A step-change for offshore wind: Securing onshore grid stability

SUMMARY REPORT OF THE INCENTIVE PROJECT (INNOVATIVE CONTROL AND ENERGY STORAGE FOR ANCILLARY SERVICE IN OFFSHORE WIND)

CARBON TRUST

THE INCENTIVE PROJECT

The INCENTIVE project is a joint industry project funded through Ofgem's Strategic Innovation Fund (SIF) and the Carbon Trust's Offshore Wind Accelerator. The project aimed to develop industry-wide consensus on how offshore wind could contribute to the electrical stability of the onshore transmission network.

The project is driven by a powerful, whole-system consortium covering the transmission industry, offshore wind industry and the supply chain. The consortium consists of:

- Project partners: SSEN Transmission, National Energy System Operator (NESO), University of Strathclyde, Carbon Trust
- Delivery partners: National HVDC Centre, Frazer-Nash Consultancy
- Offshore Wind developer partners: bp, EnBW, Equinor, Ørsted, Ocean Winds, RWE, ScottishPower Renewables, Shell, SSE Renewables, TotalEnergies, Vattenfall

Advisory Panel supply chain partners: Fluence, GE-Vernova, Hitachi Energy, Siemens Energy, SMA. This report and the recommendations within have been prepared by the project partners and delivery partners, with the exception of NESO. NESO's role has been limited to signposting publicly available information and answering non-confidential queries as required.

THE OFFSHORE WIND ACCELERATOR

The Offshore Wind Accelerator (OWA) is the Carbon Trust's flagship collaborative research, development and demonstration programme. The joint initiative, which has been running since 2008, is a collaboration between the Carbon Trust and nine offshore wind developers. It aims to reduce the cost of offshore wind to be competitive with conventional energy generation, to accelerate the deployment of offshore wind globally, and to drive industry standards and best practices.

ACKNOWLEDGEMENTS

This report provides an executive summary of the INCENTIVE project recently delivered by SSEN Transmission, National HVDC Centre, University of Strathclyde, Frazer-Nash Consultancy and Carbon Trust. The project would like to thank all those who provided input into the project, notably: bp, EnBW, Equinor, Ørsted, Ocean Winds, RWE, ScottishPower Renewables, Shell, SSE Renewables, TotalEnergies, Vattenfall, Fluence, GE Vernova, Hitachi Energy, SMA Solar Technology, Siemens Energy, National Energy System Operator, The Department for Energy Security and Net Zero and Ofgem.

This project was funded by energy network users and consumers through SIF, a programme from the UK's independent energy regulator Ofgem, managed in partnership with Innovate UK. We would therefore like to recognise the input of the GB consumer, Ofgem and Innovate UK for making this vital research possible.

1. Key findings and recommendations

1.1. Key findings

INCENTIVE has found that offshore wind in conjunction with an INCENTIVE STATCOM or INCENTIVE BESS can provide necessary and cost-effective stability services to the onshore grid.

The technical testing of the devices found that they could stabilise the onshore grid. However, the testing also found that the Grid Code requirements and the current testing best practices do not give a full picture of all the system strength benefits provided by the INCENTIVE solutions, with the tests rating other technologies more highly.

The INCENTIVE project derisked the regulatory model. However, there is remaining work to be done, and a 'pipe-cleaner' project is recommended to ensure the pathway to business-as-usual is clear in the case of developer ownership.

- The project proved the economic benefits of the INCENTIVE Solutions in providing cost-effective stability services to the onshore grid. However, incentives were determined to be unclear. By potentially undervaluing the system strength contribution of grid-forming devices, and placing onerous requirements on inertia contribution, the current stability market disadvantages novel inverter-based stability assets. Additionally, it is unclear if these services will become mandatory in the future.

INCENTIVE recommends that the Grid Code testing requirements are updated to fairly value all devices that can provide stability.

Updating this will better incentivise offshore wind developers to deploy these technologies as BAU and provide necessary stability to the onshore grid, enabling greater renewable penetration in GB and helping to reach Net Zero targets at a lower cost.

The current application of Grid Code requirements to participate in NESO's stability markets means we may only see these devices implemented for local system strength issues, and the potential inertia that could also be offered to the onshore grid may not be realised.

1.2. Conclusions

INCENTIVE is a leading collaborative project to address a highly complex issue. Through a large whole-system consortium covering the transmission industry, the offshore wind industry and the supply chain, as well as with input from Ofgem, NESO and DESNZ, INCENTIVE has addressed key issues to enable offshore wind to provide stability to the system.

