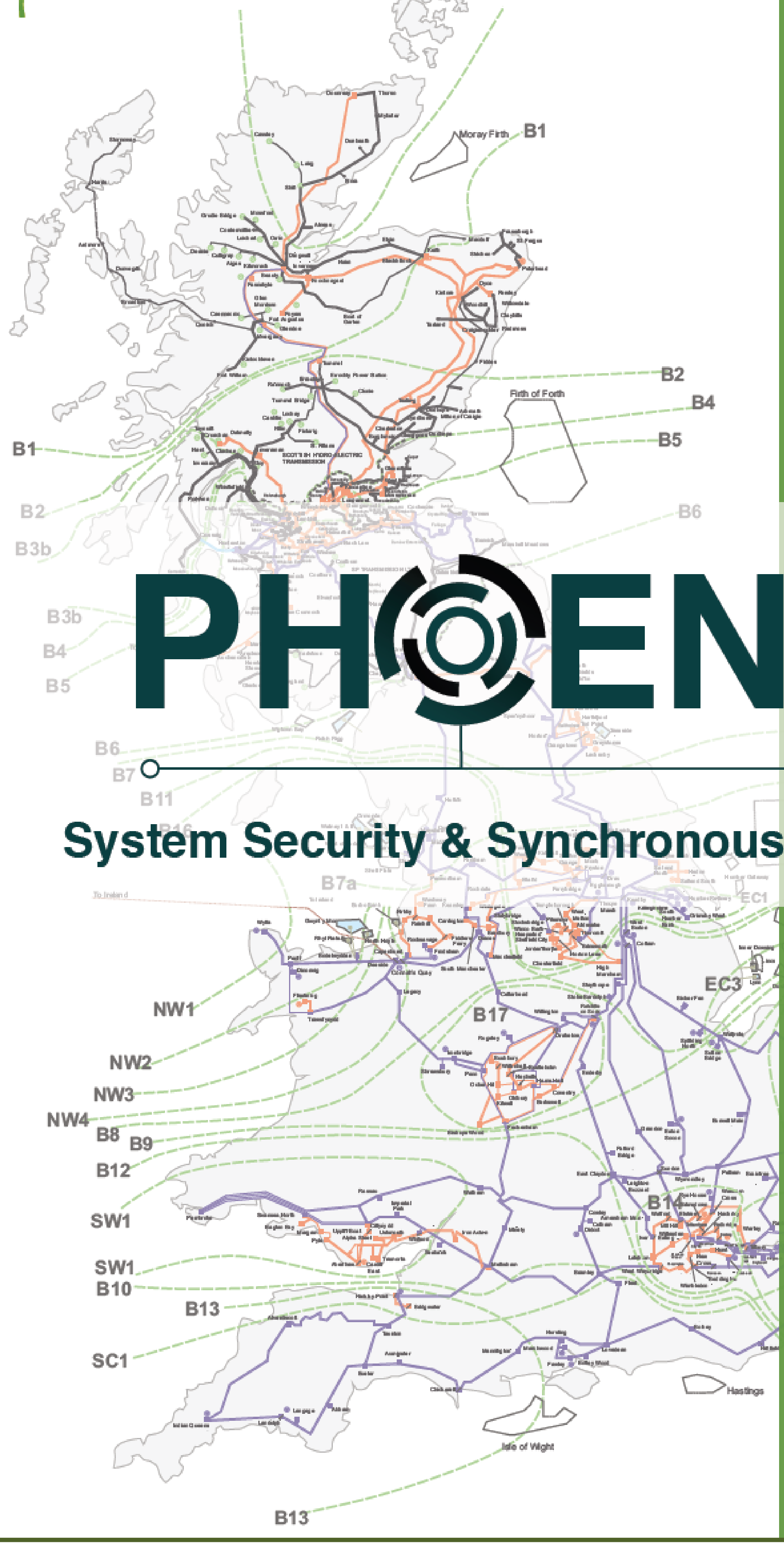
SP TRANSMISSION



PHOENIX

System Security & Synchronous Compensators

RIIO NIC 2016

ofgem

RIIO NIC NETWORK INNOVATION COMPETITION

Project Code/Version Number:
SPTEN03/V2.0

1. Project Summary

1.1. Project Title	Phoenix - System Security and Synchronous Compensators
1.2. Project Explanation	Phoenix will demonstrate a sustainable design, deployment and operational control of a **Synchronous Compensator (SC) with innovative hybrid co-ordinated control system** combined with a static compensator (STATCOM, flexible AC transmission system (FACTS) device**)** referred to in the project as **Hybrid Synchronous Compensator (H-SC).**The use of these devices is expected to mitigate serious system issues that are being encountered on the GB Transmission network as a result of the progressive closure of synchronous generation plants. This will enable future installations and essential network services to be provided for GB SO, TOs, DNOs and OFTOs. The project will enable an efficient and composite solution that will enhance system stability and security while maintaining power quality resulting in minimizing risks of blackouts and delivering significant benefits to GB customers.
1.3. Funding licensee:	SP Transmission Plc (SPT)
1.4. Project description:	**1.4.1. The Problem(s) it is exploring** The change in generation mix creates system issues that risk the security of supply to GB customers including; • Reduced inertia • Lower Short Circuit Level • Limited voltage control **1.4.2. The Method(s) that it will use to solve the Problem(s);** • Technical o Engineering design and deployment of H-SCs o Live trial and performance monitoring o Design and testing of hybrid co-ordinated control algorithms • Commercial & Regulatory o Cost benefit analysis and development of financial model for value analysis of SCs and H-SCs • Research o Component and System level studies for SCs and H-SCs **1.4.3. The Solution(s) it is looking to reach by applying the Method(s)** • Technical • Business process, technical recommendations for future procurement and installations of SCs/H-SCs • Hybrid Co-ordinated Control strategies improving system efficiency of SCs/H-SCs depending on regional requirements • Commercial & Regulatory

	• Commercial framework for financial value analysis of SCs and H-SCs • Regulatory recommendations for roll-out of SCs/H-SCs • Commercial arrangements for contracts for service providers • Research • GB roadmap for rollout of SCs and H-SCs **1.4.4. The Benefit(s) of the project** The cumulative benefits of roll-out of SC/H-SC technology at licensee scale till 2030 are • £42m in NPV terms • 662 MW capacity release • 62652 teCO2 carbon savings

1.5. Funding

1.5.1 NIC Funding Request (£k)	£15559	1.5.2 Network Licensee Compulsory Contribution (£k)	£1764
1.5.3 Network Licensee Extra Contribution (£k)	N/A	1.5.4 External Funding – excluding from NICs (£k):	£2254
1.5.5. Total Project Costs (£k)	£19897		

1.6. List of Project Partners, External Funders and Project Supporters	**Vendor:** ABB (£1954k in kind contribution) **Network Licensee:** NGET SO **Academic Partners:** University of Strathclyde (UoS) (£150k in kind contribution), Technical University of Denmark (DTU) (£150k in kind contribution) **Project Advisor:** SSE Plc.

1.7 Timescale

1.7.1. Project Start Date	January 2017	1.7.2. Project End Date	March 2021

1.8. Project Manager Contact Details

1.8.1. Contact Name & Job Title	Priyanka Mohapatra Senior Project Manager	1.8.2. Email & Telephone Number	pmohapatra@spenergynetworks.co.uk +44 (0)1416142789
1.8.3. Contact Address	SP Energy Networks Ochil House, 10 Technology Avenue Hamilton International Technology Park, Blantyre G72 0HT, Scotland		

1.9: Cross Sector Projects (only include this section if your project is a Cross Sector Project).

1.9.1. Funding requested the from the [Gas/Electricity] NIC (£k, please state which other competition)	N/A
1.9.2. Please confirm whether or not this [Gas/Electricity] NIC Project could proceed in the absence of funding being awarded for the other Project.	N/A

Section 2: Project Description

Phoenix will demonstrate sustainable design, deployment and operational control of a **Synchronous Compensator (SC) with innovative hybrid co-ordinated control** system combined with a static compensator (STATCOM, flexible AC transmission system (FACTS) device) referred to in the project as **Hybrid Synchronous Compensator (H-SC)**. The project will demonstrate technical and economic advantages of deploying H-SC over similar technologies with the aim of encouraging future rollout across the GB network. The use of SC/H-SC technology is expected to mitigate serious system issues that are being encountered on the GB transmission network as a result of the progressive closure of synchronous generation plants. This will enable future installations and essential network services to be provided for GB SO, TOs, DNOs and OFTOs. The expectation is that this will enhance system stability and reduce operating costs, with a minimum carbon footprint and with a faster deployment process in comparison to conventional synchronous generators. Phoenix will build upon the learning outcomes of a number of international schemes as well as NIA and NIC projects undertaken by GB TOs, SO, DNOs Appendix H.

Phoenix H-SC solution will be demonstrated at a strategic point on the SP Transmission network, investigating possible coordination and interaction with power electronic based compensation devices, in order to maximize customer values of these complementary technologies. The project will also undertake system studies and cost benefit analysis to further develop the commercial mechanisms available to incentivise the roll-out of SCs along with FACTS devices. The project, working in collaboration with the GB System Operator (GB SO) will also analyse the impact of installing several compensators at various strategic locations in the GB system, and their impact on the performance of the GB power system in coming decades. The project will enable an efficient and composite solution that will enhance system **stability and security** while maintaining **power quality** resulting in minimizing risks of blackouts and **delivering significant benefits to GB customers**.

SCs are not new in power system history: they have been around for more than a century. With the development of power electronic devices and the higher maintenance costs of SCs the interest this technology declined in last two decades. **Why are the SCs now being "re-incarnated"?** The reason is that it provides two main system services that power electronic FACTS devices cannot adequately provide; **inertia and short-circuit level (SCL)**. Even with the constantly evolving electricity network and many innovative power system technologies inertia and SCL remain essential for security of power system, as thyristor based HVDC systems and existing protection systems require a minimum SCL for efficient operation and inertia is required for stability.

Phoenix aims to re-incarnate synchronous compensators in the GB power system to provide dynamic voltage control, inertia and SCL in light of diminishing synchronous generation; and address technical, engineering, commercial challenges that are the main barriers for roll-out of SCs. An output from the project could be an open invitation to the market to make bids to install equipment at pre-defined locations and/or provided confidence for TOs to invest in SCs in RIIO T2. The project will also prove that SCs are a complementary technology to FACTS devices and not a replacement to them through demonstration of **globally**

innovative hybrid co-ordinated control methods. These methods can be in future rolled out to hybrid systems combining SCs with Battery Energy Storage System (BESS).

During the evolution of project Phoenix two main options for demonstration were considered: Option 1: To convert a closed down power station to SC; Option 2: To install a new standalone SC.

System studies, cost benefit analysis (NPV calculation) and feasibility of delivery of the project within the given time-frame; were closely analysed for both options. In this process Option 1 was rejected as it was deemed to be of extremely high risk to be delivered as a NIC project. [redacted] This could have seriously jeopardised the successful delivery of the project. However for avoidance of doubt with proper planning and guaranteed return on investment (ROI) from commercial mechanisms to be developed through project Phoenix this will remain a viable option for future power stations planned for closure. The technical studies undertaken for this option during the bid phase are available for future use. Hence option 2 was pursued as the main option for project Phoenix (**Appendix D**).

Providing value for money for GB customers while delivering **technical, commercial innovation** through project Phoenix is priority for SP Transmission and GB System Operator. Hence extensive stakeholder engagement (with TOs, SO, academic institutions and vendors) and market research was carried to determine a demonstration project that will best represent the role of SCs in future GB power system. Following challenges were posed during the various workshops during the development of this bid

1. Why SCs requiring higher CAPEX investment are a better option than other power electronic FACTS devices such as SVCs and STATCOMs?

SCs can provide AC system strength in the form of inertia and SCL while inherently providing dynamic voltage control while FACTS devices are mostly limited to fast voltage control. Also SCs combined with a BESS or gas turbine can play a role in Black Start strategies. This makes SC an excellent solution when rolled-out in strategic points in GB transmission network to be determined through detailed system studies in project Phoenix.

2. What is the future of existing transmission connected power electronic FACTS devices on the network, will they be replaced by SCs?

The simple answer is NO. FACTS devices are cheaper to maintain and have higher controllability aiding in active harmonic damping, limitation of flicker phenomena and power oscillation damping. Future innovation in power system will combine SCs and other FACTS devices, analyse their strengths and weaknesses and possible interaction issues hence optimizing the coordination in order to fully utilize synergies.

The conclusion to the review was: technically there is no single solution that can solve all rising network challenges. In order to achieve all the system objectives of Phoenix and maximise innovation and best represent a solution for the future of GB grid; the solution proposed in this project is a Hybrid Synchronous Compensator (H-SC) with a globally innovative hybrid co-ordinated control system combined with a STATCOM. It should be noted that the SCs and STATCOMs do not need to be collocated for future roll-out of the hybrid control strategies. They will be collocated for purpose of demonstration in this project. Phoenix will explore the full potential of these complementary technologies and to better understand the risks and benefits of an H-SC solution.

3. If SCs have such a strong business case as highlighted in the system operability framework (SOF), why are they not being rolled-out? Why is no-one investing in SCs?

The challenge lies in lack of commercial mechanisms to financially incentivise a standalone SC installation. The markets for inertia and SCL are underdeveloped and the reactive power market is mostly existent through bilateral contracts for other energy services. Thus there is no defined ROI for service providers to install SCs and generation plant owners to convert closing power plants to SCs. TOs could potentially install SCs as FACTS devices, however the capital investment is high and the added benefits in current scenario are unproven. TOs were traditionally able to maintain system security and stability as required by NETS SQSS through inertia and SCL provided by large amounts of connected synchronous generation. This is not the case anymore and the future will see even more diminishing synchronous generation resulting in a weaker AC system. TOs are also not allowed to participate in services market. **The future poses some serious threats to the security of supply and TOs and GB SO will work together in project Phoenix to facilitate commercial innovation to address these challenges.**

The future generation mix in Scotland and in the wider GB context system will mainly consist of intermittent, asynchronous renewable energy sources, with much of it uncontrollable by system operators (e.g. domestic solar) under the present operating regimes and commercial service conditions. The successful demonstration of SC technology through this innovative hybrid arrangement (H-SC) for the first time on the GB network will enable subsequent applications to:

- Boost system inertia;
- Provide dynamic voltage regulation;
- Reactive power injection support to alleviate voltage dip conditions;
- Reactive power absorption to potential overvoltage scenario in light load conditions
- Increase the system SCL and system total strength;
- Enhance the oscillation damping capability;
- Aid in maintaining power quality of the network

Phoenix will help transition to a future GB transmission network that can benefit from clean energy resources without compromising the security and quality of supply to the GB customers. Although the SOF 2015 clearly shows the technical benefits of SCs in GB, there is currently no road map ensuring the roll out of this vital technology as a permanent solution. The challenges facing the roll out of SCs in GB are:

- No financial certainties on return on investment for SCs owners/operators based on existing commercial mechanisms
- Technical challenges relating to logistics, installation and connection of SCs
- Technical challenges of optimally controlling and maintaining SC in a wider context including other interacting power electronic technologies and implementing hybrid co-ordinated control strategies
- Lack of detailed studies and GB roadmap to support roll out

2.1. Aims and objectives

2.1.1 The Problem(s) which needs to be resolved;

Technical challenges

The change in generation mix creates system issues that risk the security of supply to GB customers including;

- **Reduced inertia** which compromises the network stability and security in event of a large loss of generation or load and results in a large rate of change frequency (RoCoF).
- **Lower SCL** results in poor power quality can also result in certain protection schemes failing to operate and introduces an increased risk of loss of commutation in current-sourced (LCC) HVDC links.
- **Limited voltage control** in absence of immediate dynamic response conventionally obtained from synchronous generators can result in voltages outside the statutory limits.

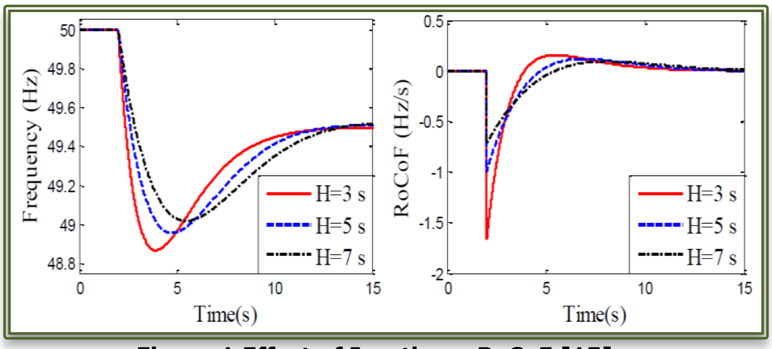


Figure 1 Effect of Inertia on RoCoF [15]

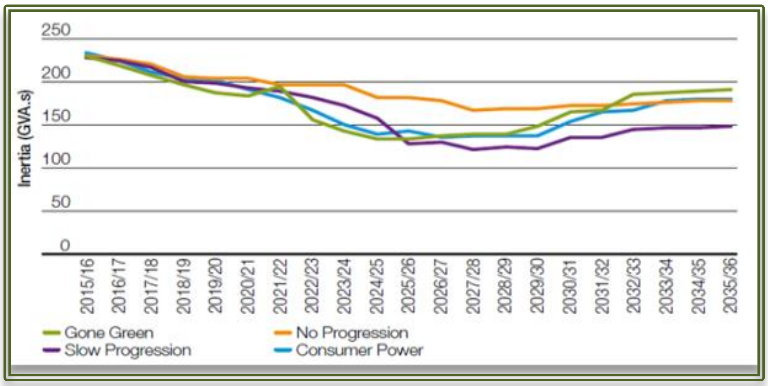


Figure 2 Reducing Inertia in GB Power system

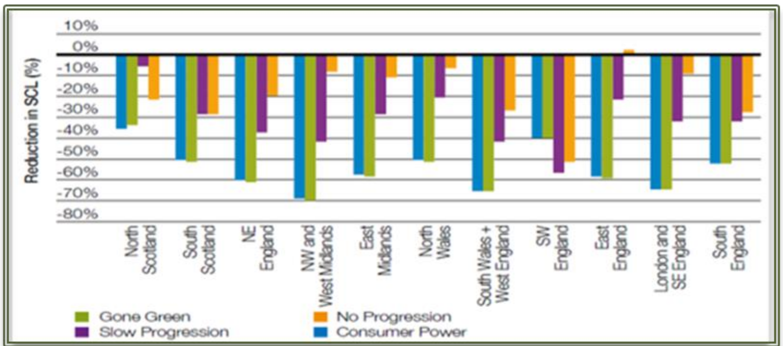


Figure 3 Reducing SCL in GB Power System

Figure 1 illustrates the smaller the inertia (H is the inertia in seconds) of a power system, the larger the RoCoF will be immediately after any given disturbance and the faster and larger the frequency deviation will be. Reduced inertia decreases the time available before the frequency deviation will violate the security limits and can resulting in cascading failures.

Figure 2 is from SOF 2015 and displays the future minimum system inertia including the contribution of embedded generation for National Grid's four future energy scenarios.

Figure 3 is from SOF 2015 illustrates the future decline in SCL expected from 2015/16 to 2025/26 and states the level in South Scotland could fall 50% under two of National Grid's four future energy scenarios. The SCL falls even more significantly in other parts of GB power system.

The reduced loading of the transmission system has also resulted in more un-damped sub-synchronous oscillations and increased levels of harmonics.

Commercial challenges

The lower system inertia requires the SO to procure larger volumes of frequency response to compensate the potentially faster and more severe frequency drops that will be experienced in future; increasing the balancing costs, which presently comprise around 1% of the average GB customer's electricity bill. The SOF 2015 predicts there will be a 30% to 40% increase in frequency response required for all scenarios by 2020 and a 300% to 400% increase in frequency response required for all scenarios by 2030, and this would clearly increase costs to system operators and customers – the balancing services may also be provided by generation or storage that is not particularly efficient and/or low carbon in nature.

The definition of "inertia" and "inertial response" in this context is important. Anything that requires the use of a control system (and the attendant delays associated with measurement and processing - particularly when frequency or ROCOF measurement are required) to provide an "inertial" response can only be classified as "fast" or "enhanced" frequency response as it is not instantaneous. This can certainly assist in improving the stability and response of the system, there still remains a need to enhance the true inertial and instantaneous response of the power system. The only way that this can be provided, in the absence of synchronous machines, is through SCs. SCs will assist greatly in improving speeds (and magnitudes) of responses. The interaction of inertial and enhanced frequency response can be best demonstrated with the H-SC solution.

Regulatory risks

To comply with various regulatory requirements, SPT is obliged to consider not only conventional transmission-based investment solutions but also alternative solutions which may be more economic on a short term or long term basis in maintaining economic and efficient operation of the national electricity transmission system. However TOs under the present regulations, cannot participate in services market and with no mechanism to provide a clear ROI against high capital investment for third parties, there is a concern that GB may not be able to exploit the benefits of large scale roll-out of SC technology and/or technologies other than synchronous generation that can provide inertia and/or SCL as a service.

2.1.2 The Method(s) being trialled to solve the Problem

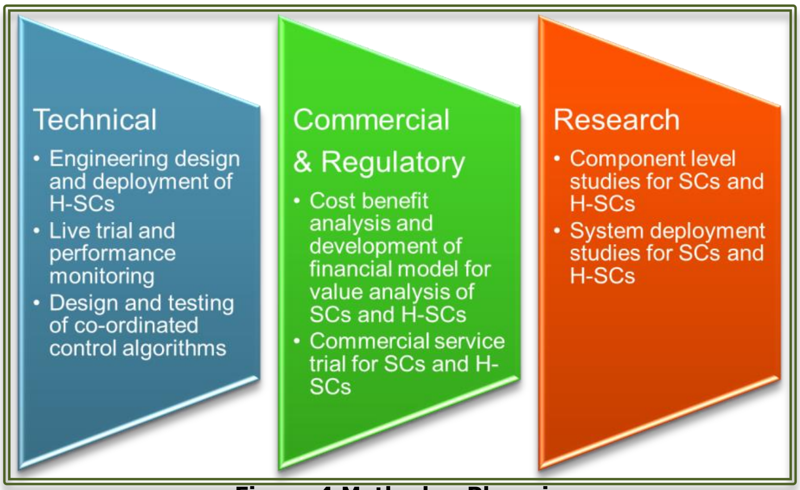


Figure 4 Methods - Phoenix

Figure 4 lists the different methods to be demonstrated in this project to address all the challenges described in section above. The methods will be trialled as part of various work packages and enable extension of the study and results to GB-wide implementation of SCs and H-SCs.

2.1.3 The Development or Demonstration being undertaken

The project will demonstrate the installation and operation of H-SC solution for the first time in GB. It will also enable innovative hybrid control methods to co-ordinate complementary technologies and assure the maximization of the end user value. The results will be relevant for a wide area context were these technologies are installed in different locations of the electric system. A commercial framework will be developed for future installations of SCs and H-SCs. There is an element of research to maximize operational efficiency, system performance and identify potential sites for GB rollout of SCs and H-SCs. The demonstration in project Phoenix will be divided into three stages

- Conceptualisation
  This stage will be the project preparation stage to choose a site out of the 3 possible sites on SPT Network and determine engineering feasibility for H-SC installation. Parallel to this a cost benefit analysis will be developed specific for value evaluation of SC/H-SCs. The research component of the project at this stage will analyse results and system models from previous innovation projects in preparation for system studies to be undertaken as a part of the project.
- Implementation
  This phase will implement the methods developed in the conceptualisation phase. The recommendations for future installations and procurement of SCs and H-SCs will be developed throughout this phase. The H-SC solution to be demonstrated will be deployed and connected to the SP Transmission network. The system and component level studies will feed into the CBA model to determine the return of investment and financial value of this and further installations of SCs and H-SCs.
- Validation
  This is the most important stage of the project which will validate the perceived benefits of the H-SC installation through performance monitoring both at component and system level. The GB roadmap for rollout of SCs and H-SCs will also be developed in this phase. Most importantly the commercial framework developed in the earlier phases will be put to test in this phase and potentially contracts will be placed by GB system operator for future installation of SC/H-SCs.

Knowledge dissemination will be an integral part of the project and as described in detail in Section 5 at every phase of the project the learnings and outcomes will be shared with the wider audience and stakeholders.

The Solution(s) which will be enabled by solving the Problem

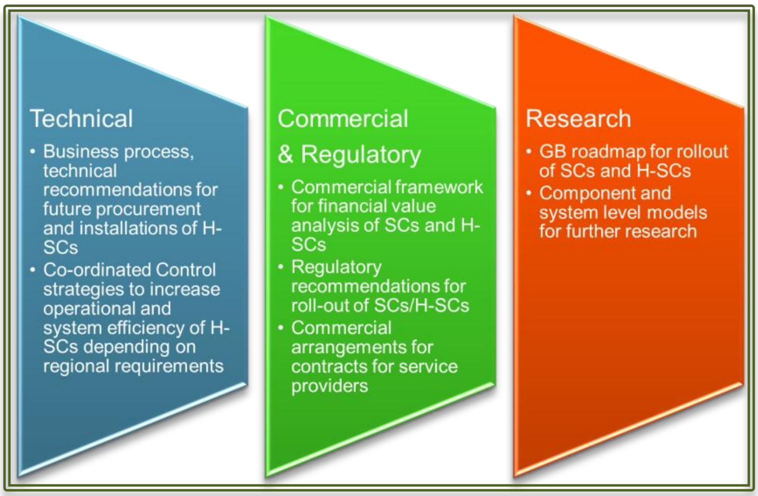


Figure 5 Solutions Phoenix

The various solutions enabled through this project are listed in Figure 5. The present GB grid codes are not specific regarding the system security and operation particularly in the context of a weak AC system in the future. There is an urgent need to define what the GB system will actually need technically and commercially, both in terms of responses to system disturbances and also under steady state conditions, in order to maintain network security and reliability of supply. This project will help enable answer these questions.

2.2. Technical description of Project

SCs can improve the voltage of the surrounding network through import or export of reactive power (MVAr). These MVArs are used to control voltage within the grid, and improve power transfer over lines and between areas. Two operating conditions are possible according to the capability curve of individual SCs are:

- **Over-excitation**: generation of reactive power with leading power factor (capacitive behaviour);
- **Under-excitation**: absorption of reactive power with lagging power factor (inductive behaviour).

Additionally because of the rotating mass and characteristics similar to synchronous generators (except for producing active power), SCs can contribute to system inertia and SCL. In regional level the effect of inertia provided by SCs is much greater than the whole system perspective. These services are increasingly important given the changes to the grid.

2.2.1 Hybrid Synchronous Compensator (H-SC)

The SC characterized by a high rotating energy and high short circuit current generation capability, is used as the main contributor to boost the system inertia, increase the system SCL. Its characteristic response time, relatively fast for large disturbances and slower for small signal control, and its specific overload capability, make the SC very suitable to play important role in providing voltage regulation support in severe dips and contributing with the regulations requiring a limited frequency response. The STATCOM device in this **H-SC combination** (Figure 6) is used as the main contributor for providing fast and highly controllable voltage regulation, also in case of voltage dips. During fault recovery and switching phenomena the STATCOM has the capability to absorb quickly the reactive power needed to maintain the over-voltages within the allowed limits. The STATCOM has also a response time more suitable for solving the power quality concerns, to actively damp harmonics in the power system and voltage fluctuations producing annoying flicker effect for industrial and domestic consumers.

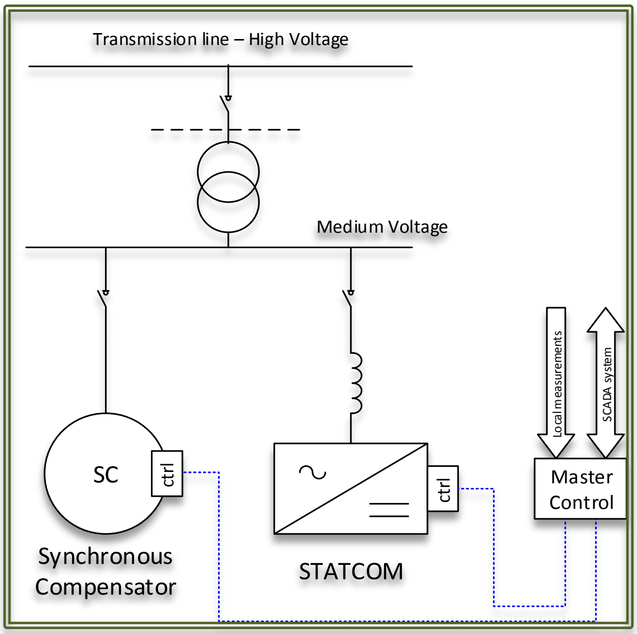


Figure 6 Hybrid Synchronous Compensator (H-SC)

Within the Phoenix scope, it is considered beneficial to investigate and test the **SC as the main technology**; combined with STATCOM's capability to contribute in operating modes, such as the boosting of system inertia, by emulating generator behaviours, with clear limitation on the energy contribution, but with advantages on the speed of response and fine tuning of the output power.

The limitations of the STATCOM in providing inertia or enhanced frequency response contribution due to low stored energy in the DC capacitors can be studied in the project, analysing solutions with enhanced energy storage, scanning possible technologies going from a pure STATCOM equipped with only DC capacitors, toward a typical Battery Energy Storage System (BESS). This analysis may be conducted through simulations at component and system level giving important input to SO and vendors on potential future requirements and technology possibilities The future GB power system will include both of these complementary technologies such as SCs and FACTS devices. Important part of the demonstration is the master control of the hybrid system which will coordinate the operation between the two technologies and assuring the best operation toward the network and system operators. After analysis of the standalone technologies, objective functions can be developed in order to reach optimal operation of the H-SC (Figure 6) for enhancing the system benefits. Examples of possible objective functions may include:

- Minimization of overall H-SC losses
- Maximization of compensation of fast transients
- Maximization of inertia contribution (including possible inertia emulation from STATCOM)
- Maximization of low frequency oscillations damping (eg. inter-area power oscillations)
- Maximization of medium-high frequency oscillations damping (eg. voltage fluctuations)

The hybrid control strategies to be delivered for the Phoenix can provide insights for:

- Possible future similar plants with the combination of the two technologies installed at the same electrical node
- Interactions and operation coordination of such technologies installed at different nodes in the network, a very likely scenario in future GB power system.
- Extension of research to apply hybrid control methods to combined SCs and BESS systems.

The details of the technical solution to be trialled as a part of the project and the network diagrams are described in **Appendix C.**

2.3. Description of design of trials

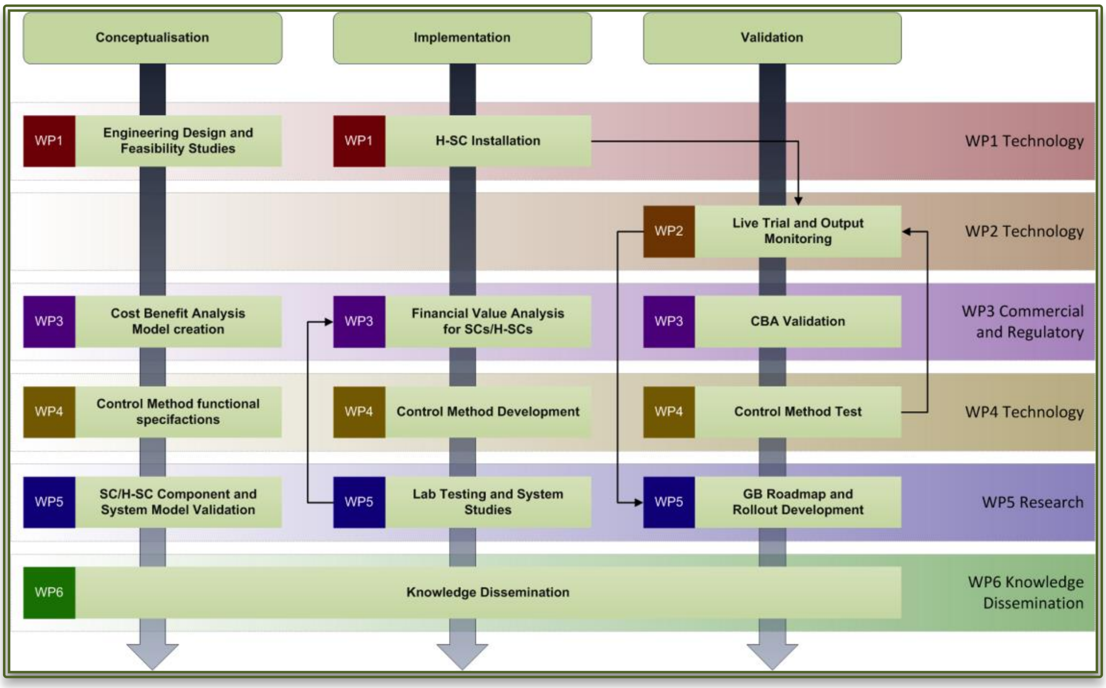


Figure 7 Phoenix Work Packages

The work packages and work streams defined in the project (Figure 7, Table 1) comprehensively cover all aspects and questions regarding future roll-out of SCs and H-SCs.

