Reserve

3.3.2.2 International Relevance

Smart home energy controls are of high relevance internationally. This activity is strongly focused in developed countries, although certain aspects are of high relevance to developing countries - in particular the use of smart microgeneration management and storage to maximise utilisation of small renewable generation.

Two international case studies of interest are those of Japan and Germany.

Japan

Demand-side response has been an issue of high prominence in Japan since the Fukushima nuclear disaster in 2011. Furthermore, as reported by RTS Corporation in 2015[38], up to 17.5 GW of feed-in-tariff-approved solar PV projects were in jeopardy due to insufficient grid capacity. Accordingly, the Japanese Government has taken a number of steps to promote smart home energy management as one part of the solution and incentivise uptake of certain components of the smart home energy control system. For example, the Government has recommended a particular protocol, ECHONET Lite, as the best candidate for Home Energy Management Systems, in an attempt to accelerate interoperability and help to drive uptake. In addition, to increase the proportion of energy demand met by solar PV and address the associated grid capacity issues, the Government is currently offering a subsidy of up to two-thirds of the capital cost of lithium ion storage systems greater than 1 kWh in capacity, available both to residential and commercial consumers[39].

Germany

Germany dominated the European market for smart home products up to the end of 2013, with 45% of the market, according to a report[40] by BSRIA Europe. A separate 2013 study[41] by Deloitte suggested that there are likely to be 1-1.5 million intelligent and networked smart homes in Germany by 2020, up from 315,000 in 2013.

To promote the demonstration of smart energy management, including smart homes, the Federal Ministry for Economic Affairs and Energy (BMWi) launched the E-Energy: ICT-based Energy System of the Future[42] program. Among the pilot

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[38] http://www.pv-magazine.com/news/details/beitrag/japan--175-gw-of-projects-set-to-be-left-stranded_100017591/#axzz46ZeQLA4T (Press coverage, Accessed April 2016)

[39] http://www.meti.go.jp/press/2013/03/20140317004/20140317004.html (Japanese, Accessed April 2016)

[40] BSRIA, Europe Smart Homes Market 2013 (2013)

[41] http://www.engerati.com/article/million-plus-smart-homes-germany-2020 (Press coverage, Accessed April 2016)

[42] E-Energy, *Smart Energy made in Germany: Interim results of the E-Energy pilot projects towards the Internet of Energy* (2012)

projects funded under this program was the E-DeMa project, which trialled the use of aggregated domestic energy demand for demand-side response in the case of homes provided with micro-CHP (combined heat and power) stations. It was found that up to 10% of electricity usage could be shifted to off-peak periods. Another E-Energy project was Moma, which trialled dynamic pricing for 200 households with home energy management systems, and found average cost savings between 10-18% and up to 30-35% in some cases. Further trials of smart home energy management include the MeRegio and Smart Watts projects, also funded through E-Energy.

A further example of Germany's leading role in the deployment of smart home energy controls is the prevalence of 'heat pump tariffs', offered by a majority of utilities. Under these tariffs, which are typically lower than standard tariffs, the utility has the option to interrupt the heat pump operation for up to two hours, up to three times per day. This is usually applied only to new build or retrofitted buildings.

3.3.2.3 User Engagement

Greater user engagement with their energy use and the energy system has been a key objective of many of the smart home energy control demonstration projects mentioned in this case study. While early findings from the ACCESS project should be available later in 2016, we have not identified other evidence on user engagement in smart home energy controls in Scotland. Looking internationally, the Low Carbon London dynamic time-of-use tariff trial reported extensively on the increased consumer engagement with their electricity use. In a survey[43] of trialled consumers, the study found that 91% of those consumers agreed or strongly agreed that the tariff should be offered to everyone; that 79% agreed or strongly agreed that they did not find the tariff complex; and that 70% agreed or strongly agreed that some new practices persisted beyond the end of the trial. Following their series of pilot projects in Germany described above, E-Energy noted[44] that there could be challenges in engaging household in demand-side response given the relatively modest economic benefits available to most households. It was also noted that the self-selection process for the pilot projects may mean that those involved in such trials are more engaged in energy use and/or new technology than the average consumer, and that the results should be interpreted with caution.

[43] Imperial College London, *Residential consumer attitudes to time-varying pricing, Low Carbon London Learning Lab Report A2* (2014)

[44] E-Energy, *Smart Energy made in Germany: Interim results of the E-Energy pilot projects towards the Internet of Energy* (2012)

3.3.2.4 Commercial or Regulatory Challenges or Barriers

Smart home energy controls are already available on the UK market. However, deployment is currently limited to a small minority of homes. Furthermore, the application of home energy controls for demand-side response services is largely at demonstration phase. Element Energy research suggests that the barriers to the wider deployment of smart home energy controls, and to their more widespread use to provide demand-side response services, are largely not technical. There are not yet clear standards to ensure interoperability between smart home devices and the wider energy system (or 'smart grid'), but it is expected that these will emerge, driven by the market 'pull' for interoperability, over the next few years. Instead, the key barriers are considered to be commercial, regulatory and consumer-related.

Commercial barriers:

Investment costs for smart home energy products are currently relatively high, presenting an important barrier to their uptake. Furthermore, the energy savings potential of smart energy control products (if any) has not yet been verified/demonstrated, meaning that the economic case for consumers is not yet clear. In addition, the value chain for demand-side response services is fragmented, potentially involving several stakeholders such as the energy supplier, the DNO, the TSO, the aggregator and others, meaning that it is challenging to capture the benefit and pass it on to the consumer (see also *regulatory* barriers below).

Regulatory barriers:

The final commercial barrier above, relating to the fragmentation of the value chain, can also be seen as a regulatory barrier. In order to realise value to the energy supplier or DNO, customers would need to be settled on a half-hourly basis; this is already possible, but is more costly than non-half-hourly settlement and is performed by a minority of energy suppliers. Furthermore, the current design of the capacity market also presents a regulatory barrier to the use of smart home energy controls for demand-side response. Long term (e.g. 15 year) capacity contracts are offered only to providers demonstrating the exceedance of a given capital expenditure threshold. While new generation assets are often able to access long-term contracts, demand-side assets (along with existing generation) rarely do, and are thus only able to access 1 year contracts. It has been suggested that this implicitly favours generation assets over demand-side assets[45].

[45] See for example IPPR, *Incapacitated: Why the capacity market for electricity is not working, and how to reform it* (2016)

It is also worth noting that the UK (and Scotland) is somewhat behind other countries in accessing the value of flexibility of household demand. For example, many utilities in Germany and Switzerland offer 'heat pump tariffs', at a lower price than typical tariffs, under which the utility has the option to interrupt the heat pump operation for up to two hours, up to three times per day[46], usually applied only to new build or retrofitted buildings. Such a tariff is not yet available in the UK.

Consumer-related barriers:

Other key barriers to the deployment of smart home energy controls relate to consumer engagement and behaviour. Research frequently finds a relatively low level of engagement of consumers with energy and heating in general, and heating controls specifically, and widespread difficulty among consumers to use the controls effectively. This lack of engagement could limit the potential uptake of smart home energy controls to the extent that this uptake is consumer-led.

3.3.3 Marketability

RAG ranking	Scotland	Rest of UK	Developed	Developing
Technological maturity	Green	Green	Green	Red
Existing market capability	Amber	Green	Amber / Green	Red
Exportability	Amber	Amber	Amber	Red
Relative cost/economics	Amber / Red	Amber / Red	Amber / Red	Red
Carbon Abatement	Green / Amber	Green / Amber	Green / Amber	Green / Amber
User engagement	Amber / Red	Amber / Red	Amber / Red	Amber / Red
Available skillset	Green	Green	Amber / Green	Amber / Red

Further descriptions of the RAG analysis rankings are described in Chapter 4.

3.3.4 Recommendations

Smart home energy controls could provide very important cost and carbon benefits to the Scottish energy system, lowering the cost of incorporating intermittent renewables on the grid, reducing grid investment and displacing fossil fuel plant for

[46] IEA HPP Annex 42: *Heat Pumps in Smart Grids: Review of Smart Ready Products, United Kingdom* (2014)

grid system services. Deployment of smart home energy controls will, to a large extent, be driven by the consumer 'pull' for enhanced convenience, comfort and experience. However, to access the large potential value to the wider energy system, it will be important to ensure the capability of controls deployed, and the associated regulatory framework, is compatible with the provision of the desired services. Furthermore, targeted intervention by the public sector could accelerate the deployment of the technology, bringing the benefits earlier.

In view of this, key recommendations include:

- Public-funded trials of home energy controls should be carried out to demonstrate and quantify the costs and benefits of home energy control. The evidence gathered should also feed into a policy debate on whether home energy controls should be included in building regulations and/or supported financially in Government-funded schemes.
- Develop a clear national roadmap for the development of domestic demand-side response, including the regulatory framework that should be put in place to ensure the wide range of stakeholders involved can be appropriately incentivised and the full value to the energy system captured.

Promote the development of innovative commercial models and the associated technologies for the use of smart home energy controls (in particular) to provide demand-side response services through the provision of competitive funding.

Key Points for Scottish Enterprise

Benchmarking

- Smart home energy products are already (or in some cases soon to be) commercial
- Scottish utilities are active in the area of smart thermostats and several Scottish SMEs are working in the sector
- Scotland has a strong skills base in a wide range of related areas including energy management, smart grids and data analytics
- However, export opportunities must consider the strong advantage in market position of existing energy suppliers and appliance manufacturers in the export markets targeted

Recommendations & Interventions

- Promote the development of innovative commercial models and the associated technologies for home energy controls to provide demand-side response services

3.4 Electricity Support from Battery Storage

Electricity storage is an established technology, with small-scale batteries having been household items for decades. Whilst batteries have become ubiquitous at the consumer end of the electricity market, the role of storage in supporting the smooth functioning of the electricity grid has historically been limited to a handful of large-scale 'pumped' storage facilities. Recent advancements in large scale battery technology have, however, led to a number of successful schemes being deployed in the UK and around the globe.

There are three main applications for battery storage at the commercial scale:

1. Co-location with renewables – coupling battery storage with renewable energy generation to overcome intermittency issues;
2. Network integration – integrating battery storage on to the distribution or transmission grid to help manage grid constraints and faults and defer the need for conventional reinforcement; and
3. 'Behind the meter' – deploying battery storage into homes and businesses on the consumer side of the meter to enable consumers to go off-grid, particularly during peak periods.

Unconstrained by geographical limitations and easily scalable, such battery devices could make a significant contribution to the interconnection, interoperability, and enhancement of energy networks.

Battery storage can provide significant flexibility to the grid network, absorbing or releasing power to smooth intermittent generation patterns and demand variability. It can also help to manage the implications of potentially more variable patterns of consumption, such as frequency imbalance, and offer an alternative to conventional network reinforcement to the grid.

3.4.1 Technology Assessment

3.4.1.1 Specifications

Advances in technology and materials have greatly increased the reliability and output of modern battery systems, and economies of scale have dramatically reduced the associated cost. The most established of these technologies is the lead acid battery. However, the significant capacity reduction following full discharge and the challenges associated with managing waste lead are such that the market for large scale storage is more focused upon higher performing (albeit more expensive) alternatives such as Nickel Cadmium, Sodium Sulphur and Lithium-ion. Of these, Lithium-ion is currently the most commercially advanced.

Alternatives to these 'solid state' batteries have also been developed in the form of flow battery technologies; the most common of which is the 'redox flow'. This technology relies upon the energy being 'stored' in a liquid electrolyte which is pumped through an electrochemical cell in order to convert chemical into electrical energy. There are various derivations of this technology which are defined by the chemical compound(s) that are dissolved in the electrolyte.

The unit costs of batteries vary across the different technology types and there is a high degree of uncertainty around the current and future costs. Current estimates for lithium ion batteries suggest the unit cost varies between £550/kW and £1,500/kW for example. [47] [48] [49] This is in part due to the emerging nature, yet fast pace of development, of the technology.

Current predications suggest that the cost of battery technologies are likely to decline over the coming decade, particularly for lithium-ion batteries which is expect to benefit rapid decline in costs, similar to that of solar PV. [50] [51]

Furthermore, the different storage services provided by these technologies determine what markets are accessible to them. Lithium-ion batteries, for example, can discharge rapidly and are therefore suited to the provision of ancillary services to National Grid, which require fast response. This increases scope for revenue opportunities. Other technologies, such as flow batteries, cannot discharge at the same speed and therefore cannot access many such markets.

As described above, the deployment of battery storage can provide greater flexibility to the grid network and defer the need for traditional reinforcement work. As a result, battery storage could deliver significant reductions in carbon emissions by facilitating greater deployment renewable power generation which is currently limited by grid constraints. There has been little work done to date to quantify this however.

3.4.1.2 Development

The TRL varies between different battery technologies. A number of battery technologies are, however, being sold and deployed globally. As such the technology can be considered commercially deployable (TRL 9).

There is currently approximately 3.3 MW of battery storage deployed in Scotland, which is largely represented by a 2 MW Lithium-ion battery trial on the Isle of Orkney. The project was jointly developed and installed by SHEPD, also known as SSE, SSEG, Mitsubishi Power Systems Europe and Mitsubishi Heavy Industries, together with financial assistance from OFGEM (via the LCNF) and New Energy and Industrial Technology Development Organisation. Operation and maintenance of

[47] KPMG (2016) Development of decentralised energy and storage systems in the UK, January 2016
[48] Carbon Trust, Imperial College London (2016), *Can storage help reduce the cost of a future UK electricity system?*, February 2016
[49] Lazard (2015), *Lazard's levelized cost of storage analysis — version 1.0*, November 2015
[50] Ibid.
[51] KPMG (2016) Development of decentralised energy and storage systems in the UK, January 2016

the facility is undertaken by SSEG. The project aims to explore the potential of using Lithium-ion batteries to mitigate the intermittency issue often experienced in areas with high concentration of renewable technologies and will work alongside the ANM (see Section 3.5) system, which was installed in the first phase of the project.[52]

SSE has also deployed a 1 MW lead acid battery as part of the Northern Isles New Energy Solution (NINES) project on Shetland which was supported by Ofgem under the LCNF. SSE is involved with a further project to deploy a 105 kW/1.26 MWh redox flow battery on the Isle of Gigha which is being funded by DECC.[53] [54]

The remaining installed capacity is derived from a number of small scale battery installations. This includes three separate micro-grid projects on Horse Island, the Isle of Muck and the Isle of Rum undertaken by Wind & Sun ltd. A further two micro installations have been deployed by Foula Community Electricity Trust on the island of Foula and Eigg Electric on the Isle of Eigg.

In addition, the Norwegian energy company Statoil has announced plans to install a Lithium-ion battery solution alongside its ‘Hywind’ floating offshore wind farm pilot project, located off the coast of Peterhead in Aberdeenshire.[55] The ‘Batwind’ project aims to optimise the energy system from the wind farm to the grid.

Whilst battery storage technology is already commercially deployable, the successful commercialisation and mass deployment of the technology is interdependent upon other emerging technologies. Intelligent control systems and related algorithms, which are able to respond instantly to instructions to charge or discharge, and even make decisions when faced with competing price signals, are required to maximise revenues and cost savings from the wide range of services that a battery can provide. This is a nascent technology and further innovation in this area is required, particularly whereby batteries are deployed in combination with renewable power generation.

Furthermore, battery storage holds interdependencies with electricity ANM, which, if integrated with the distribution networks, and deployed on a grand scale, could reduce the need for storage. However, at the same time both technologies can also be considered to be key enablers for each other.

3.4.1.3 Capability

Battery storage presents an opportunity to deliver lower cost of energy by reducing the imbalance risk associated with deployment of renewable energy and by

[52] See: www.ssepd.co.uk/DistributionInnovation/LCNFTier1/
[53] See: www.ssepd.co.uk/NINES/
[54] See: www.redtenergy.com/case-studies/gigha-utility-scale-storage
[55] See: www.statoil.com/en/NewsAndMedia/News/2016/Pages/21mar-batwind.aspx

avoiding expensive network reinforcement. A recent study by the Carbon Trust and Imperial College London suggests that deploying energy storage (including battery storage) could significantly reduce the overall cost of a future UK electricity system with savings of up to c. £2.4 billion per year in 2030. The study goes on to suggest that if 50% of this saving was passed on to households it could reduce the average electricity bill by around £50 per year. [56]

As discussed above, battery storage is already being deployed commercially, albeit mass deployment is currently hindered by both commercial and regulatory barriers, as explored below. Realising the full potential cost savings to the energy network will therefore rely on overcoming these barriers.

In addition to cost savings and reducing carbon emissions, battery storage (and the supporting control systems) enables users to play a greater role in managing the energy network. Integrating battery storage at both in front and behind the meter not only allows utilities to actively manage their networks but also allows communities to contribute to better network management. This has been demonstrated on the Island communities, as discussed above and below.

3.4.2 Market Assessment

3.4.2.1 Relevance to Scotland

Scotland contains a number of island and rural communities, many of which suffer acute grid constraint issues. Battery storage is a key technology which might be used to overcome these issues and deliver a secure energy network to these communities.

SSE's Orkney Storage Park Project was the first battery to be installed in the UK. As such, this project has facilitated the Scottish-based transmission and distribution network operator to gain a competitive advantage in its understanding of battery technology. The project not only provides SSE with significant technical knowledge in relation to designing and integrating battery systems but also the ongoing management and interaction with the energy network. SSE is already building on this knowledge to explore battery storage for other areas in Scotland, such as the Isle of Gigha.