In the summary of sections 4, 5 and 5.2, INCENTIVE has shown positive technical, regulatory and economic feasibility for INCENTIVE Solutions:

- INCENTIVE Solutions can improve system stability and the strength of the local offshore wind farm grid connection;
- There are two workable regulatory ownership modes for INCENTIVE Solutions;
- INCENTIVE Solutions can provide economic benefits to energy consumers and a positive business case to asset owners.

From these positive findings, INCENTIVE has provided a pathway for offshore wind farm developers to include INCENTIVE Solutions in their future wind farms. Indeed, Ørsted and Hitachi Energy's announcement[1] that they will install one of GB's first GFM STATCOM with supercapacitors at the Hornsea 4 offshore wind farm (subject to financial investment decision), is further evidence of the offshore wind industry's interest and confidence in these novel technologies.

1.3. Recommendations

However, INCENTIVE has found a number of remaining barriers, which should be addressed to accelerate the rollout of INCENTIVE Solutions to support system stability and offshore wind integration.

Fundamentally, the barrier is a lack of clarity. A lack of suitable technical specifications for grid-forming inverter-based assets. A lack of clarity in the Stability Market. A lack of clarity in the Grid Code. A lack of clear incentive for offshore wind developers to choose these technologies.

The following recommendations are aimed at increasing clarity, which in turn will accelerate the deployment of these beneficial technologies. These recommendations are crucial for a cost-effective Net Zero transition. If future wind farms are without these capabilities, the risk and cost of low-carbon system operation will be increased.

1.3.1. Clarity on design specifications for INCENTIVE Solutions

The key aspect is to give clarity to offshore wind developers on how to specify INCENTIVE Solutions (i.e. how to design INCENTIVE Solutions to perform optimally, which includes aspects like sizing of the energy storage, sizing of the inverter, and tuning of the inverter).

To address this, following INCENTIVE, the Carbon Trust's Offshore Wind Accelerator is working to provide guidelines for offshore wind farm developers. It may be that working towards a standard specification, such as has happened in the German transmission industry[2], would be a positive outcome.

However, to produce these guidelines or standards, clarity is required in a number of key areas.

1.3.2. Asset sizing

The cost for the INCENTIVE STATCOM is sensitive to the energy storage capacity of the supercapacitors: reduction to storage requirements will make supercapacitor options more competitive.

Currently, compliance testing requirements could be pushing offshore wind developers to specify unnecessarily large energy storage requirements, which in turn unnecessarily increases costs and hence erodes the business case.

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[1] https://www.hitachienergy.com/uk-ie/en/news-and-events/press-releases/2024/12/hitachi-energy-and-orsted-to-ensure-grid-stability-at-hornsea-4-with-a-technology-first-for-offshore-wind-in-europe

[2] https://www.netztransparenz.de/en/Ancillary-Services/Voltage-stability/Standardized-design-of-E-STATCOM

Supercapacitor storage is a relatively inexpensive and reliable way to provide short-term energy storage that can be released very quickly. This type of short, but powerful, energy storage is ideal for reacting to stability events, which typically occur over time periods of less than one second.

However, Grid Code compliance testing requires longer duration events, especially when the frequency decays from 52 Hz to 47 Hz over 5 seconds (as shown in Figure 3). This test increases the energy storage requirement for the asset, which is difficult to achieve using supercapacitors. However, this 5-second duration is not realistic in practice: stability events typically occur over less than 1 second.