Table 1 Phoenix Work Packages (WP)

WP1: Hybrid-Synchronous compensator installation	
Work Stream	• **Pre-Site Planning and Design** • **On-Site Deployment and Commissioning**
Purpose	The purpose of this work package is to do a final design of the pilot H-SC installation following the preliminary design during the bid phase. This will include addressing the building and planning requirements for deployment of H-SCs. Detailed studies and NPV calculation has been performed during bid phase to assist in site selection. Following the design phase the site commissioning of the pilot H-SC will commence and this will further generate learnings regarding the processes and procedures to be followed during installation to allow for future extension and addition of functionalities..
WP2: Live Trial	
Work Stream	• **SC and H-SC Performance Monitoring** • **SC and H-SC Output Monitoring** • **System/Operational Performance Monitoring** • **Extended Live Performance Trials Report and Recommendations**
Purpose	This is a vital work package and an integral element of the validation phase of the project. This phase will determine whether the system studies and financial model actually perform the way they were intended to. The pilot H-SC live operation should result in cost savings for the system operator confirming the financial value associated with it and most importantly resulting in savings for GB customers. This phase will monitor performance of the pilot SC in standalone mode and in H-SC mode at component level to monitor losses, vibrations, noise levels and oscillation damping. It will also monitor the system and usage of the SC and H-SC for voltage support, short-circuit level and inertia contribution. The trial phase will test the hybrid coordinated control methods developed in this project. This will also validate the system studies and apply corrections to different system and financial models developed through this project.
WP3: Commercial Model Development and Roll-Out Recommendations	
Work Stream	• **Development of Cost Benefit Analysis model for SCs and H-SCs** • **Financial evaluation based on economic and emerging energy policies** • **Validation of the CBA against actual utilization and value addition of pilot H-SC on the system**. • **Regulatory recommendations for future roll-out of SCs and H-SCs**
Purpose	This work package will aim to answer questions regarding the financial value of services that can be provided by SCs i.e. voltage support vs inertia vs SCL. It will also determine the need for availability and capability of SCs in future. Additionally, regulatory recommendations will be generated for future roll-out. In all three phases of the project will work with the GB SO to create a robust CBA model for the value evaluation. In the implementation phase this model will be put to test along-with the results from the system studies. For example it will be tested if the application of SCs and H-SCs in different parts of GB system results in similar or increasingly variable benefits. This model will then generate a return on investment (ROI) value for service providers and the learnings can be used to in future service agreements for inertia and SCL.
WP4: Hybrid Co-ordinated Control & Integration	
Work Stream	• **Hybrid coordinated control to maximize benefits from different technology solutions**

	• **Lab Simulation of Control Methods** • **Hybrid Control method Site Deployment and Testing**
Purpose	This work package will be globally innovative in demonstrating new control strategies to maximize different outputs from SCs with hybrid coordinated control methods. Depending on the future site of installation SCs may be required to maximize on certain outputs in standalone and/or H-SC mode. This work package will prove that SCs are complementary to other types of compensation devices and in the larger picture with storage services and can be operated in H-SC mode to maximize all system benefit cases. This will make roll-out of SCs and H-SCs more viable for TOs and SO. Maximizing system benefits through hybrid control methods will help reduce costs associated with system balancing and frequency reserve markets.
WP 5: Component and System Studies	
Work Stream	• **Component Level Studies** • **System Level Studies**
Purpose	This work package will bridge the gap between past and future system studies regarding system operation and role of SCs and H-SCs in different FES scenarios. The system studies will begin with analysis of results from previous innovation projects (Appendix H). The models developed through previous projects will be used in various streams of studies at component and system level. The component level studies will be extended from the existing studies regarding SC inertial and SCL performance in SCAPP (see Appendix H) project to include H-SC models. The system level studies will analyse the application of SCs and H-SCs at different locations pf GB network and will directly feed into FES and SOF studies conducted GB SO. Detailed analysis will be performed for specific use cases such as role of SCs/H-SCs in frequency response market in conjunction with fast frequency solution developed through EFCC and potential constraint of western HVDC link in low SCL conditions after planned closure of Hunterston in 2023. The research component of this project will result in GB roadmap for future rollout of SCs/H-SCs and will aid RIIO T2 planning for GB TOs and SO.
WP 6: Knowledge Dissemination	
Work Stream	• Dissemination in GB and international conferences and paper submissions • Quarterly Internal stakeholder events - WebEx and Focus Group Meetings • Annual External stakeholder events • Engagement with technical standard bodies and working groups • Engagement with GB SO for development of commercial mechanisms and participation in working group
Purpose	The purpose and main aims of this work package is described in detail in Section 5.

2.4. Changes since Initial Screening Process (ISP)

At the ISP stage SPEN was still assessing the pros and cons of the retrofit and new-build options. SPEN critically analysed the feasibility of delivery of the project within time and risks associated with each approach. Following detailed studies and extensive stakeholder engagement with vendors and system operator, SPEN has concluded that a new SC in this hybrid arrangement best represents future grid scenarios with maximizing innovation through hybrid co-ordinated control methods.

Detailed analysis of civil works and engineering design to implement the hybrid concept, addition of NGET, ABB, and University of Strathclyde to the list of partners, and detailed costing for the successful delivery of the project increased the funding request to cover all project deliverables.

Section 3: Project business case

3.1. Context

GB Transmission Owners (TOs), Distribution Network Operators (DNOs) and the System Operator (SO) are faced with growing challenges relating to increasing penetration of asynchronous renewable generation connecting to the GB system. This transition has a positive impact on the environment as renewable generation displaces conventional thermal generation. However, the change in generation mix creates system issues that risk the security of supply to the GB customers including; reduced inertia, lower short circuit capacity, limited voltage control and issues with power quality. There is currently no direct precedent for markets for system inertia and SCL as these have conventionally been provided by large synchronous generators as a by-product of their primary generating function.

3.2 SP Transmission Business Case

Project Name	MW Total	Plant Type
Torness	1,215	Nuclear
Hunterston	1,074	Nuclear
Cruachan	440	Pump Storage
Whitelee	305	Wind
Whitelee Extension	238	Wind
Clyde North	221	Wind
Fallago Rig Wind Farm	144	Wind
Crystal Rig 2	138	Wind
Clyde South	129	Wind
Harestanes	125	Wind
BP Grangemouth	120	CHP
Blacklaw	118	Wind

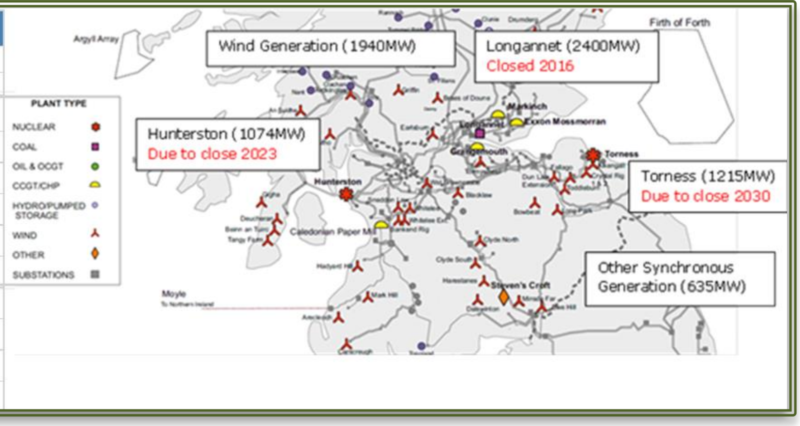


Figure 8 SP Transmission Generation Profile

In 2014, wind generation delivered 30.5% (11,664.1 GWh) of Scotland's electricity consumption; the total wind generation in Scotland increased in 2015 to 14,136.0 GWh. A geographical representation of the generation on the SPT network is shown in Figure 8. Denmark, Germany, southern California, Texas have a similarly weak AC but well interconnected system as a result of a high of renewable generation displacing conventional thermal generation. To future proof their transmission systems, these power systems have already deployed SCs to ensure the transition to a low carbon future does not compromise the system security and stability. GB TOs have a statutory duty to develop an economic, efficient and co-ordinated system for the reliability and security of transmission of electricity within its licenced area. SP Transmission also has the following relevant license obligations:

- License Obligation to comply with the National Electricity Transmission System Security and Quality of Supply Standard (NETS SQSS).
- License Obligation to comply with the System Operator Transmission Owner Code (STC), which requires our assets to be made available to NGET, as National Electricity Transmission System Operator, for efficient operation of the network.

In order to comply with these various requirements, we are obliged to consider transmission based investment solutions which may be more economic on a short term or long term basis in maintaining economic and efficient operation of the national electricity transmission system, such as SVCs/STATCOMs/MSCDNs, SCs and/or Hybrid-SCs. The most probable scenario for roll-out of SCs/H-SCs will be a combination of re-purposed closed generation plants as SCs and standalone SCs/H-SCs. The system studies and benefit analysis Appendix B suggest this combination will generate maximum benefits for GB customers.

3.3 GB Transmission Owners Business Case

The business case for Phoenix has been derived from system studies performed on a set of GB system models explained in detail in Appendix B and Appendix C. The limitations of the models and system scenarios are well understood and the results are indicative. The studies for the purpose of this bid were limited to 3 strategic locations in SP Transmission area with typical sizes and types of installation.

- Neilston (West Coast) (Single compensation size 250MVA, Hybrid Compensation Scenario of 140MVA)
- Cockenzie (East Coast) (Single compensation size 250MVA)
- Longannet (Central Scotland) ([redacted])

Phoenix proceeds with installation of a new SC with technical innovation in hybrid control methods to best represent the future combination of various technologies. As such, the project has also looked at innovation schemes such as a H-SC (SC+STATCOM) which will complement the capabilities of an SC in reactive power support, fast voltage regulation and power quality metrics such as flicker mitigation. Due to time constraints and lack of appropriate hybrid control system models, the H-SC system was not studied in great detail and will be progressed as a part of the project; however the results for the SCs remain valid for site comparative purposes also for the hybrid solution (comparative for same rating of SC installation). The actual benefits of a hybrid system have been inferred. Further studies will be carried out as a part of the project to validate and extend the results of SCs and H-SCs to the entire GB system.

3.3.1 Improved Short-Circuit Level (SCL)

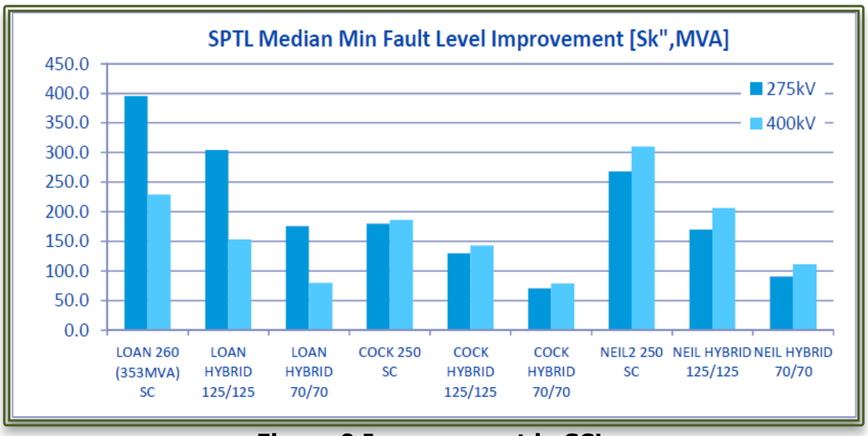


Figure 9 Improvement in SCL

SCL contribution of power electronic controlled renewable generation is significantly lower than that of synchronous generators due to the reduced amount of rotating mass. As a result, SCL in the GB system is decreasing as conventional generation is increasingly replaced by asynchronous generation. The reduction in SCL has following effects on the power system, which can be mitigated by improving SCL with addition of SCs/H-SCs:

- Challenges to maintain system voltage during short-circuit faults.

- Increased risk of failure of key protection systems
- Increased risk commutation failures in LCC HVDC links e.g. the Western link caused by disturbances on the AC side of the converter.
- Adverse effect on power quality, such as increasing levels of harmonics, flicker and voltage and current distortion.

H-SC solution due to combination of technologies and higher controllability should be particularly good at improving power quality metrics such as flicker mitigation and harmonics filtering. System studies results show that relatively speaking, median winter peak demand SCLs will increase by up to 7.8% on the 275kV network and up to 2.7% on the 400kV network with the application of SCs/H-SCs either at Longannet, Cockenzie or Neilston. Installation of multiple SCs/H-SCs can increase the median 275kV levels by 16% and 26.5% in winter peak and summer minimum cases respectively. Figure 9 shows the increment on the median SCLs in absolute terms subject to scenarios.

3.3.2 Improved Transient Stability

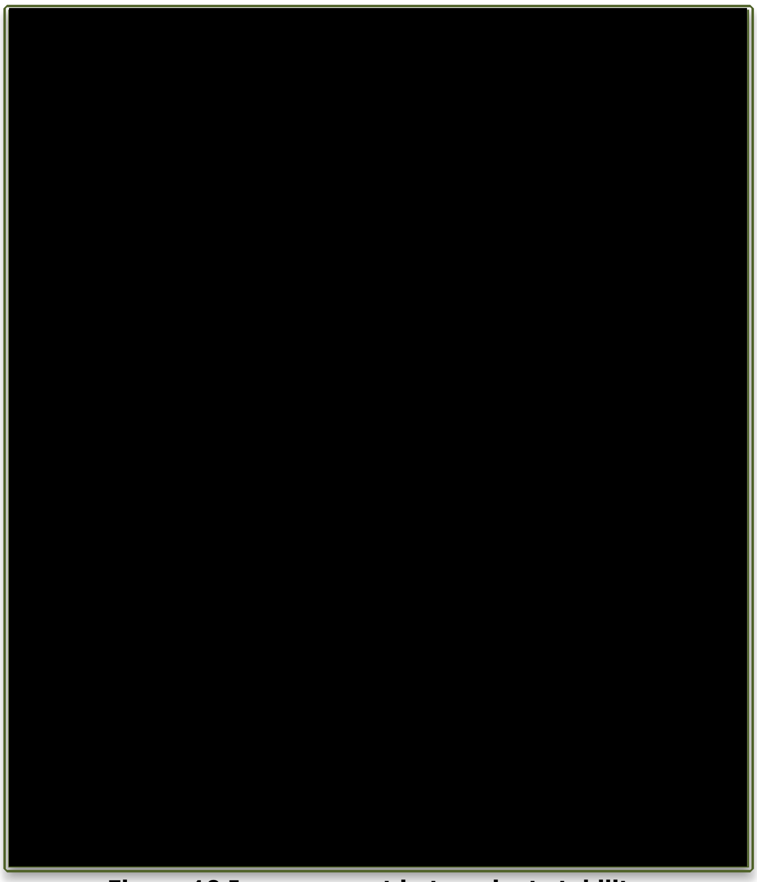


Figure 10 Improvement in transient stability

Transient stability defines the ability of the generation connected to the transmission network to maintain synchronism when subject to a severe transient disturbance like a fault on a transmission line or a large loss of generation or load. If a fault persists on the system past a critical point, the generators may lose synchronism and be disconnected by their own protection scheme. Stability limits are of primary concern when incrementing power flow over the east and west coast AC lines across the B6 boundary. The GB Grid Code requires that the voltage on the super-grid (275 and 400kV) network nodes is maintained within a time-dependent limit. Stability-related constraints limit power flows between areas to levels where transient stability can be maintained. SCs/H-SCs can be used to reduce the constraint by improving system stability. Figure 10 on top also shows installation of multiple SCs and H-SCs the power transfer capability across B6 boundary can be improved between 50MW to 250 MW.

Modern SCs/H-SCs can remain connected and provide the required system benefits even under extreme low voltage conditions. H-SCs are perceived to be particularly effective at mitigating voltage dip conditions. The results of application of SCs/H-SCs at different locations in SP Transmission area show the positive effect on voltage recovery post fault. Figure 10 that during faults (t-event), voltage profiles were significantly improved above the fault condition with multiple SCs/H-SCs; with a minimum voltage after t-event + 1.2s reaching 0.883/0.886 pu.

3.3.3 Role in Black Start Strategy

The lack of large synchronous generation combined with high levels of asynchronous generation negatively affects the SPT Black Start strategy. SCs/H-SCs can play a role in black start conditions by providing extra SCL, inertia and voltage control, including dynamic voltage control during system re-energisation. In future, if combined with a BESS and/or a gas turbine, SC can self-start-up in black start conditions, to aid faster system recovery. H-SC will better maintain the voltage stability over a standalone SC in a black start situation.

3.4. System Operator and Customer: Constraint Payments, Balancing and Grid Services

3.4.1 Steady State Evaluation: Fast Voltage Control and Reduction in Losses

Controlling the voltage on the SPT network is becoming ever more challenging. Following the closure of Cockenzie in 2013 and Longannet in 2016 the amount of suitable voltage control has diminished. The H-SC solution can act faster on control on limiting over voltage after fault clearances and switching transients. When there is little or no wind generation on the system and the system is lightly loaded, there are issues controlling system voltages. This can result in circuits being switched out of service most of the day to control high system voltages. SCs and H-SCs provide improved dynamic voltage control. If system voltage can be increased, system losses decline. SCs/H-SCs can be operated to export VARs which will raise local voltages and if the VAR flow is sufficiently small, overall losses can decrease.

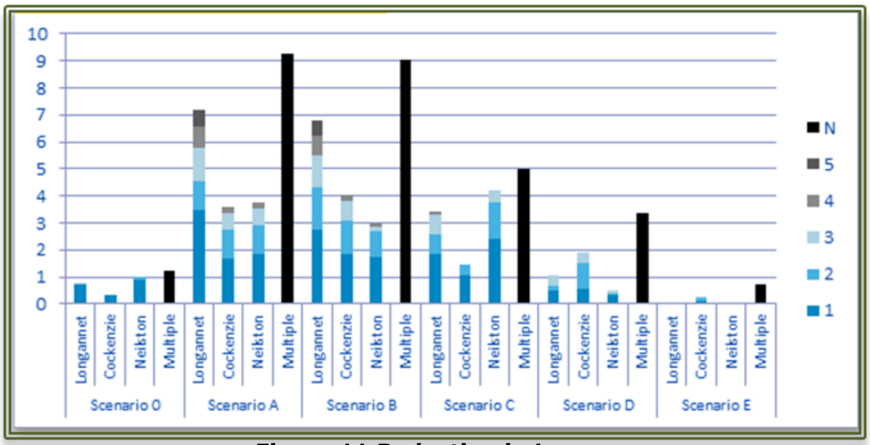


Figure 11 Reduction in Losses

Figure 11 highlights reductions in network losses under different study scenarios in transmission network and the reduction in losses up to 9MW by introduction of H-SCs at individual and/or multiple locations on the network.

3.4.2 Contribution to Frequency Response

National Grid as the GB SO has a licence obligation to control frequency within the limits specified in the 'Electricity Supply Regulations'. Traditionally high rotating inertia on the GB system was the key to maintaining frequency stability when there was a disturbance such as a loss of a large generator. The reduced inertia in current GB power system has created a requirement for increasing levels of enhanced response to manage frequency. To ensure system frequency stability under low system inertia the SO requires

- either large volumes of response from conventional thermal generation
- or smaller volumes of rapid response most likely from storage

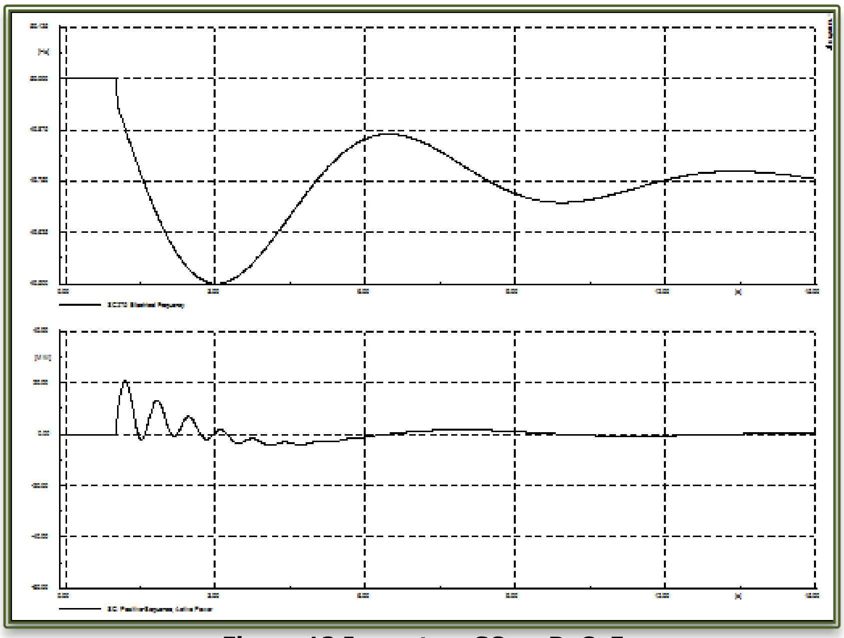


Figure 12 Impact on SC on RoCoF

If insufficient inertia results in a loss of synchronism, it will be apparent within 3 seconds of the initial disturbance. The greater the total inertia of the connected machines, the lower the rate of change of frequency (RoCoF); therefore the application of SCs/H-SCs can aid through improving system inertia.

Figure 12 shows frequency response of a 250MVA SC at Neilston and Cockenzie with minimum frequency reaching at 3 secs. The results will be similar for an H-SC with similar ratings SC or multiple smaller SCs or SCs with higher inertia constants. Phoenix will further study the concept of integrating enhanced response from BESS with inertial response of SCs in a hybrid scheme for future applications in GB network.

3.4.3 Raised Frequency nadir Loss of 1800MW Generation

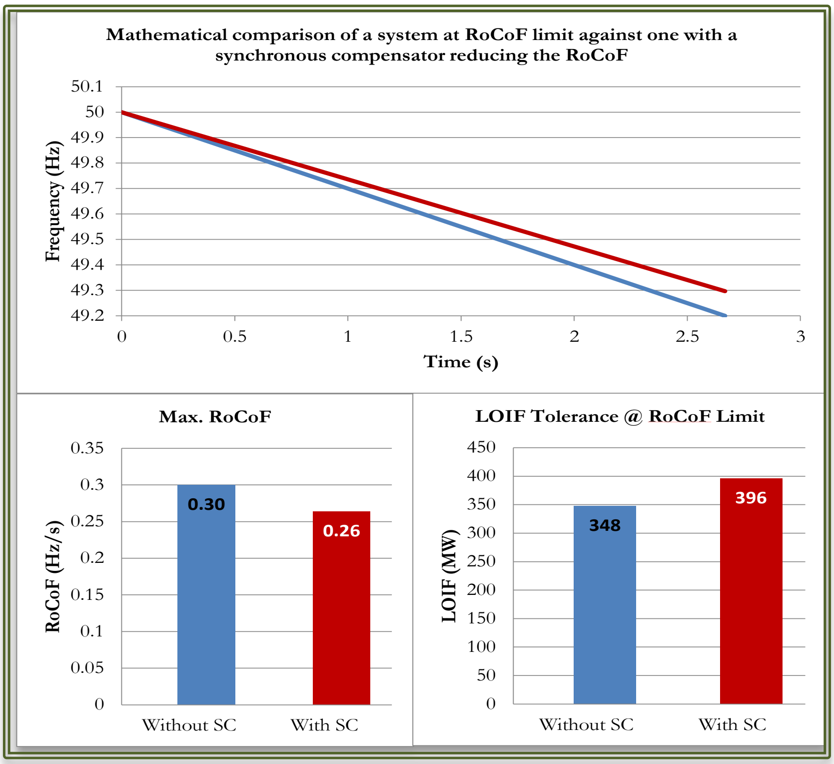


Figure 13 Raised frequency Nadir

The simulation of loss of infeed (LOIF) of 1800 MW on simplistic GB model as shown in Figure 13 produces results which suggest that 2 GVA of SCs, increases the frequency nadir following a loss of in-feed event. This would clearly have the benefit of allowing more time for other services to respond and could contribute to a reduction in the overall active power requirement (and the time for that requirement to be provided) for frequency response. In addition, a system condition that would have originally breached an assumed RoCoF limit (as stated in the SOF) falls within acceptable limits when 2 GVA of SC/H-SC is introduced to the network (Figure 13).

This can mitigate the risk of a cascading tripping event (and the potential for system blackout) as a result of the tripping of RoCoF protection applied to distributed generation, which would clearly exacerbate the initial system disturbance. Finally, the LOIF tolerance for a given scenario is increased due to the presence of 2 GVA of SC by 48MW, minimising the need for system constraints that may be required to secure the system and potentially reducing the costs associated with provision of system security.

3.5. Summary of Financial Benefits

Slow Progression	All Locations
Benefits to 2020 (£m)	£ -
Benefits to 2030 (£m)	£ 42.21
Benefits to 2040 (£m)	£ 116.67
Benefits to 2050 (£m)	£ 296.17

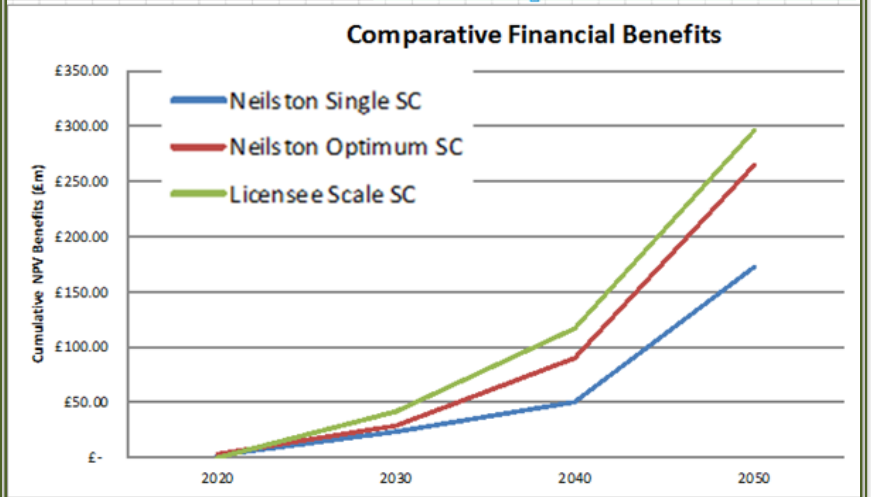


Figure 14 Licensee Scale Financial Benefits Phoenix

The sum of financial benefits (for all the system benefits highlighted in this section) have been calculated in NPV terms on a cumulative basis for 2020, 2030, 2040 and 2050 as described in detail in Appendix A and Appendix B and shown for SP transmission area for slow progression scenario in Figure 14.

It can be concluded from the analysis of financial benefits that having SCs installed across the network, with a combination of both retrofit SCs and new build SCs/H-SCs will have a greater benefit than simply installing SCs at a single location. However the increase in financial benefits is much more significant between having a single SC installed compared to having multiple SCs/H-SCs installed at a single location as compared to having multiple SCs/H-SCs installed across multiple locations. This is shown graphically in Figure 14, where the benefits of having a single SC/H-SC and optimum number of SCs/H-SCs installed at Neilston (the location with the greatest financial benefits in the SPT scenario) is compared with the financial benefits of having SCs/H-SCs across different locations in SP Transmission area.

The SC/H-SC benefits are site and size of installation specific. During the workshops with GB SO it was concluded that there will be number of sites across GB where this solution can be rolled out. For the project GB roll-out benefits calculations it was assumed that there will be 24 additional installations across 9 different sites from 2020-2050. The SP Transmission scale benefits were multiplied by a factor of 3 to conservatively calculate GB wide financial benefits.

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

SPEN is supportive of innovation accelerating GB's transition to a low carbon economy by enabling best practice throughout its transmission system. Enabling roll-out of SCs and innovative H-SCs in GB through project Phoenix will help facilitate the Carbon Plan by enhancing network strength and stability to ensure renewable energy sources can be securely accommodated and fully utilised. SCs and H-SCs are complementary technologies along with distributed and intermittent renewable generation offering essential network services such as inertia, SCL and dynamic voltage control to a lighter weaker AC system.

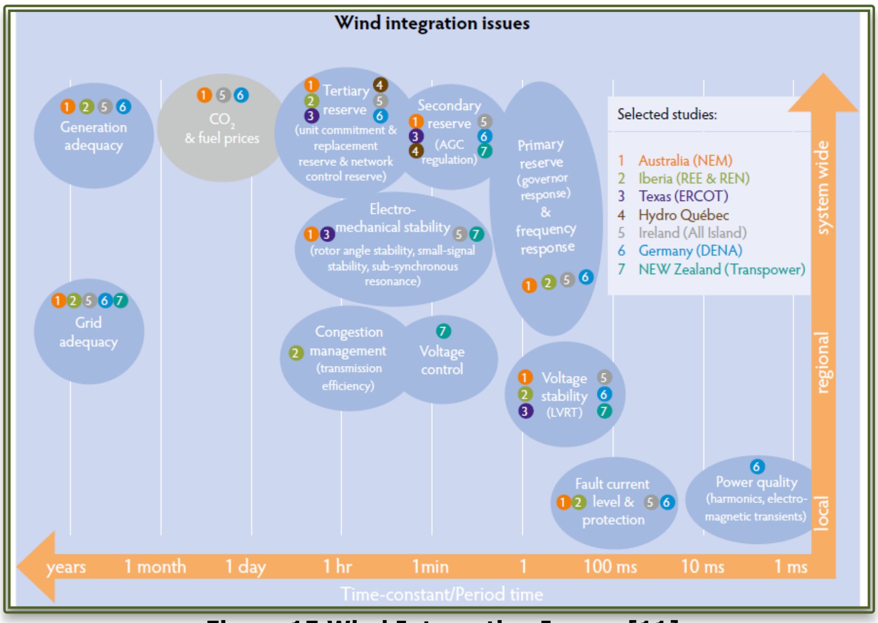


Figure 15 Wind Integration Issues [11]

The current energy policies indicate increased levels of renewable generation are required to meet the GB low carbon targets. Introducing additional reactive power sources such as SCs/H-SCs can help deal with the challenges associated with integrating more renewable generation as highlighted in Figure 15. SCs/H-SCs are non-generating plants that provide voltage support, inertia and SCL without any emissions associated with fossil power generation sources and at lower capital cost and greatly reduced footprint than large scale generation plants.

"All Island Facilitation of Renewables Studies" recommended 60-80% was the penetration limit identified for inertia less generation in systems which are frequency islands or weakly coupled like Ireland or GB. Figure 16 illustrates the findings, indicating the allowable operational range as a green and yellow area at the left side of the diagram. The figure indicates: left area (green): as no relevant technical issues and lower right area (red): technical issues jeopardising stable system operation. SCs/H-SCs can contribute to the required inertia to help enable GB to move to a system where higher percentage of energy demand is met by clean, renewable generation. As significant quantities of conventional generation providing primary reserve are displaced, the financial aspects of securing further reserve will become of concern for GB SO. The displacement of synchronous generation by asynchronous renewable generation has reduced the GB system inertia which in turn has increased the requirement of fast frequency response and increased the RoCoF following disturbances.

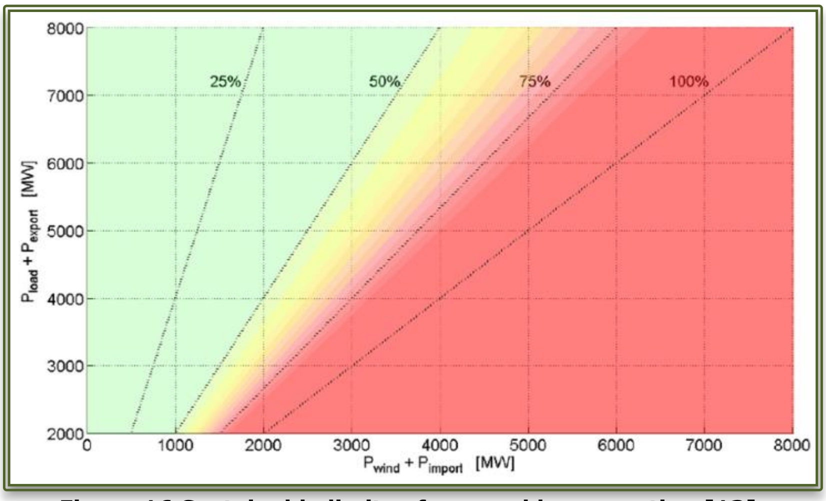


Figure 16 Sustainable limits of renewable generation [13]

However closing down conventional generators has also decreased the selection of plants capable of delivering primary frequency response. In some countries, the increase in asynchronous renewable generation has led to a requirement for minimum "must run" synchronous generation. The deployment of SCs in Denmark helped reduce the "must run" costs of thermal generation (separate from active power market) by €20m per year [14].