In addition to SSE's battery storage projects, a number of smaller island communities (which are not connected to the mainland) have integrated battery storage into their micro-grids, as described above. These projects were all designed and installed by England-based Wind & Sun Ltd. This suggests that there is a potential gap in Scottish capability in respect of the design and integration of

[56] The Carbon Trust, Imperial College London (2016), *Can storage help reduce the cost of a future UK electricity system?*, January 2016

battery storage at the small/micro level. [57] Given the number of island and rural communities in Scotland, which could benefit from battery storage, this is an area where Scottish capability should be developed through specific interventions, as discussed below.

The ‘Batwind’ pilot project described above is currently in the early stages of development and partners have yet to be confirmed. Statoil has, however, signed a Memorandum of Understanding the Scottish Government, the Offshore Renewable Energy (ORE) Catapult and Scottish Enterprise to work with Scottish universities and supply chain. The pilot in Scotland will provide a technological and commercial foundation for the implementation of ‘Batwind’ in full-scale offshore wind farms, opening new commercial opportunities in a growing market. This project, therefore, offers a significant opportunity to develop Scottish capability in this area, which could be exported around the globe.

As far as we can see, based on research undertaken for this study, there are currently no battery storage developers based in Scotland. However, a UK-based developer of redox flow batteries, REDT, recently signed a manufacturing agreement with Jabil Circuit Inc (JBL NYSE) to build the REDT technology at its Livingston plant.[58] This creates a strong commercial presence in Scotland for flow battery technology, although deployment of this product to date has been through Government-supported demonstration projects only. There is a case, therefore, for interventions to stimulate the commercialisation of this product and capitalise on this opportunity manufacturing opportunity for Scotland. The only other battery manufacturer identified is Johnson Matthey battery Systems, however whilst the company advertises commercial battery storage on its website is core business appears to be automotive batteries (see Section 3.2) and mobile batteries. There may be an opportunity therefore to support Johnson Matthey move into the commercial storage area.

3.4.2.2 International Relevance

The global deployment of battery storage is dominated by the US and is largely comprised of large Lithium-ion installations.[59] The level of installed electricity storage capacity has grown significantly in the US since California set targets for each of the utilities in the state. Collectively, this target requires over 1.3 GW of storage capacity to be operational by 2024. In addition to this target, funding has also been provided to stimulate the adoption of consumer-side energy storage while the California Energy Commission provides funding for research into increasing the effectiveness of energy storage technologies.

[57] See: www.windandsun.co.uk/case-studies/islands-mini-grids.aspx#.VxoLnvkrKCg

[58] See: www.redtenergy.com/blog/redt-signs-manufacturing-agreement

[59] See: www.energystorageexchange.org/

Following the US is Japan, which has pioneered the Sulphur Sodium technology, followed by China and South Korea respectively. Chile has the fifth largest deployment by capacity although this is from the installation of two large lithium ion facilities by AES Energy Storage (AES) to provide grid stability. Germany and the UK are the two European countries with the most installed capacity, but are currently significantly behind the US and Asia.

Within the UK, Scotland has eight deployed battery storage projects, compared to 13 projects in England and one in Wales and one in Northern Ireland. It is also worth noting that an AES project in Northern Ireland is currently the largest operational battery storage project in the UK with an installed capacity of 10MW.[60]

3.4.2.3 User Engagement

As discussed above, SSE has engaged with battery storage through various projects as a result of funding received through the LCNF and, separately, DECC innovation funding.

One of the key issues for successful engagement of DNOs with battery storage is the current classification of energy storage as a 'generation' asset and the current DNO licensing rules. DNOs are prohibited from owning and operating 'generation' assets larger than 10 MW. Smaller systems, however, qualify for a licence exemption. Whilst the integration of such small-scale storage is one route available to DNOs, restrictions also limit the amount of investment they can make in, or income they can receive from, non-distribution activities to 2.5% of business revenue.[61] Consequently, the size of the installation is an important consideration for DNOs. However, aforementioned restrictions can be overcome if the storage asset is owned by a third party and services contracted to the DNO, albeit DNOs are typically risk adverse and the preference is to retain ownership of assets.

Scottish Renewables, the trade association for renewable energy in Scotland, recently established an 'Energy Storage Network'. The network unites members of Scottish Renewables who have an interest in storage and covers all types of energy storage technology. The network mainly comprises renewable energy companies who are currently watching the storage market with interest, albeit there are some larger organisations that have deployed storage outside of Scotland.[62] Following a launch event in December 2015 the network has held a series of roundtables events aimed at establishing Scottish Renewables' policy on storage and what the

[60] UK deployment data obtained from Eunomia's in-house Electricity Storage Infrastructure database, updated 5/4/2016

[61] UK Power Networks (2015) Smarter Network Storage Electricity Storage in GB: SNS 4.7 Recommendations for regulatory and legal framework (SDRC 9.5), September 2015

[62] Personal Communication, Hannah Smith, Policy Officer, Scottish Renewables, 26th April 2016

association should be lobbying for. Scottish Renewables has recently commissioned a study into the revenue opportunities for storage and will be presenting the findings of this at their forthcoming conference Storage & Systems Conference on 30th June 2016. Scottish Renewables' Energy Storage Network provides a good opportunity for engaging users with battery storage and developing Scottish capability in this energy sub-sector.

3.4.2.4 Commercial or Regulatory Challenges or Barriers

A range of battery storage demonstration projects in Scotland and further afield have proved that many technologies work at scale. There are, however, a number of commercial and regulatory challenges in the UK, which currently function as barriers to mass deployment of the technology. These can be summarised as follows:

- **Cost of the technology** – as discussed above, the costs of battery devices, particularly lithium-ion technology, is decreasing. However, the economics still remain challenging for both large and small scale systems.
- **Classification of energy storage** – as described in detail above, electricity storage installations are currently classed as 'generation' assets, which restricts DNOs owning battery storage.
- **Contract length** - at present, services to National Grid, such as Frequency Response, are contracted for relatively short time periods (one to four years). Extending the length of these contracts would provide greater certainty for investors and help finance projects.
- **Lack of clarity of Government policy** - it is very unlikely that electricity storage will benefit from direct Government support in the form of a feed-in tariff (or similar). However, clear government policy around the technology and its role in Scottish energy strategy is needed to give the investment community confidence that this is an industry worthy of investing time in developing replicable financial models and contracts.
- **Challenges associated with the Capacity Market** – The Capacity Market represents a challenging proposition for storage technologies due to the apparent requirement to be able to deliver power for an indefinite period following a capacity market warning and system stress event. Many battery systems are designed with a shallow storage capacity to minimise costs whilst still enabling participation in ancillary services market. This reduces the ability of the technology to compete with other technologies in the Capacity Market. The UK Government is considering amendments to the mechanism to make it more viable for storage, albeit the latest reforms have done little to remove these challenges.
- **Limited role of DNOs -** The integration of storage into the distribution network could require DNOs to take a more active role in network management. This may require further evolution from DNO to DSO.

- **Interrelationship with power purchase agreements -** there is currently a lack of clarity relating to how PPA agreements will interact with energy storage which is co-located with renewable generation, particularly where the operator also wished to participate in the provision of frequency services. Further work is required to understand the implications of operating in both markets and to disseminate this to the wider industry.
- **Lack of verifiable performance data -** There is currently little publically available data relating to performance, reliability and degradation factors of battery storage. This is because vendors generally consider such data to be commercially confidential. Consequently it is difficult to obtain this data unless engaged in commercial due diligence, which presents a challenge for developers who are trying to bring project forward.

3.4.3 Marketability

RAG ranking	Scotland	Rest of UK	Developed	Developing
Technological maturity	🟢	🟢	🟢	N/A
Existing market capability	🟡	🟡	🟢	N/A
Exportability	🔴	🟡	🟢	N/A
Relative cost/economics	🟡	🟡	🟡	N/A
Carbon Abatement	🟢/🟡	🟢/🟡	🟢/🟡	N/A
User engagement	🟡	🟡	🟢	N/A
Available skillset	🔴	🟡	🟢	N/A

Further descriptions of the RAG analysis rankings are described in Chapter 4.

3.4.4 Recommendations

Battery storage is a key technology to overcoming grid constraints, providing greater flexibility to the grid, reducing carbon emissions via providing greater capacity for further renewable energy generation and by lowering the cost of operating and maintaining the energy network by deferring traditional network reinforcements.

A number of demonstration projects, including those undertaken in Scotland by SSE, have shown that batteries integrated into the network can help overcome the above constraints. Smaller projects have also shown that batteries can make a significant contribution to providing secure power supply for island and rural communities.

Whilst there has been successful deployment of battery storage in to the electricity network in Scotland, the above analysis suggests that the supply chain is very immature compared with that in England and a range of other countries.

The barriers highlighted above are, to a large extent, outside of Scottish Enterprise's control. However, there may be some provision of support that could increase Scottish capability, such that its businesses are well-placed to participate in the market in the near future. Such interventions could include:

- **Dissemination of learning from existing projects:** Scottish Enterprise should draw upon the learning gained from the operational battery storage projects in Scotland (and beyond) and facilitate the dissemination of this to the energy industry and policy-makers. This could be achieved in partnership with organisations, such as Scottish Renewables.
- **Funding for R&D of battery technologies, control systems and algorithms:** As discussed above, this nascent technology is key to maximising revenues from battery storage and therefore has a vital role to play in increasing the deployment of battery storage. Through R&D funding to academic institutions and start-up companies specialising in software development, Scottish Enterprise could help develop this capability in Scotland which could subsequently be exported internationally. This could be facilitated through the Power Networks Demonstration Centre, which Scottish Enterprise is already involved with.
- **Support renewable energy companies to expand into battery storage:** as discussed, there appears to be a gap in Scottish capability to design and integrate battery storage into micro-grids for rural and island communities. Intervention from Scottish Enterprise to overcome this could take the form of financial and/or training support to renewable energy companies to develop skills in this sub-sector. This would enable such organisations to provide a holistic energy network solution to these communities. Such capability could then be exported globally to areas with high levels of renewables deployment.

Key Points for Scottish Enterprise

Benchmarking

- Battery storage systems are fully proven in an operational environment
- Scottish supply chain is relatively immature and available skillset appears limited
- Successful implementation of projects but more to do to engage island and rural communities

Recommendations & Interventions

- Dissemination of learning from existing projects
- Funding for R&D of battery technologies, control systems and algorithms
- Support renewable energy companies to expand into battery storage

3.5 Active Network Management

ANM is an approach adopted by network operators to manage network constraints. This is via the use of automated, real-time control systems to manage generation and load for specific purposes. Predetermined limits on system parameters (i.e. voltage, power, phase balance, reactive power and frequency) are typically employed within algorithms as part of these systems.

ANM is likely to be an important element of future smart grid development. ANM technologies increase the utilisation of network assets giving operators greater control of flexible resources comprising of generation, DSR and storage. In particular they support the integration of greater amounts of renewable generation, whilst deferring reinforcement to reduce costs for DNOs.

3.5.1 Technology Assessment

3.5.1.1 Specifications

ANM involves installing a small amount of hardware onto the network that sits at each controlled generator, along with a centralised 'brain' comprising software and algorithms. These two elements are joined together to form a whole working ANM system.

DNOs can deploy ANM technologies gradually, either for each distributed energy resource connection, per feeder, or at a regional level. This flexibility is the result of modular architecture and support for many different types of devices and integration options.

Various technology providers across Europe offer a number of ANM products, which might include those designed to:

- Integrate DER to high voltage & extra high voltage grids;
- Integrate DER to medium voltage grids;
- Integrate DER with distribution grids;
- Assess DER connection feasibility.

The cost of ANM has been proven to be far cheaper than network reinforcement. The Orkney ANM project, for example, cost just £0.5 million. The alternative solution (a new subsea cable linking Orkney to the mainland GB grid), would have cost an estimated £30 million.[63]

For reasons of perceived security, DNOs have thus far preferred to own the ANM hardware, which they therefore usually finance upfront from the vendor. Perceived

[63] Kane, L., & Ault, G., (2013) *The cost of active network management schemes at distribution level*, EWEA Annual Wind Energy Event, 2013

payback on such investment appears relatively quick in terms of the value derived from faster delivery of new connections. The ANM vendor also often provides initial consultancy, maintenance and updates, whilst there might also be an ongoing charge for software licensing.

The carbon emissions reductions delivered by ANM are not easily quantified. However, assuming it allows faster and greater connection, along with increased deployment, of renewable generation onto distribution networks, then the carbon benefits could be significant.

Distributed Network Intelligence has similarities with ANM in that both offer automated data collection, analysis, decision-making with autonomous control capabilities. See Section 3.6 for more detail on DNI.

3.5.1.2 Development

From a TRL perspective, it appears that ANM is at the top-end of the scale at TRL 9, as systems are fully proven in an operational environment.[64]

Within the GB electricity market there appears to be considerable momentum towards to the implementation of ANM and it has now been successfully demonstrated and deployed by a number of DNOs.

ANM holds interdependencies with electricity storage technologies, which, if integrated with the distribution networks, and deployed on a grand scale, could reduce the need for ANM. However, at the same time both technologies can also be considered to be key enablers for each other.

3.5.1.3 Capability

ANM has proven that it can deliver an increase in connection and management DER. This reduces the level of capital expenditure required by DNOs by deferring the need for network reinforcements. Furthermore, as mentioned above, the technology is also very likely to deliver significant carbon benefits.

Following a series of successful projects funded by Ofgem's LCNF, the Energy Networks Association has stated that the technology is proven to be sufficiently fast, reliable and low-cost.[65] It therefore highlights the significant potential for considerable growth of the ANM market.

In contrast to the relative merits above, however, some current challenges to ANM projects include;

[64] SEE: www.ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf

[65] Energy Network Association (2015), *Action Network Management Good Practice Guide*, July 2015

- The current existence of inadequate communications infrastructure (either local third party systems or the DNOs own equipment), to which ANM cannot be applied without incurring prohibitive upgrade costs;
- It can be expensive to implement for customers, which are geographically remote; and
- The creation of network issues, such as transient voltage instability.

3.5.2 Market Assessment

3.5.2.1 Relevance to Scotland

Scotland's distribution networks are heavily constrained in many areas due to the high volume of renewable generation. This is particularly acute in island and rural communities, such as the Shetlands and Orkney Islands.

As ANM allows the existing distribution network capacity to be utilised more efficiently, defers the need for traditional reinforcement solutions and facilitates new connections more quickly, it is a solution well-suited to Scotland. As a consequence, both Scottish DNOs, SHEPD and SPEN, have implemented forms of ANM.

The Scottish based, Smarter Grid Solutions, is a market leader in ANM, having supplied solutions to both the above utilities. SGS is based in Glasgow and was founded in 2008 by a group based at a University of Strathclyde, which received seed funding from the Scottish Investment Bank and SSE. In addition to SHEPD and SPEN, other DNOs including WPD and UKPN both employ SGS's ANM products to overcome grid congestion and constraints.

The skillsets needed to deploy ANM technology include power systems analysis and software development. SGS has so far largely sourced related staff from Scottish Academia. However, it recognises the potential for resource constraints in the future, particularly as the business expands further into the US and the UK. This risks leaving other markets, including Europe, as a secondary focus, when these also represent good opportunities for growth. It is therefore necessary to consider how such resource constraints in Scotland might be overcome, potentially via greater funding of education and training in power systems analysis and related software development.

3.5.2.2 International Relevance

There are a number of projects and trials of ANM in Scotland and the lessons learned in these can be used to inform wider national and international projects.

The potential for ANM is a given country depends upon not only the technical need (described above) and commercial demand for the service, but it also requires a conducive regulatory environment, as discussed in further sections below.

This environment is prevalent in most US states. Northern Europe is also a key market for ANM, including Scandinavia, Germany, the Netherlands and Belgium. The German market is particularly interesting in terms of a new Energy Act, which is likely to remove barriers to ANM.

3.5.2.3 User Engagement

In Scotland, SHEPDs ongoing Orkney Registered Power Zones (RPZ) project, funded by (what was formerly) the Department for Trade and Industry (DTI) and Ofgem, started in 2004 with the ANM being 'switched on' in 2009.[66] The ANM project enables the power flows at several points on the network to be monitored, and power flows from multiple new renewable generators to be controlled. The project has widely been regarded as success with considerable cost savings, as highlighted above.

In addition, the SSE Northern Isles Energy Solutions (NINES) project, funded by special electricity distribution licence conditions, the project (2011-2016) successfully enabled a 200% increase in connection of renewables for SHEPD.[67] Furthermore, it led to deployment of electricity storage capacity and facilitated supply, generation and demand balancing.

ENW ran the CLASS project from 2012 to 2015 with funding from the LCNF. The project successfully demonstrated that ENW can increase capacity and reduce demand by controlling voltage on the electricity network.[68]

Siemens is working on an innovation project in England, developing an ANM system to cope with high renewable penetration for NPG in England.[69] Siemens is seeking to build on its existing traditional distribution platforms, with an advanced ANM technology package, albeit this is at an early stage. The project has helped NPG to achieve its goals in both developing working knowledge about ANM, and the implementation of ANM connection solutions. However, NPG did not consider the Siemens technology to be suitable at the present time.