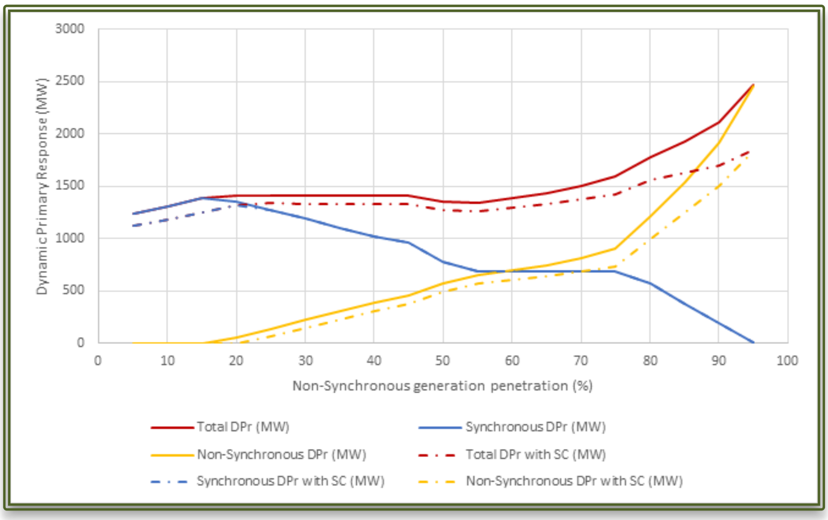


Figure 17 Offset in levels of Primary Response by SC

Studies undertaken by DTU illustrates the impact of a large-scale wind farm penetration on the frequency response of Western Danish power system and the effect of SC in enhancing frequency stability [15]. Figure 17 validates the results of the paper with simulation on GB system which highlights the offset of primary response that can be realised with increased levels of synchronous compensation as levels of asynchronous generation increase up to 100%. Furthermore, it suggests that the cost of providing additional response, and any associated curtailment requirements, will be reduced by the introduction of synchronous compensation.

In conclusion a successful demonstration of H-SC technology through project Phoenix will help meet GB's low carbon targets by addressing wind integration issues highlighted in Figure 14:

- **Boosting system inertia** to ensure the stability of the grid and limit the RoCoF (df/dt). Higher system inertia reduces the risk of a large generation infeed or load loss triggering cascading losses of large amounts of embedded generation due to their RoCoF protection relays.
- **Increasing system SCL** improving efficiency of interconnectors and mitigating the risk of failure of protection systems.
- **Improving power quality**

- **Providing dynamic voltage control** increasing power transfer capabilities of constrained boundaries in transmission circuits and enable more renewable generation to be connected to the network.
- **Provide similar services as synchronous generation** with much lower capital investment and reduced footprint

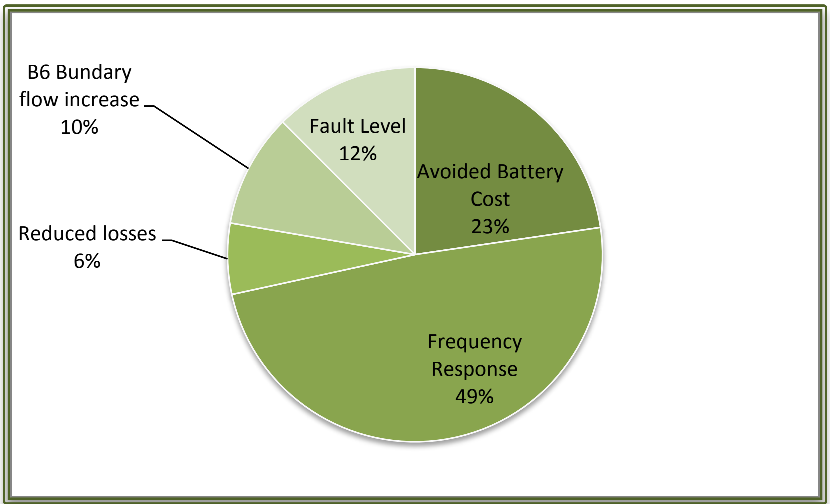


Figure 18 Percentage Breakdown of Phoenix benefits

The non-discounted financial benefits have been calculated for multiple SCs/H-SCs across GB for each benefit category and across a 30 year investment period (2020-2050). In NPV terms the cumulative financial benefits of GB-wide roll-out of SCs/H-SCs for slow progression scenario in year 2050 is £857m. The % contribution of each of the benefit categories to the overall financial benefits is presented in Figure 18 below for SP Transmission area.

The utilisation of SCs/H-SCs will have substantial environmental benefits for GB customers as they offer an economical replacement for the stability and security offered by large conventional synchronous generators without the carbon footprint associated with fossil fuels (NB: SCs do not contribute to MW generation) and large scale plant installations. SCs/H-SCs enable more renewable sources to be connected to the network as shown in Figure 17. In conclusion, SCs/H-SCs can help combat climate change by aiding more renewable energy integration while maintaining security and stability of the GB transmission network.

(b) Provides value for money to gas/electricity distribution/transmission Customers

The roll-out of SCs/H-SCs in GB system enabled by project Phoenix will deliver significant financial benefits to TOs, DNOs, OFTOs, SO and ultimately to GB customers by (Appendix B). Phoenix will reduce the constraint payments by increasing the availability of the network to generators, through increasing the active power transfer capability of the existing transmission network. It will also potentially offset costs in frequency reserve market by decreasing the dependence on "must-run" requirements of synchronous generation. The report also contains the breakdown of costs to manage constraints for the financial year 2015/16 and illustrates that £91.83 million was spent on constraining wind farms alone [16]. This is obviously a major problem in Scotland where installed wind generation capacity is significantly more than the demand, thus improving transfer capability across B6 and B4 boundaries will help reduce constraint costs paid to wind farms. Initial studies suggest the cumulative capacity released by deployment of SCs/H-SCs across SP Transmission area in RIIO T2 and T3 in year 2050 is 887 MW.

SPEN will follow SPTs procurement and legal policies to ensure contractual agreements between partners are in place, while ensuring established processes are followed and project milestone payments are aligned with project plan and SDRCs. A description and breakdown project costs have been devised is provided in Table 2.

Table 2 Breakdown of project costs by work packages and work streams (£k)

[redacted]

Labour Costs

The labour costs are the combined labour costs for SPEN and NGET, and have been built using a bottom-up approach by estimating the man-day requirements for each individual task within the project as shown in Table 3. A PM will be assigned within SPEN and NGET; each responsible for managing the day-to-day activities, liaising with different business areas and personnel, monitoring and reporting progress within their parent company. The SPEN PM will also have overall responsibility for leading the project, including managing the overall project programme, budget, and reporting. In managing innovation projects such as this, input is required from various areas of the businesses at various times throughout the project (e.g. engineering design, system planning, and regulation/commercial, finance) to assist the overall project delivery. As such, this additional resource has been combined into one "support engineer" for both project partners.

Table 3 Labour Costs in FTE terms

	SPEN	NGET
Dedicated Project Manager	1 FTE	0.9 FTE
Combined Project Support	1.2 FTE	1.2 FTE
Travel & Expenses (Knowledge Dissemination)	£200,000	

Technical University of Denmark (DTU) and University of Strathclyde (UoS)

A number of meetings have been held with both institutions to discuss and determine their roles within the project and subsequently two academic partners were chosen based on experience of similar and relevant study in the subject field, and their commitment to support the project. In order to meet the needs of the project, each partner has submitted their anticipated costs based on the required resources anticipated delivering the project; these are outlined in Table 4:

Table 4 Contractor Costs in FTE Terms

	DTU	UoS
Senior Academic Staff	0.13 FTE	0.13 FTE
PhD Research Associate	1.5 FTE	1 FTE
[redacted]		

Contractor

The contractor costs are provided as a 'turnkey' solution, with costs associated to the major project areas rather than resource allocation. For the purposes of this submission, the civil works and materials & equipment costs have been categorised as equipment, with the remaining costs categorised as contractor and extrapolated across the work packages. The "contractor" costs therefore encompass PM, detailed design, engineering, installation and commissioning.

Furthermore, the manufacturer has committed to contributing £1.95m, largely related to R&D resources, as set out below:

- £373k R&D specialists in project
- £321k Utilisation of ABBs RTDS facilities for offline testing
- £146k SC manufacturer financial contribution to the project
- £1,114k Through ABB's deployment of resource and equipment we expect to recover operational costs and overhead only - this equates to following in Kind Contribution

Additionally ABB will be incurring costs for all the unquantifiable risks involved in the delivery stage of a large scale transmission infrastructure turnkey solution such as

- Delays on site and/or transport of equipment from outside the UK
- Additional site cooling requirements depending on the type of transformer used

As the aforementioned factors are not known at the moment, the vendor requests the risks and contingencies involved to be considered as a part of their contribution. A detailed engineering design to be delivered as part of work-package 1 will confirm the final amount of in kind contribution from ABB in addition to the £1.95m already committed to the project.

SPEN site costs

To facilitate the primary asset installation, additional site works are required at the substation to establish a point of connection, which will be the HV turrets of the transformer. These additional site works will be contracted to SPEN-Iberdrola Engineering and Construction (IEC) with a forecasted duration of 40 weeks – 13 weeks for civil works, and 27 weeks for electrical works. The estimated cost includes 1 FTE project manager (for 40 weeks) and a site team of engineers equating to 1.7 FTE. These costs are based on experience of a recent similar sized (MoSC) project but given the level of uncertainty and absence of detailed design work, [redacted]

Market Specialist

[redacted]

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

The demonstration of H-SCs in this novel arrangement with globally innovative hybrid co-ordinated methods will be demonstrated for the 1st time in GB through Phoenix. The aim of the demonstration is to compare and assess performance and benefits of SCs and H-SCs against business accepted solutions such as SVCs, STATCOMs and BESS. The successful demonstration of SC and H-SC at the end of this project along with the innovation and development of commercial and regulatory mechanisms, will provide engineers, planners, service providers, GB TOs and SO the required confidence and incentives to roll-out SCs and H-SCs as retrofits, new-builds and in hybrid combinations as business as usual. Future applications of SCs and H-SCs for improving network security and stability requires technical confidence in the technology, understanding of interactions of complementary technologies in order to maximise benefits, practical assessment of the business case and suitable commercial mechanisms to define ROI, all to be developed throughout the course of this project.

SCs and STATCOMs are well-known, proven technologies. Large synchronous machines have been widely used in the GB, however the utilisation of synchronous machines as compensators has significantly declined in the last two decades. There has been renewed interest in SCs to maintain security and stability in weak AC grid systems with high penetration of renewable asynchronous intermittent generation in countries like Denmark and New Zealand where the levels of renewable generation are comparable to GB and in particular Scotland. In GB few generators such as those at Indian Queens and Cruachan are also sometimes operated in compensator mode. However there is no defined mechanism and/or roadmap to incentivise generation plant owners to repurpose power plants planned for closure as SCs or for TOs to own and operate standalone SCs due to high capital investment and potential maintenance costs. Vendors have redesigned and introduced new improved standalone SCs into the market which claim to have reduced mechanical issues, losses, footprint and better design requiring less maintenance. These standalone SCs with improved performance have never been demonstrated in GB before.

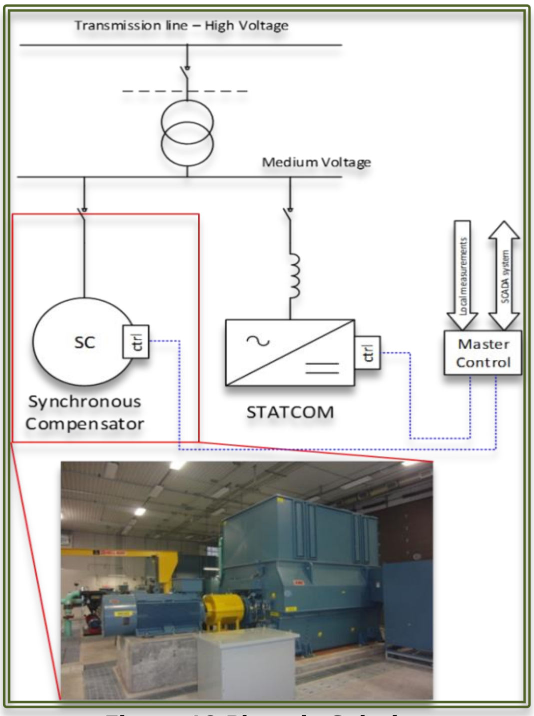


Figure 19 Phoenix Solution

Additionally there are no hybrid control schemes currently in use in GB to maximize benefits through combination of various compensation technologies and reduction in network investment costs. In an ideal world, complementary technologies such as SCs, STATCOMs, BESS should be used together and the benefit of each one could be maximized through hybrid control schemes. Phoenix with support of its project partners aims to develop and demonstrate innovative hybrid control methods through deployment of a Hybrid Synchronous Compensator (H-SC=SC+STATCOM) unit as shown in Figure 19.

The project will also deliver commercial innovation as generation owners; service providers require well-developed commercial mechanisms to be confident that investing in retrofit and/or new-build SC/H-SC is financially viable and generate sufficient ROI. There could be a debate as to whether SCs and H-SCs should be deployed through an open market to tender and/or be owned by TOs. There are some clear regulatory guidelines to be defined to provide all parties the required confidence. Phoenix will help answer these questions thus providing clear guidelines and processes for future roll-out of SCs/H-SCs.

Initial system studies suggest there is a clear requirement of SCs around the GB transmission network in light of diminishing inertia and SCL. However there are no mechanisms or structured roadmap to support and define the appropriate steps for such roll-out of SCs/H-SCs. Phoenix with support from academic project partners, vendors, market experts and most importantly GB SO will create GB roll-out roadmap for SCs/H-SCs. The roadmap will identify strategic locations for installations, define size and constraints, analyse appropriate hybrid control methods and most importantly assess investment vs returns. This research will feed into future SOF, NOA and ETYS through close collaboration with GB SO.

SCs largely address emerging issues rather than immediate concerns. Although the benefits have been demonstrated in countries with similar levels of renewable generation, the technology in this novel hybrid arrangement is globally innovative. As BaU aims to deploy low cost, low risk, proven technologies, H-SCs due <u>to their unproven perceived benefits in GB coupled with the high capital investment required means they cannot be classified as BaU</u>. The risks associated with roll-out SCs and H-SCs warranting NIC funding for this transmission scale demonstration project requiring significant capital investment can be classified into following categories:

- **Technical**
  Although largely SCs are a proven technology, the Hybrid-SC proposed in this project has never been demonstrated or tested on a live network and thus the operational risks and resulting control interactions are unknown. Phoenix will deliver innovation and help mitigate these technical risks by:
    - Developing in-depth understanding of each of combination of the technologies' strengths and weaknesses in hybrid perspective
    - Developing models to support evaluation of the concept in different grid scenarios and investigating effects of different equipment sizes and control strategies
    - Defining innovative control strategies with network values such as system stability, network efficiency, compensation plant efficiency that can be set as objective functions to be maximized with the right relative priorities
    - Testing and evaluating hybrid innovative control strategies and their effect in simulation environment, also with hardware in the loop arrangements
    - Developing and delivering the demonstration to be installed and operated in order to validate models, control strategies and results in a field applications
- **Commercial**
  There are only limited established commercial mechanisms to incentivise ownership and operation of SCs/H-SCs in GB. There is also a reluctance to invest

in and implement this technology without a thorough demonstration and establishment of ROI. The commercial innovation of Phoenix is essential to maximise the chance of a future commercial roll out by minimizing financial risks and will include GB specific:

- Valuation of services, cost of operation and business case
- Change in market dynamics and rules for roll out of competitive tendering
- Analysis of asset owners' financial expectations and requirements
- Assessment of impact on ancillary services markets and other existing contracts

(e) Involvement of other partners and external funding

SPT carried out extensive internal and external stakeholder engagement with other TOs (GB and worldwide), generator owners, service providers and with multiple vendors and has received extremely positive response and generated industry-wide interest in the potential learning outcomes of this NIC project. Phoenix was conceptualised by analysing the key areas for innovation requirements in SPT. SPTs Innovation Strategy review (2014) identified controllability, interoperability, intelligence and commercial mechanisms as key areas for innovation. In light of recent developments in SPT network and overall GB system operation with the closure of Longannet and changing dynamics in network operation Phoenix delivers a solution is deemed to be promising to handle future network challenges.

SPT has engaged extensively with NGET SO from the very early stages of this proposal and intents to partner with GB SO should this bid be successful. Through TO, SO collaboration Phoenix will demonstrate a holistic and unified approach for managing and operating GB transmission network and the learning generated can be fed back into TO, SO system analysis and forecasting studies for short long-term system planning and design. The successful transition of SCs/H-SCs to BaU and knowledge captured will result in financial benefits in the RIIO T2 period for all GB TOs, DNOs and SO. The idea of deploying SCs and H-SCs in RIIO T2 was discussed with the Network Planning and Regulation team. The feasibility of delivery and demonstration of an H-SC in project Phoenix was assessed by SPT's Engineering Design team.

The scope and innovation components were then verified by engaging with GB TOs, [redacted] and San-Diego Gas and Electric (SDG&E). A brief scope was sent to vendors to gauge interest in the supply chain for innovation in Synchronous Compensators. Major suppliers including ABB, Siemens and GE proved willing to participate in the project and offered help in identifying key deliverables of the project. ABB was chosen to deliver the innovative H-SC and hybrid control methods to be demonstrated in project Phoenix. ABB will also contribute £1.95m to the project through discounted equipment costs, testing facilities and free R&D resources. GB commercial experts; [redacted] Phoenix has a large component of research in it to analyse deployment of SCs/H-SCs in GB rollout scale. We have commitment from Technical University of Denmark (DTU) to conduct the component level studies and The University of

Strathclyde (UoS) to perform the system level studies for GB system as a part of the project. The details of project and partner selection are described in Appendix D.

(f) Relevance and timing

System Operability Framework, Future Energy Scenarios and UK Carbon Plan

Phoenix addresses the immediate problem that TOs, SO, DNOs and OFTOs are facing of facilitating the transition to a low carbon future whilst extracting greater value for customers by optimising and enhancing the usage of existing network and infrastructure. If GB is to meet its carbon reduction targets, the percentage of low carbon generation in the total generation mix needs to increase considerably. To accommodate an increasing penetration of low carbon generation it is necessary that system operability is improved. System operability is the ability to maintain system stability, security and protect the network infrastructure. The low carbon targets need to be met in a safe, reliable, economical and sustainable manner. This is challenging, as the system becomes more dynamic with reduced inertia, short-circuit level and intermittent generation. SCs can deliver huge network benefits by improving the stability and security of the GB system, and greatly improve network performance acting as a complementary technology to other innovative technologies in an H-SC mode.

The timing of Phoenix is critical with Scotland's largest thermal generation plant closing in March 2016 and the imminent commissioning of the Western Link. There is currently around 2000 MW of wind connected and 3000 MW of synchronous generation (nuclear, pumped storage, CHP, gas, biomass) on the SPT transmission network. If the current projections under different energy scenarios and ten year statement are to be realised the last of synchronous generation in SP Transmission area; Torness and Hunterston B are planned for closure in 2030 and 2023 respectively. Thus by 2030 there could be 9300 MW of wind and only 635 MW of synchronous generation (pumped storage, CHP, gas, biomass) connected to the SPT transmission network [7][6][18].

The aim of having no coal generation by 2025 across GB will result in the loss of over 11 GW of coal generation including Fiddlers Ferry, Cottam and West Burton A. There is also over 9 GW of nuclear generation due for closure by 2035 including Dungeness B (2028), Hartlepool (2024), Heysham 1 (2024) and 2 (2030), Hinkley Point B (2023) and Sizewell B (2035). These synchronous generators offer a great opportunity to be repurposed as SCs and/or replaced by standalone SCs/H-SCs [6][17].

Chapter 8, Future Operability Strategy of the System Operability Framework 2015 (SOF) identifies and highlights the benefits of SCs on the GB network as follows [2]:

"***RoCoF Management:*** *A synchronous compensator will increase the level of system inertia (although the amount of inertia which is contributed is less than when operating at part load) and will limit the rate of change of frequency (df/dt).*

Frequency Management: *The additional inertia from a synchronous compensator may help in frequency management. In addition, certain areas of the network will benefit from a synchronous compensator to ensure the stability of the grid.*

Voltage Management: *The synchronous compensator will provide natural fault infeed to the grid and increases the system strength. Such resource may also be capable of providing limited voltage support subject to some technical limitations.*

Protection System Effectiveness: *The fault infeed contribution from a synchronous compensator increases the system strength.*

Commutation of HVDC Links: *The fault infeed contribution from a synchronous*

GB TO business model and price control reviews

Phoenix will have a direct impact on RIIO T2 planning for GB TOs and SO. The successful demonstration of an H-SC will provide the necessary learning and build confidence for roll-out in future transmission price control reviews. The timing of Phoenix, with respect to planning for RIIO T2, is critical. Planning for RIIO T2 will start mid-way through RIIO T1 (i.e. ~2018-2019). Phoenix aims to successfully prove the concept by the end of 2019 and if successful, standalone SCs will be a viable option for RIIO T2 along with existing SVCs and STATCOMS as a standalone or in combination as a hybrid solution.

This proof of concept project is critical with both Torness and Hunterston nuclear power plants due to be closed by 2030. Both of these plants are owned by EDF, who during our stakeholder engagement suggested they may consider converting these stations into SCs if Phoenix successfully delivers commercial framework to generate a ROI against the capital investment required for the retrofit.

SP Transmission currently requires a faster black start strategy. GB system wide huge payments are being made for maintaining black start capability. These payments come out of customers' energy bills. SCs/H-SCs combined with a gas turbine or a diesel generator in future can play a role in black start strategies and reduce the time and investment required for black start. This has already been proposed by vendors in other countries and the engineering design for extending a standalone SC or an H-SC to accommodate his technical solution is simple and effective. This could potentially result in huge socio-economic benefits.

Technology Readiness Level and Suppliers Engagement

The deployment of SCs in this novel hybrid arrangement will be demonstrated for the 1st time in GB. The aim of the demonstration is to compare and assess performance and benefits of SCs in combination with business accepted solutions such as SVCs and STATCOMs in a hybrid and standalone mode. The concept and need for this demonstration project has been discussed extensively with different suppliers, TOs in GB and Europe. Our partners in this project have a keen interest in the outcomes as it will help the supplier base to evolve their technology and control methods to best suit GB transmission and operation needs. This will also encourage multi-vendor market competition to bring down the capital costs.

Recent international SC digital pilot projects in Denmark, Norway and USA demonstrate the readiness of the technology and supply chain availability. These projects have provided a body of knowledge and practical experience that will be applied in the GB system context in Phoenix. As regulations, practices and economics vary significantly from country to country, whilst the learning outcomes will help in assessing the risks associated with the technology to be demonstrated, for all benefit cases, there is a need to have experience in the GB grid to assess the benefits in the GB environment.

Research outcomes of previous innovation funded projects

There has been significant research and development to address future challenges in GB system. The outcome of the previous innovation projects strongly indicate need for innovation and development of a technical, commercial solution as proposed in project Phoenix to address the underlying problem of lack of inertia and short-circuit level. The link between Phoenix and previous innovation funded projects, such as SCAPP, VISOR and EFCC, is highlighted in Appendix H.

Section 5: Knowledge dissemination

Phoenix will provide valuable learning regarding the design, planning, deployment, control and operation of the world's first H-SC and will define how SC/H-SC can support the future needs of the GB power system. Specifically, the project is anticipated to achieve the following:

1. Verify the capability of SC/H-SC to improve system stability and security of supply and quantify the actual benefits for GB customers;
2. Recommendations on operations and practises for H-SC co-ordination to ensure optimised performance;
3. Inform future decisions regarding potential new commercial frameworks, mechanisms and/or markets necessary to facilitate the rollout of SC/H-SC in GB.

Knowledge generated within Phoenix must be disseminated effectively to a variety of stakeholders to ensure the knowledge generated is shared and considered from a range of perspectives beyond the core project team; this helps ensure that any hidden dependencies, flaws or opportunities can be identified and the maximum benefit can thus be extracted from the knowledge generated. There has been significant interest in this project throughout the proposal preparation stage as is obvious from considerable number of Letters of Support received. It is the responsibility of the Phoenix project team to build on this stakeholder base and keep stakeholders actively engaged throughout the project to ensure all learning and recommendations are disseminated effectively. The dissemination strategy is important for the Phoenix project team to deliver relevant information to the appropriate audience, easily understood and accessible, at the appropriate time in order to capitalise on learning opportunities for all concerned. The stakeholder engagement matrix below depicts the management strategy for the various stakeholder types (Figure 20).

The primary focus of knowledge dissemination will be to share the learning generated by the project with key stakeholders, facilitate the debate regarding the future requirements of the system and the means by which these needs can be met in terms of funding, ownership and operation. Furthermore, the project will study the benefits of deploying the SC and H-SC by drawing comparisons with existing practices and, through the live trial, provide potential owners of SC/H-SC with the technical confidence and commercial readiness as a basis for future investment.

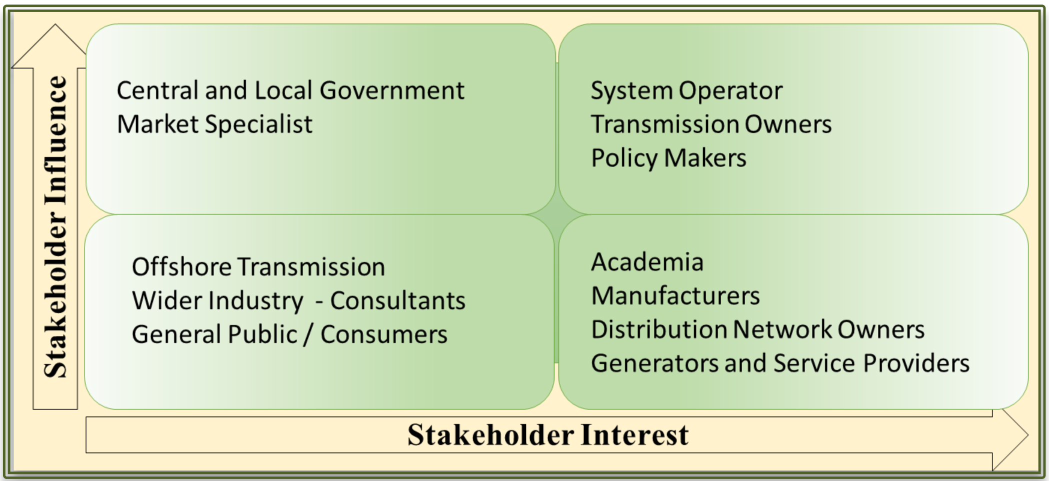


Figure 20 Phoenix Stakeholder Matrix

5.1. Learning generated

The anticipated learning will inform the whole industry of the role SC/H-SC may play in providing critical grid support services. The following tables outline the main learning expected to be generated by the project, how this learning will be generated and who the main beneficiaries are.

Table 5 Technical Learning Generated, Route to Learning, and Beneficiaries

#	Technical Learning Generated	Route to Learning	Beneficiaries
1	Insight into the requirements for the specifications of H-SC hardware and software to ensure optimised performance and co-ordination between the individual components.	WP1: Hybrid-Synchronous Compensator Installation WP4: Hybrid Co-ordinated Control and Integration	A, DNO, G, **M**, OFTO, **SO, TO**
2	New skills, procedures and learning from planning and engineering design of the world's first H-SC.	WP1: Hybrid-Synchronous Compensator Installation	G, M, SO, **TO**
3	New skills, experience and practise recommendations for deployment and commissioning of H-SC including innovative control method.	WP1: Hybrid-Synchronous Compensator Installation WP4: Hybrid Co-ordinated Control and Integration	G, M, SO, **TO**
4	Quantified benefits of H-SC in operation by monitoring performance of SC in standalone mode and H-SC mode for voltage regulation, inertia and short circuit level, identify any unforeseen issues and identify best practice for H-SC co-ordination. H-SC performance output compared with performance of conventional solutions. Assess H-SC over a range of existing and new application areas and disseminate new benefits realised.	WP2: Live Trial WP4: Hybrid Co-ordinated Control and Integration WP 5: Component and System Studies	C, DNO, G, M, OFTO, **SO, TO**
5	Recommendations for future H-SC design and specification requirements by evaluating each H-SC component performance by monitoring output, losses, vibrations, noise levels and oscillation damping.	WP2: Live Trial WP 5: Component and System Studies	A, C, G, **M, SO, TO**
6	New maintenance/operating practices to guide staff when working with SC/H-SC.	WP2: Live Trial	G, M, SO, **TO**
7	Verification of the reliability of H-SC and the degree to which reliability assumptions and models are consistent with this.	WP2: Live Trial WP 5: Component and System Studies	A, **M,** PM, **SO, TO**
8	Transfer times for control room signals and H-SC operating time.	WP2: Live Trial WP4: Hybrid Co-ordinated Control and Integration	M, TO, **SO**
9	Results of testing the hybrid local and wide-area control methods developed during the project.	WP2: Live Trial WP4: Hybrid Co-ordinated Control and Integration	**M, TO, SO**

10	Learning from globally innovative demonstration of new control strategies to maximise different outputs from H-SC with hybrid local/wide-area control methods	WP2: Live Trial WP4: Hybrid Co-ordinated Control and Integration	**A, M,** PM, TO, SO
11	Industry recommendations based on laboratory simulation of control methods verified by control method site deployment and testing.	WP2: Live Trial WP4: Hybrid Co-ordinated Control and Integration	A, C, M, **PM, TO, SO**
12	Verification that SCs are complementary with other types of compensation devices including potentially energy storage and can be operated in H-SC mode to maximise benefits to GB customers. This will make the GB roll-out of SCs and H-SCs more viable.	WP2: Live Trial WP4: Hybrid Co-ordinated Control and Integration WP 5: Component and System Studies	A, C, **M, PM,** TO, SO
13	Developed specification for H-SC model for simulation studies.	WP 5: Component and System Studies	**A,** M, PM, TO, SO
14	System level studies analysing the optimal size, placement and application of SCs and H-SCs at different locations of GB network to directly feed into FES and SOF studies conducted by the SO.	WP 5: Component and System Studies	A, C, M, **PM, TO, SO**
15	Detailed analysis for specific use cases such as the role of SC/H-SC in frequency response and potential constraint of Western HVDC Link in low short circuit level conditions after planned closure of Hunterston in 2023. The research component of this project will result in GB roadmap for future rollout of SCs/H-SCs and will aid RIIO T2 planning for GB TOs and SO.	WP 2: Live Trial WP 5: Component and System Studies	C, DNO, G, M, OFTO, **PM, TO, SO**

Table 6 Commercial Learning Generated, Route to Learning, and Beneficiaries

#	Commercial/Regulatory Learning Generated	Route to Learning	Beneficiaries
1	Robust CBA model for SC/H-SC evaluation, this model will be validated through system studies and will then generate a return of investment value for service providers and will be used as the basis for future contracts and service agreements.	WP3: Commercial Model Development and Roll-Out Recommendations WP 5: Component and System Studies	C, DNO, **G,** M, OFTO, **PM, SO,** TO
2	Evaluate impact of H-SC on existing balancing services markets (e.g. Did H-SC reduce the amount of primary reserve required by the SO?).	WP 2: Live Trial WP3: Commercial Model Development and Roll-Out Recommendations	**C,** G, **PM, SO**
3	Verification of the financial incentives available to H-SC operators to enable the roll out across the GB system (post trial).	WP3: Commercial Model Development and Roll-Out Recommendations	**G,** M, **PM, SO,** TO
4	Potential recommendations for regulatory changes to facilitate large scale roll-out of synchronous compensators	WP3: Commercial Model Development and Roll-Out Recommendations	**DNO,** G, M, PM, **OFTO,** SO, **TO**

Table 7 List of Beneficiaries

Beneficiaries			
A	Academia	OFTO	Offshore Transmission Owners
C	Consumers	PM	Policy Makers
DNO	Distribution Network Owners	SO	System Operator
G	Generator and Ancillary Service Providers	TO	Transmission Owners
M	Manufacturers and Solution Providers		
In the table of learning generated the **bold** type face is used to denote the primary beneficiaries			

5.2. Learning dissemination

The Phoenix dissemination strategy has been developed to ensure robust mechanisms are in place throughout the project to ensure relevant learning and knowledge is identified and shared effectively to key stakeholders and interested parties. In the first six months of Phoenix the project team will:

- Establish a visual identity for Phoenix that allows any dissemination material produced by Phoenix to be immediately recognisable. This identity will also extend to establishing a pack of materials that include other aspects, e.g. identifying the project partners (names/logos) and the funding source;
- Establish a knowledge dissemination coordinator who will refine and update the dissemination strategy throughout the course of the project to maximise the benefits of Phoenix for all stakeholders. They will be responsible for identifying dissemination opportunities, ensuring all dissemination is consistent with the Phoenix identity, liaising with other relevant projects, maintaining an up to date list of stakeholders and establish contacts within them;
- Identify project champions within each relevant department who ensure the project remains visible and relevant to their department. These project champions need not be a part of the core project team;
- Prepare a range of materials (e.g. posters, presentations, leaflets and videos) that clearly define what Phoenix is and what the goals and benefits are. These materials will include different versions; each of which are tailored for audiences with a different level of technical and commercial knowledge;
- Establish an online portal to serve as the hub for conference papers, journals etc.

In order to ensure the stakeholders, remain engaged and informed a number of key activities have been identified that will be conducted and assessed on an annual cycle, including:

- Biannual stakeholder events to notify and educate stakeholders;
- Biannual progress reports and marketing material to be circulated amongst stakeholders;
- Provisions for attendance and presentations at key industry innovation events;
- Continuous improvement of dissemination effectiveness.

Towards the end of the project the focus will shift toward ensuring the captured learning is transferred into plans for subsequent roll-out of SC/H-SC. The knowledge dissemination strategy for Phoenix can be broken down into internal and external activities and informing standards, practices and codes.

5.2.1 Internal awareness and engagement

Internal knowledge dissemination, within each partner business, is a key part of ensuring the proper execution of any innovation project. It helps ensure that the personnel necessary for the projects delivery, who are not a direct part of the innovation team, 'buy in' to the project and the benefits of innovation. It provides staff with the opportunity to identify the benefits and gaps in the new technology from various perspectives. To maximise the benefits, Phoenix will require 'buy in' from many departments within the business, which will require the staff responsible for this day-to-day operation to engage with the innovation. The dissemination coordinator and project champions will be at the heart of this dissemination, using materials prepared by the core project team, and other forums, such as existing internal innovation days and dedicated workshops. This dissemination will allow the exchange of key skills and experiences relevant for understanding Phoenix.

5.2.2 External engagement with the wider industry and academia

The many possible benefits of SC/H-SC mean that their design and operation is an area of great interest for the wider industry and academia, both within GB and internationally. Therefore, as the first live trial of H-SC in the world, Phoenix will be of great interest. Knowledge sharing with other researchers and projects will help ensure that Phoenix considers as many viewpoints as possible to maximise the benefit. Engaging with TOs, SO, DNOs and OFTOs through the planned workshops and existing channels will be an essential part of external knowledge dissemination for Phoenix. The project website will serve a major role in ensuring the visibility of Phoenix and that project results/reports are available to a wide audience. The academic partners will also participate actively in relevant national/international bodies to help maximise the benefit of Phoenix, e.g. EPSRC, HubNet, Cigre/IEEE working groups and related activities. Furthermore, the academic partners will identify new calls for proposals at all levels, e.g. Department of Business, Energy and Industrial Strategy, Horizon 2020, collaborative projects with USA, Denmark and New Zealand, to ensure on-going exploitation of the knowledge generated by Phoenix. The annual Low Carbon Network Innovation (LCNI) conference has been identified as one of the key venues for knowledge dissemination for Phoenix. The Phoenix team will also encourage information exchange with other demonstration projects such as DTU's SCAPP project.

5.2.3 Standards, codes and practices

Electricity code NETS SQSS requires GB TOs to maintain security and stability of supply. The proposed H-SC will provide SCL, improve power quality, dynamic voltage support and system inertia. This however unless proven does pose a risk to the obligations under NETS SQSS and thus requires a proof of concept. Direct interaction with the other GB licensees is vital to help ensure any regulatory recommendations to allow roll-out of SC/H-SCs are applicable to all other GB licensees and service providers. The best way to achieve this is on-going dissemination and interaction through establishment of a dedicated working group.

5.3. IPR

Phoenix will conform to the default intellectual property rights (IPR) arrangements. It is not anticipated that the developments carried out in Phoenix will fall outside IPR arrangements defined in the NIC governance document. SP Energy Networks legal and procurement team have developed a detailed collaboration agreement specifically for

NIC projects based on the NIC governance document. This collaboration agreement is reviewed and updated every year based on changes to the NIC governance document and experience gathered from previous NIC projects.

- **how the project intends to conform to the default IPR arrangements?**

All partners were made aware of the NIC IPR requirements and were provided with a copy of the NIC governance document before initial agreement on partnership in the Phoenix project. All partners in principle agree to the IPR requirements of the governance document; this will be further made legally-binding upon signing of the SPEN NIC collaboration agreement which is created in line with the NIC governance document.

The IPR requirements listed in Schedule 2 of this collaboration agreement is comprehensive and covers all aspects of requirements of default IPR arrangements required for an NIC project. During the contract/collaboration agreement signing process vendors, academics and other partners are advised not to deviate from any of the clauses detailed in the Schedule 2 of the agreement. According to this agreement all foreground IPR and embedded background IPR required to use the relevant foreground IPR is made available royalty free to all network licensees. SPEN also reserves the right to sublicense all relevant foreground IPR and embedded background IPR to project participants.

- **your approach to agree fair and reasonable terms for the future use of any Background IPR and Commercial Products needed for other Licensees to reproduce the Project outcomes.**

SPEN ensures that for relevant foreground IPRs

- All other Network Licensees will have the automatic right to use Relevant Foreground IPR for use within their network royalty-free.
- All other Network Licensees will have the automatic right to use the background IPR, limited to facilitating use of the Relevant Foreground IPR to reproduce the Project outcomes, for use within their network royalty-free.

For example, in project Phoenix all component and system models will be made available by the vendors and academics for use by other network licensees and, within reason, by other vendors to replicate the solutions enabled by Phoenix. This will be required for quicker roll-out of Phoenix solution and to ensure competition in market prices to reduce future costs. The component models for the hybrid co-ordinated control system will be the relevant background IPR to enable roll-out considerations of the control system in future and this will be made available to all network licensees.

For other proprietary commercial products and software of the partner used as a part of the project which the partner lists in the collaboration agreement for use by network licensees following successful completion of the project, will be provided with a set of Terms & Conditions by the partner as an appendix to the collaboration agreement for use beyond the completion of the project and won’t fall into the category of relevant foreground IPR. SPEN reviews the T&Cs and ensures it is fair and facilitates use of the required commercial product beyond the project to reproduce the project outcomes.

Section 6: Project Readiness

6.1. Overview

Phoenix is planned to start in January 2017 and deliver the necessary learning by March 2021, in time to apply the SC/H-SC technology in business-as-usual rollout in the RIIO T2 planning and investment period. The emphasis of the project is on proving SCs standalone and/or in hybrid combination H-SC enhances system stability and security of supply to GB customers. In order to achieve this proof of concept project, an experienced project team comprising experts from SP Transmission, SPEN Network Planning and Regulation, SPEN Engineering Services, NGET SO, other generation companies, ancillary service providers and different vendors with access to the world's leading product ranges and have been selected and involved from pre-proposal stage, and will continue involvement during project delivery.

Level of Protection. The overall level of protection of 5% for cost-overruns for the project is appropriate for Phoenix, in alignment with the NIC default. There are no Direct Benefits expected in the project, so it is not vulnerable to shortfall.

6.2. Project start

The project partners have been selected through extensive stakeholder engagement prior to full proposal submission, as described in Appendix D. The selection takes account of the partners experience in related projects in GB and internationally, the product range offered, and engagement in the collaboration and innovation process. The management team and technical experts involved in the proposal development will provide continuity to commence the project quickly following a positive funding decision. Additionally, SP Transmission Investment Review Group has approved the project for business investment to account for licensee compulsory contribution.

The expertise and leadership in the partnership for Phoenix are key to the timely start of the project. The Iberdrola group and particularly SPEN are leaders in integrating renewable generation into both distribution and transmission network Siemens, GE Grid Solutions and ABB were identified as the global leaders in SC technology, with all 3 in a position to deliver a full turnkey solution.

There is currently no direct precedent for a market for system inertia or SCL as conventionally these have been provided by large synchronous thermal plant as a by-product of their primary generating function. The recent development of enhanced frequency response does cater for faster response however inertial response is essential for the stability of the system and for mitigating the risks of cascading events. It was therefore not only critical to engage with the SO and TO but also commercial experts such as [redacted] integrating them amongst the various operational tools procured by the SO. With both Torness and Hunterston B due to close in the near future, it was critical to engage with EDF to discuss if repurposing the power stations into SCs and/or installing SCs/H-SCs at Hunterston or Neilston. EDF are supportive of project Phoenix. This will be particularly of value to

mitigate any risk of constraint on Western HVDC link post closure of Hunterston nuclear power station.
GB currently has 4GW of interconnector capacity linking the GB system to France, Netherlands, Northern Ireland and Republic of Ireland. The interconnector capacity is set to increase by 7.3 GW to 11.3GW by 2022. Although interconnectors provide much needed capacity during periods of high demand, a higher proportion of asynchronous sources such as wind generators, solar PV and also interconnectors present operational challenges due to lack of inertia, limited SCL and voltage control. The challenges will continue to increase with plans to deploy the additional interconnectors.

Throughout the full submission process, SPT has engaged with academic partners DTU and University of Strathclyde. Both academic partners have a strong track record of innovation and leadership in studies relating to the integration of renewable generation.

SPEN and its selected lead partners have been involved in previous NIC funding rounds, and therefore have a precedent of collaboration and working under the NIC contractual framework. The risk of delays on contractual agreement is therefore minimal. The Steering Committee comprises senior SPEN personnel with decision-making authority in the project to follow through a successful Phoenix outcome to business-as-usual strategy. An Advisory Board brings a wider GB perspective as well as international co-ordination.

SP Transmission engaged with NGET SO right from the outset of the project. As SO, National Grid is keen to collaborate with SPT on this project so that the network licensees can produce a holistic and unified approach to managing and operating the electricity network and use the knowledge generated to feed back into future system analysis and forecasting studies that inform our long-term planning strategies. Phoenix will facilitate TOs and the SO in deploying these new products as assets for improved network management whilst establishing the necessary commercial mechanisms through which they can deliver grid support services, particularly with regards to system inertia, SCL, and voltage and frequency stability management. Phoenix proposes a solution that innovatively combines the capabilities offered by SC with variety of standalone devices into one convenient hybrid solution and develops new control mechanisms to support a number of the above support functions.

Project managers will be assigned from the start of the project by SPEN and the partners to participate in the Project Delivery Team, providing continuity from the proposal stage. Technical personnel will be initially assigned from within the partner engineering teams. Where appropriate, project managers and technical personnel will be hired as the project progresses, but continuity of senior engineers overseeing the project will be maintained. Pen portraits of the key personnel are included in Appendix I.

Phoenix plans to deliver a large scale transmission project. SPT has been careful in its planning during the bid-phase. Extensive system studies were undertaken to identify 3 suitable sites for installation to deliver maximum system benefits.

- Neilston (West Coast, Proximity to Hunterston)
- Longannet (Central, Best suited for B6 boundary constraint management)
- Cockenzie (East Coast)

SPEN engineering planning and design team led by our design manager Fraser Ainslie performed site surveys and detailed costing for civil works and site management costs. The design team also produced design diagrams to assess any impact on civil costs. The details of planned costs are added as appendix in the main submission spreadsheet.

Vendors were asked to provide turnkey solution estimations and they were cross examined by the bid preparation team. Due to lower NPV of demonstration and engineering design challenges Cockenzie was ruled out. Neilston is the preferred site due to proximity to Hunterston and maximum system benefits. Further design work will be carried out in the pre-site installation phase to finalise the engineering design produced at this stage.

6.3. Project plan and delivery structure

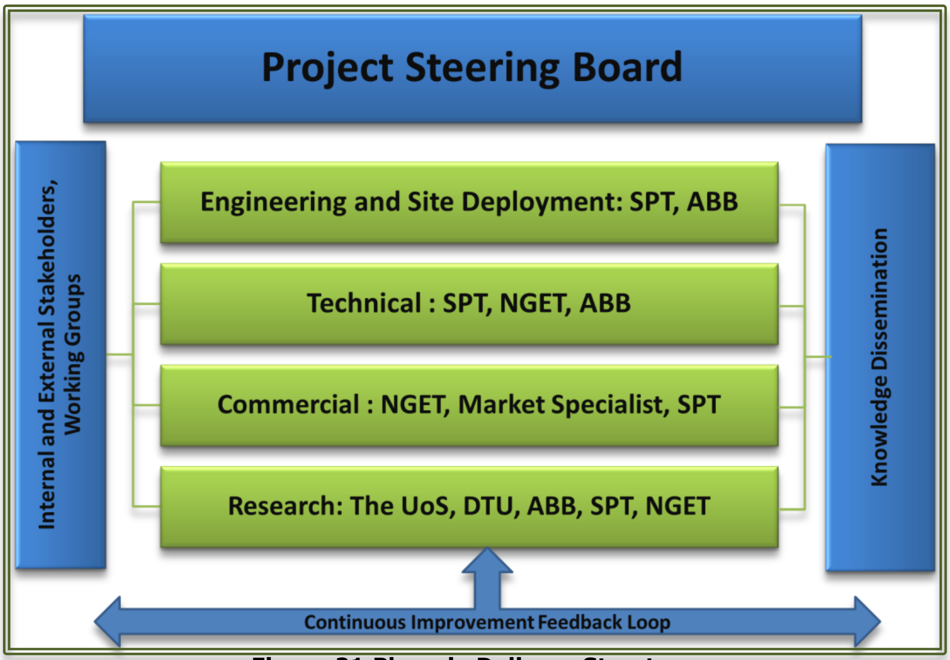


Figure 21 Phoenix Delivery Structure

A project plan is detailed in Appendix E and the project delivery team presented in Figure 21. For acceptable risk, this project has been co-ordinated to largely address emerging issues rather than immediate concerns however if this proof of concept project is delayed the emerging concerns could become immediate concerns. As BaU aims to deploy low cost, low risk, proven technologies, H-SCs due to their unproven nature in GB coupled with the high capital investment required means they cannot be classified as BaU. The project duration is four years and 3 months and includes an extended period of live operation to allow the H-SC technology to be thoroughly tested, analysed and verified. The project also includes a review of future applications of the SCs/H-SCs and feasibility studies. This allows the project team to run desktop system studies to develop a GB roadmap for the deployment of SCs/H-SCs.

The project comprises six work packages:

WP1 Hybrid-Synchronous compensator installation.

- Design and deliver H-SC infrastructure including communications and hybrid control methods.

WP2 Live Trial.

- Component and system performance monitoring of the H-SC. Live operation and testing of hybrid co-ordinated control functionality to provide required network services and maximize system benefits.

WP3 Commercial Model Development and Roll-Out Recommendations.

- TO and SO collaboration to develop commercial mechanisms to financially incentivise future investments by service providers for roll-out of SCs/H-SCs in GB.

WP4 Hybrid Co-ordinated Control & Integration

- Research and development of hybrid co-ordinated control algorithms to maximise benefits of complementary technologies in hybrid constellation at the same or different electrical nodes. Compare contrast control methods with those developed through EFCC project.

WP5 Component and System Studies

- Review of future applications of the SCs/H-SCs and feasibility studies.
- Develop model(s) for desktop system studies for optimal placement and GB roadmap.
- Produce technical and functional specifications taking into account future applications of SCs/H-SCs across GB.

WP6 Knowledge Capture and Dissemination.

- Capture key industry findings and share recommendations to facilitate the GB wide roll out of SCs/H-SCs

Selected key dates and milestones of the project are:

- **Phoenix Kick-off 01/01/2017**
- **WP1 Hybrid-Synchronous compensator installation 31/06/2019**
- **WP2 Live Trial complete 31/03/2021**
- **WP3 Commercial Model Development and Roll-Out Recommendations complete 31/12/2020**
- **WP4 Hybrid Co-ordinated Control & Integration 31/12/2020**
- **WP5 Component and System Studies 31/12/2020**
- **WP6 Knowledge Capture/Dissemination complete 31/03/2021**
- **Close down 31/03/2021**

There are 3 important phases in the project; each will essentially be a key milestone in the project delivery phase

- **Conceptualisation 31/12/2017**
- **Implementation 31/06/2019**
- **Validation 31/03/2021**

6.4. Cost-benefit estimation methodology

Cost benefit estimation was carried out to provide the information presented in Sections 3 and 4, and described in Appendix B. The sources of information used in this evaluation included:

1. System studies including SPT and GB wide analysis of SCs/H-SCs benefits
2. SPEN's internal experience of the business-as-usual cost baseline for major project costs
3. Supplier-provided equipment, conversion and services costs
4. International experience from vendors on trials with SCs conversion/deployment, such as cost, logistics, operational and maintenance analysis
5. Learning from related NIC, NIA and IFI projects
6. SPEN's Transmission Investment plans
7. National Grid's Monthly Balancing Services Summary, SOF, FES, ETYS, Transmission Investment plans, and projections of key planning scenarios

8. Commercial engagement with industry experts such as [redacted]
9. GB SO experts David Phillips (generation compliance), Ed Mellish (commercial mechanisms)
10. Experience of power system expert Steven Nutt from application of SCs in New Zealand
11. ABB's experience with FACTS devices and advanced control algorithms

The slow progression scenario was used generally among all other scenarios in FES, as a conservative assumption for benefits, and the sensitivity to various scenarios tested. The project costs were assessed and validated through SPEN's engagement with suppliers. The extensive engagement described in Appendix D provided information to ensure that the project delivers value for money. The selection of partners was reviewed and approved by the SPEN innovation board and management.

The Cost Benefit Analysis (CBA) is described in Appendix B, which is the result of an extensive process of reviewing anticipated benefits, which vary according to the future scenario and level of uptake of the technology. A CBA model approved for ED1 was updated and used for the assessment, allowing the proposal development team to test the sensitivity assumptions made. The CBA tool is available on request from SPEN. The CBA was developed by SPEN with input and review by the partners (supplier and academic) and by independent consultants. The results were further reviewed within SPEN by the innovation team before a final review and approval by the SPEN Board of Directors through data assurance process.

6.5. Minimising risk of cost over-run

The risks of cost over-run in Phoenix are generally are considered to be modest, and in line with the general expectations for an NIC project. In general, the three main areas of cost over-run risk are related to:

- Unproven deployment of H-SC on the GB system.
- Civil engineering costs for a large-scale infrastructure project
- SPEN are not in control of the ancillary services markets in GB.

Post demonstration of the project the risk of stranded asset has been discussed thoroughly during the project bid preparation stages. Detailed analysis of the system benefits, engagement with GB SO, engagement with a vendor with well-established and known experience in innovation mitigates the risk. Table 8 highlights these risks and planned mitigation measures

Table 8 Mitigation Measures for Cost Over-Run

Risk of Cost Over-Run	Mitigation
On-site implementation of a large scale transmission infrastructure project	1. SPEN engineering design team has done feasibility analysis of all three sites and costs for infrastructure development were created by experienced engineers involved in design work for other SPT infrastructure projects 2. Vendor quoted the turnkey solution price based on previous experience of delivering turnkey solutions and engaged with local substation delivery team for providing detailed quotes

	3. All aspects of site design and works have been assessed and proper margins have been applied to avoid cost-overrun
Unproven hybrid technologies with no live network experience of the control interactions between a SC and a STATCOM	1. Vendor's extensive experience with delivering SCs and FACTS solutions internationally and availability extensive R&D expertise with proven track record in substation control technologies mitigates this risk. 2. Vendor has offered its lab facilities for extensive pre-site testing to avoid any delays on site and minimize risks of failure of trial on site. 3. DTU and UoS will independently assess and test new hybrid models to identify and highlight any issues pre-site trial 4. Technologies will be implemented in parallel the benefits of SC will be proven within the H-SC configuration as well as a standalone technology.
Although the civil infrastructure is satisfactory, civil changes may be required to accommodate the conversion to a SC.	1. Vendors were informed that it is an innovation project and that any cost-overruns above the quoted price after contractual agreements have to be covered by them as a part of the turnkey solution. This reduces the risk on NIC funding.
SPEN are not neither responsible nor a participant of the ancillary services markets in GB.	1. The scope of Phoenix is limited to the benefits of SCs/H-SCs and how best to incentivise the roll out of SCs/H-SCs. 2. The commercial mechanisms to be developed through Phoenix with GB SO will be subject to extensive review and will be ultimately a collaborative decision to determine the best practice for implementation.
Risk of stranded asset post demonstration	1. Extensive system studies have been undertaken prior to Phoenix bid submission and will be pursued during the project to prove the system and financial benefits and to provide the required confidence in roll-out of SC/H-SC technology. 2. Involvement of GB SO in the project will ensure right level of collaboration to make SC/H-SC technology business as usual after proper demonstration.

6.6. Technology & Market Readiness Level

The core of Phoenix relates to demonstrating the benefits provided by SCs/H-SCs. The benefits of H-SCs are yet to proven on the current GB system. There is also key innovation related to incentivising the roll out of H-SCs in GB to improve system stability, security and power quality of the GB network by maximising and complementing benefits of both SC and FACTS technology. The lower Market Readiness Level (MRL) could be seen as the main constraint in future for roll-out of technologies that would offer inertia and SCL as services rather than by products. The enhanced frequency market does address faster frequency response however does not resolve the underlying issue of low inertia. Phoenix does not aim to develop new markets but only commercial mechanisms to provide a ROI for investors who in future may want to roll-out SCs/H-SCs. The outcome of the project may be that SCs/H-SCs should be TO and SO owned. The commercial mechanisms will still provide essential learning for future development of inertia and SCL markets. The project includes a range of Technology Readiness Levels (TRLs) and Market Readiness Levels (MRLs). It may be noted that a H-SC has never been tested in the GB power system so cannot be considered "proven in operational environment" (TRL 9).

Taken as a whole, the TRL of the project (Table 9) is sufficiently high that there is high confidence in a successful installation and valuable learning without risks of safety or loss, while the application of H-SC is not proven for business-as-usual deployment.

Table 9 Technology Readiness Level of Key Phoenix Components

Item	**TRL**
State-of-the art standalone Synchronous Compensators	**8**
STATCOM standalone	**9**
Component simulation model for hybrid synchronous compensators.	**6**
H-SC hybrid control equipment	**7**
H-SC hybrid control algorithms	**5**
Full H-SC equipment and operational integration with external information and control requirements.	**6**

Taken as a whole, the MRL of the project (Table 10) is not sufficient to incentivise the roll out of SCs/H-SCs. There is currently a reactive power market where synchronous generators are obligated to perform. There is no inertia market but there is an ever increasing requirement for the SO to provide more reserve to make up for the lack of inertia on the GB system. NGET's EFCC project is also looking to procure a smaller volume of rapid responses to be used after a system event. This project is required as a result of the lack of inertia. There is currently no market for SCL. There is high confidence that a successful technical demonstration will provide learnings for the development of the required markets to facilitate the GB wide roll out of SCs/H-SCs.

Table 10 Market Readiness Level of Key Phoenix Components

Item	**MRL**
Reactive Power Service Market	**8**
Inertia Service Market	**4**
Short Circuit Level Service Market	**3**

6.7. Verification process for accuracy of information

The overall process for verification of the project involves a number of stages of stakeholder engagement:

- Initial engagement, information exchange on needs, ideas and offering;
- Selection of lead partners and consultants, on basis of quality of solution offered, innovation delivered and engagement with the innovation process
- Workshop on proposed project scope, SPEN stakeholders and suppliers, reviewing and refining the planning for the project.
- Workshops with NGET SO to inform them about project progress and gather feedback

The proposal is drafted by the SPEN team with support from partners. The accuracy of the information was verified as follows:

- Review by SPEN Future Networks Team with partners on the accuracy of the information in the proposal;
- Draft approved by SPEN Future Networks Team for review by wider SPEN stakeholders;
- Review by engineering management stakeholders, particularly in system analysis and Transmission Network Policy;
- Draft reviewed by GB System Operator
- Review and approval by SPEN data assurance board.

Regarding costs, SPEN initially carried out a request for information and costing prior to partner selection. Suppliers were encouraged to propose innovative solutions, and SPEN engaged with the suppliers to discuss and review the project scope. While the pricing was not like-for-like, the process provided some validation of the costs vs content of the offerings. Furthermore, information was compared against similar installations in other countries, although it there is no direct comparison it provided a level of assurance on the final project cost. The benefits were assessed in detail by SPEN. While some consulting support was requested and provided, the cost and projected benefits were derived from SPEN's own experience and records. Assumptions were stated and checked by SPEN's innovation board.

SPEN has engaged extensively with the SPT Business, SO, GB TOs, generation companies, service providers and key vendors during proposal development. The information sources for the project can be categorised under three categories:

1. Technology and innovation;
2. Commercial information;
3. Future needs of GB Transmission Network.

Technology and innovation related information is crucial for NIC projects to ensure the technology and solutions demonstrated have future applications and have not yet been proven in GB. Commercial information related to future of GB Transmission networks are crucial in estimating the possible benefits that Phoenix could deliver after successful completion.

Technology and innovation

- Key sources for technology readiness and innovation components for Phoenix include:
- GB TOs experience in delivering major projects;
- GB SOs experience with markets and system operation
- International SOs/TOs experience in design and deployment of SC
- Suppliers base and projects undertaken and executed internationally and in GB;
- System studies undertaken by the UoS and DTU for bid preparation and in previous innovation projects
- Detailed system studies undertaken by PB power for purpose of this bid

Commercial information

Key sources for commercial information include:

- [redacted]
- RIIO T1 business plans from SPT (internal)
- RIIO T2 estimates from SPT Network Planning and Regulation Team;
- Constraint Payments from MBBS National Grid website [16];
- Irena's report on "Battery storage for renewables, market status and technology outlook" [19]

Future needs of GB transmission network

Key sources for information on the future needs of GB transmission networks include:

- FES, ETYS, SOF, UK Carbon Plan
- VISOR, FITNESS project delivery experience
- EFCC project delivery experience
- SCAPP project
- Previous NIC and NIA projects.

6.8. Impact of policy changes and lower uptake of renewables in the trial area

To the best of SPT's knowledge within the next decade there are no plans for installation of large scale synchronous generation in SPT area. As highlighted in other parts of the bid, the future of generation in SPT area is mostly dependent on renewable asynchronous generation. However even if there is a radical change to this plan this project will still deliver extensive learning in

- System studies highlighting importance of inertia and SCL in the changing generation mix
- Cost benefit analysis of SCs/H-SCs compared to large scale thermal/nuclear power plants
- Hybrid control schemes and applications which will applicable in a variety of scenarios with combination of different technologies
- Commercial learnings and findings regarding new market structures

6.9. Project Delivery and Evaluation Criterion

The project SDRCs are outlined in Section 9. The project delivery team will monthly review progress of the project based on the SDRC. All project risks, issues and learnings will be detailed in the 6 monthly project reports. The project steering board will be informed through internal and external stakeholder events and dedicated steering board meetings. Any risks jeopardising successful delivery of the project will be escalated 1st to steering board and if unresolved to Ofgem project officer. Any major delays (more than 6 months) in key milestone dates will be considered as a high risk stage and following a year from the key milestone date if issues are unresolved and the cost-overrun is greater than 10% the project will be stopped and all stakeholders and Ofgem will be informed as shown in Figure 22.

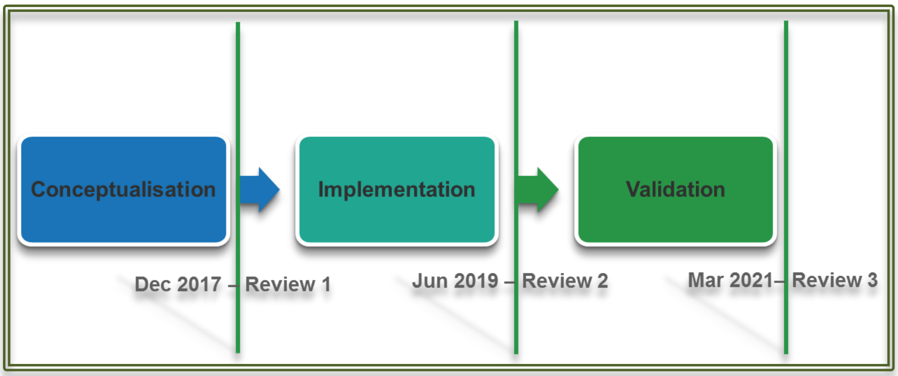


Figure 22 Phoenix Review Process

6.10 Project Partners

The partnership between SPT (TO) and NGET SO will maximize the benefits of the project by developing new and robust commercial mechanisms, using learnings from Phoenix for developing future FES, SOF and ETYS. It will also help influence the RIIO T2 planning mechanisms to support future roll-out of SCs/H-SCs. NGET SO's key role in the project will be to

- Provide technical and compliance guidance for Phoenix
- Provide information and critically assess system studies and integrate key learnings into SOF and Network Options Assessment (NOA0
- Inform, engage and develop in commercial mechanisms development in Phoenix
- Inform and engage in system control methods and model validation for Phoenix

ABB were selected as project partners because the ABB solution proposed for this project is globally innovative with its hybrid SC concept. ABB is a leader in power technologies with proven experience in SCs and FACTS devices. ABB also pledged a substantial contribution to the project of the order of £1.95m through R&D and discounted equipment costs. The key role of ABB in Phoenix

- Develop and deploy hybrid co-ordinate control methods
- Deliver and implement turnkey solution for pilot H-SC solution
- Participate in key system and component level studies

During the literature review in preparation for Phoenix, it became apparent to the project proposal team who the global leaders in SC academic research were. DTU has substantial experience in SC/H-SC modelling/control and world-leading academic knowledge and facilities. DTU started the Synchronous Condensers APPlication in Low Inertia Systems (SCAPP) project in 2014 along with Danish System Operator, Energinet and Siemens. DTU were identified to provide expertise in SC/H-SC modelling/control and inform on SC applications in the Danish system. Partnering with DTU also enables a detailed knowledge transfer between Phoenix and the SCAPP project; ensuring Europe's best practise for SC deployment is integrated into the GB wide roll out. Key role : SC/H-SC component level studies Contribution: £150k

Through Phoenix, the project proposal team planned to initiate a knowledge transfer between DTU and a GB university to ensure the post-project knowledge and expertise would remain in GB. UoS presented the relevant research recently carried out by their department of Electronic and Electrical Engineering. UoS also made a very compelling case for undertaking the GB wide system studies, building on previous innovation projects and integrating SC (modelling and control) into dynamic studies to measure whole system response and benefits on the GB network. University of Strathclyde has a proven track record of excellent research for SPEN. UoS will also aid the Phoenix delivery team in knowledge capturing and dissemination activities including through national and international working groups. Key role: SC/H-SC system level studies. Contribution: £150k

All partners and SPT have strong commitment to participate and deliver in all knowledge dissemination activities and generate maximum learning through extensive engagement with internal and external stakeholders.

Section 7: Regulatory issues

It is not anticipated that the project will require any derogations, exemptions or changes to the regulatory arrangements. SP Transmission will not participate in any ancillary services market and as the SC will produce no usable energy it will not be considered derogation for SP Transmission to own the pilot installation. If any service agreements to come to place it will be led by GB SO with the 3rd party.

Section 8: Customer Impact

It is not expected that Phoenix will have any adverse impact on customers or require access to customers' premises. The nature of this proof of concept project means there is no adverse effect on day to day operation of the grid, the stability and security of supply to customers should improve as a result of the project.

The pilot demonstration is a new build and appropriate planning studies will be undertaken not to affect customer's security of supply.