In the US, the aforementioned SGS now has 8-10 staff based in a New York office. It is hoping to deploy its technology with a range of clients, and has provided advice to a number of organisations. This includes providing Con Edison with research on DER integration to outline the stakeholder requirements for micro grids in New York State, the technical deployment options for control technology and a cost

[66] See: www.ssepd.co.uk/OrkneySmartGrid/
[67] See: www.ssepd.co.uk/NINES/
[68] See: www.enwl.co.uk/class#
[69] See: www.siemens.com/press/en/pressrelease/?press=/en/pressrelease/2016/energymanagement/pr2016020158emen.htm&content[]=EM

benefit analysis. SGS is also currently working with Southern Company to implement ANM within a micro-grid solution.[70]

SGS has also engaged with markets in northern Europe. In Belgium, for example, it has worked with Elia, Belgium's electricity transmission system operator, and ORES, a Belgian public utility company to implement ANM. This work consisted of congestion management in the Belgian transmission system East Loop. [71]

Similar products to ANM are being marketed outside of the UK, including the SAG Group's, Intelligent Distribution Grid Management System (iNES).[72] iNES offers an alternative solution to conventional grid reinforcement in Germany by monitoring, analysing and controlling grids intelligently with gradual updates. In 2013 iNES won the Smart Grid Award in the grid category of the Hessian State Prize for intelligent energy.

Similarly in the US, Schneider Electric has been providing utility companies with software suites that provide solutions to managing and optimising daily system peak, distribution and transmission system efficiency and reliability, and DER - including renewables, energy storage systems, and electric vehicle charging systems.[73] One of Schneider's featured products includes the Advanced Distribution Management System (ADMS). ADMS includes monitoring, analysis, control, optimisation, planning and training tool, providing an overall comprehensive management package for utility companies in the US.

3.5.2.4 Commercial or Regulatory Challenges or Barriers

As mentioned above, ANM technology is dependent on the right regulation and market structures being in place. In this respect, some countries are not currently sufficiently advanced to support the technology, and therefore continue to rely on more costly, traditional reinforcement.

Regulatory barriers in the UK include the EDW1 price control mechanism in 2015, to which DNOs are struggling to adjust. At the same time, a range of other flexible generation connection issues and a greater focus on flexibility by Ofgem has created an environment which is likely to result in favourable outcomes for ANM, but which is difficult for DNOs to navigate in the short term. As a result, there is a reasonably large degree of inertia, and it is challenging (but by no means impossible) to initiate new ANM projects at the present time.

The key threat to current providers of ANM in Scotland, such as SGS, comes from large, vertically integrated vendors such as General Electric (GE), Schneider, IBM

[70] See: www.smartergridsolutions.com/media/112351/case-study-southern_2016.pdf
[71] Durieux, Olgan, et al (2011), Smart Grid Technologies Feasibility Study: Increasing Decentralised Generation Power Injection using Active Network Management, CIRED June 2011
[72] See: www.sag.de/de-en/services-products/smart-technologies/smart-grids.php
[73] See: www.schneider-electric.us/en/products/smart-grid.jsp

and other well-established organisations, which are seeking to sell similar products, which they often claim represent a form of ANM. Furthermore, in the US, a range of small start-up organisations are offering similar products to those being sold by SGS.

3.5.3 Marketability

RAG ranking	Scotland	Rest of UK	Developed	Developing
Technological maturity	🟢	🟢	🟢	N/A
Existing market capability	🟡/🟢	🟡	🟢/🟡	N/A
Exportability	🟡/🟢	🟡/🔴	🟢/🟡	N/A
Relative cost/economics	🟢	🟢	🟢	N/A
Carbon Abatement	🟢/🟡	🟢/🟡	🟢/🟡	N/A
User engagement	🟢/🟡	🟢/🟡	🟢/🟡	N/A
Available skillset	🟡	🟡	🟡	N/A

Further descriptions of the RAG analysis rankings are described in Chapter 4.

3.5.4 Recommendations

The overall the direction of travel for ANM, both in Scotland and internationally, is positive. It is a technology which is proven at a commercial scale and which has successfully delivered savings for network operators. As support grows for 'smart' grids in both Scotland and beyond, therefore, ANM is likely to represent a key enabler.

In Scotland, the aforementioned SGS has a strong foundation upon which to build its UK and global business. Early in its development, as mentioned above, it received seed funding from SSE and the Scottish Investment Bank. This was critical to it commercialising the technology, which was originally developed as part of a project at the University of Strathclyde. This clearly demonstrates an opportunity for Scottish Enterprise to assist other Scottish ANM providers at an early stage.

It is also a critical time to build upon recent demonstration projects funded by Ofgem in Scotland. This might be achieved by Scottish Enterprise supporting other Scottish businesses in moving into commercial ANM product development towards developing Scotland's status as a market leader in ANM.

It is also important to consider how Scottish Enterprise might further support SGS. This would be both to maintain its market-leading position (and expand to offer job creation), and to continue to innovate to deliver ANM solutions for network operators to better manage network constraints in Scotland. This support might be to help SGS move away from very technology driven and innovation trial activity, into a more solid product development and management approach with a better product portfolio management.

At the same time, regulatory change and development risks stifling the speed of roll-out of ANM technologies in the UK (and Europe). Working with Scottish technology vendors, therefore, Scottish Enterprise might therefore begin to engage in national (UK) and European Consultation exercises relating to network developments and constraints.

As mentioned above, it is also necessary to consider how potential skills constraints in Scotland might be overcome. This might be achieved via greater funding of education and training in power systems analysis and related software development.

Key Points for Scottish Enterprise

Benchmarking

- ANM systems are fully proven in an operational environment
- Scottish company SGS is an emerging market leader in ANM but there appears to be no other Scottish company with similar expertise
- Successful implementation of projects in Scotland and further afield in Germany and the US
- Potential for ANM requires a conducive regulatory environment, as well as technical need and commercial demand

Recommendations & Interventions

- Support SGS move away from very technology driven and innovation trial activity, into a more solid product development and management approach with a better product portfolio management
- Support other Scottish businesses in moving into commercial ANM product development towards developing Scotland's status as a market leader in ANM
- Greater funding of education and training in power systems analysis and related software development

3.6 Distributed Network Intelligence

DNI systems are defined here as systems which facilitate advanced, automated data collection, analysis, decision-making and/or autonomous control capabilities. DNI systems focus on management and control of assets within the distribution network and are complementary to ANM systems (which are based on automated management and control of customer loads).

Some examples of this technology include automated network reconfiguration to optimise network capacity, minimise losses and customer interruptions (CI)/customer minutes lost (CML), automated network reconfiguration in the event of a fault and during restoration, dynamic thermal ratings and voltage control through substation transformers. These systems are based on monitoring at key locations across network assets and can also apply to condition monitoring, diagnostics and prognostics.

The definition of DNI also implies decentralised control i.e. rather than management and control via the centralised network control room through the network management system and SCADA, DNI is realised through a localised, distributed network of monitoring and "intelligent" remote terminal units (RTUs). These have the capability to communicate with one another with a network zone. Status signals and metrics are then sent back to the central control room which has the facility to take control in the event of DNI system malfunction of failure.

DNI may also integrate elements of "big data" in that systems are capable of processing and analysing large volumes of complex data to deduce the network condition and take the appropriate control action to ensure the integrity of the network is not compromised.

Application of this technology is widely applicable to support enhanced planning and operation of electricity and heating networks, as well as interconnection and interoperability.

3.6.1 Technology Assessment

3.6.1.1 Specifications

DNI systems should incorporate the following generic technical specifications:

- Ability to handle and analyse large volumes of monitoring data across a network area;
- Ability to take control actions on network assets in a safe and secure manner;
- Robust communication platform that is contained within existing SCADA or can interface with it;

These systems are typically a number of discrete monitoring, analysis and/or control devices connected via communication links to a decentralised hub contained within a local substation. Algorithms may be contained within the local monitoring/control units or at the hub. The hub then communicates status signals to the network management system.

Control devices may include overhead line reclosers, automated circuit breakers, substation ring main units and on-load transformer voltage control units.

There are significant overlaps with active network management technology. Unit costs for monitoring and control devices are generally of a similar scale.

Deployment of a DNI system may enable the deferment or avoidance of traditional network reinforcement through a more optimised distribution of loads within the network, reducing peak loading. This can reduce carbon through lower losses and avoidance of embedded carbon in new network assets.

As stated in Section 3.5, DNI and ANM are complementary technologies in that both offer automated data collection, analysis, decision-making with autonomous control capabilities.

3.6.1.2 Development

There is significant opportunity to deploy DNI systems in Scotland to reduce the need for network investment due to increasing connection of low carbon technology resulting in higher loading of networks. There is also wide international applicability as utilities seek to cost-effectively improve management and control of distribution networks.

TNEI supported **SPEN** as a project partner on the LCNF Tier 2 project Flexible Networks for a Low Carbon Future. As part of this project, an innovative flexible network control scheme was trialled on the St Andrews primary network in Scotland[74]. The aim of this was to provide capacity headroom increase through strategic network reconfiguration and avoid costly traditional reinforcement. Logical sequence switching logic was implemented using the Automation Manager functionality within the network management system.

New generation automation equipment was tested and installed at a number of secondary substations and HV circuit locations in the St Andrews primary network and a Central Communications Units with enhanced radio bandwidth was also

[74] SP Energy Networks, Methodology and Learning report Work Package 2.2: Flexible Network Control, July 2015,

http://www.spenergynetworks.co.uk/userfiles/file/Work%20package_22_Flexible_Network_Control.pdf installed at 5 primary substations. This is now being rolled out as a technique for other constrained network areas.

University of Strathclyde has expertise in distributed network intelligence R&D, combining capabilities in artificial intelligence and power engineering. University of Strathclyde were also a partner in the Flexible Networks project.

Other companies such as Bellrock Technology and Open Grid Systems are excellent examples of Scotland leading in this area.

Bellrock Technology's Lumen® is a proprietary intelligent software platform for decision support. Lumen intuitively determines the relevant data each end-user needs and flexibly adapts to their precise requirements. The package integrates sensors and monitoring technologies without the need for a central unit, automatically determines how data can be best interpreted, and helps utilities monitor and interpret live data from their equipment and operations.

SHE Transmission investigated condition monitoring decision support capabilities in a 2012 Innovation Funding Incentive project. The benefits include improved decision making for assessing maintenance requirements at local and remote sites, increased maintenance intervals and decreased overall costs through better targeted use of engineers' time, materials and equipment. Also, for major projects, better informed refurbishment vs. replacement decisions, greater evidence to support refurbishment verdicts when appropriate, asset life extension and deferred capital expenditure.

Open Grid System's GridⓘView® is a mobile application that provides asset and electrical network information to personnel in the field. It allows users to visualise consolidated Geographical Information System (GIS), network and asset health data around a location on both a map and augmented reality view. Open Grid Systems is a Scottish company.

The **Power Network Demonstration Centre** in Cumbernauld, Scotland is testing a number of new technologies associated with DNI systems such as advanced communication, coordinated protection and control and advanced sensors and monitoring.

A number of companies outside Scotland such as Nortech and CG are developing DNI system technology including "intelligent" RTUs, which facilitate the automation of networks by collecting, analysing and distributing data from substations.

BitStew's Mix Core platform and **Mix Director** combine real-time data management from various physical assets, analytics and visualisations. Their area of expertise is in software defined operations, artificial intelligence and advanced analytics space. The platform is based on centralised approach however, there is potential to decentralise some operations. Bitstew is based in Canada.

Siemens, ABB and **GE** all have some broad capabilities in development of DNI systems.

3.6.1.3 Capability

DNI systems enable improved management and control of distribution networks and assets, resulting in improved performance and reduced energy system costs through greater efficiency. They also support the connection of more renewable generation through the capability to better optimise network configuration and loading, thereby reducing carbon emissions.

It also has the potential to improve engagement with customers through fewer customer interruptions and minutes lost.

Deploying DNI systems has been shown to be more cost efficient than traditional network reinforcement. For example, the estimated rollout cost of implementing a flexible network control scheme on the St Andrews Network as part of the Flexible Networks project was estimated as £188,000 as an alternative to spending £6.2million on upgrading a 33kV Primary Substation. This was combined with an enhanced transformer thermal rating technique to provide 20% additional capacity headroom.

3.6.2 Market Assessment

3.6.2.1 Relevance to Scotland

This capability is relevant to Scotland as it will support the increased connection of more distributed generation as well as low carbon technology demand such as electric vehicles and heat pumps. These loads are forecast to increase significantly over the next 10-20 years. DNI systems are also very applicable to assets on islanded or isolated networks, facilitating improved operation, management and minimisation of disruptions through a more decentralised approach that does not rely on communications with the central network management system.

University of Strathclyde and the PNDC both have strong research and development capabilities in this technology area. Bellrock Technology and Open Grid Systems are successful spin-offs from the University of Strathclyde and are developing a local and international market in this space. Scottish transmission and distribution network companies have some leading innovation trial credentials on DNI systems.

BitStew is currently working with SSEPD which has 3.7 million customers across Scotland and Southern England. The project involves developing a LV Connectivity Model using software to align meter supply points with local substations, which removes much of the need for extensive fieldwork and manual interaction with the LV network. As a result, the process can be quicker, less costly without compromising accuracy. Whilst this is not a DNI system as per the definition above, it facilitates the future rollout of DNI systems through improved understanding of the network.

The **Big Data Lab** at the University of St Andrews aims to identify, engineer and evaluate innovative technologies that address current and future data-intensive challenges. There is a significant opportunity to collaborate locally on the development of DNI systems where large volumes of data are increasingly involved.

3.6.2.2 International Relevance

There is significant international interest in developing and deploying DNI systems to accommodate greater amounts of distributed generation and increasing demand. Also, as this technology does not rely on the participation of customers, it can often be rapidly deployed to where it is required on the network. This includes in both developed and developing countries.

For example, Siemens and Netze BW (Baden-Wurttemberg Utility provider) recently concluded a DNI demonstration project and have migrated to a pilot phase with a view to deploy it on a wider scale soon. This involved a distributed regional controller that acts as an automation unit in the Niederstetten substation to control and monitor the medium-voltage grid. The controller is based on a Siemens Sicam automation system and is responsible for voltage control and fault management as well as providing the communications connection. The distributed regional controller also forwards compressed data from intelligent field devices to the central SCADA system[75].

Developing countries like Botswana for example are showing an increasing interest in the capability to improve electrical network planning and operation and are keen to adopt innovative but proven technologies. In some cases there is development bank funding for schemes aiming to improve network performance. A roll-out of smart meters was recently piloted on distribution networks in some Botswanan cities to allow better management of customer loads and to enable automatic (dis)connection of customers.

Open Grid Systems report that they are undertaking applied research with international research institutes and universities to explore cutting edge technologies for the Smart Grid.

3.6.2.3 User Engagement

Network operators have generally been engaging with DNI as part of innovation projects, with system providers as well as suppliers of individual components that make up a DNI system. DNI system providers have been working closely with

[75] Siemens, "Siemens and Netze BW put smart grid solution for the distribution network into operation", 30th October 2015.

http://www.siemens.com/press/en/pressrelease/?press=/en/pressrelease/2015/energymanagement/pr2015100056emen.htm&content[]=EM

network operators to understand specific requirements where DNI systems can provide the most value and collaboratively designing products/functionalities as the technology is trialled on the network and specifications evolve.

3.6.2.4 Commercial or Regulatory Challenges or Barriers

As DNI systems do not require significant engagement with customers, this poses less regulatory and commercial challenges. Systems can be procured and deployed similarly to traditional network reinforcement.

One potential regulatory barrier is Engineering Recommendation P2/6 which is often interpreted using a simplistic methodology to determine network capacity; however this is currently under review. It does not currently consider the impact of techniques such as flexible network control and generation and demand response on network capacity calculations.

3.6.3 Marketability

RAG ranking	Scotland	Rest of UK	Developed	Developing
Technological maturity	🟢	🟢	🟢	🔴
Existing market capability	🟢	🟡	🟢	🔴
Exportability	🟢	🟢	🟢	N/A
Relative cost/economics	🟢	🟢	🟢	N/A
Carbon Abatement	🟢	🟢	🟢	🟡
User engagement	🟢	🟢	🟢	N/A
Available skillset	🟡	🟡	🟡	🔴

Further descriptions of the RAG analysis rankings are described in Chapter 4.

3.6.4 Recommendations

The potential for development and application of DNI systems to electricity networks is significant. Whilst the technology is to an extent dominated by large multi-national companies such as ABB and Siemens, there is certainly market potential for more bespoke applications such as those being developed by Scottish companies, as well. Seed funding can help to support these companies as well as support for research institutions through project funding and encouragement of cross-institute collaboration, where these spin-off companies often begin.

Additionally, the CIRED 2017 International Conference and Exhibition on Electricity Distribution in Glasgow is an excellent opportunity to showcase the leadership of Scotland in this technology area. This is based on both the innovation projects that have been delivered on DNI systems by Scottish DNOs as well as the companies developing expert DNI systems for export.

Key Points for Scottish Enterprise

Benchmarking

- Distributed Network Intelligence systems are new and have a diverse range of applications
- Market is growing globally and Scottish capability already exists with the University of Strathclyde, Bellrock Technology and Open Grid Systems being excellent examples of Scotland leading in this area

Recommendations & Interventions

- Seed Funding to promote smaller, innovative companies providing bespoke services
- Promote, support or incentivise academic and R&D opportunities, and International conferences showcasing Scottish expertise

3.7 HVDC

HVDC is used in the bulk transmission of electrical power across long distances. Where long distance, high voltage transmission has traditionally been achieved through the use of AC current, HVDC has proven to be a reliable and cost-effective alternative that can actually offer additional benefits, such as reduced losses, above certain distances.

As a result of the benefits it can offer, HVDC has become a useful tool in supporting the interconnection and enhancement of the electricity transmission networks in Scotland (and elsewhere). Large quantities of power generated in the North of Scotland can be transported to load centres in the South of England through new HVDC links which will be connected down the East[76] and West[77] coasts of the UK.

In addition, HVDC export systems are a viable option for the connection of offshore wind farms to the onshore grid and is being considered for connection Dogger Bank Round 3 offshore wind farm. Several offshore wind farms in Germany are connected using HVDC technology.

3.7.1 Technology Assessment

3.7.1.1 Specifications

CSC HVDC is the traditional technology in which HVDC transmission was achieved and there are around 100 such links installed worldwide. Thyristor-controlled CSC HVDC technology was developed in the 1970s and requires AC harmonic filters, reactive compensation and DC filters to manage a number of associated effects of its operation.

Going forward however, it is VSC HVDC technology that is being developed. This method uses Insulated Gate Bipolar Transistors (IGBT) and is considered self-commutating as a result, since it has less reliance on the characteristics and operating conditions of the AC system(s) it is connecting to compared to CSC HVDC. The VSC HVDC technology also offers improved flexibility and controllability of power flows at both ends of a link.

Multi-terminal HVDC refers to systems which have more than two terminals i.e. not just a point-to-point connection. Multi-terminal systems can be achieved through either CSC or VSC technology.

Aside from the converter technology (AC/DC and DC/AC converters), the other important technology components in an HVDC system include DC cables or

[76] https://www.ssepd.co.uk/EasternHVDClink/

[77] http://www.westernhvdclink.co.uk/

overhead lines to transmit power, DC boost technology to step voltage levels up or down and DC circuit breakers to provide protection.

In practice, HVDC systems are very large installations and converter stations can require a large amount of space depending on the size of the system (DC systems increment relatively linearly in size physically as they increase in voltage and power specifications).

3.7.1.2 Development

The TRL of HVDC components varies. CSC converter technology has a TRL of 9 and is well established throughout the world. VSC converter technology is considered to be mature but not yet fully commercially competitive i.e. TRL 8. Other components such as DC transformers and DC circuit breakers are at lesser stages of development (in the range of 1 to 6). Thus far there have been AC 'workarounds' for HVDC systems without these specific technologies being available. For example, DC voltage level transformation can be achieved by a DC/AC conversion, an AC transformer to step the voltage up or down, and a final conversion from AC back to DC. This method, although technically feasible, can be economically prohibitive. DC boost technology is a method of increasing the voltage level of DC current through a DC/DC converter. This technology is not currently available for high voltage applications however, and has a considered TRL of 1.

ABB are considered to be the world leader in the HVDC field. Their **Classic HVDC** is CSC technology which was developed and has been deployed across the world for various applications encompassing very long transmission connections within countries (up to 1,700 km), and also interconnectors between Sweden and Germany, Italy and Greece and Sweden and Poland. ABB have also developed Ultra-high voltage DC systems and these can provide connections up to ±1,100 kV (present HVDC applications are up to around ±600 kV).

More recently, **ABB's HVDC Light** system has been developed using VSC technology. In addition the benefits of VSC technology to the long distance, high power/voltage systems, the HVDC Light system makes DC transmission and interconnection at lower voltage and power levels more accessible to smaller scale (shorter distance) projects. This technology is also referenced in the MVDC case study to follow (see Section 3.2.6).

Siemens are also one of the leading global companies involved in pioneering DC technology. Their **HVDC Classic** solutions offer CSC technology systems up to 6 GW and ±600 kV. They also have an Ultra-high voltage DC offering which provides up to 10 GW at ±800 kV. The system has been deployed globally in long distance transmission applications including an interconnector from England to the Netherlands. Siemens also have a VSC technology offering, the **HVDC PLUS**, which has been used in the connection of several offshore wind farms in Germany. In response to requirements for supporting functionalities within HVDC systems, the

HVDC PLUS technology offers additional services such as AC voltage control and black-start capability.

Deployment in Scotland is at an early stage; however three significant projects (Eastern HVDC Link, Western Link and Caithness Moray[78]) are underway. The Western Link is expected to be completed in 2017, Caithness Moray in 2018 while the Eastern HVDC link is planned for completion beyond 2021. A number of other HVDC projects have also been proposed or are in planning in Scotland, including links from the mainland to Shetland[79], the Western Isles[80] and Orkney[81].

Despite the reasonably high TRL of HVDC components and systems, the deployment levels remain reasonably low owing to the lengthy timescales necessary for design, planning and most significantly, cost. Additionally, the implementation of multi-terminal systems still requires a lot of research, test and development to be carried out since they are very complex systems. Scottish and Southern Energy, alongside National Grid and Scottish Power Transmission are developing the **Multi-Terminal Test Environment**. The project will create a facility (The National HVDC Centre) which will be set up in Scotland, specifically to develop and test control and protection philosophies of HVDC systems in real-time, most prominently multi-terminal systems, in the hopes of developing and de-risking these systems and facilitate further deployment.

The application of HVDC for the connection of offshore wind is also in its early stages with the majority of offshore wind farms in planning and construction opting for HVAC connections to shore. This is due primarily to the high capital costs associated with HVDC equipment. However, there is also an inherent increased risk of equipment operating offshore where any fault or failure results in long timescales for repair and loss of revenue. The use of high specification VSC HVDC to connect offshore wind has also been affected by some early issues[82].

3.7.1.3 Capability

The capital cost of an HVDC system is higher than the HVAC equivalent due to the high costs of converter station technology. Above a certain transmission distance however, the lifetime costs of a project tend to favour HVDC systems owing to improved in performance aspects such as current carrying capacity over long

[78] https://www.ssepd.co.uk/CaithnessMoray/

[79] https://www.ssepd.co.uk/Shetland/

[80] https://www.ssepd.co.uk/WesternIsles/

[81] SSEPD “Orkney Caithness Connection.pdf”

[82] Renews, 'Dirty electricity' probe at BorWin1, June 2014, http://renews.biz/68145/dirty-electricity-probe-at-borwin1/

distances (no capacitive charging effect), lower heat losses and no requirement for reactive power compensation.

The lifetime cost saving afforded by HVDC implementation compared with a like-for-like AC transmission solution could therefore lower the overall cost of energy for offshore wind generation. The figure below shows the HVDC vs. HVAC lifecycle costs for a typical 1 GW offshore wind project.

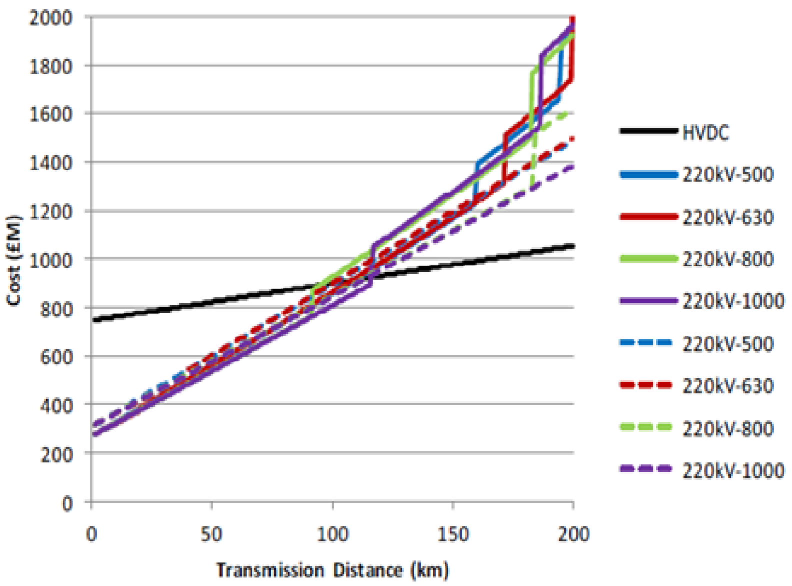

Figure 2: HVAC versus HVDC life-cycle costs for a typical 1GW project (Source: TNEI Report "HVDC Multi-Test Environment Study", 2013)

Although HVDC is not a direct means by which to reduce carbon emissions, it indirectly supports carbon emission reduction by providing more efficient transmission of large volumes of renewable generation, with the aim of displacing conventional fossil fuel generation.

3.7.2 Market Assessment

3.7.2.1 Relevance to Scotland

A number of HVDC links are being considered or under construction in Scotland owing to the significant and growing surplus of renewable generation as well as distance from large demand centres located in England. In order to facilitate this power transfer whilst avoiding causing further constraints on an already constrained transmission network, the transmission owner/operator National Grid are involved in two separate offshore HVDC projects with the Scottish transmission owners: the Eastern HVDC Link with SHETL, and the Western HVDC Link with SPT. Caithness Moray is another SHETL project which aims to reinforce the network in the Highlands of Scotland and facilitate the integration of large volumes of renewable generation from the North. HVDC projects connecting Shetland, Orkney and the Western Isles to the Scottish mainland are also under consideration to provide and/or improve export links for renewable generation.

Another benefit of DC links is the ability to connect multiple asynchronous grids. Scotland has an existing HVDC link with Northern Ireland (the Moyle interconnector) and a planning application was submitted in 2015 to build a 650 km HVDC circuit from Scotland to Norway. These links enable surplus (renewable) energy to be transmitted across long distances and between countries which also serves to improve security of supply on a larger scale and contribute to the wider initiative of a European Electricity Grid[83].

With the exception of technology component manufacturing, Scotland has strengths across the HVDC supply chain, from state of the art research & development and test & demonstration facilities. This includes organisations such as The National HVDC Centre (SHETL's Multi-Terminal Test Environment), the University of Strathclyde, PNDC and the University of Aberdeen. Both Scottish transmission owners have experience in the early stages of design and implementation for HVDC projects (with the aforementioned HVDC projects). There is also limited experience of later stages i.e. construction, commissioning, maintenance, gained through the deployment of the Moyle interconnector and this will develop further as the planned and proposed projects progress.

Aside from universities, demonstration facilities and the network operators, a range of Scottish businesses also have expertise in the field including:

- Designers/Consultants e.g. TNEI, Sgurr
- Contractors (cables, converter stations) e.g. Daviot Group Ltd, McNicholas
- Burntisland Fabrications Ltd has leading expertise in the construction of offshore jackets (support structures)

A small but significant number of large international engineering groups are headquartered or located in Scotland where they also have retained design and in some cases, manufacturing capabilities. This includes companies such as Arup, Parsons Brinckerhoff, Mott MacDonald, Doosan Babcock, Howden, the Wood Group, Petrofac and the Weir Group.

There is significant potential for HVDC to be deployed in the connection of offshore wind farms although some further de-risking of the technology for offshore application would increase its attractiveness to developers and investors. Additionally, if the technology becomes more commercially competitive (e.g. at shorter distances) with AC alternatives, it is likely to be considered for connection of greater numbers of offshore wind projects in the future.

[83] http://www.gridplus.eu/eegi

It is unlikely that Scotland will develop a manufacturing capability for HVDC power electronic equipment since these are well established elsewhere e.g. RXPE in China, ABB in England, Siemens. It would be more beneficial to concentrate support efforts in other areas along the supply chain e.g. test and demonstration, installation and maintenance.

3.7.2.2 International Relevance

A number of countries in Southern Africa have HVDC links installed owing to their reliability benefits over AC transmission. Both Namibia and Democratic Republic of Congo have internal links and there is an interconnector delivering power from South Africa to southern Mozambique. The potential for expansion of the African transmission network is massive with increasing funding from organisations such as the World Bank and Scottish expertise across the supply chain could be well utilised.

South East Asia, including China, has multiple HVDC point to point systems in operation, most using CSC technology. The region is also leading the way in Multi-Terminal HVDC systems with the first VSC HVDC multi-terminal system deployed in Nan'ao Island. It consists of three converter terminals connected through a combination of DC land and subsea cables and DC overhead lines. SHETL's National HVDC Centre facility is being built specifically to do research, development and testing on multi-terminal HVDC systems and the complex technical considerations involved and collaborative partners could be very beneficial.

3.7.2.3 User Engagement

The typical users of HVDC systems are the network owners/operators who initiate and manage engagement across the supply chain, including R&D. In Scotland to date, there has been a high level of engagement from SHETL and SPT with the supply chain. It was also SHETL who won funding to build the National HVDC Centre facility and will work in collaboration with SPT and National Grid such that resources and knowledge can be shared more widely.

3.7.2.4 Commercial or Regulatory Challenges or Barriers

There are some ongoing commercial or regulatory challenges for the wider rollout of HVDC systems. The high cost of offshore HVDC technology is a major barrier to deployment and coupled with the increased technology risk for high specification designs makes particularly VSC HVDC systems less attractive.

In terms of regulatory aspects, HVDC systems are physically very large and as such, present a significant challenge to gaining planning permission. Also, Ofgem require a reasonable level of certainty on renewable generation build to support the needs case for large transmission links facilitating generation export before approving spend and this has proved to be a stumbling block, for the Western Isles HVDC Link for example, in the past.

3.7.3 Marketability

RAG ranking	Scotland	Rest of UK	Developed	Developing
Technological maturity	Green	Green	Green	Amber
Existing market capability	Amber	Amber	Amber / Green	Red
Exportability	Green	Green	Green	Red
Relative cost/economics	Red	Red	Red	Red
Carbon Abatement	Amber / Green	Green	Green	Amber
User engagement	Green	Green	Green	Amber
Available skillset	Amber	Amber	Green	Red

Further descriptions of the RAG analysis rankings are described in Chapter 4.

3.7.4 Recommendations

As it stands, the market for HVDC systems in Scotland can be considered relatively new. Both of the Scottish transmission owners are embarking on large scale projects however, and this is hoped to have the knock-on benefit of market growth. They are also investing in local expertise through building the National HVDC Centre facility. The niche requirements of the UK electricity network i.e. high generation in the north, high demand in the south and significant offshore wind generation connections, support the relevance of wider deployment of HVDC. External links from Scotland to other countries are also being developed or under consideration and would contribute to the longer term stability and security of supply for Scotland and the UK.

Scottish strengths currently lie in the areas of research, test and development with a number of university research groups (Strathclyde, Aberdeen) and laboratory facilities (PNDC, University of Aberdeen DC lab) focusing specifically on DC and power electronic equipment design and operation. There is also some consultancy expertise specifically in HVDC design. The National HVDC Centre is expected to attract further expertise to the area as well as enable further opportunities for international collaboration. Clustering of the knowledge and experience from these research groups and laboratory environments could potentially lead to Scotland becoming a world leader in various aspects of HVDC planning and design.

With the roll-out of the large scale Eastern and Western Link projects and the Caithness Moray link, there is also the opportunity for Scotland to develop skills along the supply chain e.g. installation, commissioning and maintenance of equipment, in the coming years.

Key Points for Scottish Enterprise

Benchmarking

- HVDC technology considered mature
- Emerging market in many developed countries, including Scotland
- Scottish capabilities strong early in the supply chain i.e. in R&D

Recommendations & Interventions

- Support for academia and test facilities e.g. through research grants, investment in The National HVDC Centre
- Seek out, foster and support relationships with international capabilities

3.8 MVDC for Distribution Network Reinforcement

MVDC is commonly used in the shipping and rail industries to provide their electrical supplies. More recently, the power system applications for MVDC technology have been explored for electricity distribution networks. The technology can be applied in a number of ways:

- Offshore collector arrays;
- Distribution network reinforcement; and
- Reduced-scale testing & demonstration of HVDC.

The key attraction for MVDC technology to be used to provide distribution network reinforcement is that a single MVDC installation can provide the solution to multiple network issues at once e.g. increased network capacity, reduced fault level and improved voltage. In network areas that are subject to a number of constraints, MVDC may prove to be a cost-effective means of network enhancement. In particular, it can be used to facilitate greater integration of renewable generation.

Since DC systems are scalable, there is also the potential for MVDC technology to provide learning and experience for HVDC applications, for example, in the area of multi-terminal DC systems which is still in relatively early stages of development for VSC HVDC technology.

3.8.1 Technology Assessment

3.8.1.1 Specifications

Like HVDC, VSC technology is the preferred technology for MVDC implementation going forward owing to the benefits it can offer over CSC technology.

The application of MVDC for distribution network reinforcement is typically envisaged as being implemented in either point-to-point or back-to-back configurations depending on the requirements. Point-to-point configurations differ from back-to-back connections as they have a length of DC cable or overhead line connecting the converters at either end while the converters in the back-to-back configuration are connected directly to one another as shown in Figure 3 below. While both configurations solve many of the same network issues, back-to-back links have the advantage of being able to be installed on existing AC circuits and essentially increase its current carrying capacity.

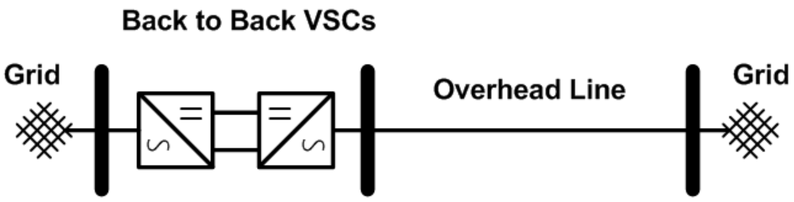

Figure 3: Back to Back VSC Arrangement

In future, this could be extended to deployment of multi-terminal DC systems that overlay or are more integrated with AC networks. There are DC breakers that have been developed for lower voltages, although this is still a challenge these types of systems at higher voltages.