Section 9: Successful Delivery Reward Criteria (SDRCs)

9.1 Architecture, Design and Availability

SDRC 1	*9.1 Architecture, Design and Engineering feasibility*	**Due Date**	*01/12/2017*
Criterion		**Evidence (WP1.1)**	
SPECIFIC Engineering design and feasibility analysis for pilot H-SC deployment and demonstration. Site selection and planning consent for H-SC installation. Detailed layout, civil designs and approval through system review group for finalising tender for site works and ordering equipment. **MEASURABLE** Design recommendations, procurement and equipment specifications for future installations of SC/H-SCs on GB network. This will prove that SC/H-SC installations can be done under current grid code, connection requirements, environmental consents and technical standards for assets to be connected to the transmission network. **ACHIEVABLE**. Such installations have been successfully executed in Denmark, Germany and parts of the US. The learning outcomes from these pilot installations will help mitigate any risks. **RELEVANT** This is an important step to be followed for mitigating risks of delays on site. This will also minimize risks of faults during operation and/or failure to comply by grid code and technical standards. **TIME-BOUNDED** Completion by Dec 2017 in preparation of on-site installation		1. Report on engineering and design feasibility analysis WP1 01/12/2017 2. Report on environmental studies and life cycle analysis WP1 01/06/2017 3. Report on detailed installation diagrams and site layouts WP1 01/08/2017 4. Report on routine and type testing procedure and results WP1 01/12/2017	

9.2 Financial Value Evaluation and Regulatory Recommendations

SDRC 2	*9.2 Financial Value Evaluation and Regulatory Recommendations*	**Due Date**	31/01/2021
Criterion		**Evidence (WP3)**	
SPECIFIC Develop and demonstrate a commercial framework to financially incentivise services provided by synchronous compensators. Enable service providers to participate in a new market for inertia and other ancillary services provided by SCs. Create recommendations for regulatory considerations for future roll-out of SCs/H-SCs. **MEASURABLE** CBA model for financial evaluation of SC/H-SCs. Resulting return of investment for SC/H-SCs for service providers. Prototype service contract for pilot H-SC demonstration. Recommendations for future roll-out SCs/H-SCs. **ACHIEVABLE** GB system operator and other transmission owners will be involved through working groups and stakeholder engagement mechanisms to help enable different aspects of market and regulatory		1. Cost benefit analysis model for SCs and H-SCs WP3 01/12/2017 2. Report on cost benefit analysis of SCs and H-SCs based on system studies and FES WP3 01/03/2019 3. Report on international application of SCs and benefit analysis WP3 01/06/2019 4. Report on value evaluation of SCs/H-SCs based on pilot installation and performance WP3 01/06/2020	

changes. **RELEVANT** This SDRC will help overcome the challenge of commercialisation of SC/H-SC services. Such methods have already been trialled as a part of EFCC project. The technological solution needs to be supported by changes in market and regulatory framework. **TIME-BOUNDED** Ongoing input in RIIO-T2 planning studies informing business as usual deployment. Completion by Jan 2017.	5. Report on impact of SCs/H-SCs on existing balancing schemes and markets WP3 01/01/2021 6. Report on value analysis from roll out of SCs/H-SCs in GB in future potential sites WP3 01/01/2021 7. Report on regulatory considerations and recommendations for future roll-out of SCs and H-SCs WP3 01/12/2020

9.3 Control Methods Development and Testing

SDRC 3	*9.3 Control Methods Development and Testing*	**Due Date**	Initial 01/03/2020 +revisions
Criterion		**Evidence (WP4)**	
SPECIFIC Innovative control methods to maximize benefits of SC/H-SC installations in different network conditions and different locations across GB. Simulation of co-ordinated control schemes with other network components such as SVCs, STATCOMS and battery storage. Development and on-site testing of hybrid control scheme for H-SC. **MEASURABLE** Innovative control schemes simulation and development and deployment of hybrid co-ordinated control strategies. Recommendations for future installations and matrix to match control method to network requirements. **ACHIEVABLE** Existing control methods have been already trialled as a part of SCAPP project in DTU. Recent development in power electronics, protection and control methods and power system control software should help achieve development of innovative control techniques. Vendor's global experience with control schemes and extensive expertise available mitigates the risk of unproven technology. **RELEVANT** System conditions and need for various services varies from location to location and at different times of the day and season in GB network. The maximum efficiency of SCs and system benefits can be realised through application of different control strategies. **TIME-BOUNDED** Completion by March 2020 for live trial of pilot demonstration and future recommendations		1. Report on methods and functional specifications of hybrid control mechanisms to developed and trailed in pilot demonstration WP4 01/06/2017 2. Report on output of SCAPP project on protection and control of synchronous compensators and simulation results of new control methods WP4 01/06/2018 3. Report on performance of pilot hybrid co-ordinated control system WP4 01/03/2020, 01/03/2021 4. Report on methods and functional specifications of innovative control schemes for future roll-out WP4 01/12/2017 5. Report on FAT test procedure and results of pilot hybrid co-ordinated control system WP4 01/06/2019 6. Report on SAT test procedure and results of	

	pilot hybrid co-ordinated control system WP4 01/10/2019

9.4 Lab Functionality and Component Model Testing

SDRC 4	*9.4 Lab Functionality and Component Model Testing*	**Due Date**	31/12/2018
Criterion		**Evidence (WP5, 5.1)**	
SPECIFIC Testing of different operational scenarios in laboratory environment to generate results to better understand performance of SC/H-SCs under various limits and constraint conditions. Lab testing will test different operational parameters of SC/H-SCs. Use of RTDS to facilitate simulation of technical models and control algorithms. **MEASURABLE** Technical study reports and papers to be reviewed by international experts to cross examine findings of the lab simulations. Development of different prototype models for system studies during and further studies after the completion of this project. Test results of innovative control algorithms. **ACHIEVABLE** Lab simulations and testing are carried out in various innovation projects and regularly at universities will provide the right level of expertise, equipment and facility for this deliverable. Academic partner DTU has already carried out and demonstrated lab simulation results as a part of SCAPP project specifically for SCs. These preliminary results will form the right foundation for further work as a part of project Phoenix. **RELEVANT** Lab testing provides a safe environment to simulate conditions at system and component limits. Hardware in loop testing identifies any problems and issues with the operations and functionality of SC/H-SC. This provides the right tools for future innovations in design and control methods. **TIME-BOUNDED** Completion by December 2018 for live trial of pilot demonstration and GB roadmap development		1. Component model adapted to pilot demonstration and for further system studies WP5 01/12/2017 2. Report on component level studies from SCAPP project and relevance to pilot demonstration and future installations WP5 01/12/2018 3. Report on co-simulation for faster prototyping for new designs and controls WP5 01/12/2017	

9.5 Application of synchronous compensators: GB system studies

SDRC 5	*9.5 Application of synchronous compensators : GB system studies*	**Due Date**	31/12/2020
Criterion		**Evidence (WP5, 5.2)**	
SPECIFIC System studies using SC/H-SC component model and GB system model developed through EFCC project and SOF studies to critically analyse impact of future roll-out of SC/H-SCs in GB network. Case studies for specific system cases on GB network. **MEASURABLE** Roadmap for roll-out of SC/H-SCs on		1. Report on System Studies and Quantification of overall benefits from application of SCs/H-SCs in GB system WP5 01/06/2019 2. Report on case studies on	

GB system. System studies to feed into future FES and SOF report. **ACHIEVABLE** Involvement of two academic partners DTU and University of Strathclyde with the combined experience from SCAPP, EFCC and other research projects conducted on Danish and GB system should feed into achieving this SDRC. **RELEVANT** Research will enable to extrapolate results from the pilot demonstration to future roll-out. This will also provide more options for transmission owners for planning and development of future operability frameworks. System studies will also help validate financial models. **TIME-BOUNDED** Completion by Dec 2020, in preparation for RIIO-T2 planning	system characteristics of SCs/H-SCs in conjunction with other innovative solutions proposed through EFCC and HVDC converters WP5 01/06/2019 3. Report on optimal placement and Capacity evaluation of SCs/H-SCs in GB WP5 01/03/2020 4. GB roadmap for roll-out of SCs/H-SCs WP5 01/12/2020

9.6 Pilot Installation and Operational Trial

SDRC 6	*9.6 Pilot Installation and Operational Trial*	**Due Date**	31/06/2019 (+Revisions)
Criterion		**Evidence (WP1 1.2, WP2 2.4)**	
SPECIFIC On-site installation and commissioning of pilot H-SC demonstration. Civil work and electrical connection of H-SC to the transmission network. **MEASURABLE** Future recommendations for installations: electrical and civil. Commissioning reports and test results to develop site and equipment specifications and technical standards for H-SC deployment. **ACHIEVABLE** Involvement of SP Transmission engineering design and standards department and Iberdrola Engineering and Construction with vast experience in delivery of asset based and civil work projects will mitigate risks for this key deliverable. **RELEVANT** The on-site deployment of the pilot H-SC demonstration will help enable the important validation phase of the project for performance monitoring and financial evaluation. **TIME-BOUNDED** Completion by June 2019, in preparation for live trial and performance monitoring		1. Report on site installation process, details and recommendations for future - Civil WP1 01/03/2019 2. Report on site installation process, details and recommendations for future - Electrical WP1 01/10/2018 3. Report on SAT procedure and test results WP1 01/06/2019 4. Report on electrical layout of H-SC design with protection and control architecture WP1 01/03/2019 5. Report on extended live trial and recommendations for future installations (Revision 01/03/2021)	

9.7 Performance Monitoring

SDRC 7	*9.7 Performance Monitoring*	**Due Date**	31/01/2021 + revisions
Criterion		**Evidence (WP2)**	
SPECIFIC Monitoring of equipment performance such		1. Report on pilot H-SC	

as losses, vibrations and maintenance requirements of rotating parts of the pilot H-SC. condition monitoring of the H-SC output and impact on the regional and wider power system. **MEASURABLE** Detailed reporting and metering of energy consumed during H-SC starting and for over speeding and under speeding. Energy produced by H-SC during steady state operation and system recovery conditions. Record of maintenance requirements and component failures of any and performance in fault conditions. **ACHIEVABLE** There are various monitoring and metering options available in the market to help enable this deliverable. Recent developments in monitoring software and wide are monitoring systems deployed through project VISOR can be used to monitor the impact of pilot H-SC on the transmission network. **RELEVANT** Performance monitoring is vital to the validation phase to test control methods, examine system studies and financial model. **TIME-BOUNDED** Preliminary reports complete by Jan 2021, in preparation for close-down report and development of GB roadmap	installation component level - SC, STATCOM condition monitoring WP2 01/12/2020 2. Process documentation for SC type testing requirements for future installations WP2 01/12/2019 3. Functional specifications for H-SC output monitoring- Methods and User Interface WP2 01/06/2018 4. Functional specification for H-SC wider system operational performance monitoring WP2 01/12/2018 5. Report on pilot H-SC installation output data logging and monitoring WP2 01/01/2021 6. Report on H-SC system impact in local and wider system context - Usage, Control methods and Interactions WP2 01/01/2021

9.8 Knowledge Dissemination

SDRC 8	*9.8 Knowledge Dissemination*	**Due Date**	31/06/2021
Criterion		**Evidence (WP6)**	
SPECIFIC Stakeholder engagement and dissemination of learnings and outcomes of the pilot H-SC demonstration through project **MEASURABLE** Working group findings and reports, technical standards and recommendations reports for innovation and development of SC/H-SCs. Technical paper publications and participation in national and international conferences. Publication of results through dedicated web-page. **ACHIEVABLE** Experience gained from past innovation projects will help with knowledge dissemination in this project. Project partners will play a significant role in dissemination activities. **RELEVANT**. Knowledge dissemination is essential to every NIC project to ensure the learnings are shared in right groups and wider stakeholders. **TIME-BOUNDED** Ongoing annual reporting with completion of Close Down Report marks completion of the project in Mar 2021		1. Report summarizing findings of TO SO working groups WP6 01/12/2019 2. Report on emerging technical standards for synchronous compensators WP6 01/06/2020 3. Project Phoenix Close down report WP6 01/06/2021 4. Project Phoenix six-monthly project progress reports WP6 06/17,12,/17,06/18,12/18, 06/19, 12/19, 06/20, 12/20, 06/21	

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RIIO NIC NETWORK INNOVATION COMPETITION

Appendix A: Benefits Table

KEY

Method[1]	Method name
Method 1	[redacted]
Method 2	[redacted]

All benefits calculated for Slow Progression Scenario

A.1 Electricity NIC – financial benefits

	Cumulative net financial benefit (NPV terms; £m)								
Scale	**Method**	**Method Cost (cumulative over 30 year period)**	**Base Case Cost**	**Benefit**				**Notes**	**Cross-references**
				2020	**2030**	**2040**	**2050**		
Post-trial solution *(individual deployment)*	Method 1	[redacted]	[redacted]					The base case cost includes early network reinforcement expenditure. Benefits highlighted for a H-SC solution (70/70MVAr). The benefits are lower for gone green and higher for consumer power scenario.	**Appendix B, B.5**
	Method 2	[redacted]	[redacted]	-0.12	6.30	14.91	23.96		
Licensee scale *If applicable, indicate the number of relevant sites on the Licensees' network.*	Method 1+2	[redacted]	[redacted]	0	42.21	116.67	296.17	(Number of sites: [redacted] Note: no split between method 1 and method 2 – includes both new build and retrofit SCs/H-SCs. System studies were carried for roll-out scale and the best case scenario was achieved for a combination of retrofit and new build SCs/H-SCs. The optimal case of benefits against capital investment is achieved is through a combination of both solutions. [redacted]	**Appendix B, B.3.4**
GB rollout scale *If applicable, indicate the number of relevant sites on the GB network.*	Method 1+2	[redacted]	[redacted]	0	120.97	332.52	857.40	(Number of sites: Same as Licensee scale multiplied by a factor of 3 – 12 x retrofit and 12 x new build). As system studies and benefits are site specific and have many possible locations for roll-out across GB, especially close to interconnectors. Detailed GB analysis will be an outcome of this project.	**Appendix B, B.3.5**

[1] Note: Method 1 retrofit and Method 2 new build are only applicable for post-trial solution, licensee scale and GB rollout scale have a combination of both retrofit and new build solution.

A.2 Electricity NIC – capacity released

	Cumulative capacity released (MW)								
Scale	**Method**	**Method Cost**	**Base Case Cost**	**Benefit**				**Notes**	**Cross-references**
				2020	**2030**	**2040**	**2050**		
Post-trial solution *(individual deployment)*	Method 1							Capacity released is limited with the trial solution because of the smaller size and with the assumption of closure of Hunterston in 2023. There is no effect on the B6 boundary AC power flow through this trial H-SC solution mostly due to the smaller size of installation.	**Appendix B, B.6**
	Method 2			0	59	59	59		
Licensee scale *If applicable, indicate the number of relevant sites on the Licensees' network.*	Method 1+2			0	665.91	887.88	887.88	Number of sites: [redacted] Note: no split between method 1 and method 2 – includes both new build and retrofit SCs/H-SCs. The capacity released is mostly due to SCL increase and increase of boundary power flow across B6 boundary. It should be noted the models analysed the angular stability as well as voltage stability. The results did not take into account any future network re-enforcements post 2024 planned due to un-surety about the nature and scale of such.	**Appendix B, B.6.3**
GB rollout scale *If applicable, indicate the number of relevant sites on the GB network.*	Method 1+2			0	1,997.73	2,663.63	2,663.63	([redacted]	**Appendix B, B.6.4**

A.3 Electricity NIC – carbon and/or environmental benefits

	Cumulative carbon benefit (tCO_2e)								
Scale	**Method**	**Method Cost**	**Base Case Cost**	**Benefit** 2020	2030	2040	2050	**Notes**	**Cross-references**
Post-trial solution *(individual deployment)*	Method 1			0				[tCO2e associated with losses and reduced constraints] Same assumptions as in above tables	**Appendix B, B.2**
	Method 2			0	16261	27124	30477		
Licensee scale *If applicable, indicate the number of relevant sites on the Licensees' network.*	Method 1+2			0	62,652	127,212	150,817	([redacted]) Note: no split between method 1 and method 2 – includes both new build and retrofit synchronous condensers.	**Appendix B, B.2**
GB rollout scale *If applicable, indicate the number of relevant sites on the GB network.*	Method 1+2			0	187,956	381,637	452,450	([redacted])	**Appendix B, B.2**
If applicable, indicate any environmental benefits which cannot be expressed as tCO2e.		**Post-trial solution:** [Explain any environmental benefits which cannot be expressed as tCO2e] - Smaller footprint than similar sized synchronous generation - Faster installation thus lesser time spent on site - Higher percentage of renewable generation penetration (detailed analysis is required to determine approximate rise in percentage outside the scope and time of the bid-studies)							
		Licensee scale: [Explain any environmental benefits which cannot be expressed as tCO2e] Same as above							
		GB rollout scale: [Explain any environmental benefits which cannot be expressed as tCO2e] Same as above							

Appendix B Cost Benefit Analysis

B.1 Benefits Summary

A comprehensive CBA has been carried out for the Phoenix project. Summary key benefits realised through the project are:

- Reduction in system losses associated with installation of SCs/H-SCs;
- An increase in the B6 boundary flow capability;
- SCL improvements;
- Quicker frequency response,
- Carbon benefits (presented in the CBA analysis as tonnes CO2 equivalent, rather than in £m).

It is to be noted that all benefits highlighted in this section are incremental as the network models used present a scenario w/o any plans of SCs/H-SCs installation. Where applicable, savings have been highlighted against deferred investments.

B.2 Assumptions

The projected benefits for the uptake of SCs/H-SCs on the SP Transmission network have been carried out based on an investment period between 2019 and 2050. The installation rate of SCs has been based on the RIIO investment schedule for GB TOs. The benefits vary subject to the location of the SCs/H-SCs either in Longannet, Cockenzie or Neilston. During the bid phase the benefits for both repurposed power stations and new installations were analysed and presented as Method 1 and Method 2 respectively. Although the project proceeds with a H-SC demonstration with a new SC, the future roll-out of SCs through repurposed power stations is not discarded as it still remains a viable option if proper commercially mechanisms are made available post Phoenix to provide generation owners the confidence to undertake such conversions.

Due to time constraints and lack of suitable models the benefits are presented taking only for SC part of the H-SC solution. It should be noted that these benefits will only be further increased through the H-SC solution especially those related to power quality and voltage control. The CBA is based on the system studies carried out for the project at the three potential locations in SP Transmission area. The GB roll-out benefits have been conservatively extrapolated due to lack of appropriate models and time constraints at this stage. [redacted] The number of SCs is different when there are SCs installed across all locations simultaneously, as described for the Licensee Scale and GB Roll-Out cases.

At a licensee scale (SP Transmission area) the benefits are considered where full potential SC/H-SC uptake takes place at all three locations concurrently. The system studies were run on the basis of [redacted] along with existing SVCs, MSCDNs and FACTS devices on the network. Finally, the overall benefits for the GB roll-out scale are calculated, where SCs/H-SCs may be installed in other locations across GB. As all benefit cases are site-specific it is difficult to study what the actual financial benefits would be for SCs/H-SCs across the whole of the GB network without analysing the whole GB model. Therefore the analysis makes the assumption that the benefits for GB roll-out are equivalent to those at the licensee scale, multiplied by a factor of 3.

The asset costs and O&M costs for both retrofit and new build SCs/H-SCs is set out in Figure 23. The first SC/H-SC installed incurs the highest O&M cost, with the second installation costing proportionally less. After the first two SC installations the O&M cost remains unchanged for each additional SC/H-SC. Despite the new build solution incurring a higher asset cost, this method has a lower O&M cost, as well as an asset life of 40 years, compared with 15 years for retrofit. Due to the 40 year asset life for new build SCs it should be noted that the benefits for both Cockenzie and Neilston extend beyond the period of the analysis which is only 30 years.

[redacted]

Figure 23 Phoenix SC/H-SC cost profile

The projected benefits of the SC uptake are subject to the future characteristics of the network in terms of the amount of conventional thermal generation that will be decommissioned, coupled with the amount of renewable generation that is to be connected in the coming years. These characteristics are defined by National Grid's 2015 Future Energy Scenarios (FES) and have been used in the CBA. The FES have been used as a form of sensitivity analysis. However for the results presented in this report SPEN has recommended Slow Progression is the most realistic FES case and provides the most moderate view on the benefits.

[redacted]

Figure 24 SC/H-SC assumed roll out years

All benefits are based on the installation profile of SCs (H-SCs) for each location. Figure 24 sets out the number of SCs that SPT considers is optimal in terms of benefits (both financial and technical), as well as the years they will be installed. For the benefits of the single H-SC (individual deployment) case, it is assumed that the SC comes in the first year set out in the table below for each location in order to make the results comparable. Figure 24 sets out the equivalent installation dates for the Licensee Scale and GB Roll-Out scenarios assuming [redacted]

The assumptions made for the individual benefit cases are described in the following sub-sections:

B.2.1 Losses

The system studies assessed the effect of SCs/H-SCs on six network scenarios. SCs were added until a target voltage of 1.03pu or higher were achieved. Based on the optimum number of SCs for each scenario the MW loss reduction was calculated. The calculated losses were then converted to MWh, and each of the six network scenarios was given an annual % apportionment subject to each FES. The apportionment for the Slow

Progression scenario is laid out in Figure 25 below. The annual MWh loss reduction and subsequent cost saving was then calculated based on an assumed cost for losses of £54.74/MWh (Energy UK). The loss savings also have a carbon saving associated with the losses which have been calculated separately.

[redacted]

Figure 25 Phoenix System Studies Scenarios

B.2.2 B6 Boundary Flow

The second benefit involves the effect of SCs/H-SCs on increasing the power transfer capability across the B6 boundary. For each of the FES there is an expected growth in the economy-required transfer for the B6 Boundary, which is currently 6520MW with Longannet out of service (including Western Link). This has been laid out in the National Grid Electricity Ten Year Statement (ETYS) and illustrated in Figure 26 below.

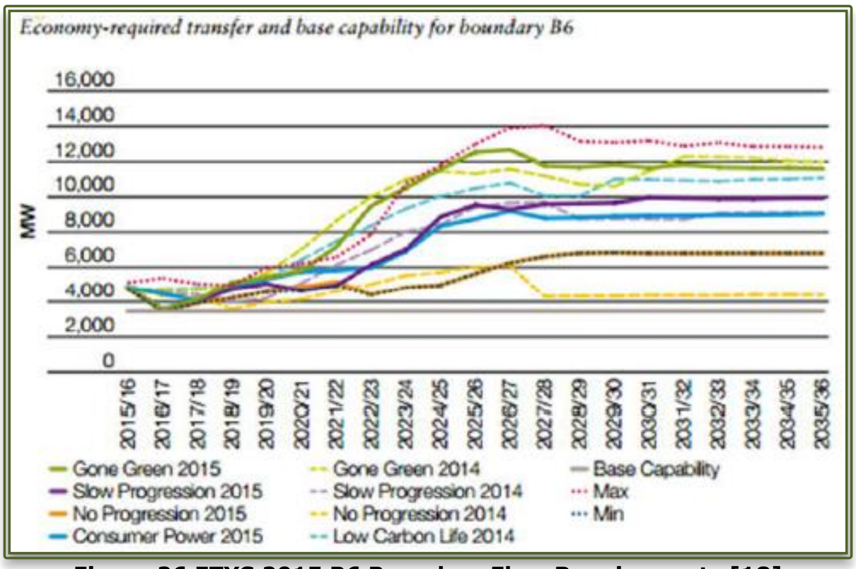


Figure 26 ETYS 2015 B6 Boundary Flow Requirements [18]

The B6 Boundary capability increase has been calculated from the system studies for each additional SC added to the network. The required transfer shortfall between the base capability of the boundary and the projected transfer requirement of the boundary for each FES has been calculated. The same shortfall has been derived using a revised base capability including SCs. The boundary shortfall represents the requirement for additional network reinforcement across the boundary. The inclusion of SCs defers the shortfall across the boundary; hence deferring the requirement for additional network reinforcement. The benefit is then calculated as the difference between the NPV of the network reinforcement investment without SCs and the NPV of the network reinforcement investment being deferred due to SC installation. For the Slow Progression scenario additional network investment has been deferred by 7 years. The assumed cost of Network Reinforcement is presented in Figure 27 below.

[redacted]

Figure 27 Phoenix Assumed Future Transmission Investments

B.2.3 Frequency Response

The benefits for primary frequency response have been split in to two categories; the first is the benefits associated with the market cost of peak active power response (MW), and the second is the avoided asset cost of installing and operating an energy storage device (e.g. battery) that would achieve the same frequency response as SCs.

[redacted]

[redacted]

B.2.4 Short-Circuit Level

The benefits from SCL improvements are based on the increased Short Circuit Level (SCL) at Hunterston due to the installation of SCs/H-SCs. [redacted]

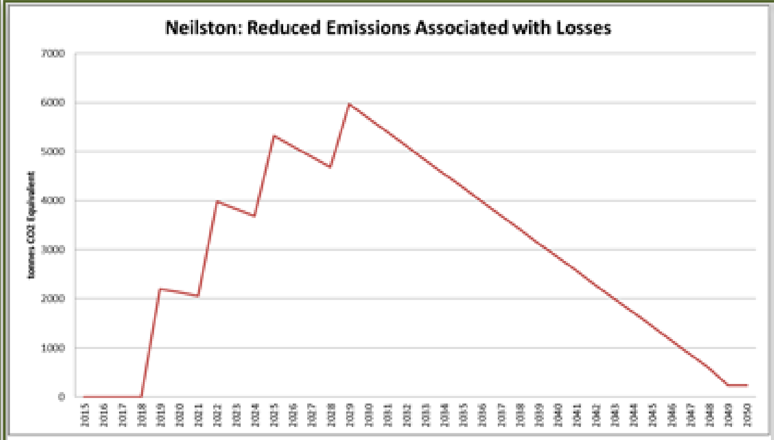
[redacted]

B.2.5 Carbon benefits

The carbon benefits have not been quantified in monetary terms for the CBA but have been presented as tonnes CO2 equivalent. The carbon benefits for optimum SC/H-SC installation at Neilston are shown in Figure 28 below. The shape of the graphs is representative of the installation profile of SCs, where the spikes occur at dates where an SC is installed.

ofgem

RIIO NIC NETWORK INNOVATION COMPETITION



	Cumulative tonnes CO2 Equivalent Saving			
	2020	**2030**	**2040**	**2050**
Longannet	-	26,759	58,256	63,968
Cockenzie	-	25,933	67,174	80,251
Neilston	4,327	49,540	90,781	103,858

Figure 28 Phoenix Carbon Benefits

The losses and constraints relieved in MWh are multiplied by the Electricity GHG conversion factor in tonnes per MWh for each year. The conversion factor is based on the assumption that the power sector should target a reduction to 10g CO2 equivalent/KWh by 2050, which translates to a 12.10 annual reduction in carbon intensity. Hence the carbon savings profile is falling year on year. The figure shows that the highest carbon savings is realised by Neilston, whilst the lowest carbon savings is at Longannet. The results are listed in Figure 28.

B.3 Phoenix Financial Benefits

As described in the assumptions section, the financial benefits depend on the FES as well as the deployment of SCs/H-SCs across the RIIO investment periods. The benefits vary depending on the location of the trial solution, whether it is Longannet, Cockenzie or Neilston. In the results [redacted]

B.3.1 Single SC Deployment at each Location

In the single SC/H-SC deployment case, the benefits have been analysed for each location with only 1 SC/H-SC installed in each case. The non-discounted financial benefits for each benefit category across the 30 year investment period have been calculated. The % contribution of each of the benefit categories to the overall result are presented in Figure 29 below for each location.

[redacted]

Benefits to 2020 (£m)	£	-	£	-	£	2.76
Benefits to 2030 (£m)	£	22.04	£	11.35	£	24.08
Benefits to 2040 (£m)	£	45.94	£	30.44	£	50.00
Benefits to 2050 (£m)	£	151.62	£	136.39	£	172.71

Figure 29 Phoenix single SC/H-SC Financial Benefits (NPV)

[redacted]

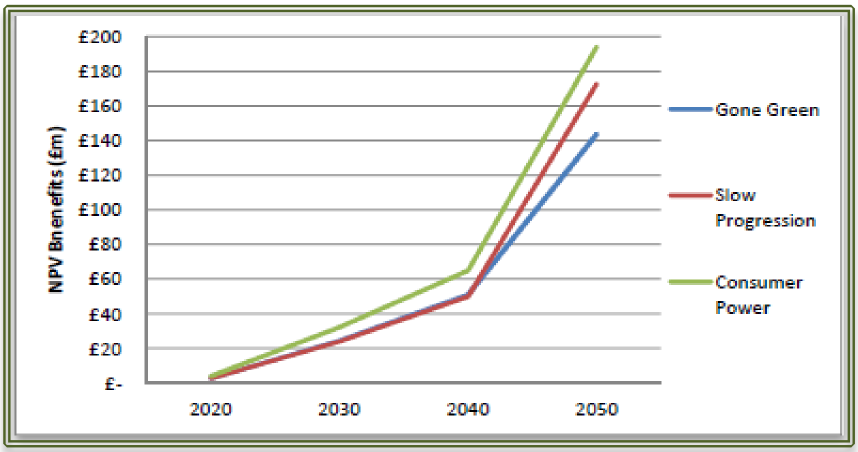
[redacted]

B.3.2 Sensitivity analysis of Single SC/H-SC deployment

As described in the assumptions above, the financial benefits were evaluated based on sensitivity analysis using the National Grid FES for base, low and high scenarios. The results in Figure 30 show sensitivity analysis for the financial benefits of [redacted] with a single SC/H-SC installed, which is the location with the highest benefits.

[redacted]	*Benefits to 2020 (£m)*		*Benefits to 2030 (£m)*		*Benefits to 2040 (£m)*		*Benefits to 2050 £m)*	
Gone Green	£	2.78	£	24.57	£	51.08	£	143.68
Slow Progression	£	2.76	£	24.08	£	50.00	£	172.71
Consumer Power	£	4.20	£	32.21	£	64.98	£	194.09

Figure 30 Phoenix Sensitivity Analysis FES 2015 Scenarios



[redacted]

The benefits are very similar for Gone Green and Slow Progression for the years 2020, 2030 and 2040, as represented in Figure 30. However the long term benefits up to 2050 diverge, where the benefits for Slow Progression (SP) exceed the Gone Green (GG). The benefits for Consumer Power (CP) are consistently higher than both SP and GG for all years. Form this analysis we can establish SP as the base scenario, GG as low and CP as high. No Progression has been discounted from the sensitivity Analysis as it is thought to be an extreme scenario that is not deemed realistic for the future of GB Network.

It may seem counterintuitive to have GG as the low scenario and CP as the high scenario; however this is mainly caused by the benefits realised through increased flow across the B6 Boundary. This benefit for increased flow is determined by the deferral of additional Network Reinforcement due to the increase in boundary capacity from installation of SCs. The required flow across the B6 boundary, given the future characteristics of the network, is given in the 2015 ETYS. The required flow is the greatest in the GG scenario, and becomes less and less through the SP and CP scenarios, down to the lowest requirement in No Progression. Hence the network reinforcement is deferred by longer under the scenarios where there is a lower transfer requirement across the boundary. In the analysis, Gone Green has a deferred investment of 5 years releasing a benefit of £66.8m across the 30 year analysis period. [redacted]

B.3.3 Optimal SC/H-SC deployment at each location

[redacted] The non-discounted financial benefits for each benefit category across the 30 year investment period have been calculated. The % contribution of each of the benefit categories to the overall result are presented in Figure 32 for each location. [redacted]

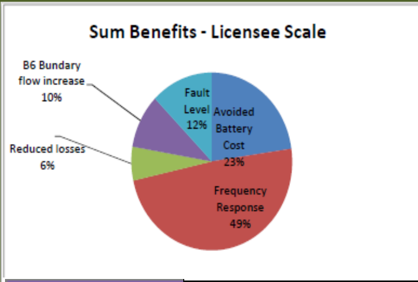
[redacted].