3.8.1.2 Development

There are presently no commercially deployed MVDC systems in Scotland in a distribution network application. The technology required for this particular application is still very much considered to be in development and according to stakeholder engagement carried out at the beginning of 2015, a maximum TRL of 4 is considered for MVDC back-to-back links, DC disconnectors and MVDC cables. Other components such as DC generator integration technology, DC/DC boost technology and DC circuit breakers have lower TRLs of between 1 and 3. Despite the technology being well established in rail and marine applications, the risk-averse DNO's require a more substantial track record of reliability of overall MVDC systems in a relevant operational environment.

WPD's Network Equilibrium project won funding as part of the Network Innovation Competition to investigate methods of controlling power flows and voltages across their distribution networks and one of these methods is the use of a back-to-back MVDC converter. The converter will be used to connect two networks that have not been previously connected owing to issues with fault level, phase angles and circulating current.

SPEN's AngleDC project won Network Innovation Competition funding from Ofgem in 2015. The project will see the deployment of an MVDC network demonstration on the island of Anglesey in Wales. The project is being undertaken as a follow on to some scoping work carried out on behalf of Scottish Enterprise in late-2014/early-2015. An MVDC point-to-point link is being trialled as a method of reinforcement on the existing network.

The University of Aberdeen has DC laboratory facilities which have been used to study medium voltage applications. The PNDC also carries out research and development work on power electronics relevant to MVDC applications.

The widespread deployment of MVDC will depend on the technology being de-risked to progress towards commercial scale deployment. Both the Network Equilibrium trial and the AngleDC project will provide a network demonstration track record which will serve to both de-risk and boost the TRLs of the components used in the deployment. More diverse application of MVDC such as multi-terminal networks will depend on the development of technologies such as DC generator integration technology, DC/DC boost technology and DC circuit breakers which have low TRLs.

3.8.1.3 Capability

The capital cost of MVDC is unlikely to be favourable against a conventional AC solution when there is only a single issue to be solved. However, in instances where MVDC can resolve a number of system issues e.g. thermal, voltage and fault level, which would otherwise have to be addressed individually with AC solutions, MVDC can become the most cost-effective solution. Both WPD and SPEN network demonstrations are in areas where there are multiple issues to be resolved.

In the 2015 study into MVDC technology and economics[84], a cost benefit analysis was performed to compare AC and MVDC reinforcement solutions on the Anglesey network. The costs were calculated encompassing capital costs, electrical losses and unavailability. There are a number of network issues to be solved on Anglesey and conventional AC solutions that have been explored previously are both extensive and costly.

The most significant element of the costs of an MVDC solution is the converter. For the Anglesey network, this was estimated to be around £9.7m (based on costs provided by a converter manufacturer) which is approx. £2m less than the overall cost of the combined AC solutions required for Anglesey to mitigate the various issues.

Electrical losses for an MVDC solution are understood to be much lower than for a conventional AC solution owing to the converter's ability to control power flow and power factor which results in better overall voltage profile on the AC network at both ends of the link. MVDC availability is also understood to be higher than for the conventional AC reinforcement solutions.

3.8.2 Market Assessment

3.8.2.1 Relevance to Scotland

The development of MVDC systems for use in electricity distribution network applications in the UK is in its early stages with substantial research, testing and demonstration to undergo before it becomes a commercially viable option for UK

[84] TNEI report for Scottish Enterprise "MVDC Technology Study: Market Opportunities and Economic Impact, http://www.evaluationsonline.org.uk/evaluations/Search.do?ui=basic&action=showPromoted&id=562

network operators to implement as a reinforcement solution. And, despite the two network demonstrations for MVDC being located in England and Wales, there is a very strong research, development and test capability for DC in Scotland. The University of Aberdeen DC lab carries out a significant amount of research and demonstration on DC technologies that will be important for widespread deployment such as DC/DC converters and DC protection. The National HVDC Centre (SHETL's MTTE facility) will also be located in Scotland attracting a wealth of expertise to the area.

Similar to the HVDC sector, there are no businesses in Scotland at present involved in the supply or manufacturing sectors of MVDC technology. There are however, strong capabilities along the supply chain, most prominently at present in the research, test and development areas. The University of Aberdeen and the University of Strathclyde both have large groups involved in HVDC research.

Areas that suffer from multiple constraints due to renewable connections or high demand loads i.e. in the North of Scotland, Scottish city centres, could stand to benefit from MVDC reinforcement solutions. According to heat maps published by SSEPD[85] and SPEN[86], a large number of GSP substations in the North and South of Scotland (areas with large volumes of generation connecting) are constrained, many possibly with multiple constraints e.g. thermal and fault level, thermal and voltage, in which case an MVDC solution could prove to be technically acceptable and cost-effective when compared to multiple conventional AC solutions.

The technology could also be used to provide more substantial links to remote islands as a lower cost alternative to existing proposals for HVDC links to Shetland, Orkney and the Western Isles.

Presently there are no MVDC installations on Scottish electricity networks. This is largely due to the risk and uncertainty associated with un-trialled technology. There is potential for Scottish Enterprise to provide intervention or support to the MVDC technology area following the WPD and SPEN trials should they provide the business case for the technology. Improvement in the TRL of equipment and de-risking this option for distribution network reinforcement could be bolstered by commercial assistance.

3.8.2.2 International Relevance

Germany has a keen interest in MVDC technologies and systems for electricity network applications. The **Siemens SIPLINK** solution is a deployable system which can be used to provide network reinforcement. It has been deployed on several networks, most notably in Saudi Arabia where it connects two dissimilar networks;

[85] https://www.ssepd.co.uk/GenerationAvailabilityMap/

[86] http://www.spenergynetworks.co.uk/pages/sp_distribution_heat_maps.asp

one operating at 50 Hz and another at 60 Hz. The 30 MVA SIPLINK installation allows the controlled exchange of power between the two networks and prevented the complete modification of the 50 Hz network. Another application in Germany was a 1.2 MVA back-to-back link that connects two sub-networks while preventing thermal overloading on the cable leading to a transformer and also providing reactive power on both sides of the link to optimise the voltage.

Also in Germany is the **EON Energy Research Centre/RWTH Aachen University,** where the Institute for Power Generation and Storage Systems (PGS) put forward a proposal to start a research group focused on MVDC technology. Research will be carried out on low, medium and high voltage systems, however there is a clear focus on medium voltage technologies, and the German government has granted €2m funding each year for the next 5 years up to 2019, possibly longer, dedicated to this. There are four main MVDC project themes that will be explored initially;

- DC grid planning, which looks at interconnections and intersections to DC grids (with/to AC grids). There are also elements of acceptance research, landscape architecture and legislation;
- MVDC components;
- Automation and control;
- Setting up an MVDC demonstration grid[87].

The MVDC demonstration grid is intended to connect up to power existing DC nodes (test benches) as part of a larger campus DC grid topology such that it will not only facilitate work on the other three themes noted above, but also on wider DC research.

A minimum voltage of 5 kV DC is being considered. The topology of the MVDC grid will be flexible such that different configurations can be studied in terms of equipment set up as well as protection and control philosophies.

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

ABB's HVDC Light technology can be compared to what is considered to be MVDC technology in terms of voltage level (between 1 kV and 80 kV). It is an adaptation of their existing HVDC technology and is being applied increasingly at lower voltages. The most relevant project examples of use of HVDC Light technology at MV are:

[87] "Preparation of a Medium-Voltage DC Grid Demonstration Project", Florian Mura, Rik W. De Doncker, E.ON Energy Research Center Series, 2012

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

3.8.2.3 User Engagement

Engagement with DNOs is paramount to ensuring MVDC technology can be implemented successfully on networks. The two ongoing network demonstration projects in the UK are being overseen by the DNOs, WPD and SPEN, and this should ensure successful development and deployment.

3.8.2.4 Commercial or Regulatory Challenges or Barriers

In general, it is the high cost of power electronic components and control system design that are the main challenges facing MVDC technology. The high capital cost of MVDC systems is a major barrier to its widespread deployment when compared to AC alternatives. Proven reliability of the technology and associated control systems is required since DNOs are fundamentally risk averse.

The ongoing work in the WPD and SPEN innovation project network demonstrations should serve to overcome both of these barriers. Through de-risking the technology in a real network environment and developing suitable control systems for safe and flexible operation, the status of MVDC as an effective and reliable solution will improve, thus encouraging the market by introducing demand. And once there is increased demand, the market can become competitive and reduce costs.

3.8.3 Marketability

RAG ranking	Scotland	Rest of UK	Developed	Developing
Technological maturity	🟢	🟢	🟢	N/A
Existing market capability	🔴	🔴	🟡	N/A
Exportability	🟡	🟡	🟢	N/A

RAG ranking	Scotland	Rest of UK	Developed	Developing
Relative cost/economics	Red	Red	Amber	N/A
Carbon Abatement	Amber/Red	Amber/Red	Amber/Red	N/A
User engagement	N/A	Green	Green	N/A
Available skillset	Amber	Green	Green	N/A

Further descriptions of the RAG analysis rankings are described in Chapter 4.

3.8.4 Recommendations

As it stands, the market for MVDC in Scotland is very nascent and there is minimal activity ongoing.

Similar to HVDC, Scottish strengths currently lie in the pre-deployment areas of research, testing and development of DC systems although there is not a strong focus on medium voltage applications at present so support in this area is crucial to future development. Clustering of DC expertise and knowledge in Scotland could potentially lead to world leading Scottish capability in the area and knowledge learned for HVDC can be easily applied to MVDC owing to their linear incremental design characteristics.

With the network demonstration projects ongoing in England and Wales, there is the opportunity for Scottish DNOs to benefit from any learning outcomes and potentially install MVDC solutions in areas they identify with multiple constraints to solve. Scottish Enterprise could facilitate future trials, demonstrations or deployments in MVDC on Scottish networks should the WPD and SPEN demonstrations prove favourable to meet Scottish requirements.

Key Points for Scottish Enterprise

Benchmarking

- MVDC systems for distribution network reinforcement require network demonstration and validation prior to commercialisation
- Very nascent market in Scotland with potential to grow pending the outcomes of two UK trials
- Scottish capabilities strong early in the supply chain i.e. in R&D

Recommendations & Interventions

- Promote and support further network demonstrations and trials
- Promote, support and incentivise R&D opportunities

3.9 Demand Forecasting and Power System Modelling

Demand forecasting in various forms has been undertaken for many years by a range of energy network stakeholders spanning energy vectors such as electricity, natural gas and transport fuels. With the increasing electrification of heating and transport as well as the growing volumes of electricity generation from renewables, the forecasting of electricity loads and power systems requirements has, in particular, increased in complexity and scale. Furthermore, electricity load forecasting and power systems modelling is now fundamental to the effective interconnection, interoperability and enhancement of the electricity, heat and transport energy networks as the adaptation of the electricity system is central to each of these functions.

As such, this case study focuses on electricity load forecasting and power systems modelling for its crucial role in ensuring the capacity, infrastructure and systems are available to allow for the effective interconnection, interoperability and enhancement of energy networks in Scotland and more broadly. Load forecasting and power systems modelling also captures the latest forecasting and modelling technologies for predicting the uptake and impact of low carbon technologies such as electric vehicles and heat pumps (which link the electricity, transport and heat systems) as well electricity generation from wind, solar and combined heat and power (CHP) – all of which are essential for reducing energy systems emissions at lowest cost.

Electricity load forecasting is undertaken by a range of energy system stakeholders including DNOs, TSOs, suppliers, and governments, to estimate future electricity demand and generation. In the short term, it is used to provide an estimate of diurnal variations in demand, and of the expected power output from variable renewables such as wind and solar. Hence suppliers can ensure that sufficient baseload and dispatchable generation is available to meet the requirements of their customers, and DNOs and TSOs can ensure that assets are available to cope with the network loads and that the grid is balanced. In the long term, load forecasting is used to plan generation capacity, to plan network infrastructure, and to set government targets for e.g. penetration of renewable generation.

Power systems models estimate the impact of loads on electricity network assets and equipment, both currently, and based on load forecasts for the future. This allows DNOs and TSOs to determine the reinforcement, replacement and/or demand side response requirements of their network assets, and the relative costs of the options available. In this way, power system modelling enables system operators to plan and design optimised investment strategies for new network infrastructure.

Load forecasting and power systems modelling support better planning of electricity networks and their interaction with other energy networks (such as heat and transport), enhancing the efficiency, stability and cost effectiveness of the various energy systems involved. By modelling the expected network impacts of uptake of LCTs such as heat pumps, plug-in electric vehicles and renewable generation, they also provide visibility of future network requirements for optimal interconnection with renewables and heat and transport networks.

Renewables generation in Scotland is set to approximately double by 2020 (from current levels of 19 TWh[88]) and as much as an additional 1.3 TWh of annual electric vehicle demand[89] and about 1.7 TWh of additional heat pump demand[90] could also be active in Scotland by 2030 (compared to current gross electricity consumption levels of about 38 TWh/year in Scotland[91]). Therefore, effective electricity load forecasting and power systems modelling are particularly important in the coming years to ensure that these large-scale changes to the electricity network are managed appropriately. Load forecasting and power systems modelling underpins the transition to smart, efficient and responsive low carbon networks, which brings associated energy network stability and cost and carbon savings.

3.9.1 Technology Assessment

3.9.1.1 Specifications

Historically, before LCTs were adopted in significant quantities, broad, high-level approaches to load forecasting were sufficient for planning electricity network requirements. Using these approaches, it was possible to identify long term load growth by combining projections of economic and population growth with historic consumption trends that reflected simple and progressive changes in energy efficiency and appliance ownership. However, as the uptake of LCTs and interactions between energy systems has increased, more detailed, bottom-up analyses of demand, generation and technology adoption are now required to accurately identify the complex and disruptive changes in customer demands, distributed generation and system interconnectivity.

The new class of load forecasting and power systems models that are emerging in this sector are very region and client specific, and so there is a large range of specific modelling methodologies, which vary by level of detail and the corresponding level of complexity and amount of data involved. As such, the new approaches to load forecasting and power systems modelling are characterised by

88 The Scottish Government, Energy in Scotland 2016

89 Based on recent modelling by Element Energy of the Scottish electric vehicle fleet under strong policy support

90 Based on heat pump uptake levels under the high uptake scenario of the Smart Grids Forum's Work Stream 3 analysis: Smart Grids Forum Work Stream 3, 2012, Assessing the Impact of Low Carbon Technologies on Great Britain's Power Distribution Networks

91 The Scottish Government, Energy in Scotland 2016

significantly higher resolution across the following parameters and system specifications:

- Geospatial resolution. Customers and loads can be forecast on a nationwide scale, or can be broken down to network, regional or smaller geospatial components. The most advanced of these systems are now capable of modelling customers and network loads down to postcode sector or street level geospatial resolution.
- Asset-level resolution. Loads can be forecast at various levels of asset aggregation from the network as a whole right down to individual low voltage assets on the distribution network (i.e. secondary substations and feeders). Several system operators are in the process of increasing the asset resolution of their forecasting and systems modelling to the secondary substation level.
- Customer-level resolution. Customers can be disaggregated into residential and commercial archetypes based on building characteristics, household sociodemographic factors, business sector and size details, etc. to individually model different consumption and LCT adoption behaviours. The most advanced of these approaches make use of large smart meter and half-hourly datasets to identify detailed disaggregated customer archetypes across the residential and commercial sectors as well as to take account of diversity factors that smooth loads over larger population sizes.
- Technology-level resolution. Demand and generation characteristics can be determined for different LCTs, such as plug-in electric vehicles, heat pumps, wind power, solar PV, biomass, and CHP, either individually or aggregated, and at a range of sizes, from large commercial operations to small domestic installations. Large trial and operational datasets characterising technology performance and load profiles are typically employed.
- Timescales. Long term load forecasting typically deals with load growth on a yearly basis (with seasonal, peak day and minimum day considerations) out as far as 2050. On the other hand, shorter term load forecasting typically focuses on the near-term impacts of seasonal, weather and customer behaviours on diurnal variations in demand and renewable generation.

In the context of Scotland, it is particularly important to be able to accurately forecast the short-term output of variable generation, particularly wind power which makes up the majority of renewable generation in Scotland. This is critical to ensuring that the right amount of dispatchable generation is available and that the grid remains balanced, while facilitating maximum penetration and minimum curtailment of wind power. The simplest wind power forecasting method is “persistence”, where the wind power generated by a turbine at a time $t+\Delta t$ is approximated by the power at time t. More complex wind power forecasts are derived from Numerical Weather Prediction (NWP) models. These models use measurements of the current state of the atmosphere in terms of temperature, pressure, wind speed etc. and project these into the future based on equations describing the motion of fluids (such as conservation of momentum).

The output variables from NWP are then transformed into predictions for the wind power from individual wind turbines through one of three methods. The first uses computational fluid dynamics (CFD), which applies physical modelling of the behaviour of the wind in the locality of the wind turbine, accounting for terrain. The second uses statistical methods to correlate historic measurements of local wind speed with the power output from a particular wind turbine. The third, most recently developed method uses artificial neural networks and big data from meteorology equipment and anemometers built in to wind turbines to “learn” what the output of each wind turbine is given the local wind speed and other atmospheric conditions.

Power systems modelling techniques are evolving from deterministic models which ensure that the load on each asset does not exceed its rated capacity, to probabilistic techniques where the distribution through time of the load on an asset becomes more important. In addition, as load forecasting techniques become more detailed, power systems modelling must also be improved and performed in finer detail to account for the much larger quantities of input data that are available. Planning for new infrastructure now must also account for a variety of active network management and smart grid techniques, helping to reduce required levels of network reinforcement, while accommodating increasing loads from economic growth and uptake of LCTs.

3.9.1.2 Development

For longer timescale load forecasting and power systems modelling, simplified, high-level modelling techniques have been in use for some time and hence are at full technology readiness. The newer, bottom-up, high resolution, big-data approaches to load forecasting and power systems modelling are at an earlier stage of technology development but have been successfully demonstrated in a variety of innovation projects and are now employed as business-as-usual processes for many network operators, suppliers and government bodies. However, these more detailed approaches are still emerging in the sector and have not yet reached full technology penetration into the market.

One technology currently in widespread use for high-level electricity load forecasting is the Transform Model®, developed by EA Technology for Ofgem and DECC as a general tool available to network operators, regulators, and policy makers to help optimise the electricity network. The model helps DNOs in particular to optimise their investments by integrating smart grid technologies, upgrading the network in the most cost-effective way, and with the least additional engineering work. Similarly, various UK DNOs also use the Element Energy Load Growth (EELG) model which takes a higher resolution view of the specific network structure of each DNO and the unique mix of customers (along with their consumption and technology adoption behaviours) at each substation. This approach gives a more detailed and network-specific view of evolving loads across the network under a variety of future scenarios. Both of these models are used by DNOs across the UK to produce long term load forecasts to inform cost-effective network investment decisions and planning.

Other technologies used in network and generation planning are energy systems models. The ETI's ESME[92] model is one such model, covering the whole UK energy system, and the Scottish TIMES[93] model, currently under development for the Scottish Government, applies specifically to the Scottish energy system. They find the lowest cost combination of technologies that meets given sustainability and security criteria for the future, which for networks includes a combination of reinforcement and integration of smart grid and demand side response strategies. Other systems models such as OpenEI's EnergyPLAN and Energy Exemplar's PLEXOS® perform simulations of the impact of various policy and economic environments on the energy system. Thus, these energy systems models help to enhance cost effectiveness, stability, and efficiency of the electricity network in the context of broader energy strategies.

For short term load forecasting (used for grid balancing and readying dispatchable generation and demand side response capacity), the incumbent, high-level techniques are at full technology readiness. New, more detailed techniques are required for assessing the impact of LCTs, and are already implemented to an extent, but are still undergoing technical development in some areas. Techniques for forecasting the output of variable generation are developing significantly. The accuracy of wind power forecasting is improving year on year, due in particular to progress in artificial neural network methods and improved input data for NWP modelling from new wind speed measuring technologies such as lidar, as trialled in the Wind Forecasting Improvement Project (WFIP) in the USA[94]. National Grid is incentivised to improve day ahead wind forecasting based on targets of a mean absolute error (the variation between forecast and actual generation) of 3.25-4.75% in each year from 2015-17[95].

There is still scope for significant improvements in wind power forecasting, particularly in identifying ramps in generation, where the wind power increases or decreases by large amounts over short timescales, which has the potential to

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[92] ETI, eti.co.uk/project/esme

[93] The Scottish Government, Energy in Scotland 2016

[94] US DOE 2013, WFIP NOAA Final Report

[95] National Grid Wind Generation Forecasting: www2.nationalgrid.com/UK/Industry-information/Electricity-system-operator-incentives/wind-generation-forecasting

introduce instability into the electricity network and cause damage to turbines. These improvements in accuracy will facilitate increased penetration and reduced curtailment of wind generation, with corresponding enhancement of cost and CO_2 reduction benefits.

New power systems modelling techniques that use detailed load forecasting information to perform much more detailed analysis of power systems are also at a high level of technological readiness and are already being applied within Scotland. Trial projects including the Orkney Smart Grid and the NINES project (an ANM project in Shetland) have also been run to test smart grid and active network management applications of power systems modelling.

3.9.1.3 Capability

In the short to medium term, load forecasting and effective network planning are fundamental to maintaining grid stability and balance of demand and generation as penetration of LCTs increases, thus reducing the cost and carbon intensity of electricity, and removing barriers to user engagement with LCTs. This will be enabled both by improved demand forecasting enabling implementation of demand side response strategies, and by improved forecasting of variable generation, particularly wind power.

Wind power forecasting is more accurate the shorter the forecasting timescale and the capabilities it provides also depend on the timescale. At shorter timescales (~1 hour), improved accuracy allows dispatchable generation and demand to be used to counter the intrinsic variability of wind power. At medium timescales (~1 day), additional dispatchable generation can be scheduled to run as a backup when required. Improved accuracy means that less dispatchable generation must be kept idle, reducing emissions from idle generation.

On long timescales, load forecasting and power systems modelling aid in the planning of electricity generation and network investment. Use of wind power forecasting techniques, as outlined above, can be used to model the expected power output of new sites, allowing wind farms to be sited in locations with high wind speeds, leading to higher average power output. In addition, improved accuracy in seasonal and yearly wind power forecasts will allow investment in other power plants and in electricity transmission and distribution infrastructure to be optimally scheduled, reducing costs.

Accurate load forecasting and power systems modelling are important for facilitating the integration of smart grids and active network management, reducing the need for investment in network reinforcement. Figure 1 shows the net present value of DNO infrastructure investments under a range of scenarios. We see that investment costs are considerably lower when incremental or top-down smart grid investment strategies are used, compared to using a conventional (BAU) investment strategy. The BAU level of investment in scenario 3 is roughly the same as the smart grid level of investment in scenario 1, at ~£13 billion. Scenario 1 corresponds to 13 million heat pumps, 28 million EVs, and nearly 40 GW of installed PV capacity by 2050. By contrast, scenario 3 corresponds to 5 million heat pumps, 20 million EVs, and under 5 GW of installed PV capacity in the same timeframe. As such, it is clear that the smart grid capabilities enabled by load forecasting and power systems modelling will allow far greater penetration of LCTs by 2050, with significant benefits by 2025, for no net increase in cost compared to BAU.

This increased penetration of LCTs, as well as improved energy system efficiency, means that the net impact of load forecasting and power systems modelling will be to facilitate reduced CO_2 emissions and increased network stability, to provide cheaper electricity, and to facilitate interconnection and interoperability with heat and transport network from uptake of heat pumps and plug-in vehicles.

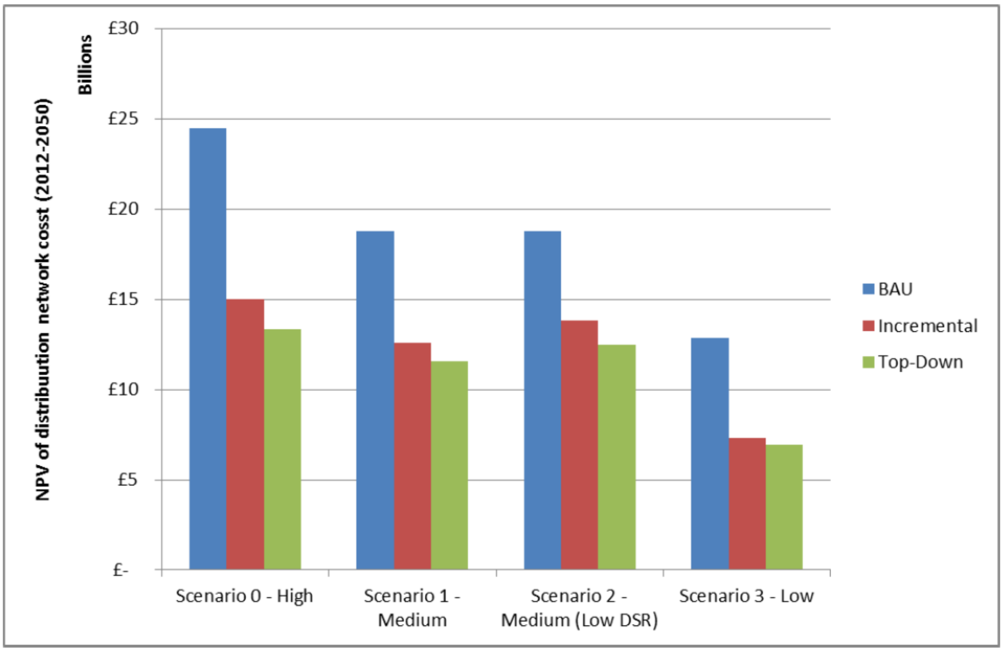

Figure 1: The net present value of network investment costs, in a range of scenarios for low carbon technology uptake, and under both conventional (BAU) and smart grid (incremental/top-down) investment strategies.[96]

3.9.2 Market Assessment

3.9.2.1 Relevance to Scotland

Improvements in wind power forecasting will allow increased penetration and reduced curtailment of wind energy in the Scottish electricity network, helping Scotland to meet its target of 100% equivalent of electricity coming from

[96] Smart Grids Forum Work Stream 3 2012, Assessing the Impact of Low Carbon Technologies on Great Britain's Power Distribution Networks

renewables by 2020. Since Scotland already has comparatively high penetration levels of wind energy, there are excellent opportunities to make use of the extensive datasets that are available for further research into wind power forecasting, giving Scotland a competitive advantage as a relatively early adopter. Heriot Watt University is an example of a Scottish organisation that is currently actively involved in researching wind power forecasting. The University of Edinburgh also performs probabilistic wind power modelling, the data from which is used in the Scottish Electricity Dispatch Model, which helps Scotland to plan investments in electricity generation.[97] Prevailing Wind (based in Glasgow) are also experts in wind modelling.

In rural/island regions of Scotland, the average length of network per customer is five times the GB average, due to the low density of customers.[98] As a result, network maintenance and investment costs are proportionally higher than elsewhere. In addition, Scotland has a particularly high proportion of customers using electric heating (13% compared to the UK average of 9%)[99]. The system efficiency benefits from the improved planning facilitated by load forecasting and power systems modelling will hence be particularly beneficial to Scotland. There are also more constrained networks in rural/island regions. In order to achieve a stable supply of electricity in these regions, robust load forecasting and smart grid services are particularly important.

The following organisations (in alphabetical order with Scottish organisations shown in bold) support electricity load forecasting (including wind forecasting) and power systems modelling for electricity suppliers, network operators and governments in the UK:

[97] University of Edinburgh 2015, "Intermittency and Renewables", ClimateXChange Annual Meeting

[98] SSE 2013, RIIO-ED1 Regional Factors Supporting Paper

[99] The Scottish Government, Energy in Scotland 2016

Load Forecasting	Power Systems Modelling	Whole Energy System Modelling
EA Technology	Brunel University	E4Tech (Scottish TIMES)
Element Energy	Edif	Energy Exemplar (PLEXOS model)
Heriot Watt University	Imperial College	ETI (ESME)
Matrica	Siemens	OpenEI (EnergyPLAN model)
Ricardo AEA	**Smarter Grid Solutions**	University College London (UK TIMES)
University of Bath	TNEI	University of Cambridge
University of Edinburgh	University of Bath	University of Leeds
University of Oxford	University of Cardiff	
Vaisala	University of Durham	
	University of Edinburgh	
	University of Glasgow	
	University of Manchester	
	University of Strathclyde	

3.9.2.2 International Relevance

As countries across the world aim to reduce their CO_2 emissions, cost-effective utilisation of low carbon technologies is of increasing importance. This means that network operators, infrastructure providers, energy suppliers and governments in all countries will have to engage with load forecasting and power systems modelling to some extent, to best facilitate uptake of LCTs.

In the majority of developed countries, at least a basic level of load forecasting is used for planning of generation and network investment. The load forecasting and power systems modelling sector is diverse and is often conducted internally by a range of stakeholders or in conjunction with universities and consultancies. In the future, as LCT uptake levels and system complexity increase, the majority of developed countries are expected to move to increasingly detailed and higher resolution load forecasting and power systems modelling strategies to support the cost-effective evolution of the electricity network and its integration with other energy networks.

At present, some load forecasting is undertaken in developing countries, but in many countries growth in electricity generation and infrastructure lags behind demand, leading to blackouts, brownouts, and some customers not having access to electricity. In these countries, load forecasting and power systems modelling currently play a smaller role, as generation and infrastructure investment are planned primarily to address these capacity and access needs. However, load forecasting for grid balancing and integration of smart networks could be used to optimise these existing processes and improve the stability and cost-effectiveness of the electricity network and strategies in these countries.

There is a definite need for load forecasting and power systems modelling all over the world going forward, and improving datasets from LCT demand/consumption profiles and smart meters mean that there is potential to capture additional value via more detailed analysis than is the present norm internationally. As such, there are currently excellent opportunities for Scottish organisations and UK organisations operating in Scotland, to apply their load forecasting and power systems modelling expertise and market leading innovation learnings in broader international markets.

3.9.2.3 User Engagement

Load forecasting and power systems modelling continue to support the optimisation of system design for uptake of low carbon technologies. This has made it possible and more cost-effective for users to connect various LCTs to the network, particularly distributed renewable generation. There have been significant user engagement successes in this area, but uptake of other LCTs such as heat pumps and plug-in electric vehicles is still in the early stages. Effective load forecasting and power systems design are essential to ensuring that the electricity network of the future is able to accommodate ongoing user engagement in these technologies.

In the future, improved understanding of consumption and generation patterns coming from detailed analyses of smart meter and LCT datasets will improve network load visibility and forecasting. This will allow stakeholders to better engage with their customers through an increased understanding of customer requirements and an optimised capacity to deal with higher levels of technology adoption and changing usage behaviours – all while ensuring the cost effectiveness and stability of the energy system. Through improved visibility and understanding of current and future network loads, suppliers, network operators and policy makers will also be better positioned to identify effective user engagement incentives and the cost/benefit considerations involved.

3.9.2.4 Commercial or Regulatory Challenges or Barriers

There are currently no significant regulatory barriers around implementing more detailed load forecasting and power systems modelling techniques, though there are some technical and commercial challenges related to the additional complexity of a more detailed approach and its integration into existing planning and investment processes. These challenges are not prohibitive as has been illustrated by the many organisations within the UK and internationally that have already migrated to such approaches.

In addition, there are also challenges in relation to processing, cleaning and transferring the big datasets involved in load forecasting and power systems modelling at increasing levels of resolution. For some organisations, this involves new data processing and management requirements. However, most network operators and energy suppliers have existing processes, facilities and capabilities for handling such requirements.

There are also challenges to overcome regarding data security and public perception in some areas. With data playing an increasingly important role for load forecasting and power systems modelling, there are challenges around access to data, data security and public perception that will also require ongoing care and appropriate commercial arrangements.

3.9.3 Marketability

RAG ranking	Scotland	Rest of UK	Developed	Developing
Technological maturity	Amber	Amber	Amber / Red	Red
Existing market capability	Amber	Amber	Amber / Red	Red
Exportability	Green	Green	Green	Amber
Relative cost/economics	Green	Green	Green	Amber
Carbon Abatement	Green	Green	Green	Green
User engagement	Green	Green	Green	Amber
Available skillset	Green	Green	Green / Amber	Red

Further descriptions of the RAG analysis rankings are described in Chapter 4.

3.9.4 Recommendations

The niche requirements created by grid constraint challenges in isolated networks within Scotland combined with the high penetration of wind generation and electric heating, make advanced load forecasting and power systems modelling of particular importance to energy network planning in Scotland. The evolving nature of these networks and the expected increases in renewables deployment and electrification of heating and transport over the coming years mean that electricity network challenges around intermittent generation and increasing peak network loads will exacerbate this need.

Since Scotland's electricity networks are already facing many of these challenges on an advanced timescale compared to many other countries, there are opportunities to exploit the load forecasting and systems modelling learnings from various electricity network innovation projects already being conducted in Scotland (e.g. funded by Local Energy Scotland's Challenge Fund, the Scottish Government and Councils, Innovate UK, Ofgem's LCNF, Network Innovation Allowance and Network Innovation Competition, Horizon 2020, the European Regional Development Fund, DECC's Smart Grid Demonstration Grant, etc.). Given the large number of innovation projects and stakeholders in this area, there are challenges around ensuring that all innovation learnings and synergies between projects are fully exploited. Comprehensive systems are already in place within these projects to ensure that project findings are appropriately disseminated. However, there is potentially scope to provide support to ensure that businesses are able to pursue broader commercial opportunities arising from the learnings of these various electricity system innovation projects in Scotland.

There are also specific Scottish strengths arising from the high penetration of wind generation (and access to the accompanying datasets) and ongoing research into wind generation forecasting, which have strong potential for international commercial exploitation. These capabilities could be supported to capitalise on the commercial opportunities to provide improved wind generation forecasting for developers, suppliers, network operators and policy developers.

Key Points for Scottish Enterprise

Benchmarking

- Load forecasting and systems modelling tools are already commercial, with newer higher resolution, bottom-up approaches currently undergoing wider deployment
- The grid challenges tackled by various remote networks in Scotland, combined with the high levels of renewables deployment, have meant that Scotland has led innovation in various aspects of network planning and management

Recommendations & Interventions

- Ensure forecasting learnings are exploited from various electricity network innovation projects already being conducted in Scotland
- Leverage Scottish strengths arising from the high penetration of wind generation for ongoing opportunities to improve wind generation forecasting in particular

3.10 Ancillary Services (Grid Support) by Wind

Variable renewable energy sources generally present challenges to the network by increasing the requirement for ancillary services especially Reserve and Frequency Response. These services affect scheduling and wholesale electricity prices. However, variable/intermittent generation such as wind may increasingly be able to provide some ancillary services to support the system, and reduce their impact on wholesale prices.