[redacted]

Benefits to 2020 (£m)	£ -	£ -	£ 2.88
Benefits to 2030 (£m)	£ 25.86	£ 11.24	£ 28.70
Benefits to 2040 (£m)	£ 72.56	£ 38.65	£ 90.14
Benefits to 2050 £m)	£ 213.94	£ 163.97	£ 264.74

Figure 32 Phoenix Optimal Placement Financial Benefits (NPV)

B.3.4 Licensee Area Deployment



Slow Progression	All Locations
Benefits to 2020 (£m)	£ -
Benefits to 2030 (£m)	£ 42.21
Benefits to 2040 (£m)	£ 116.67
Benefits to 2050 (£m)	£ 296.17

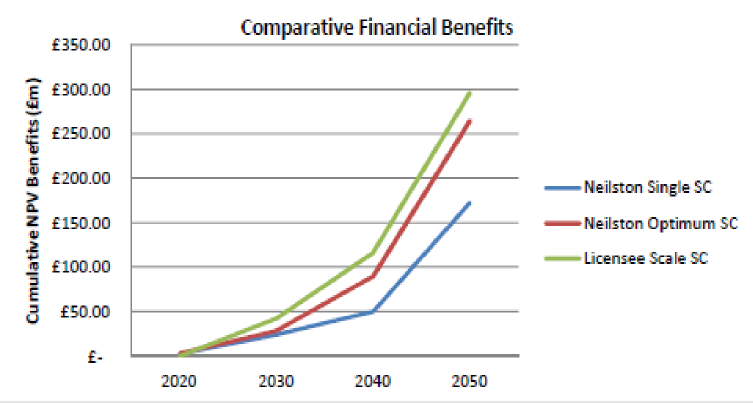


Figure 33 Phoenix Licensee Roll-Out Financial Benefits (NPV)

[redacted] The benefits of avoided BESS cost also increase in this scenario. For the Licensee area scenario SC/H-SC installation is assumed to begin in 2022 at all three locations, Details of installation timescale is laid out in Figure 24. The financial benefits in NPV terms have been calculated on a cumulative basis for 2020, 2030, 2040 and 2050, as with the Single SC/H-SC and optimal deployment options above. [redacted] the first year that the cumulative financial benefits have been calculated for is 2030. These results are set out in Figure 33.

<u>It can be concluded from the analysis of financial benefits that having SC/H-SCs installed across the network, with a combination of both retrofit and new build SC/H-SCs, will have a greater benefit than simply installing SC/H-SCs at a single location.</u> However the increase in financial benefits is much more significant between having a single SC/H-SC installed compared to having multiple SC/H-SCs installed at a single location vs. having multiple SC/H-SCs at a single location and having multiple SC/H-SCs installed across multiple locations. [redacted]

B.3.5 GB Roll-Out of SCs/H-SCs

Slow Progression	All Locations
Benefits to 2020 (£m)	£ -
Benefits to 2030 (£m)	£ 120.97
Benefits to 2040 (£m)	£ 332.52
Benefits to 2050 (£m)	£ 857.40

Figure 34 GB Roll-Out Financial Benefits (NPV)

The benefits for GB scale deployment of SCs are difficult to calculate with a great level of accuracy. This is due to the nature of SC/H-SCs and that the effect they have on the network in terms of benefits is very much site specific and subject to the local conditions of the network. It is also very difficult to predict without suitable model validation how many potential sites that SC/H-SCs could be installed at across GB in the future.

If SC/H-SCs are considered a worthwhile investment post project Phoenix, it is likely there will be a mixture of new build and retrofit SC/H-SCs across the GB network. Hence it is reasonable to assume the financial benefits will have a similar pattern to those in the Licensee scale scenario. A factor of 3 has been applied to the licensee benefits which are assumed reasonable and conservative based on the scale of the GB transmission network compared to SPT Licensee area. The benefits for GB Roll-Out are shown in Figure 34.

B.4 Breakeven Analysis

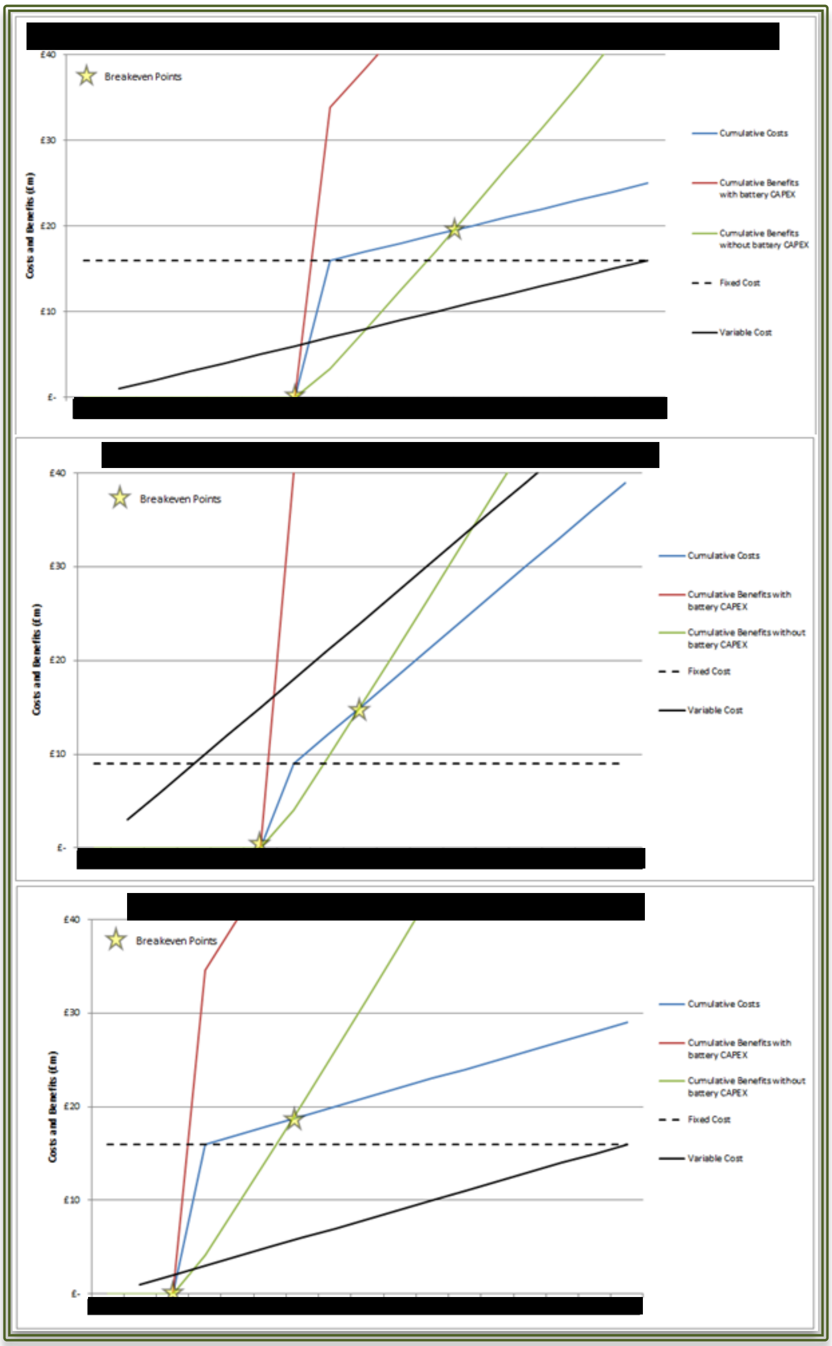


Figure 35 Phoenix Breakeven Analysis

The breakeven point has been established for the case of a single SC trial solution, [redacted]

The key element of the analysis is that in the first year 2023, there is an avoided battery cost [redacted] which almost single-handedly leads to net benefits accruing immediately from year one. All other benefits are relatively minor in comparison for year one. When this avoided battery cost is taken into account there is no concept of a payback period or breakeven point; the cumulative discounted net benefits are positive from the first year of investment.

However, if the avoided battery capex cost is not calculated in net benefits, and only assume the lower figure of £1.25m Open cost for the battery per year from 2024 onwards, there is a completely different outlook, as Figure 35 shows. In this case cumulative discounted net benefits are negative for the first 5 years after the initial investment takes place, and do not turn positive until after 2027, hence the breakeven point in this case would be during this year. The analysis incorporates all of the investment costs before calculating the cumulative net benefits which is why a value for cumulative discounted net benefits above zero determines the breakeven point.

B.5 Trial Solution

The cost of a trial hybrid solution based on a 70 Mar Synchronous Condenser and 70 Mar STATCOM was estimated to be in the region of £10m; with maintenance and operation costs of £0.05m per annum. [redacted] Break-even at this location will be achieved by year 2023, assuming installation in 2019 (i.e. within four years).

[redacted]

[redacted]	[redacted]					
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

[redacted]

B.6 Capacity Released

The installation of SC/H-SCs in project Phoenix will release capacity onto the network through increases in capacity of the B6 boundary, as well as increase in SCL allowing interconnectors to transfer MW at their maximum capacity. The levels of capacity have been calculated for the single SC/H-SC scenario, optimum SC/H-SC, Licensee Scale and GB Roll-Out for the years 2020, 2030, 2040 and 2050.

B.6.1 Single SC/H-SC deployment at each location

	[redacted]		
2020 (MW)	0	0	211
2030 (MW)	197	163	211
2040 (MW)	0	163	211
2050 (MW)	0	163	211

Figure 37 Capacity Release Single Installation

[redacted]

Due to this short asset life this makes a new standalone SC/H-SC more desirable option in terms of capacity released as its benefits are realised for 40 years after initial installation. [redacted]

[redacted]

B.6.2 Optimal SC/H-SC deployment at each location

	[redacted]		
2020 (MW)	0	0	211
2030 (MW)	343	315	575
2040 (MW)	321	345	575
2050 (MW)	0	345	575

Figure 38 Optimal SC/H-SC placement Capacity Release

As described in earlier sections, the optimum SC/H-SC installation scenario has a number of SC/H-SCs installed at each location over a range of years. [redacted]

B.6.3 Licensee area SC/H-SC deployment

	All Locations
2020 (MW)	0
2030 (MW)	666
2040 (MW)	888
2050 (MW)	888

Figure 39 Licensee Roll-Out Capacity Release

[redacted] As the installation rate of SC/H-SCs is staggered, presented in Table 26 above, the total capacity benefits are apportioned as a % of the total number of SC/H-SC installed each year. For example, 3 SC/H-SCs are installed across the 3 locations in 2022; hence the total capacity released of 350 MW for B6 Boundary is only increased by 38%. Across all 3 locations for licensee scale the total capacity released in 2020, 2030, 2040 and 2050 is presented in Figure 39.

B.6.4 GB Roll-Out SC-HSC deployment

	All Locations
2020 (MW)	0
2030 (MW)	1998
2040 (MW)	2664
2050 (MW)	2664

Figure 40 GB Roll-Out Capacity Release

High Level assumptions have been applied in order to calculate both financial benefits and capacity released at the GB Roll-Out Scale. This assumption has to be made due to the lack of information on potential sites across the whole GB Network that could facilitate SC/H-SCs, as well as the site specific benefits of SCs. Due to these reasons a multiplier of 3 has been applied to the Licensee Scale capacity release benefits. The results are presented in Figure 40.

Appendix C: Technical Description

C.1. Standalone Synchronous Compensator

C.1.1 Operating principles

Figure 41 ABB Synchronous Compensator

A synchronous compensator is a device that supports network voltage by providing reactive power compensation and additional short circuit power capacity. Fundamentally, a SC is a synchronous generator operating without a prime mover. Generation/consumption of reactive power is achieved by regulating the excitation current.

An important benefit of a SC is that it contributes to the overall short circuit capacity in the network node where it is installed. This, in turn, improves the chances that equipment connected to the network will be able to "ride through" network fault conditions. A SC is also well suited to operating during overload duty for shorter or longer periods of time. SCs can support the power system voltage during prolonged voltage sags by increasing the network inertia. They can therefore be utilized as VAR compensating devices in situations where voltage instability must be prevented at all cost.

C.1.2 Dynamic properties

As with any synchronous motor/generator, the electrical dynamics of a SC are largely determined by the reactance of the condenser and by the nature of its excitation system. Low transient reactance and comparably high rotor inertia ensure high transient stability margins and excellent fault ride-through capability. SCs can be equipped with a brushless or static excitation system which allows for considerable over-excitation (field forcing) in case of network contingencies. Excitation control is performed by an AVR which is tuned to match the requirements of the specific application.

C.1.3 SC solution for project Phoenix

Phoenix will install a module-based synchronous condenser solutions with active components designed according to project-specific needs. This allows for a flexible product as well as a short time to in-service. The SC modules are compact and fully functional units, with minimal footprint on site and minimal need for external auxiliary support. A complete SC module solution includes equipment such as condenser cooling, lube oil supply, auxiliary power distribution, excitation system, starting equipment and computer simulation models. Therefore the SC solution for project Phoenix is a complete, self-sustained package tailored for specific performance requirements, site conditions and optimal costs. In order to achieve effortless control co-ordination, the vendor will provide condenser control panels with all necessary monitoring, protection and regulation functions configured in accordance with customer requirements.

The main benefits of the SC technology to be installed as a part of Project Phoenix are

- **Additional short circuit power** SC enhances grid strength at connection points.
- **Capability to ride through network disturbances** SCs can provide voltage support to the power grid during prolonged voltage sags.
- **Complete modular package** With customizable modular design, time to in-service for a synchronous condenser can be as low as 12 months.
- **Compact Design** The modular solution ensures the smallest possible footprint, fast installation and minimum assembly on site.
- **Cutting-Edge** technology synchronous condensers are carefully designed for minimum losses, noise levels, vibrations and weights.
- **Uniform and compatible control equipment** that can provide uniform and fully compatible excitation and protection control equipment to simplify control interaction.
- **Long track-record and reliable operation** the technology and its operating principles are well known and the vendor has been developing and manufacturing large synchronous motors and generators for more than a century.
- **Long operating lifetime** some synchronous motors and generators supplied by the vendor are still in operation after more than 40 years.
- **Easy maintenance and life cycle support** Vendor's network of worldwide service centres provides excellent support during the product life cycle. SCs can operate for a long time between inspections and services, and are therefore also suitable for installation in remote areas. The vendor can provide all the tools necessary for maintenance to be performed at the site, as well as good spare parts availability.

C.2. Hybrid Solution

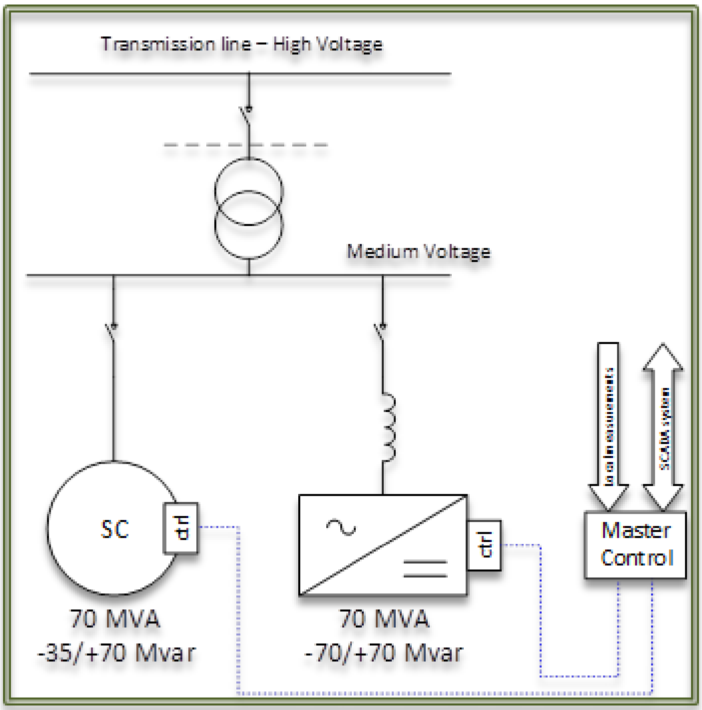


Figure 42 Phoenix trial H-SC Solution

The synchronous compensator hybrid solution (H-SC) to be installed as a part of project Phoenix is represented in Figure 42. In a scenario where the production by renewable generation represents a dominant part of the power portfolio in the network, with the consequential reduction of system inertia and short circuit power, the system operators face increasing challenges in keeping the electric frequency within the allowable deviation limits increasing requirements on spinning reserve capability and response time.

The operation of existing power electronic based equipment such as HVDC link and FACTS devices may become more critical due to the decreasing SCL level. These phenomena will translate into a weaker power system with lower stability margins, with the increased potential to negatively affect industrial and domestic consumers.

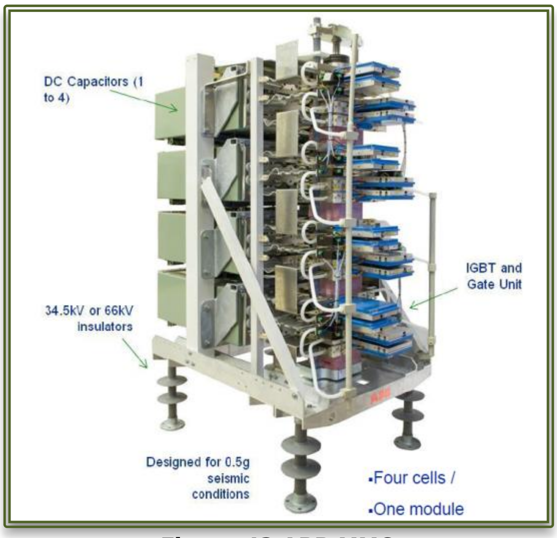


Figure 43 ABB MMC

In order to address these new concerns of decreased system inertia and SCL, technologies such as SCs replacing the rotating machines of the generation plants being decommissioned, or converting synchronous generators into synchronous compensators, is considered today a viable solution. At the same time this technology has limitations for solving other typical transmission needs such as quick control of small and transient voltage fluctuations at the different network busses, active harmonic damping, limitation of flicker phenomena and medium-high frequency oscillation damping, normally solved with FACTS devices as shown in Figure 43 (ABB's Modular Multilevel Converter – MMC – STATCOM module) due to their quicker response time with high controllability.

No single technology solution, solving all rising network challenges seems to be available in the coming years; therefore a future power grid would most probably include both of these complementary technologies such as SCs and power electronic based FACTS devices. The challenge will be to refine each technology, understanding their strengths and weaknesses, possible interaction issues and optimizing the coordination of the two in order to fully utilize synergies. Phoenix proposes a hybrid solution with an integrated system comprising a SC and a STATCOM device.

The plant and electrical configuration is explained in the provided single line diagram. The concept of the hybrid system is seen as very good fit for the Phoenix project which aims to evaluate solutions to address the following main network concerns:

- Boost system inertia;
- Increase the system short circuit level and system total strength;
- Provide dynamic voltage regulation;
- Reactive power injection support to alleviate voltage dip conditions;
- Reactive power absorption to potential overvoltage scenario in light load conditions;
- Enhance the oscillation damping capability;
- Aid in maintaining power quality of the network.

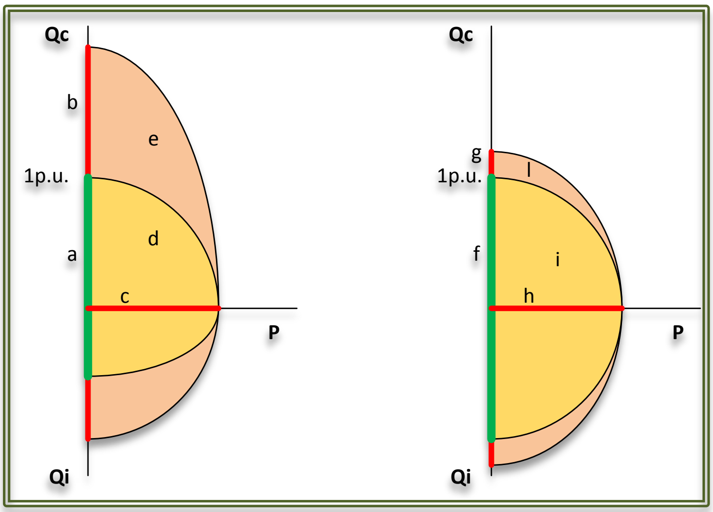


Figure 44 H-SC Characteristics

As illustrated by Figure 44, a simplified and general 2-quadrant PQ representation of the reactive and active power operation, the two technologies have different characteristics.

<u>Synchronous compensator</u>

a) Continuous reactive power compensation – asymmetric for stability reasons

b) High temporary reactive power overload – duration limited by machine thermal conditions

c) Transient active power generation – duration limited by inertia constant, typically 0,5 – 2 sec. Reduced controllability and response time for small signal control.
d) Transient operation region with active and reactive power generation – main constrain is inertia
e) Transient overload operating region with overload – main constrains are inertia and thermal limits

STATCOM

f) Continuous reactive power compensation – symmetric operation (-Q=+Q)
g) Transient reactive power overload – limited by semiconductor thermal conditions
h) Transient active power generation – duration limited by stored energy in capacitors, typically equivalent to an inertia of about 10 – 30 ms. High controllability and fast response.
i) Transient operation region with active and reactive power generation – main constraint is energy stored in DC capacitors
j) Transient overload operating region with overload – main constrains are energy stored in DC capacitors and thermal limits

The two technologies with their particular strengths in the different operating regions are complementary to reach the above mentioned Phoenix objectives and the coordinated operation of the two technologies combined will aim to maximize the strengths of each of them and to mitigate the weaknesses, as explained in Table 11.

Table 11 H-SC solution and Phoenix Objectives

NIC project proposal values	Synchronous compensator	STATCOM
Boost system Inertia	Main contribution, higher stored energy	Limited capability, Inertia emulation (to be proven)
Increase system short circuit level	Main contributor, high overload	Limited capability
Provide dynamic voltage regulation	Support with high overload capability	Main contributor with fast response
Reactive power injection for alleviate voltage dip	Support with high overload capability	Main contributor with fast response
Reactive power absorption at potential overvoltages	Good contribution for low load situations	Fast reaction at fault recovery and switching events
Enhance oscillation damping capability	Main contributor for low frequency oscillations	Main contributor for high frequency oscillations
Aid in maintaining power quality in the network	Contributes with possible overload	Contributes with high controllability and fast response

The SC characterized by a high rotating energy and high short circuit current generation capability, is used as the main contributor to boost the system inertia, increase the system SCL. Its characteristic response time, relatively fast for large disturbances and slower for small signal control, and its specific overload capability, make the SC very suitable to play important role in providing voltage regulation support in severe dips and contributing with the regulations requiring a limited frequency response. The STATCOM device is used as the main contributor for providing fast and highly controllable voltage regulation, also in case of voltage dips. During fault recovery and switching phenomena the STATCOM has the capability to absorb quickly the reactive power needed to maintain the over-voltages within the allowed limits. The STATCOM has also a response time more suitable for solving the power quality concerns, to actively damp harmonics in the power system and voltage fluctuations producing annoying flicker effect for industrial and domestic consumers.

Within the Phoenix scope, it is considered beneficial to investigate and test STATCOM capability to contribute in operating modes where the SC is the main technology, such as the boosting of system inertia, by emulating generator behaviours, with clear limitation on the energy contribution, but with advantages on the speed of response and fine tuning of the output power. The limitations of the STATCOM in providing inertia or enhanced frequency response contribution due to low stored energy in the DC capacitors can be studied in the project, analysing solutions with enhanced energy storage, scanning possible technologies going from a pure STATCOM equipped with only DC capacitors, toward a typical Battery Energy Storage System (BESS). This analysis may be conduct trough simulations at component and system level giving important input to SO and vendors on potential future requirements and technology possibilities.

Important part of the demonstrator is the master control of the hybrid system which will coordinate the operation between the two technologies and assuring the best operation toward the network and system operators. After analysis of the standalone technologies, objective functions can be developed in order to reach optimal operation of the H-SC for fulfilling the wanted results. Examples of possible objective functions may include:

- Minimization of overall H-SC losses
- Maximization of compensation of fast transients
- Maximization of inertia contribution (including possible inertia emulation from STATCOM)
- Maximization of low frequency oscillations damping (eg. inter-area power oscillations)
- Maximization of medium-high frequency oscillations damping (eg. voltage fluctuations)

[redacted]

Figure 45 Hybrid Co-Ordinated Control Example

[redacted]

[redacted]

In Phoenix solution this important role of the master control for the H-SC is assigned to the STATCOM control system since high performance level and flexibility are important requirements for innovation projects where the architecture and the fine tuning of functionalities to be implemented are subject to changes during the project. The ABB proposed hybrid configuration to be delivered for the Phoenix demonstrator will provide insights for:

- Possible future similar plants with the combination of the two technologies installed at the same electrical node.
- Interactions and operation coordination of such technologies installed at different nodes in the network, very likely scenario in the future Power grid asset. This will give important input for a possible future application of the methodology on a wide area control environment.

In order to increase the observability of system contribution from the two technologies used in the proposal hybrid solution, both in a coordinated and in a stand-alone operation, it is suggested to have similar sizes of SC and STATCOM (both up to 70 MVA). The project will analyse the optimal sizing principles in order to give methodologies for choice of future H-SC power rating and optimal sharing between SC and STATCOM. This would of course realize the important learning objectives set by the Phoenix project to future installations of this type of equipment. The Phoenix project represents an opportunity for both the UK and global System Operators to understand the benefits of this type of hybrid approach.

C.3. Network and Engineering Diagrams

Phoenix has undertaken initial engineering design and feasibility assessment to identify three different sites for the installation of the SC and hybrid solution during the project. The three sites are located at strategic points of SP Transmission network as shown in Figure 46: **Neilson (West), Longannet (Central), Cockenzie (East)**. The final choice of site will be based on the **best case trade-off between site installation costs and system benefits** generated along with time to **completion within the time frame of the NIC project**. The vendor has been contracted to deliver a turnkey-solution with site-supervision provided by SPEN contractors. The final design and site selection will be completed as a part of the project delivery. The typical time for pre-site preparation and

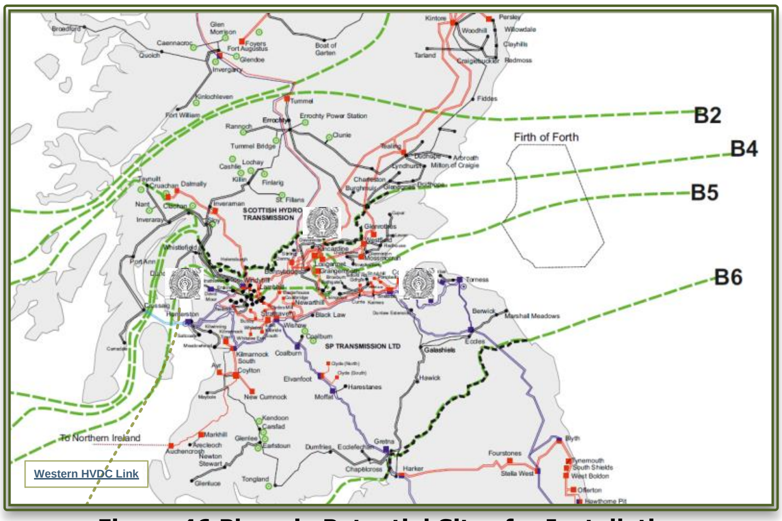


Figure 46 Phoenix Potential Sites for Installation

site installation for such projects are 16-19 months. Typical time spent on site for such installations are 12-14 months. Work package 1 and 2 are designed to complete the engineering design and site installation and site testing. The work will be carried out in the following manner during the 3 phases of the project

- **Conceptualisation**: Detailed engineering design and economic feasibility assessment to ensure that the costs are comparable with the benefits generated through the demonstration enduring best value for money for GB customers. A preliminary civil design and circuit connection diagram is represented in Figure 47. The single diagram showing the electrical components and connection of the Phoenix hybrid solution is represented in Figure 48.
- **Implementation**: SPEN will provide the connection point for the hybrid solution to connect to the transmission network. The vendor will deliver a turnkey solution including
    - Site preparation
    - Foundation
    - Civil works, building
    - System studies
    - Site management
    - Project management
    - Installation & Commissioning
    - Training
    - Maintenance & Service

  SPEN will provide site supervision and access to the vendor for completion of the site works. SPEN will also ensure there are appropriate communication links between the substation and the central control centre with TO SCADA system for remote wide area control of the hybrid synchronous compensator equipment.

- **Validation**: The site acceptance test and performance monitoring of the component interactions between the SC and the STATCOM will generate globally innovative findings and learnings to be disseminated through various stakeholder engagement activities and white paper publications. The GB system operator can control the Phoenix SC solution from system operator control centre thus proving the system benefits of this demonstration. This will be a great leap in assessing future wide-area control methods with complementary technologies on the network and also in dynamic model validation reducing uncertainty in system operation.

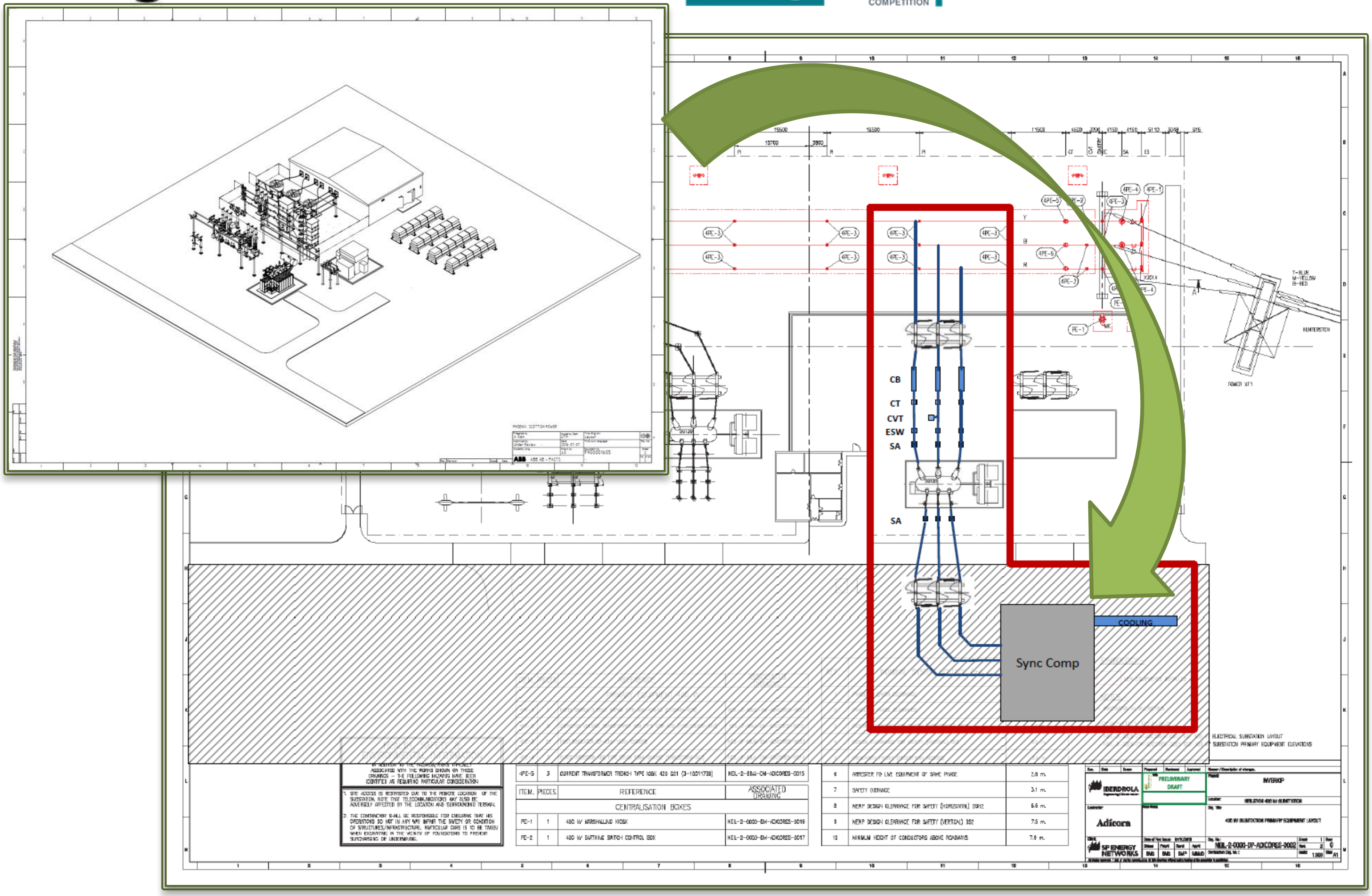


Figure 47 Neilston Site Installation Diagram

[redacted]

Figure 48 Phoenix H-SC installation single line diagram

C.4. System Studies

C.4.1 System Model

The system studies were carried out on a set of Power Factory models, defining the system in extreme conditions for the SPTL network. Seven scenarios were defined, which represent different load and generation states that lead to varying export (or import) from the SP network across the B6 boundary. The boundary conditions are defined by the DC export (via the Western Link HVDC scheme) and the AC export (via 400kV overhead line circuits to Harker; and from Eccles to Stella West and Blyth). The scenarios are summarised in Figure 49.