Ancillary Services include:

- Frequency Response [100]: Mandatory response which includes Inertial/Primary Response (<10secs); Secondary response (30s – 30mins); Enhanced Frequency Response (<1sec); Firm Frequency Response, FFR Bridging; Frequency Control by Demand Management
- Reserve[101] : Fast Reserve; Balancing Mechanism Start Up; Short Term Operating Reserve (STOR); STOR Runaway; Enhanced Optional STOR
- Reactive Power[102] : Obligatory Reactive Power; Enhanced Reactive Power
- System Security services[103] : Black-Start; Demand Side Balancing; Supplemental Balancing; Max Generation; System Operator Trades

Generally, wind farm controllers or the wind turbines themselves are able to provide a relatively fast response to signals from the system operator to adjust the active or reactive power of the wind farm. The response depends on the turbine type – variable speed wind turbines are able to respond more rapidly.

[100] Frequency Response: System frequency is a continuously changing variable that is determined and controlled by the second-by-second balance between system demand and total generation. National Grid has a licence obligation to control frequency within specific limits i.e. ±1% of nominal system frequency (50.00Hz) except in abnormal situations. National Grid must therefore ensure that sufficient generation and / or demand is held in automatic readiness to manage all credible circumstances that might result in frequency variations.

[101] Reserve: National Grid need to access to sources of extra power in the form of either generation or demand reduction, to be able to deal with unforeseen demand increase and/or generation unavailability.

[102] Reactive Power describes the background energy movement in an Alternating Current (AC) system arising from the production of electric and magnetic fields. Devices which store energy by virtue of a magnetic field produced by a flow of current are said to absorb reactive power; those which store energy by virtue of electric fields are said to generate reactive power. The flows of Reactive Power on the system affect Voltage levels.

[103] http://www2.nationalgrid.com/uk/services/balancing-services/system-security/

3.10.1 Technology Assessment

3.10.1.1 Specifications

Provision of Reactive Power is already obligatory for all transmission connected generators including wind farms over 50 MW in the UK. This allows Power Factor Control and Voltage Control by the system operator.

In addition to this, there are other ancillary services which wind generators could provide. For example, although rarely called on for this, wind farms could provide **Frequency Response** in low demand periods e.g. summer nights, when wind farms could be de-loaded but could offer a frequency response service. Wind farms could also provide Enhanced Reactive Power Service (ERPS) which is the provision of **Voltage support** (beyond the Obligatory Reactive Power Service) or **Reactive Power Capability.**

Due to the proliferation of wind generation in Scotland connected at transmission level, their capability to provide additional ancillary services would give the Transmission System Operator more diversity in provision of system stability support. This may also lead to additional revenue streams for wind farm developers, encouraging the connection of more renewable generation and resulting in a reduction of carbon emissions.

Other ancillary services such as Black Start could also be provided by wind farms, especially offshore wind farms with VSC HVDC Interconnectors (described in Section 3.7) and if equipped with load supplying devices such as diesel generators or co-located with Storage devices, although it is not a guaranteed service/availability[104].

3.10.1.2 Development

The technology and capability for some wind ancillary services are already being harnessed in some European countries. For example, inertia is provided by wind generators in Germany and research has been carried out in Denmark by DTU Wind Energy, Technical University of Denmark. Also, Ireland has identified synthetic inertia as part of DS3[105].

The UK's National Grid's 2015 System Operability Framework[106] has indicated that there is a greater need to diversify system services to enhance the grid's strength and resilience including utilisation of flexibility services from wind farms.

National Grid currently allows generators including wind, to bid for ERPS tenders of an initial period of 12 months (and thereafter in 6-month increments) and

[104] http://www.ecofys.com/files/files/ecofys-2015-flow-dynamic-grid-wp2-2-market-interaction.pdf

[105] http://www.smartgridireland.org/en/smart-grid/irish-projects/ds3/

[106] http://www2.nationalgrid.com/WorkArea/DownloadAsset.aspx?id=44046

participants can request an Available Capability and/or Synchronised Capability and/or Utilisation price[107] (i.e. depending on whether they are available to provide the service but not used, or available and used) however the capability requirements for other ancillary services such as Reserve, pose barriers for the participation of wind generators. For instance, STOR providers in the UK must be able to[108]:

- *Offer a minimum of 3MW or more of generation or steady demand reduction (this can be from more than one site);*
- *Deliver full MW within 240 minutes or less from receiving instructions from National Grid; and*
- *Provide full MW for at least 2 hours when instructed.*

Also, the GB Grid Code currently specifies that balancing mechanism participants provide day-ahead forecasts and Bid-Offer Data to National Grid which for wind farms corresponds to quite a high degree of uncertainty. The TWENTIES project reportedly estimates that the potential volume of wind generation contribution to the German balancing markets would significantly increase if the service timescales were reduced[109].

3.10.1.3 Capability

Under existing ancillary service market arrangements, increased response requirement to accommodate variable/intermittent generation is anticipated to increase the cost of controlling frequency to £200m-£250m per annum by 2020[110]. Capability of wind generators to provide additional grid support should help reduce this cost, give the Transmission System Operator more diversity in provision of system stability support and thereby encourage the connection of more renewable generation, resulting in a reduction of carbon emissions.

Inertia is being provided by wind generators in Germany and research has been undertaken on this capability in Denmark and whilst this is likely to increase the cost of the generators, it is feasible and could provide an additional revenue stream for generators.

[107] http://www2.nationalgrid.com/uk/services/balancing-services/reactive-power-services/enhanced-reactive-power-service/

[108] http://www2.nationalgrid.com/uk/services/balancing-services/reserve-services/short-term-operating-reserve/

[109] Malte Jansen, Patrick Hochloff, Michael Schreiber, Amany von Oehsen, Boris Peñaloza. Report on the portability of VPP concepts to Germany Economic Impact Assessment. TWENTIES Deliverable D16.4. http://www.twenties-project.eu/system/files/D16.4%20VPP%20to%20Germany_FINAL.pdf

[110] https://www.ofgem.gov.uk/ofgem-publications/87210/ispefccnget.pdf

3.10.2 Market Assessment

3.10.2.1 Relevance to Scotland

TWENTIES (a Horizon2020 project which designed and developed a Virtual Power Plant with various stakeholders including University of Strathclyde) showed that wind turbines can be used to effectively deliver ancillary services and could be applied to islanded systems, including those in Scotland. The greater deployment of wind ancillary services could provide a further revenue stream i.e. an incentive for more wind farm development in Scotland (where there is a significant wind resource) and therefore contribute to carbon reduction targets. It could also act to displace the construction of new carbon-emitting power plants e.g. diesel generators, to otherwise provide this service. For example, in the EU TWENTIES project, IWES Fraunhofer estimated the economic impact of wind turbine participation on the German balancing services market for frequency control (for the entire German wind portfolio). Under adequate conditions wind turbines could generate cost reductions in the secondary control reserve market by up to 24% with 99.99% reliability[111].

Other Grid Support service providers in Scotland include consultants **Natural Power** who have significant experience in wind farm asset management and optimisation of lifecycle revenue streams. Natural Power's Advanced Performance Engineering Services (APES) provides health checks and includes enhanced reactive power capabilities as part of Cost of Energy Optimisation studies for operational wind farms.

A complementary and enabling service to grid support is "Footroom" provided by **Flexitricity**, a demand response service provider based in Edinburgh. Their clients are paid to consume excess generation from wind or to reduce their generation to allow wind generators to export onto the grid. Customers such as cold storage or water pumping stations could increase their loads, whereas Generators such as CHP and Anaerobic Digestion plants could turn down their outputs.

3.10.2.2 International Relevance

Flexitricity's parent company ALPIQ is based in Switzerland so there is scope to expand their capabilities into Europe. Natural Power's Advanced Performance Engineering Services (APES) could be applied to their French clients and marketed further afield.

[111] Malte Jansen, Patrick Hochloff, Michael Schreiber, Amany von Oehsen, Boris Peñaloza. Report on the portability of VPP concepts to Germany Economic Impact Assessment. TWENTIES Deliverable D16.4.

http://www.twenties-project.eu/system/files/D16.4%20VPP%20to%20Germany_FINAL.pdf

In Germany, wind generators are obliged to provide inertial control whereas in Denmark and the UK, which both have a high proliferation of wind on their network, there is no existing obligation. However, TSOs in several European countries have started implementing requirements for the provision of inertial control by wind generators in their Grid Codes.

In terms of emerging/developing markets, Brazil added 2.8 GW of wind in 2014 (4th largest market for new installed wind farms) and would be a prime candidate country to which this capability could be exported.

3.10.2.3 User Engagement

For these services, TSOs e.g. National Grid, would procure these ancillary services directly from the wind farm owners or potentially aggregators. Therefore National Grid has partnered with and is engaging with wind farm owners, other distributed generators and Scottish Transmission Owners on the **Enhanced Frequency Control Capability (EFCC) project**. This is building the framework for future commercial relationships for ancillary services. It should be noted that there is an evolving view within the industry of what the role of a future distribution system operator might be including aspects such as contracting of more localised ancillary services.

3.10.2.4 Commercial or Regulatory Challenges or Barriers

One of the main barriers is regulatory i.e. the existing service timescales stipulated in Grid Codes mean that forecasting of availability of service from wind farms is too uncertain and the potential revenue that wind generators may have to forego, from subsidy payments which are based on MWh, to provide ancillary services would be prohibitively high to be able to provide Reserve[112].

As mentioned previously, there is an ongoing UK-based Enhanced Frequency Control Capability project headed by National Grid and includes University of Strathclyde and Flexitricity, aimed at obtaining rapid response from new technologies such as battery storage. The outcome of this project will establish if and how the GB Grid Code could be adapted to enable this capability and potentially access to more ancillary services.

Also there is currently a technical constraint with limited deployment of monitoring and control systems that could be used to provide ancillary services for smaller scale wind farms. Improved forecasting tools (such as those developed by Glasgow-based **Prevailing Analysis**) and techniques/equipment would help reduce the uncertainty of wind generation output for provision of day-ahead information.

[112] Megavind, Increasing the Owners' Value of Wind Power Plants in Energy Systems with Large Shares of Wind Energy, October 2014.

http://www.ens.dk/sites/ens.dk/files/ny-teknologi/3.pdf

3.10.3 Marketability

RAG ranking	Scotland	Rest of UK	Developed	Developing
Technological maturity	Green	Green	Green	Red
Existing market capability	Green	Amber	Green	Amber
Exportability	Green	Green	Green	N/A
Relative cost/economics	Amber	Amber	Amber	Red
Carbon Abatement	Green	Green	Green	Amber
User engagement	Green	Green	Green	N/A
Available skillset	Green	Green	Green	Red

Further descriptions of the RAG analysis rankings are described in Chapter 4.

3.10.4 Recommendations

There is scope for wind generators to provide more ancillary services than they currently do – provided monitoring techniques improve considerably and the ancillary service market is adapted to incentivise wind farm owners in terms of capability requirements and service timescales.

Scotland has existing strengths in terms of several grid support service providers looking to work with wind farm owners in Scotland and wider GB to take advantage of revenues from ancillary services. There is also academic research and involvement in related innovation projects with National Grid and European entities. These organisations could be supported by Scottish Enterprise through seed funding and research grants.

This service expertise has significant potential to be replicated in other countries with increasing penetration of wind generation on the grid.

Key Points for Scottish Enterprise

Benchmarking

- Ancillary Services (Grid Support) is a mature system management "product" but wind generators currently constitute a small fraction of the market
- There is ongoing research to establish if and how the GB Grid Code could be adapted to further enable this capability. Also there is limited monitoring and control systems that could enable participation of smaller wind farms

Recommendations & Interventions

- Support for academic and industry research through Innovation Grants and Seed Funding

4 Benchmarking Summary

A benchmarking exercise was carried out for each of the energy system technology case studies and presented as RAG tables in the previous section. The capability of Scotland with regards to each of the energy system technologies was benchmarked firstly against the rest of the UK, and then against relevant developed and developing countries for a number of criteria, described in Section 3.1.2. The following sections summarise the benchmarking for each case study.

4.1 Electric Vehicle Charging, Dispatch Control and Grid Services

Technological maturity

A number of smart EV charging trials, linked to the provision of grid services, have been completed. There are no significant technical barriers to deployment. Rather, regulations and market structures will need to be revised to provide revenue streams for services. Inertia of an inherently cautious industry will need to be overcome to allow charging loads to be turned on as well as off in response to a centralised signal.

Existing market capability

Uptake of EVs remains low while costs are high, but significant cost reductions and range improvements are expected to support accelerated uptake. Scottish utilities are active in the area of smart grids, while the UK TSO is highly proactive in trialling provision of services from the Demand Side.

Exportability

Expansion of the EV market will drive innovation in services in smart charging, given that EV related services (as well as potential network problems) are proportional to overall EV fleet size. Provision of TSO services via dispatching of demand may, for some time, be restrained by DNOs concerned with local grid impacts. High RES uptake means Scotland is a natural testbed for technologies and regulations. However there is likely to be competition from regions with vertical integrated utilities where deployment will be easier.

Relative cost/economics

While hardware cost of smart EV chargers is expected to be low, the cost of service provision / back office may be significant. A main constrain is the relatively dilute revenue available per household, with estimates of c. £100p.a., this will require efficient business models to ensure that enough of this can be passed on to customers to incentivise their engagement.

Adding the “revenue stack” of potential revenues from TSO, Generators, DNO and suppliers is untested given the potential for conflict in dispatch calls from each revenue source. The technology is being deployed in a heavily regulated environment which is likely to retard uptake.

Carbon

Significant potential for Carbon abatement, primarily through replacement of Internal Combustion engines with EVs. With the move from passive to smart charging, carbon savings may arise via high carbon intensity power plants being pushed down the merit order; also supporting high RES uptake by matching RES supply with controllable demand, which reduces curtailment payments (e.g. via demand turn up).

User engagement

The impact of delaying charging times upon residential EV owners is as yet untested. While smart grid services can be provided while avoiding any inconvenience to EV owners, the minor reduction in flexibility of EV use could be problematic. This may be overcome via tariffs, although whether there is sufficient value generated per EV to support strong financial incentives is open to question.

Available skillset

Scotland has a strong skills base in a wide range of related areas including energy management, smart grids and data analytics. It is trialling DSM technologies, for which there is significant overlap with smart EV charging.

4.2 Home Energy Control Systems

Technological maturity

Smart home energy products are already or soon to be commercial.

Existing market capability

Scottish utilities active in the area of smart thermostats and several SMEs working in the sector; overall capability in energy management and smart grids strong; however, relatively few companies identified in the specific area of smart home energy controls.

Exportability

A number of successful smart home energy control products in the UK market originated from outside the UK (such as the Nest thermostat and the Tesla Powerwall, both from the US). Common standards for the communication between smart devices, such as the emerging ETSI M2M standards, should increase the exportability of smart home energy control products. However, to the extent that existing energy suppliers and appliance manufacturers offer these products, exportability could be limited by the strong advantage in market position of those players.

Relative cost/economics

Basic cost of implementing smart controls is low (several pounds); however, smart energy control products are currently significantly more expensive than their non-smart counterparts as they are targeted at the premium market. This is limiting uptake. Potential economic benefit due to demand-side response services is significant for smart heating and smart microgeneration products, lower for smart controls for other appliances. However, benefits are fragmented and there are significant commercial and regulatory challenges to overcome before households use these technologies to contribute to demand-side response widely. Note also that smart energy controls could, in different cases, lead to energy savings or to a 'rebound' effect and increased energy use and energy bills, albeit for a higher level of comfort, convenience, user experience etc.

Carbon

Large potential to increase penetration of renewables on the electricity grid and displace fossil fuel plant for grid services. As above, expected in many case to lead to energy and carbon savings but could in cases lead to a 'rebound' effect and an increase in carbon emissions.

User engagement

Consumer engagement in energy use and heating is typically found to be relatively low across a large fraction of the population (this is usually in the context of heating and heating controls).

Available skillset

Scotland has a strong skills base in a wide range of related areas including energy management, smart grids and data analytics.

4.3 Electricity Support from Battery Storage

Technological maturity

Battery storage systems are fully proven in an operational environment.

Existing market capability

Based on research undertaken for this study, it appears that there are currently no battery storage developers based in Scotland and the supply chain is very immature compared with that in England and a range of other countries. However, there are a number of operational battery storage systems in Scotland, including the first large scale battery installations in the UK. As such, there is existing knowledge and capability among some island communities and the DNOs which could be built upon to expand Scottish capability in this energy sub-sector.

Exportability

As discussed above, as far as we can see there are no existing battery storage developers in Scotland. As such there is no opportunity for exporting the technology itself. There is some capability among island communities and the DNOs, however neither of these are likely to engage with overseas markets and are therefore unlikely to export the knowledge gained from existing projects.

Relative cost/economics

The unit costs of batteries vary across the different technology types and there is a high degree of uncertainty around the current and future costs. Current predictions suggest that the cost of battery technologies is likely to decline over the coming decade. At present however, the economics for battery storage remain challenging due to both the capital costs and the relatively insecurity and short contract lengths associated with the available revenue streams.

Carbon

The carbon emissions reductions delivered by battery storage are not easily quantified. However, assuming the technology facilitates increased deployment of renewable generation onto distribution networks and among island and rural communities, then the carbon benefits could be significant.

User engagement

Battery storage projects in Scotland appear to have been implemented successfully to overcome issues relating to grid stability on island communities and grid constraints arising from the deployment of renewable energy generation. The trade association, Scottish Renewables, is actively promoting energy storage albeit its energy storage network is in the early stages of development. There is perhaps further work to do to engage other island and rural communities to promote the benefits of storage.

Available skillset

Whilst there has been successful deployment of battery storage in to the electricity network in Scotland, our analysis suggests that the supply chain is very immature compared with that in England and a range of other countries. As far as we can see, there are currently no commercial battery developers in Scotland. As discussed in Section 3.4 the battery storage projects on the island communities were all designed and installed by England-based Wind & Sun Ltd. This suggests that there is a potential gap in Scottish capability in respect of the design and integration of battery storage at the small/micro level.

4.4 Active Network Management

Technological maturity

ANM systems are fully proven in an operational environment

Existing market capability

SGS is an emerging global market leader in ANM, and has worked with both DNOs in Scotland to implement solutions. However, there appears to be no other Scottish company with similar levels of expertise, which is operating in this space.

Exportability

The potential for ANM is a given country depends upon not only the technical need and commercial demand for the service, but it also requires a conducive regulatory environment. This environment is prevalent in most US states. Northern Europe also represents a key potential market, including Scandinavia, Germany, the Netherlands and Belgium.

Relative cost/economics

The cost of ANM has been proven to be far cheaper than traditional network reinforcement. The Orkney ANM project, for example, cost just £0.5 million. The alternative solution (a new subsea cable linking Orkney to the mainland GB grid), would have cost an estimated £30 million.

Carbon

The carbon emissions reductions delivered by ANM are not easily quantified. However, assuming it allows faster and greater connection, along with increased deployment, of renewable generation onto distribution networks, then the carbon benefits could be significant.

User engagement

ANM projects in both Scotland and England (delivered by SGS) appear to have been implemented successfully to deliver greater deployment of renewable generation capacity and facilitation of supply, generation and demand balancing. Whilst one project in England run by Siemens, in collaboration with NPG, seems to have been less successful, this was based on a less mature ANM technology. Furthermore, there appear to have been a number of positive outcomes from ANM projects in Germany and the US, delivered by the likes of Schneider Electric and the SAG Group.

Available skillset

The skillsets needed to deploy ANM technology include power systems analysis and software development. In Scotland, SGS has so far largely sourced related staff from Scottish Academia. However, there are likely to be resource constraints in the future if the business is to expand further into the US, the UK and Europe.

4.5 Distributed Network Intelligence

Technological maturity

Distributed Network Intelligence applications are new and diverse. They are generally based on a combination of innovative monitoring and control technology along with innovative algorithms for (automated) decision support.

Existing market capability

Alongside global players such as ABB and GE, there are a number of smaller spin-offs including companies from Electrical Engineering Departments of Scottish Universities.

Exportability

Several Scottish institutions and research laboratories have strong research and development capabilities in this area. There is also significant international interest in developing intelligent systems to better manage the network and also accommodate greater amounts of distributed generation and increasing demand in a cost-effective manner.

Relative cost/economics

DNI applications are relatively new and specialist so it is difficult to compare like-for-like costs and features. In terms of potential savings from implementing them, the estimated rollout cost of implementing a flexible network control scheme on the St Andrews Network as part of the Flexible Networks project was estimated as £188,000 as an alternative to spending £6.2million on upgrading a 33kV Primary Substation.

Carbon

Better visibility and management of Distribution Network assets could result in improved utilisation of assets to end-of-life and facilitate connection of more renewable generation and low carbon demand i.e. heat pumps, electric vehicles, which in turn avoids carbon emissions from conventional generation, heat and transport.

User engagement

DNOs are the main users of this application and they are closely involved in working with service or product providers to develop specifications and define performance requirements.

Available skillset

Scotland has a strong skillset in this area from network trials, academia and innovative commercial companies and could play a major role in defining standards and Best Practice Guidance.

4.6 HVDC

Technological maturity

HVDC systems are well established globally and proven in an operational environment. Some HVDC components are still under development which would serve to enhance the adaptability of HVDC systems, particularly multi-terminal systems.

Existing market capability

ABB and Siemens are considered to be the market leaders in HVDC technology and systems. In Scotland the market is limited, but anticipated to grow rapidly in the next 10 years with the number of proposed and planned projects in and around Scotland.

Exportability

Scotland has an existing interconnector to Northern Ireland and a number of potential projects for the country. Scottish transmission networks are very adequate for implementation of HVDC systems and technologies. The application of HVDC technology is relevant and of increasing interest to a number of other developed and developing countries across the world to support increasing electrification and interconnection so significant opportunities to export Scotland's expertise.

Relative cost/economics

HVDC systems are very expensive owing to the capital cost of large power electronic equipment. The systems can offer a cost effective (lifetime costs) option over long distances however, when their operational characteristics provide an advantage over AC transmission. This is true for network applications as well as connections from offshore wind farms.

Carbon

HVDC systems are not a means to achieving carbon emission reductions directly. Such reductions can be supported however, in the provision of more efficient transmission of large volumes of renewable generation (displacing conventional generation).

User Engagement

The end users of HVDC systems are the network operators, and thus far in Scotland there has been a high level of engagement with SHETL and SPT with the HVDC supply chain.

Available skillset

Scottish strengths with HVDC systems presently lie in the R&D and testing & demonstration areas. Several Scottish universities undertake HVDC systems research and there are also state of the art demonstration facilities either existing (PNDC) or under construction (The National HVDC Centre/MTTE).

4.7 MVDC for Distribution Network Reinforcement

Technological maturity

MVDC technology components are considered reasonably mature. MVDC systems for use in electrical distribution network applications are considered somewhat less developed due to the general lack of experience in the sector. However, since rail and marine applications are well developed, it is thought the challenges for adoption into power systems will not be insurmountable.

Existing market capability

There is no market in Scotland for MVDC systems in the power systems context. Ongoing demonstrations are seeking to kick start the market through successful trials prompting the increase of demand.

Exportability

The applicability of MVDC for distribution network reinforcement is relatively niche, and since it is only cost effective in areas with several issues then its exportability cannot be well-defined. However, it is expected to be most exportable to developed countries where integration of MVDC system controls should be more easily achieved.

Relative cost/economics

MVDC systems are very expensive owing to the high capital costs associated with power electronic equipment (much like HVDC). The systems become cost effective on networks with multiple simultaneous issues by providing a single solution which would otherwise require multiple AC reinforcement solutions to solve.

Carbon

There is no direct link between MVDC systems for distribution network reinforcement and the reduction of carbon emissions however there is potential for savings to be made through MVDC indirectly facilitating increasing levels of renewable generation.

User Engagement

The end users of MVDC systems for distribution network reinforcement are the DNOs. Presently there are two UK DNOs fully engaged in network demonstrations on their networks.

Available skillset

As with HVDC, Scottish strengths in MVDC are primarily in the R&D and test & demonstration areas of the supply chain. The modular nature of DC systems means skills at other (higher or lower) voltage and power levels i.e. HVDC or LVDC, are largely transferable.

4.8 Demand Forecasting and Power System Modelling

Technological maturity

New, higher resolution, bottom-up approaches to load forecasting and power systems modelling are already deployed commercially, but are still undergoing innovation and wider deployment.

Existing market capability

The higher resolution, big data approaches are available and are currently in the roll-out phases.

Exportability

The grid challenges tackled by various remote networks in Scotland, combined with the high levels of renewables deployment, have meant that Scotland has led innovation in various aspects of network planning and management. Leveraging these learnings, organisations that have been active in these areas are in a strong position to export such capabilities.

Relative cost/economics

Load forecasting and power system modelling enable better planning and grid balancing, as well as enabling smart grid strategies. The expected cost benefits relative to a traditional reinforcement scenario are large.

Carbon

Load forecasting and power system modelling are key to increasing the uptake of LCTs while maintaining a stable and cost-effective energy supply. As such, they have large potential for facilitating CO_2 savings.

User engagement

Load forecasting and power systems modelling underpin optimal user engagement with LCTs, demand side response and energy efficiency by facilitating identification and targeting of the strategic requirements and commercial costs/benefits of doing so.

Available skillset

Detailed, bottom-up load forecasting and power systems modelling techniques are already being implemented, and as such, the required skills and organisational capabilities are already active in Scotland.

4.9 Ancillary Services (Grid Support) by Wind

Technological maturity

The technology to provide ancillary services such as frequency support are available although not generally deployed at smaller-scale. There are some research projects underway to investigate technical and commercial aspects as well as adoption into Grid Codes.

Existing market capability

The ancillary services market is well established but regulatory and technical constraints limit the adoption/implementation of ancillary services from wind.

Exportability

There is significant opportunity to test and prove the provision of wind ancillary services in Scotland due to the high levels of wind generation. Providing the regulatory conditions are supportive, learning and expertise could then be exported to other parts of the UK and other countries with high penetration of wind and solar. European countries such as Germany and Denmark are also actively exploring the use of wind ancillary services.

Relative cost/economics

The cost benefit for ancillary services from wind is potentially substantial for both wind farm owners as well as transmission system operation.

Carbon

The provision of ancillary services from wind would help to support a greater penetration of renewable on the grid without impacting on grid security, displacing conventional fossil-fuel plants and resulting in a reduction in carbon emissions.

User engagement

TSOs, wind farm owners, academia and flexibility service providers have been engaged in various research projects, workshops and consultations in this area.

Available skillset

The required academic and commercial skills for this service are already active in Scotland.

5 Summary of Recommendations for Scottish Enterprise

Based on this benchmarking exercise, a number of recommendations can be provided to Scottish Enterprise to inform future decision making on energy system technologies.

5.1 Recommendations for Existing Capabilities

A number of the energy system technologies presented in the case studies have demonstrated strong Scottish capability which can/should be promoted and supported by Scottish Enterprise.

In terms of the domestic scale technologies investigated i.e. EV charging and home energy controls, the key recommendation is the continued support of innovation and development of technologies and associated regulatory aspects. There is massive potential for Scottish households to contribute to the more efficient operation of the electricity network through increased demand side activity. Existing activity in the sector, from DNOs and vendors, should be maintained and increased and new technologies and businesses can be promoted further through various mechanisms e.g. competitive funding.

ANM has a positive outlook both in Scotland and internationally, with SGS leading the way as a solutions provider. In order to maintain this position, and improve long term resilience, Scottish Enterprise could not only provide support to other Scottish businesses moving into commercial ANM product development, but it could also offer over-arching support in regulatory areas and risk mitigating through consultations with national and international bodies.

Distributed network intelligence for a wide range of electrical network enhancements has significant potential in Scotland with a number of Scottish companies involved in product development. Many of these companies are spin-outs from universities and recommendations to foster these capabilities and expand the market are through seed funding and encouragement of cross-institute collaboration with universities and research organisations.

Market growth in HVDC systems in Scotland is expected to grow in the coming years with a number of projects ongoing, planned or proposed. The technologies themselves are considered to be mature and it is in other areas of the supply chain that Scotland can expand. Existing strengths in the R&D and test & demonstration areas can be supported by Scottish Enterprise for example, through research funding for universities or investment in the development of The National HVDC Centre. Relationships with foreign capabilities could also be fostered.

Scotland’s electricity networks are facing many challenges associated with high penetrations of renewable generation on accelerated timescales thanks to the plentiful resources. As a result, there are already a number of innovation projects that have investigated the intricacies of demand forecast modelling. So much so that comprehensive systems have been set up to ensure alignment of learning outcomes such that synergies and opportunities can be fully exploited. A recommendation for Scottish Enterprise would be to provide support to ensure businesses are able to pursue broader commercial opportunities in the area. Closely related work on wind generation forecasting could be promoted internationally with help from Scottish Enterprise, given the right commercial opportunities are available.

5.2 Recommendations for Intervention

Through the energy system technology assessment, a number of areas where Scottish capability could be improved were identified and suggestions for possible interventions to assist development were provided.

To improve the outlook for demand side activity i.e. EV charging and home energy controls, targeted intervention could accelerate the deployment of technology and bring benefits sooner. Recommendations on how to achieve this include public-funded trials to create an evidence base on the benefits of domestic scale technologies. The development of a national roadmap would also be a very useful tool to involve and incentivise stakeholders to continue to support the area.

Battery storage has been shown to have great potential in overcoming a number of constraints and offering improved flexibility. The supply chain in Scotland presently however, is somewhat nascent and could benefit from a number of interventions. These include dissemination of learning from existing Scottish trials to promote and publicise the tangible benefits storage can provide, the provision of funding for R&D to improve storage technologies and associated control systems, and support for companies with existing links to the energy sector but limited resource and/or expertise specific to storage.

MVDC systems for distribution network reinforcement are a very new sector, and network demonstrations are taking place in England over the next few years. In Scotland, the characteristics of MVDC as a reinforcement solution could be well suited to the network's niche requirements and issues so Scottish Enterprise, assuming successful completion of the network demonstrations by WPD and SPEN, could promote and support trials, demonstrations or deployments on Scottish networks by incentivising DNOs. Existing capabilities in R&D could be supported in the meantime through research funding opportunities e.g. help Scottish universities be successful in European funding bids.

The provision of ancillary services by wind generation is at early stages of commercial and regulatory development although there are no significant technical barriers. Scotland has some limited existing capabilities in grid support services but significant amounts of wind generation. Scottish Enterprise could support the ongoing academic research and innovation projects with both National Grid and other European entities through seed funding or research grants as well as engagement between wind farm owners and consultancy/commercial expertise to explore opportunities further.

6 Appendices

Appendix 1: Further technology specification

Smart heating controls

Boiler-compatible smart heating controls

A majority of smart heating control products are designed to be compatible with boiler heating systems. Examples of this include *Nest, British Gas's Hive, PassivLiving Heat, HeatMiser Neo, Netatmo Thermostat, Evohome, Heat Genius, Scottish and Southern Energy's Tado, Scottish Power's Connect, Cosy, Climote, Wattio* and others. Across this range of products, the main control device currently has a unit cost in the range £120-250. Where the product has the capability for control of wireless TRVs, the unit cost of the TRVs is in the range £20-62 per valve.

Direct electric heating with integrated smart controls

There is also a range of direct electric heating systems with integrated smart heating controls. These include the *Dimplex Quantum* radiator, *EHC Smart Combination Electric Radiators, Curvo+ iVista* and the *Rointe Delta Ultimate*. The 1 kW models of the *Dimplex Quantum* and *Rointe Delta Ultimate* are in the region £500-700, although wholesale prices can be significantly lower.

Heat pumps with integrated smart controls

The latest model of the Daikin Emura air-source heat pump includes the option for remote on/off control and connection to a web-based control application. The 2.25 kW model has a unit cost in the region of £740 for the basic system, with the Wi-Fi accessory to connect to the online controller an additional £40 and an adaptor for remote on/off control an additional £75.

Smart lighting

Smart lighting products currently on the market include the *Philips Hue, Lightwave RF, Lifx, WeMo Smart LED, Osram Lightify, Connected by TCP* and others. The functionality of these products includes remote/external control via a web-based app; timer programmability; colour and brightness control; notification/alerts (e.g. when a text message is received); motion sensing; and others.

Typical unit costs are currently in the range £14-50 per bulb and up to £55 for the central control device where one is required.

Smart wet appliances

Smart wet appliance products currently on the market include the *Samsung WW9000, LG Series 2* and *Series 3* and *Hoover Wizard* washing machines, and the *Samsung DV8000* tumble dryer. The functionality of these devices typically includes remote/external control via a web-based app, energy use monitoring, the ability to programme the timing of washing and drying cycles and to download new cycle options, and remote diagnostics via the app.

Current unit costs for smart washing machines are in the range £499-1,700, and the Samsung smart tumble dryer costs in the region of £670.

Smart cold appliances

Products including the *Samsung Family Hub* fridge-freezer and the *Whirlpool Smart French Door Refrigerator* have been showcased at technology roadshows[113], with indicative unit costs of £2,650-3,500, though it is not clear what the market price will be on their UK release.

The functionality of these smart cold devices includes remote/external monitoring (via in-fridge cameras) and programming via a web-based app, notification of power loss and other issues and interoperability with *Nest* providing the ability to shift the defrost cycle to off-peak hours.

Smart microgeneration management

A number of products are available to enable smart management of solar PV with thermal storage, including the Solar iBoost and SolarImmersion. The current unit cost for these products is in the range £200-300, not including the immersion heater and storage tank. Sunamp, a company based in Scotland, is developing heat storage batteries based on phase-change materials, which offer higher density thermal storage than hot water. A Sunamp PV unit for a household currently costs in the region of £1,700 excluding VAT, accessories and installation[114].

Home electrical storage products available on the UK market include the Tesla Powerwall, which costs £2,100 excluding installation for the 7 kWh model; and the Moixa Maslow, BYD EnergyHub, Sonnen and Powervault systems, which cost in the range £2,650-5,250 including installation for systems in the 3-4 kWh range. The unit cost of home electrical storage systems is expected to continue falling rapidly as the underlying cost of the battery pack falls.

[113] See for example: http://www.cnet.com/uk/products/samsung-family-hub-refrigerator/ (Accessed April 2016)

[114] http://sunamp.co.uk/wp-content/uploads/2014/03/Updated-PV-Flyer-R-20151002-b.pdf (Accessed April 2016)