[redacted]

Figure 49 Phoenix Summer/Winter Scenarios for System Studies

C.4.2 Figure 50 Comparative summary of System Studies in SP Transmission Area

[redacted]

Figure 50 Phoenix System Studies Site Comparison

Appendix D: Project and Partner Selection

D.1. Project Selection

SPT carried out extensive internal and external stakeholder engagement for selecting Phoenix for the NIC 2016. Phoenix was conceptualised by analysing the key areas for innovation requirements in SPT.

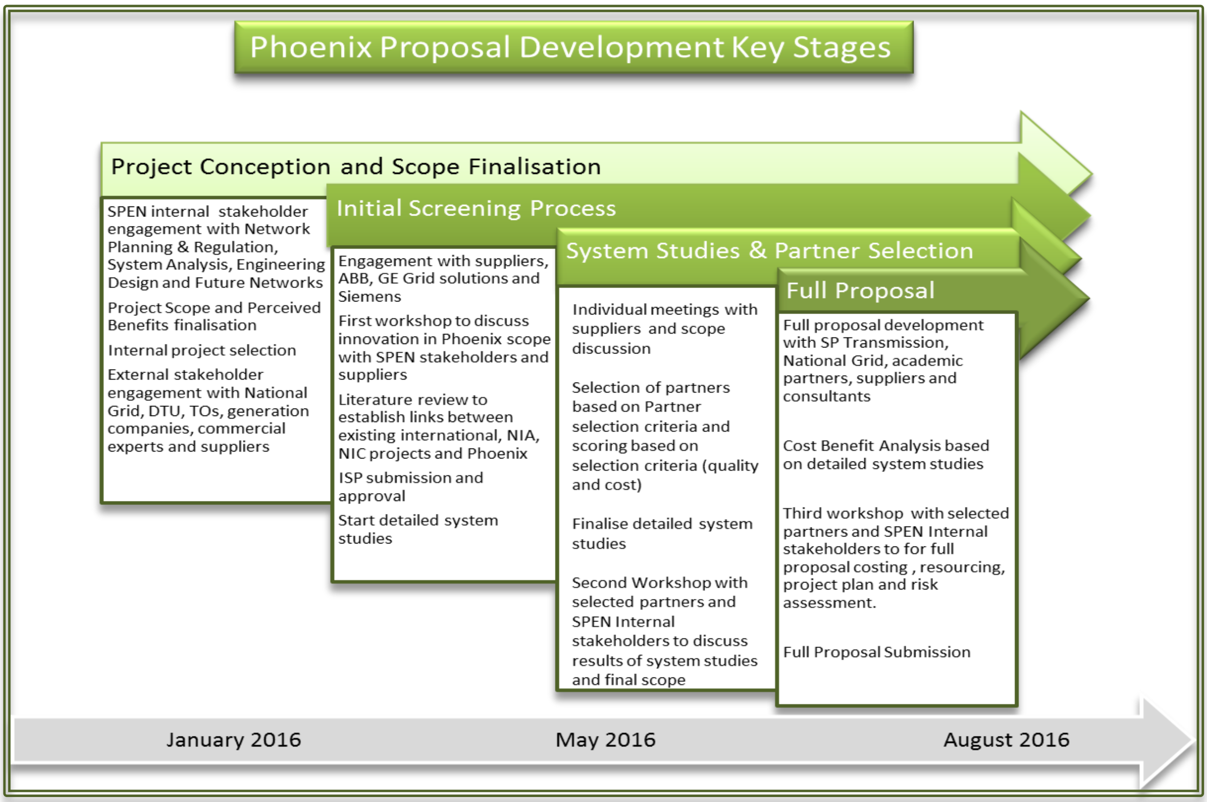


Figure 51 Phoenix Project and Partner Selection

The changing generation mix of the Scottish and wider GB system has created a requirement for innovation to address important system requirements such as inertia and short-circuit level. The displacement of large synchronous generation by smaller, intermittent renewable energy resources has created a need to replace the dynamic voltage control, short circuit level and inertia previously delivered as a by-product of large thermal power stations like Longannet and Cockenzie.

The prospect of undertaking a demonstration project to deploy a SC either by converting a retired power station or by installing a new SC was one of five concepts developed throughout 2015, in preparation for NIC 2016. A two staged internal review process was staged in February 2016 to identify the submissions for NIC 2016. Phoenix was selected as one of two project proposals to go through the ISP stage. Phoenix was selected based on the need of the SPT (and wider GB) network, the experience of resources available and the timing of the project. The internal review process started with SPT's Engineering Services department before being analysed by SPT's Network Planning and Regulation department. The internal review concluded a demonstration was required to gain the necessary experience and quantify the benefits of SCs against the comparatively higher capital cost to enable business-as-usual deployment. It was also identified through engagement with GB SO that commercial mechanisms needed to be developed to financially incentivise SC installations and open the prospect of bidding for future installations to wider market. The timing of the project is critical if Synchronous Compensators are to be rolled out as a TO asset in RIIO T2.The Phoenix proposal team and key SPT stakeholders were identified in January 2016 and the first workshop was held in February 2016. The key SPT stakeholders included representatives of the System Planning and Analysis team and Engineering Design team. The workshop finalised the project scope and the timeline for the project. Phoenix was submitted for Initial Screening Process (ISP) in April 2016 and after being successful in the screening process was developed further into a full proposal.

[redacted]

[redacted]

With no plans to build large scale synchronous generation on the SPT network in the near future, a short term SC conversion was not seen as the optimum solution. To ensure longevity of the SC/H-SC, a new installation capable of delivering 40 years of benefits (albeit of a smaller size which can be scaled for future installations) was seen as the best option. 3 sites Neilston, Longannet and Cockenzie were identified as possible sites and detailed system analysis was carried out to assess the benefits of each site. Cockenzie was later removed as an option based on the site's proximity to local residents in case the noise level proved unacceptable and due to the lower NPV compared to the other 2 sites. Detailed Dig SILENT Power Factory system studies (Section 3 and Appendix C) were undertaken to determine the technical benefits of SCs/H-SC on the SPT network. The system study results were then used to create a detailed CBA to quantify the financial and environmental benefits of Synchronous Compensators.

During the ISP to Full Submission process, the Phoenix proposal team began carrying out rigorous partner selection activities to assess each against a number of criteria including experience, innovation, quality and costs, with key partners being identified through this process. In July 2016, Phoenix received investment authorisation for the Network Licensee Compulsory Contribution at the SPEN Investment Review Group Meeting.

D.2. Partner Selection

The scope and innovation components were verified by engaging with academic bodies, generation companies and GB SO, National Grid. A brief scope was sent to suppliers to gauge interest in the supply chain for innovation in Synchronous Compensators. The major global suppliers were identified as ABB, GE Grid Solutions and Siemens. All three suppliers proved willing to participate in the project and offered support in identifying key innovation components. Individual meetings were carried out with all 3 suppliers, academic bodies, generation companies and international stakeholders.

D.2.1 Network Licensee Partner Selection

There is currently no direct precedent for a commercial market for system inertia or short circuit level as conventionally these have been provided by large synchronous thermal plant as a by-product of their primary generating function. As the System Operator and responsible body for electricity markets, NGET SO was identified as desired partners at a very early stage. The partnership between SPT (TO) and NGET SO will maximize the benefits of the project by developing new and robust commercial mechanisms, using learnings from Phoenix for developing future FES, SOF and ETYS. It will also help influence the regulatory mechanisms to support future roll-out of SCs/H-SCs. [redacted] to ensure mutually agreeable commercial arrangements for the procurement of such services, integrating them amongst the various operational tools procured by the GB SO.

D.2.2 Supplier Partner Selection

Phoenix proposal team engaged will 3 main vendors during the proposal preparation phase GE, Siemens and ABB. All vendors proposed different solutions and showed interest to partner should the project be successful. SCs by nature require higher capital investment and it was not considered value for money for GB customers for a larger SC to be funded through this mechanism. For proof of concept and to demonstrate innovation, vendors were requested to add value to the project by contributing through globally innovative control strategies, contributing to project through R&D and accepting certain risks involved. Vendors were assessed based on innovation, quality of technical solutions offered, previous experience and ability to deliver a turnkey solution within cost constraints while strictly adhering to the objectives of the project.

ABB were selected as project partners because the ABB solution proposed for this project is globally innovative with its hybrid SC concept. ABB is a leader in power technologies with proven experience in SCs and FACTS devices. SCs from ABB ensure efficient and reliable operation of power grids through reactive power compensation and additional short circuit power capacity. ABB has a great commitment to innovation in GB. ABB also pledged a substantial contribution to the project of the order of £1.95m through R&D and discounted equipment costs.

D.2.3 Academic Partner Selection

During the literature review in preparation for Phoenix, it became apparent to the project proposal team who the global leaders in SC academic research were. DTU has substantial experience in SC/H-SC modelling/control and world-leading academic knowledge and facilities. DTU started the Synchronous Condensers APPlication in Low Inertia Systems (SCAPP) project in 2014 along with Danish System Operator, Energinet and Siemens. DTU were identified to provide expertise in SC/H-SC modelling/control and inform on SC applications in the Danish system. Partnering with DTU also enables a detailed knowledge transfer between Phoenix and the SCAPP project; ensuring Europe's best practise for Synchronous Compensator deployment is integrated into the GB wide roll out.

Through Phoenix, the project proposal team planned to initiate a knowledge transfer between DTU and a GB university to ensure the post-project knowledge and expertise would remain in GB. SPT were contacted by University of Strathclyde after the Phoenix ISP was published on the internet. UoS presented the relevant research recently carried out by their department of Electronic and Electrical Engineering. UoS also made a very compelling case for undertaking the GB wide system studies, building on previous innovation projects and integrating SC (modelling and control) into dynamic studies to measure whole system response and benefits on the GB network. University of Strathclyde has a proven track record of excellent research for SPEN. UoS will also aid the Phoenix delivery team in knowledge capturing and dissemination activities including through national and international working groups.

D.3. Value for Money

SPEN endeavours to deliver value for money for GB customers through Phoenix. Phoenix endeavours to bring SCs/H-SCs to business-as-usual deployment to ensure the security and stability of the supply to the GB customers. The deployment of Synchronous Compensators will also enable TOs to save on asset investment and the SO will benefit from reduced constraints. SPEN will follow SPT's procurement and legal policies to ensure contractual agreements between partners are placed after decision on funding request has been made following established processes and project milestone payments are aligned with project plan and SDRCs. SPEN has reviewed cost-estimations from various partners to ensure Phoenix benefits from discounted rates and in kind contributions from partners in terms of material and labour. These estimations have been further scrutinised to ensure appropriate levels of risk mitigation contingency and to avoid cost overruns to our best estimate.

Appendix E: Project Plan

[redacted]

[redacted]

ofgem RIIO NIC NETWORK INNOVATION COMPETITION

Appendix F: Risk Register

Key for New Technology Risk Register

Financial impact	
Score	**£k**
1	<10
2	10-100
3	100-500
4	500-1000
5	>1000

Probability of risk occuring	
Score	**Probability**
1	V. Low
2	Low
3	Medium
4	High
5	V. High

Overall Impact	
Score	**Impact**
0-9	Low Risk
10-29	Medium Risk
30-40	High Risk

Reputation Impact	
Score	**Impact**
1	Minor: Department awareness
2	Medium: Company awareness
3	Major: National awareness

Risk Type	Risk No.	Issue	Risk Description	Potential Impact	Probability (1-5)	Financial Impact (1-5)	Reputation Impact (1-3)	Overall Risk (1-40)	Control Measure(s)	Action Taken
WP		WP1 - Synchronous compensator installation								
WP	1	Choice of Substation	Phoenix will be demonstrated within an existing substation, therefore site installation logistics may be subject to external delays or restrictions	Delay in commissioning of live system and reduced live trial period	2	3	2	10	New build will require outage window to complete installation. Delivery and site commissioning will be coordinated between vendor and site contractor. SPT and primary contractors IEC follow a strict delivery schedule to avoid negative financial impact to the business.	
WP	2	Costs	Degree of uncertainty in installation costs of large asset that may be higher than forecast.	Limited project budget	2	5	2	14	Detailed project costing during project scoping to minimise risk of overspend. Contingency added to civil works pending final design & site	
WP	3	Outage Window	An outage window will be required in order to commission the live solution, and may be subject to delay	Delay in commissioning of live system and reduced live trial period	2	3	2	10	Preliminary and back-up sites identified, with decision pending confirmation in WP1.	
WP	4	FAT Testing	Unsatisactory FAT may lead to delays in project programme in order to remedy problem	Delays in project programme	3	1	2	9	Well defined and comprehensive laboratory tests, that are closely managed and evaluated to ensure minimial risk at SAT.	
WP	5	Commissioning new technology	New technology brings inherent risk for site installation and commissioning/SAT	Delays in project programme	2	3	2	10	Training of new technology to be provided for installation teams. Comprehensive FAT tests will reduce probability of unsuccessful SAT.	
WP		WP2 - Live Trial								
WP	6	Solution performance	H-SC performance monitoring report identifies issues that require physical tuning or site access	Outage may be required	2	3	2	10	Outages deferred subject to severity and taken if critical. Extended performance trial in project scope to safeguard against outages.	
WP	7	External communication network	External communication network is not fit for purpose	Upgrades required to communication network, delays in the demonstration	2	3	2	10	Communication links need to be checked early in project delivery stage and all necessary communication requirements will be communicated and agreed with SPEN IT and Security department. SPEN has recently placed a contract with Vodafone to upgrade their comms network.	
WP	8	Performance analysis	Insufficient or inadequate events captured to inform performance analysis and network modelling that hinders business case development	Reduced impact of business case	2	2	3	10	Regular review of analytical studies to ensure learning is maximised	
WP		WP3 - Commercial Arrangements and Ownership								
WP	9	Commercial Expertise	Market analysis and modelling requires input from commerical experts	Reduced accuracy of market assessment and potential underestimation of services / benefits	3	2	3	15	NETSO to provice commerical expertise. External commercial experts have also been engaged for potential support	
WP	10	Establishing new market / regualtory barriers	The project fails to determine the mechanisms, or services, by which investment decisions can be made.	Uptake of new technology is reduced	3	1	3	12	Collaboration with the SO and market experts to ensure owernship and investment strategies are identified	
WP										

WP		**WP4 - Control & Integration of H-SCs**								
WP	**11**	New Technology / Innovation	New control and protection methods required further laboratory testing to verify operation, and result in delayed commissioning	Delays in commissiong. Diminish confidence in new control technology	4	2	2	16	DTU involvement will ensure learning from SCAPP taken onboard. Laboratory testing used to verify operation with findings published and disseminated to stakeholders	
WP	**12**	Operation	Undesirable performance of control function during live trial may hinder performance monitoring assessment	Delays in commissiong. Diminish confidence in new control technology	3	2	2	12	Laboratory tests to confirm all control functions from which comparisons made to determine cause and solution. If outage required to remedy problem, a decision will be made regarding severity and value-added.	
WP		**WP5 - Component and System Studies**								
WP	**13**	Modelling accuracy	SCAPP SC Model does not provide accurate respresentation of Phoenix H-SC and require additional time to develop	Increase resource required to develop model to sufficient accuracy	4	2	1	12	Early DTU and vendor engagement to ensure model accuracy is sufficiently verified	
WP	**14**	Modelling accuracy	Access to full GB system model may not be possible	Modelling accuracy compromised	3	1	1	6	Access to full model is expected to be granted through project, however, the University of Strathclyde have a reduced GB model that can be used	
WP	**15**	Business Case	Roll-out may be degraded by lack of analytical evidence or unsatisfactory business-case	Uptake of new technology is reduced	3	3	3	18	Ongoing learning is captured and disseminated effectively to ensure stakeholder concerns are addressed and a strong business case is developed to support decision for further roll-out.	
WP		**WP6 - Knowledge Dissemination**								
WP	**16**	Effective knowledge sharing	Challenges from within the industry are not fully recognised and addressed through the project	Impact of the project is lower than expected	2	1	3	8	Stakeholder engagement matrix has been produced to ensure key stakeholders are identified and suitable engaged throughout the project	
WP	**17**	Academic involvement	Academic partners do not have enough resources and involvement in innovation aspects	Academic partners contribution to project will be limited	1	1	2	3	Academic partners have been chosen based on their experience in related projects (SCAPP/Inertial response) and have sufficient resource available to safeguard their contribution	
G		**General Risks**								
G	**1**	Post-Project operation	Risk of stranded asset post demonstration if appropriate continuation plan not determined	Stranded asset	4	5	3	32	Key focus of project to determine continuation plan. There will be a possibility of making ownership decision at the last phase of this project after proof of concept and the if the owner of the asset is not a TO/SO the service provider could potentially return some investment to the NIC mechanism.	
G	**19**	Contractual agreements timing	Contractual agreements can be complicated for innovative projects where project risks must be covered off	Delays in receiving agreements result in delay start	3	1	2	9	Contractual negotiations to commence upon successful project award.	
G	**24**	Health and Safety	Lack of experience and knowledge regarding new pieces of equipment	Health and safety risks present as a result of lack of experience. Inefficient working, errors and high costs could result	2	1	1	4	Manufacturers to provide support in terms of training, and supervision of installationsolutions. However as conventional equipment will also be installed in parallel H&S guidance will be provided to all site contractors. Site engineers will need to respect all H&S standards set out for work on site.	
G	**22**	Key experts involvement	Continuity of the involvement of key experts is not ensured because of other critical projects running in parallel or group strategy imperatives (change in management, focus on other areas)	Project advisory board will not be effective in design of key deliverables and knowledge dissemination.	2	1	2	6	Advisory board and market experts to be engaged regularly to maintain project involvement	
G	**23**	Project Management	Lack of resources from any project partners will lead to lack of project management within the project.	Loss of project management may lead to delays	1	3	2	5	Companies to ensure contingency measures in place to alleviate loss/lack of resource	
G	**10**	Equipment delivery and Spares	Delay in equipment delivery and lack of spares.	This will delay of related workstreams	2	4	2	12	Close coordination with suppliers and site contractors to minimise risk, with spares of critical held	
G	**11**	Contractors and Sub Contractors	Disagreenents between contractors and sub contractors on site	Delay in installation and commissioning	2	3	3	12	Interface documents and clear division of tasks on site will mitigate this risk. All contractors and sub contractors will be selected on their previous experience and will professionally deliver the project.	
G	**3**	Failure of new equipment	New equipment - never tested in realistic conditions previously - does not meet the performance requirements	Targets for the demonstrations are not met	3	4	2	18	The equipment will be tested extensively in test environment	

Appendix G: Base Case Value Derivation (Derived from all references listed in Appendix L)

G.1 Value Proposition

The financial value of Phoenix to TOs and DNOs comes from three key areas:

- Improved utilisation of network assets deferring asset investment;
- Optimised utilisation of LCC HVDC interconnectors;
- Decreased switching of existing power electronic based reactive power compensation

While the value to the SO and the GB customers come from:

- Reduction in network constraints, constraint payments, balancing and ancillary services.

There are additional value streams from Phoenix to the GB system as a whole. These include:

- Improved GB System security and stability;
- Reactive power injection to alleviate voltage dip conditions;
- Maintain power quality of the network in the event of harmonics and power system imbalances;
- Ensure correct protection system operation;
- Increased system inertia;
- Reduced carbon and environmental impact of power generation by replacing stability characteristics conventionally only available from large thermal generators.

G.2 Phoenix Base Case

G.2.1 Overview of Future GB System

The future GB system will most likely have very little synchronous generation, large quantities of asynchronous renewable generation like wind and solar, large volumes of energy storage, increased reactive power electronics and increased penetration of interconnectors. As well as a change in the technology mix, there will also be more flexible services available on the future GB system with demand side response offering to vary demand based on market signals and DSO services utilising the collective effect of an accumulation of smaller scale embedded demand, generation and storage assets.

Asynchronous Renewable Generation

The future GB system will undoubtedly have more generation capacity from renewable sources like wind and solar. Renewable generation is commonly connected at both transmission and distribution. The fast response ability of solar and wind farms can be used to contain the frequency and limit the RoCoF, this commonly referred to as "Synthetic Inertia". The voltage regulating ability of wind turbines varies with generator technology and manufacturer. Wind turbines based on induction generators have no inherent voltage controllability. Wind turbines with power electronic converters can provide the ability to regulate reactive power to achieve voltage control. Many wind farms connected to the transmission system already provide voltage support. As long as renewable generation is converter connected, the generators will not provide system inertia and their short circuit contribution will be limited by the converter.

Demand Side Services

Demand side response financially incentivises customers to decrease or shift their electricity use at peak times. This improved flexibility helps manage load and voltage profiles. Demand side response can be utilised to provide further flexibility to help control the frequency and limit the RoCoF. A potential new service from demand side response participants maybe the disconnection of demand during emergency low frequency conditions.

Storage Services

Energy storage will also offer additional flexibility to the future GB system; supplying electricity onto the network when required but also absorbing excess electricity during times of high generation and low demand. Fast acting energy storage technologies like battery storage can provide fast response to limit RoCoF and contain the frequency in a low inertia system. Storage can also offer steady, continuous response to help control frequency. Energy storage may be able to be used as reactive power compensation by locally supplying or absorbing real and reactive power although the benefits are based on the location of the storage assets.

HVDC Interconnector Services

In the last five years, GB's HVDC interconnectors have been used to import nearly four times more electricity than has been exported. Interconnectors enable GB to import electricity if there is a shortage of generation and export when there is a surplus. GB already has four interconnectors totalling 4 GW of capacity. This capacity is expected to double in the next ten years. The fast response capability (Synthetic Inertia) of HVDC interconnectors (especially VSC links) can be used to contain the frequency and limit the RoCoF. VSC based HVDC interconnectors have independent control of active and reactive power so and are able to provide voltage support to the network. HVDC links are not rotating masses therefore do not contribute to system inertia and their short circuit contribution will be limited by the converter.

DSO Services

The increase in distributed energy resources such as renewable generation, energy storage and demand side response is leading to a substantial industry change, as DNOs move towards becoming DSOs (Distribution System Operators). DSOs will balance generation and demand across the DNO network through the use of new commercial agreements with generators, storage and demand side response. The operations of each DSO will have to be closely coordinated with the SO, National Grid, to ensure the actions of one party do not inhibit the other. DSOs could also potentially provide some ancillary services to the SO. DNOs operating as DSOs will use customer response and network assets to keep voltage within statutory limits. DSOs will have the ability to actively control the reactive power exchange at Grid Supply Points. Voltage services from the DSO may include using DNO assets like transformer tap changers, circuit switching or reactive compensation devices. Voltage control may also be achieved through distributed embedded generation de-loading or directly to provide reactive power services. DSOs will be able to actively reconfigure their network to release capacity to manage constraints. The DSO can also engage with a wide range of distributed energy resources to provide "Synthetic Inertia" frequency response services formed by an accumulation of services including embedded generation, storage and demand side response.

Synchronous Compensator (SC)

The future GB system will be very different from the GB system of the past. Generation will continue to become more distributed and intermittent. GB customers will also continue to benefit from new ways to observe and manage their energy use. Although there are challenges associated with the move to a low carbon economy, there are also fantastic opportunities for new business models, services and technologies to emerge and develop. The increased flexibility offered by new services like the DSO and demand side response coupled with new technologies such as energy storage are critical to optimise the use of the existing and future GB network. SPT strongly believes that the most efficient method to deliver GB system security and stability is to supplement the above technologies and services with the deployment of SCs. SCs increase the level of system inertia to manage the frequency and limit the RoCoF. SCs also provide dynamic voltage support and their short circuit level contribution is significant given the transient overload ability of synchronous machines.

Flexible AC Transmission Systems (FACTS)

Flexible AC Transmission Systems (FACTS) such as Static Synchronous Compensators (STATCOMs), Static Var Compensators (SVCs), Series Compensation and Mechanically Switched Capacitors (MSC/MSCDNs) also have a critical role to play in the future GB system; these devices can be deployed to improve transmission quality and efficiency of power transmission by supplying or absorbing reactive power. STATCOMs are like SVCs only faster. Both SVCs and STATCOMs respond to changes in system operating conditions fast and continuously. Both devices significantly improve the transient voltage behaviour of the system. Although SVCs and STATCOMs work on different principles, their ability to increase power transfer capability is comparable. STATCOMs operate according to voltage source converter (VSC) principles. STATCOMs generate and absorb reactive power by electronically processing voltage and current waveforms in the VSC, meaning there is no requirement for any physical capacitor and reactor branches for generating or absorbing reactive power. The speed of response from a STATCOM is unequalled. STATCOMs function with a very limited requirement for harmonic filters, contributing to a small physical footprint. Installing a STATCOM at one or more suitable points in a network increases power transfer capability by enhancing voltage stability and maintaining a smooth voltage profile under varying network conditions. STATCOMs also have the ability to perform active filtering to improve power quality. FACTS devices are not rotating plant so do not contribute to system inertia and the SCL contribution is limited by the converter.

Hybrid Synchronous Compensator (H-SC)

The novel Phoenix H-SC solution combines the strengths of a SC and a STATCOM to allow each device to compensate for the weaknesses of the other. The H-SC solution results in enhanced dynamic voltage control. STATCOMs operate much faster than SCs, since no moving parts are required. STATCOMs consist of passive elements like inductors, capacitors and resistors combined with semiconductors such as insulated-gate bipolar transistors (IGBTs) that have the ability to turn off. A STATCOM also assists with correcting power quality challenges such as harmonics, voltage flicker and oscillations. However SCs also have the added benefit of boosting system inertia and SCL.

Optimise the Utilisation of LCC HVDC Interconnectors

The successful interaction between the AC network and LCC HVDC links (like the Western Link) depends on the short circuit level of the AC system at the HVDC converter stations. LCC HVDC links can be susceptible to commutation failures caused by disturbances on the AC side of the converter. The AC system connected to the Western Link HVDC converter must be sufficiently strong so faults occurring on the AC system do not result in a significant disturbance to the voltage waveform, resulting in commutation failure which interrupts the correct operation of the converter. After the closure of Hunterston nuclear power station the short circuit level at the Hunterston converter station will decrease significantly. H-SC could play a vital role in strengthening the SPT system by increasing short circuit level to minimise commutation failures and ensure full use of the Western Link.

Reactive power support to alleviate voltage dip conditions

The magnitude and duration of voltage dips need to be minimised due to their damaging effects on generators and loads affected by the voltage dip. The impact of the voltage dip is fundamentally dependent on the system strength, voltage support available and the electrical distance. The increase in asynchronous renewable generators and interconnectors has reduced the dynamic voltage support capability of the GB system. The Phoenix H-SC solution results in enhanced dynamic voltage control by reinforcing the STATCOM with a SC. H-SC operates much faster than a conventional SC due to added value of the STATCOM which can operate within 1 electric cycle. H-SC also offers improved system redundancy as H-SC can operate on partial system voltage control when one of the devices is out for maintenance or refurbishment.

Maintain power quality of the network in the event of harmonics and power system imbalances

Power quality is affected by the converters of asynchronous generation like wind and solar as well as reactive power compensation equipment.

Power quality issues include aspects such as

- harmonics;
- flicker;
- voltage/current distortion due to unbalanced faults.

H-SC could play a vital role in strengthening the SPT system by increasing short circuit level to avoid power quality issues associated with low short circuit level. STATCOMs also have the ability to perform active filtering to improve power quality. The SC part of the H-SC is not a source of harmonics and can even absorb harmonic currents. A roll out of H-SC across the GB system could address the issues associated with power quality by damping new harmonic orders and stabilising the modal shift.

Ensure correct protection system operation

Protection is delivered by a combination of overcurrent, distance and differential protection schemes. Protection operates as quickly as possible to distinguish faulted sections and isolate them from the wider system. For overcurrent protection, the operating time of the relay is inversely proportional to the magnitude of the short circuit current. Lower short circuit level results in the overcurrent protection taking longer to operate. H-SC can facilitate correct system protection by significantly increasing the short circuit level.

Increased System Inertia

The GB system is more vulnerable to sudden changes in load or generation due to the lack of system inertia. SCs are large, rotating, synchronous machines so they help keep the system stable by increasing system inertia. The SC part of the H-SC provides inertia. Increased system inertia means the SO can procure less frequency services, resulting in cheaper bills for the GB customers.

Carbon and Environment

Like for Like Replacement for Security and Stability Offered by Thermal Generation
H-SC reduce the carbon and environmental impact associated power generation by replacing stability characteristics conventionally only available from large thermal generators.

Constraining wind and rebalancing with thermal generation.
The SO uses a number of balancing services to operate the GB system in an efficient, economic and co-ordinated manner ensuring supply of energy matches the demand. Large scale generators pay for firm 24 hour, 365 days a year access to the GB transmission system so it is in their control when and how much to generate. When a generator is stopped from fully utilising the access paid for, they receive compensation in the form of a constraint payment. Network constraints arise when active power cannot be transmitted to where it is required, as a result of congestion at one or more points on the transmission network. H-SC will increase the active power transfer capability of the existing transmission network thus reducing the constraint payments made by the SO. By reducing the balancing actions of the SO, Phoenix will lower the balancing costs that make up around 1% of the GB customer's bill.

The balancing services market value was £868.4 million for the 2015/16 financial year. The total constraint payments paid across GB in 2015/16 was £349.3 million. Phoenix will reduce the constraint payments by increasing the availability of the network to generators, through increasing the active power transfer capability of the existing transmission network. For the financial year 2015/16, £91.83 million was spent on constraining wind farms alone.

G.3 Post-Phoenix Roll-out

Phoenix will trial H-SC technology to boost short circuit level, deliver dynamic voltage control and increase system inertia.

The costs associated with the deployment of H-SC have been outlined in the Full Submission Spreadsheet. Through Phoenix, a GB rollout roadmap built on detailed system studies and different control methods for hybrid systems will be established. Developments, demonstrations and knowledge gained through Phoenix will lead to a reduction in costs associated with the method in the post-project rollout due to:

- Improvements in GB's market readiness for H-SC, higher market readiness level enables consistent, clear investment decisions on the financial benefits of rollout.
- Production of technical/delivery specifications and best practise design guides, lessons learned during design process will lead to optimisation of future deployments, optimum plant transportation, reduced vendor, contractor design costs and reduced civil/labour costs.
- Successful demonstration of H-SC technology in a live substation on the GB system for the first time, Phoenix will open up the GB market to suppliers of H-SC and generate increased levels of competition.

G.4 Phoenix Base Case – Additional Value of Hybrid Synchronous Compensator

Figure 52 illustrates the comparison between the base case method and Phoenix, the most efficient method for the GB transmission system for delivering system security and stability.

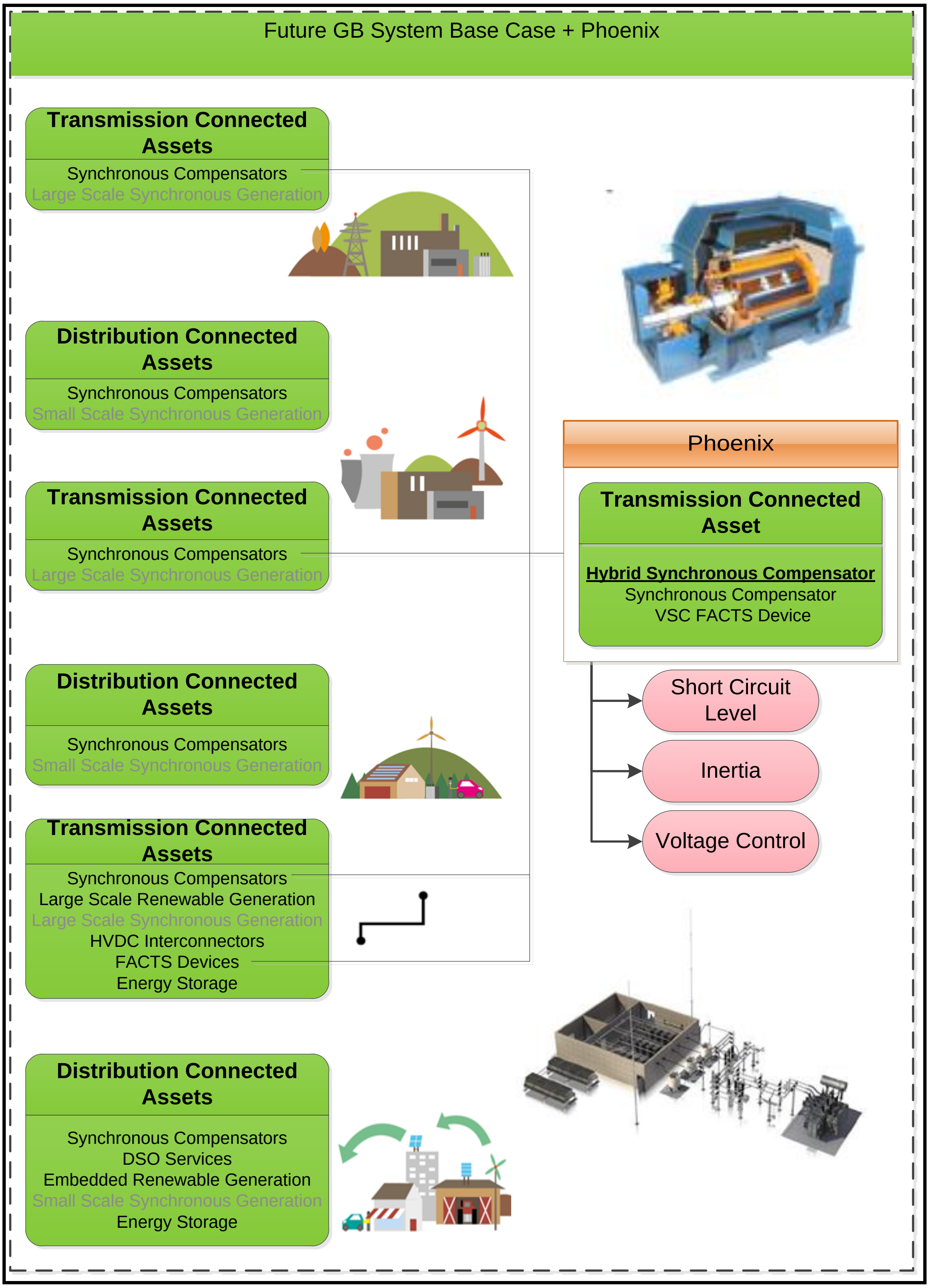


Figure 52 Phoenix Base Case Derivation

Appendix H: Links to Previous Innovation Funded Projects

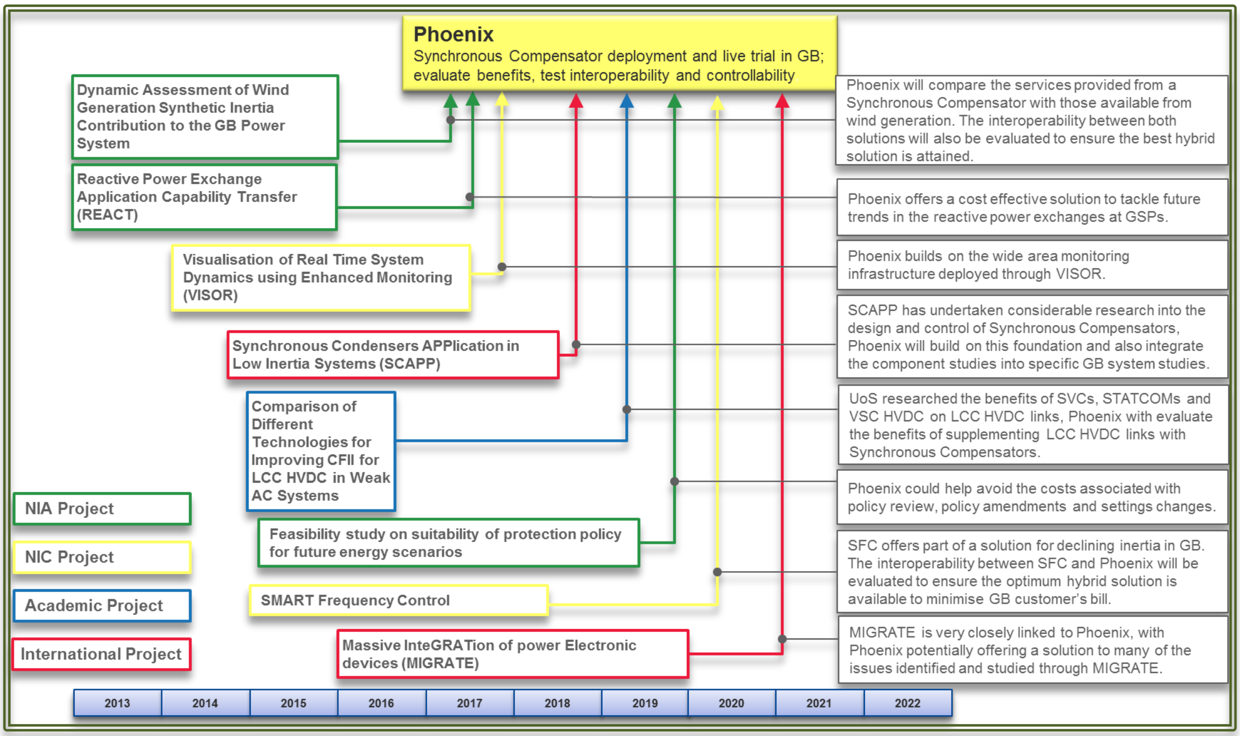


Figure 53 Links to previous innovation projects

Synchronous Condensers APPlication in Low Inertia Systems (SCAPP) Licensee: Danish transmission system operator Energinet.dk	SCAPP is a collaborative project between DTU and Siemens. The project is sponsored by Danish transmission system operator Energinet.dk under the Electrical Energy Research Program. In this project, DTU and Siemens set out to investigate the characteristics of a renewable-energy-based power system and identify the future requirements for Synchronous Compensators. DTU and Siemens recognised most renewable generators are connected to the grid by electronic power converters, which gives rise to protection and control difficulties during disturbances. Synchronous Compensators offered a solution to these problems; possessing all the advantages of a synchronous generator during fault conditions and eliminating the protection issues that otherwise exist. By undertaking the SCAPP project, DTU and Siemens have ensured Denmark maintains a leading position in the integration of renewable energy.
Visualisation of Real Time System Dynamics using Enhanced Monitoring (VISOR) Licensee: SP Transmission Funding: NIC	SP Energy Networks VISOR project showcases the contribution that a real time Wide Area Monitoring System (WAMS) could make to improve the efficiency and security of the GB system in the near term. The increased amount of power electronics on the GB system (power converters and controllers) has increased the risks of sub-synchronous resonance, torsional interactions and control interactions. Phoenix will incorporate studies and demonstrations to prove the concept of closed loop damping control and if required supplementary control to be made available in case sub-synchronous interactions are detected on the system using enhanced monitoring units deployed in project VISOR.
Enhanced Frequency Control Capability (EFCC) Licensee: National Grid Funding: NIC	The NIC SFC/EFCC project addresses the issue of reducing inertia leading to a need for much faster frequency response. The project includes an innovative wide area control system to trigger and co-ordinate rapid frequency response capabilities of wind farms, solar PV, energy storage and demand-side response. Reduced inertia is a threat to frequency control as it reduces the time available before the deviation will violate the security limits, Synchronous Compensators with their increased contribution to system inertia can extend the timeframe where the smart frequency can operate.

Feasibility study on suitability of protection policy for future energy scenarios Licensee: National Grid Funding: NIA	The increasing deployment of power electronic converter based technology such as wind turbines, HVDC links and PV is fundamentally changing the nature of system faults and their detection using the traditional methods. There is the increasing possibility of new scenarios where the existing methods and policies may not be sufficiently reliable to detect and clear faults, thus increasing the likelihood of wider network stability issues and possible black-outs. National Grid's project involves researching the capability of existing protection solutions to detect and clear power system faults in networks which are dominated by the technology changes envisaged in the future energy scenarios. The deployment of Synchronous Compensators as demonstrated by Phoenix could be an alternative to changing the current protection solutions.
Reactive Power Exchange Application Capability Transfer (REACT) Licensee: National Grid, SPEN, ENW, NPG, SSE, UKPN and WPD Funding: NIA	The REACT project was established to understand the reasons behind the decline in reactive power demand as seen by National Grid during minimum load. The project will allow DNOs and National Grid to establish future trends in the reactive power exchanges at GSPs and adopt the most cost-effective actions as well as assigning responsibilities for ongoing data provision, planning, design and operational management in this area. Synchronous Compensators could play a vital role in dynamically generating and absorbing reactive power on both the distribution and transmission networks in the future.
Western Link Licensee: National Grid and SP Transmission	The Western Link is a joint £1 billion project between National Grid and SP Transmission to deploy a subsea marine Line-commutated Converter (LCC) HVDC cable between Hunterston, North Ayrshire and Deeside, Flintshire to transmit 2,200MW of power, to strengthen and increase the capacity of the GB transmission system. Whilst power is often expected to flow from renewable generation in the north to homes and businesses in the south, the Western Link will be bi-directional so power can also be made to flow in the opposite direction according to future electricity supply and demand requirements. Compared to Voltage Source Converter (VSC) HVDC, LCC HVDC has higher power rating/efficiency and the lowest cost of the two technologies. However, LCC HVDC is susceptible to commutation failures caused by disturbances on the AC side of the converter. This disadvantage means that the AC system connected to the LCC HVDC converter must be sufficiently strong so faults occurring on the AC system do not result in a significant disturbance to the voltage waveform, resulting in commutation failure which interrupts the correct operation of the converter. Synchronous Compensator as demonstrated through Phoenix will increase the strength and stability of the AC network resulting in less commutation failures on the HVDC Western Link.
MIGRATE Licensee: 25 consortium partners including SP Transmission	MIGRATE is very closely linked to Phoenix, with Phoenix potentially offering a solution to many of the issues identified and studied through MIGRATE. Synchronous Compensators could safeguard network stability; Phoenix aims to improve system security and stability by reacting to events detected on the system using enhanced monitoring units deployed in project VISOR.
Dynamic Assessment of Wind Generation Synthetic Inertia Licensee: SP Transmission Funding: NIA	This NIA project focused on investigating the prospect of utilising wind generation to provide synthetic inertia to improve system stability. Although synthetic inertia can help improve system stability, there is still a requirement for synchronous machines to deliver an immediate inertial response. The future scenario will most likely involve both inertia and synthetic inertia working together.
Comparison of Different Technologies for Improving Commutation Failure Immunity Index for LCC HVDC in Weak AC Systems	University of Strathclyde's research project investigated locating FACTs and VSC devices near a LCC HVDC converter to support the performance of the LCC HVDC. The research paper shows how well VSC HVDC, STATCOM and SVCs are able to support LCC HVDC based on their improvement of the LCC HVDC Commutation Failure Immunity Index (CFII) and presented a comparison of their relative capabilities. VSC HVDC. CFII has been shown to increase with reduced LCC HVDC power flow. However, VSC HVDC acting as a source to the AC system reduces CFII due to the loss of power during a fault. As part of Phoenix the performance of LCC HVDC when supported by a Synchronous compensator will be evaluated.

Appendix I: Organogram and Key Personnel

Figure 54 Phoenix Organogram

SP ENERGY NETWORKS

Dr Cornel Brozio, System Analysis Manager
Dr Cornel Brozio is the System Analysis Manager in the Network Planning & Regulation section of SP Energy Networks. Cornel worked with Eskom in Johannesburg before receiving his PhD degree from the University of Stellenbosch. He previously worked with National Grid before moving to SP Energy Networks in 2003. He heads up a team responsible for a broad range of network analysis and simulation activities. Cornel has contributed to a wide range of transmission system projects, including HVDC and series compensation schemes. Cornel has given technical guidance and recommendations throughout the system studies carried out as part of the Phoenix proposal preparation. In Phoenix, Cornel will be a key stakeholder and a member of the steering board providing guidance and direction to the delivery team.

Fraser Ainslie, Engineering Design Manager
Fraser Ainslie is the Engineering Design Manager at SP Energy Networks. As the head of engineering design team, he ensures that all network asset related projects for SP Manweb and SP Transmission are technically deliverable and commercially viable. His past experience comprises of transmission protection and engineering solutions for major projects. Fraser will be a key stakeholder and a member of the steering board offering invaluable engineering design experience to the Phoenix delivery team.

Priyanka Mohapatra, Senior Project Manager
Priyanka Mohapatra is currently working as a Senior Project Manager at SP Energy Networks and is the project lead for VISOR. She has previously worked as a software developer and project manager for real-time solutions for power substation automation at Siemens AG, Germany and as senior engineer and product owner at Siemens Protection Devices Limited, UK (global R&D). Priyanka offers considerable experience and expertise in successful delivery of transmission innovation projects. Priyanka is the proposal lead for Phoenix.

Chris Halliday, Project Engineer
Chris Halliday works in Future Networks within the Engineering Services directorate of SP Energy Networks focusing primarily on transmission innovation. Chris started at SP Energy Networks in September 2013 as a Graduate Engineer. As part of SPEN's IET accredited Graduate Programme, Chris received a variety of internal and external training. Before Chris started at SP Energy Networks, he studied Electronic and Electrical Engineering at the University of Strathclyde. Chris has provided project support in Phoenix.

nationalgrid

David Phillips, UK Generator Compliance Manager
David Phillips C Eng., is the UK generator compliance manager for National Grid, with responsibility for ensuring generation connecting to the GB network meets Grid Code requirements and for dynamic modelling of generation in transmission network analysis. David will provide technical and management guidance to Phoenix.

Ed Mellish, Operational Strategy Manager
Ed joined National Grid as a Trader in 2014 with responsibility for developing and executing an optimised day-ahead system operating strategy.
Ed will provide commercial and strategy guidance to Phoenix.

Jay Ramachandran, Power System Engineer
Jay Ramachandran is currently working as Power System Engineer in GB Operability Assessment team at National Grid, Warwick. He is currently working in Northern Security Joint Technical project and assessing system voltage and stability operational issues. Jay will give technical analysis support to Phoenix.

Mark Krajniewski, Power System Engineer
Mark Krajniewski is currently working as a Power Systems Engineer at National Grid's Electricity National Control Centre, responsible for ensuring that the Great British Electricity Transmission system operates within statutory security and quality of supply standards. Mark will provide regularity guidance and control direction.

ABB

Dr Marcio Oliveira, Lead Engineer
Dr Marcio Oliveira has been with ABB for 16 years and he is currently System Lead Engineer, with focus on technical marketing and sales support to FACTS pursuits worldwide. With his extensive experience in power system and related control strategies he will contribute to the technical success of the project

Per Halvarsson, Business Development Manager (FACTS)
Per has held many different positions during his many years with ABB. Starting as an electrical converter design engineer and working with several R&D projects as a development project management. Today Per work with Business Development for the ABB FACTS unit in Västerås, Sweden.

Anders Stiger, Product Manager Turbine Generators and Synchronous Compensators
Anders Stiger M.Sc. has been with ABB for 25 years and he is currently Product Manager turbine generators, with focus on technical marketing and has a degree in industrial engineering. Anders, together with other colleagues in his team, will support Phoenix project with his competence and experience.

Mauro Monge, Global Product Manager FACTS Shunt Compensation
Mauro has been within ABB during the past 8 years holding different positions including R&D engineering, R&D project management and R&D management. He has contributed in the definition of Phoenix project proposal as solution for maximizing consumer benefit out of available and future technologies.

Jacob Østergaard, Professor
Jacob Østergaard has been Professor and Head of the Centre for Electric Energy (CEE) in the Department of Electrical Engineering, Technical University of Denmark, since 2005. Jacob will be a key member of the Phoenix steering board providing technical guidance and direction to the delivery team.

Dr Guangya Yang, Associate Professor
Dr Guangya Yang is currently Associate Professor at Center for Electric Power and Energy, Technical University of Denmark. He has been working with power system operational issues in the presence of renewable generation and application of optimization techniques in modelling and control over the recent years. Guangya will be the overall technical lead from DTU for Phoenix.

Dr Campbell Booth, Reader
Dr Campbell Booth is a Reader at the University of Strathclyde. Campbell has been a member of the Strathclyde community since studying as an undergraduate student in the department of Electronic and Electrical Engineering in 1987. Campbell will be the overall technical lead from UoS for Phoenix.

Dr Qiteng Hong, Research Associate
Dr Qiteng Hong is a Research Associate at the University of Strathclyde. His main research interest is on power system protection and control. Qiteng will contribute considerable experience in GB system analysis to Phoenix.

Marcel Nedd, PhD Student
Marcel Nedd is a student in the second year of his Future Power Networks and Smart Grids CDT at the University of Strathclyde. Marcel will provide expertise in component level modelling and analysis.

Appendix J: Letters of Support

Phoenix received letters of support from following stakeholders, due to space constraints the letters of support are not added in the main proposal. All letters of support are available upon request. **GB TO, SO:** NGET, SSE **International TO, SO:** San Diego Gas and Electric, EirGrid **Vendors:** GE Grid Solutions, Siemens Denmark, ABB Ltd**Academic:** The University of Manchester, The University of Strathclyde, Technical University of Denmark **Market Specialist:** KiWi Power **Others:** IEEE PES, Chiltern Power, Energy Systems Catapult ofgem RIIO NIC NETWORK INNOVATION COMPETITION

Appendix K: Glossary of Terms

AC	Alternating Current	**IFI**	Innovation Funding Incentive
ARC	Accelerating Renewable Connections	**IPR**	Intellectual Property Rights
AVR	Automatic Voltage Regulator	**ISP**	Initial Screening Proposal
BaU	Business as Usual	**LCC**	Line-Commutated Converter
CBA	Cost Benefit Analysis	**LCNF**	Low Carbon Network Funding
CCGT	Combined-Cycle Gas Turbine	**LCNI**	Low Carbon Network Innovation
CFII	Commutation Failure Immunity Index	**LFDD**	Low Frequency Demand Disconnection
CHP	Combined Heating and Power	**LOIF**	Loss of Infeed
CO2	Carbon Dioxide	**LVRT**	Low Voltage Ride Through
DECC	Department of Energy and Climate Change	**MBSS**	Monthly Balancing Services Summary
DNO	Distribution Network Owner	**MFR**	Mandatory Frequency Response
DSO	Distribution System Operator	**MIGRATE**	Massive Integration of Power Electronic Devices
DTU	Technical University of Denmark (Denmark Technical University (Danish))	**MRL**	Market Readiness Level
EFCC	Enhanced Frequency Control Capability	**MSC**	Mechanically Switched Capacitor
ENS	Energy Not Supplied	**MSCDN**	Mechanically Switched Capacitor with Damping Network
ENW	Electricity North West	**MVA**	Mega-Volt-Ampere
ETYS	Electricity Ten Year Statement	**MVAr**	Mega-Volt-Amperes Reactive
FACTS	Flexible AC Transmission Systems	**MW**	Megawatt
FAT	Factory Acceptance Testing	**NETS SQSS**	National Electricity Transmission System Security and Quality of Supply Standard
FES	Future Energy Scenarios	**NGET**	National Grid Electricity Transmission
FFR	Fast Frequency Response	**NIA**	Network Innovation Allowance
FITNESS	Future Intelligent Transmission Network Substation	**NIC**	Network Innovation Competition
FTE	Full Time Employee	**NOA**	Network Options Assessment
GHG	Greenhouse Gas	**NPG**	Northern Power Grid
GSP	Grid Supply Point	**NPV**	Net Present Value
H2	Hydrogen	**OCGT**	Open Cycle Gas Turbine
HVDC	High Voltage Direct Current	**OFTO**	Offshore Transmission Owner
IEC	Iberdrola Engineering and Construction	**O&M**	Operation & Maintenance
IEC	International Electrotechnical Commission	**PSS**	Power System Stabilizer
IEEE	Institute of Electrical and Electronics		

	Engineers		
PU	Per Unit	**VSC**	Voltage Source Converter
PV	Photovoltaic	**WAMS**	Wide Area Management System
REACT	Reactive Power Exchange Application Capability Transfer	**WP**	Work Package
RIIO	Revenue = Incentives + Innovation + Outputs	**WPD**	Western Power Distribution
ROCOF	Rate of Change of Frequency		
ROI	Return on Investment		
RTDS	Real Time Digital Simulation		
SCADA	Supervisory Control And Data Acquisition		
SCAPP	Synchronous Condensers APPlication in Low Inertia Systems		
SC	Synchronous Compensator		
SCL	Short Circuit Level		
SCR	Short Circuit Ratio		
SDRC	Successful Delivery Reward Criteria		
SFC	Smart Frequency Control		
SME	Small to Medium Enterprise		
SO	System Operator		
SOF	System Operability Framework		
SPEN	SP Energy Networks		
SPT	SP Transmission		
SSE	Scottish and Southern Energy		
STATCOM	Static Synchronous Compensator		
STC	System Operator Transmission Owner Code		
SVC	Static VAr Compensator		
TO	Transmission Owner		
TRL	Technology Readiness Level		
UKPN	UK Power Networks		
UoS	University of Strathclyde		
VISOR	Visualisation of Real Time System Dynamics using Enhanced Monitoring		

Appendix M: GB Roll-Out Scenario

Phoenix will build the capability to respond to future security and operability challenges, through sharing of learning and collaboration with industry as a whole. While it is difficult to predict exactly how many units might be required in future, we are confident that this project will enhance network owner's and system operator's ability to deliver solutions when the need does arise.

We believe that H-SC forms a part of the solution to the problems we are facing in transitioning to low carbon networks, and this is supported by evidence from around the world where there has been something of a "synchronous compensator renaissance", particularly to tackle problems associated with reduced inertia and low SCL.

Various factors will influence the GB roll-out scenario of Phoenix H-SC solution; the main driver will be end consumer benefit as shown in Figure 55.

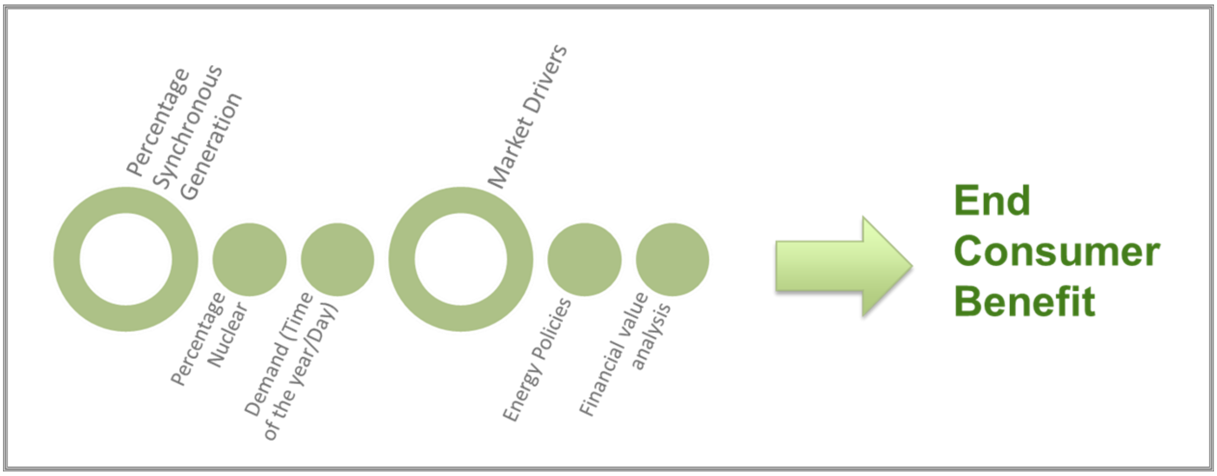


Figure 55 Factors influencing GB roll-out scenario

M.1 Estimation of future roll-out unit numbers

The requirements for SCL, power quality and voltage control are constant throughout the year and the average number of H-SCs required for these services can be estimated based on system security requirements. The number of H-SCs required for inertia contribution depends on the need throughout the year vs. the cost of alternatives.

A simplified calculation using the Gone Green scenario (chosen because of highest percentage of nuclear/synchronous generation) and assuming an average size of installation of 250 MVA (SC) or 200MVA/100MVA (H-SC) shows that the 20-25 units will be required to be installed between 2020-2035 providing the network services until 2040-50.

Figure 56 and Figure 57 show how H-SCs will contribute to inertia levels at times of low system demand

- H-SCs will be used to reduce must-run and constraint costs. i.e. run H-SCs instead of constraining renewables off and synchronous generation on. This will deliver carbon benefits.
- As more H-SCs are installed, some may only be needed for shorter times for inertia. This may become uneconomic after certain number of installations compared to other options.

- The number of units required will also depend on the amount of nuclear generation on the network (assumed to be always on in this analysis).
- Amount of enhanced frequency response service available.

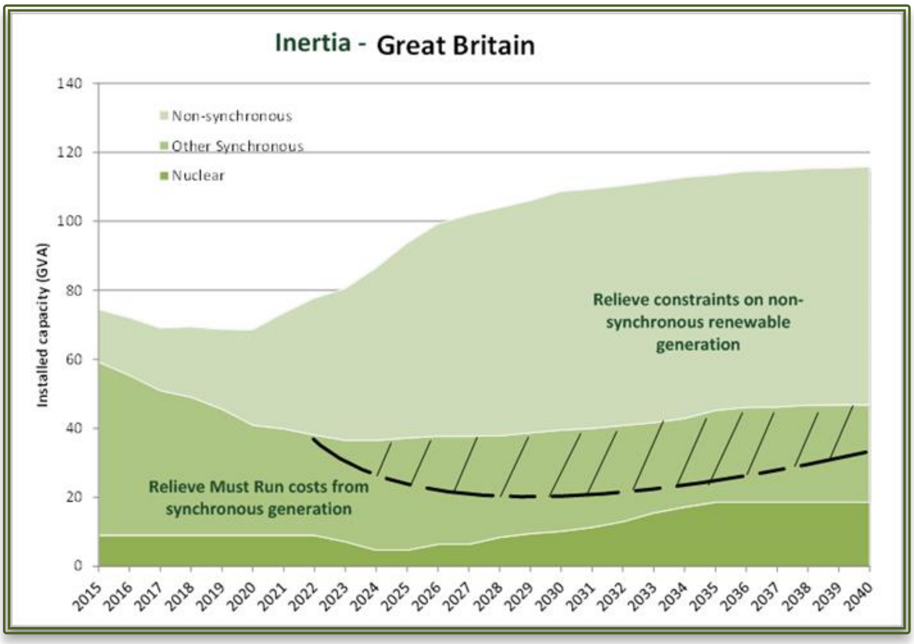


Figure 56 Displacement of must run costs of synchronous generation and reduction in constraint on renewable generation through roll-out of H-SC solution

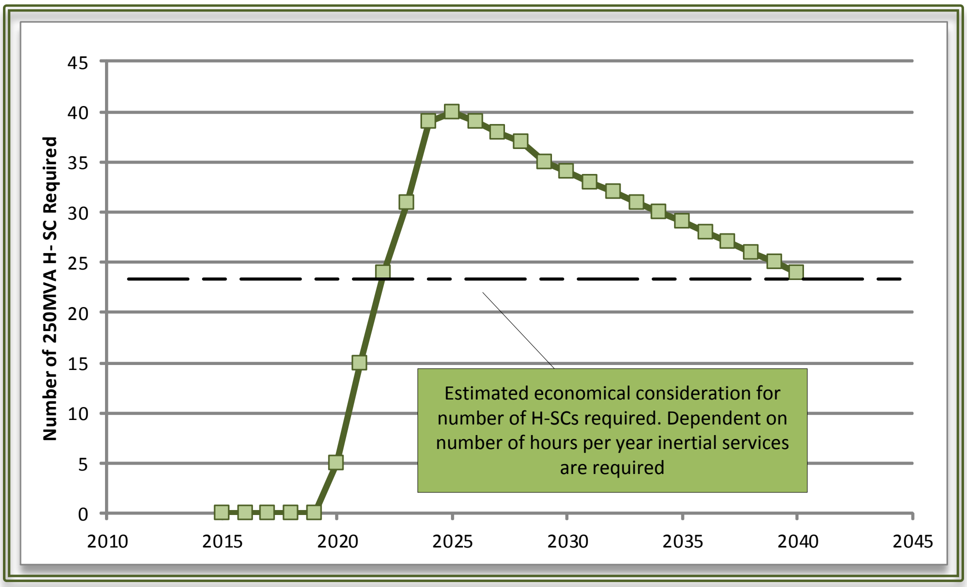


Figure 57 Requirement vs Economical cut-off on number of H-SC installations

M.1 Roll-Out Variants Enabled by Phoenix

Phoenix through technical and commercial innovation and through regulatory recommendations will enable the following 4 variants of H-SC compensation as shown in Figure 58.

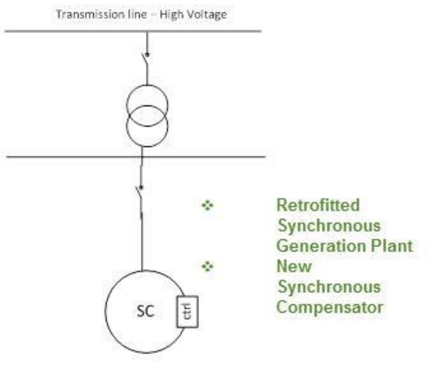
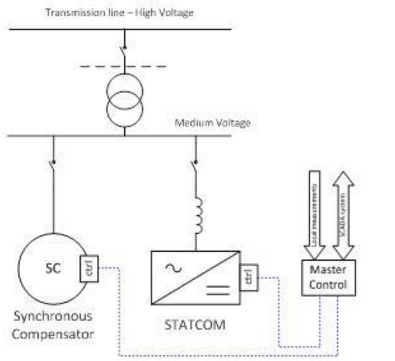
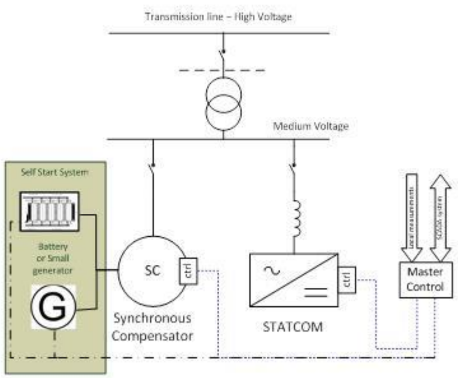
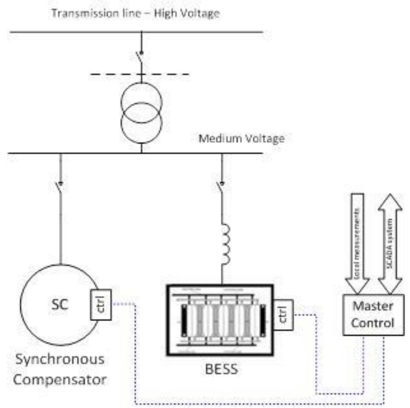
1. Standalone 	• Enable commercial mechanisms to enable procurement of services from service providers • Prove engineering feasibility and performance	**2. H-SC SC + STATCOM** 	• Design, develop, simulate and deploy on live system hybrid-coordinated control mechanisms • Maximise strengths of both technologies minimise weaknesses
3. H-SC SC + STATCOM + Self Start up - Blackstart 	• Simple extension from variant 2 with self start mechanism	**4. H-SC SC + Battery Energy Storage System (BESS)** 	• Simple extension from variant 2 moving from DC-capacitors in pure STATCOM to battery energy storage system. • The component models for this variant will developed and simulated in Phoenix research studies

Figure 58 Variants of H-SC solution enable by Phoenix

M.2 Estimation of Number of H-SC Units by Type of Service and Variant Type

The optimal number of SC/H-SCs required in the GB system can only be determined through detailed system studies and financial value analysis across all services provided. This will be performed as a part of the project. Figure 59 provides an initial estimate of the number of units required based on the variant type (last column) and type of service provided (last row).

System Services	Boost system Inertia	Increase system short circuit level	Provide dynamic voltage regulation-1	Provide dynamic voltage regulation-2	Enhance oscillation damping capability-1	Enhance oscillation damping capability-2	Aid in maintaining power quality in the network	Frequency Management	Role in BlackStart-1	Role in BlackStart-2	Column1
	ROCOF Management Enhanced Inertial Response	System Strength Protection System Effectiveness Commutation of HVDC Link	Overload /Underload Capability Over and Under Excitation	Fast Response and Managing Voltage unbalances	Low Frequency Oscillations	High Frequency Oscillations		Enhanced MW Response	Reduce Restoration Time	System Restoration Capability	Estimated Number by Variant Type
Standalone	✓	✓	✓		✓		✓				[redacted]
H-SC SC+STATCOM	✓	✓	✓	✓	✓	✓	✓				[redacted]
H-SC SC+STATCOM+ Self Startup	✓	✓	✓	✓	✓	✓	✓		✓		[redacted]
H-SC SC+BESS	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	[redacted]
Regional Services	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	[redacted]
[redacted]											

Figure 59 Number of H-SC units by variant type and type of service required

Appendix L: References

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