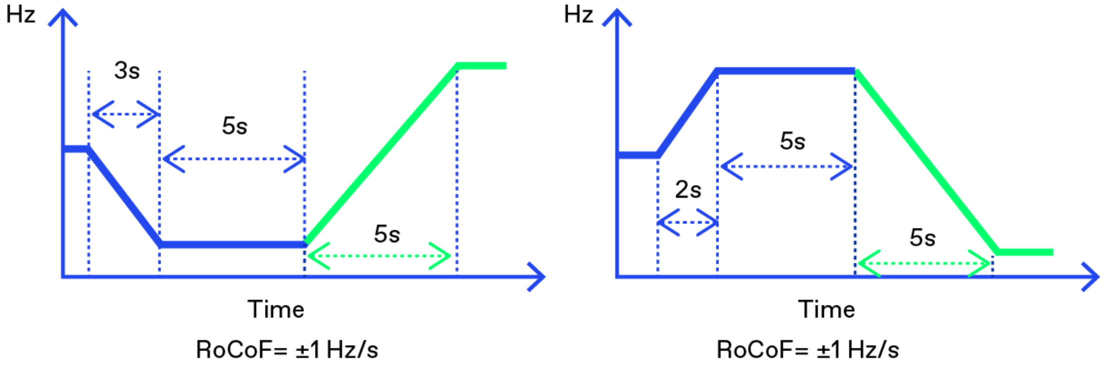

Figure 1: Long duration events involving 5s frequency ramps

This arduous compliance testing event, which requires significant energy storage, is preventing super-capacitor technology from being used for the short-term energy bursts for which they should be used. By relaxing these requirements, the GB power system will see a greater diversity of inertia providing devices which would work to lower the cost of inertia. The GFM STATCOM with supercapacitors could inject more power in the first 1-2 seconds to slow the initial frequency decline. After that, other frequency response sources take over. These sources are slower but would still react within seconds. It would also help with downsizing physical devices, and thus, reducing the cost of INCENTIVE solution deployment.

1.3.3. System strength from GFM assets

GFM devices are often not rated correctly for one of their most valuable functions: enhancing system strength. This is due to metrics being used to describe system strength, which do not assess the entire offer of INCENTIVE devices.

Based on the current methods of measuring system strength, synchronous condensers appear as the preferred device to address system strength (see section 1.3.4 below). However, synchronous condensers come with substantial operating energy requirements (~1 to 1.5% of rated capacity). If metrics for system strength evolve to better capture the contribution of grid-forming devices, then they will likely offer capability with lower whole-life costs.

To improve future assessments, incorporating small-signal scanning methods and prioritising system strength from a small-signal perspective is recommended in the Grid Forming Best Practice Guidance, and in Grid Code testing requirements.

1.3.4. Stability market issues

The INCENTIVE project recommends that the Stability Market considers the benefits of longer contracting periods for stability assets, particularly those with longer operational lifespans. This would improve the overall cost of inertia provided, as the return on the stability asset would be over a longer period closer to the asset's lifetime, rather than the current 10-year contract length. However, as this is a rapidly evolving area. The need for stability provision and what technology is best to provide it will be impacted by many different future factors, such as the pace of future renewable development, the pace of storage development, the pace of future nuclear development, and the pace of technology development. Therefore, there may also be downsides to giving stability contracts of greater than 10 years. The design of NESO's Long-term Stability Market allows for longer than 10-year agreements where value can be derived.

Additionally, aligning Contracts for Difference (CfDs) and Stability Market tenders is a key practical future consideration. CfDs are the main revenue stream for offshore wind farms. The financial importance of the CfD to an offshore wind farm's financing will always eclipse the Stability Market. The Stability Market will be a secondary consideration when financing an offshore wind farm. Unless stability services are part of the CfD assessment, there is a likelihood that a Stability Market that is not aligned with the CfD tender will not be sufficient to incentivise offshore wind developers to include stability assets in their wind farm designs.

2. Background on INCENTIVE

The problem

With the UK's commitment to achieving 30GW of offshore wind by 2030, offshore wind capacity is expected to increase dramatically. However, to facilitate the required rapid rollout of non-synchronous, inverter-based renewable generation necessary to meet these targets, innovation is needed to prevent grid stability challenges from arising.

As inverter-based generation (i.e. renewable generation, including offshore wind) increases and synchronous generation decreases, the power system is becoming less stable. Nationally, inertia in the GB grid is falling, which is already leading to curtailment of renewable generation. Locally, there are areas of the GB network with increasingly low system strength, particularly at the edge of the network where offshore wind seeks to connect, which is already leading to issues in connecting new renewable generation.

Without innovative, low-cost solutions, onshore grids will become continue to become less stable, which will lead to issues in system operation and the curtailment of renewable generation. Ultimately, this will increase the likelihood of instability events, increase the cost of system operation, and slow the transition to Net Zero by maintaining reliance on synchronous fossil fuel generators on stand-by.

INCENTIVE's story

Offshore wind is due to become one of the main sources of electricity in GB by 2050. In 2021, preliminary work conducted within the Offshore Wind Accelerator[3], identified an opportunity to enable offshore wind farms to stabilise the onshore network using innovative technologies.

The INCENTIVE project was set up to seize this opportunity: to demonstrate how the electrical grid can be stabilised by installing innovative **energy storage and inverter technologies at the point of onshore grid connection of offshore wind farms** (i.e. the onshore substation). INCENTIVE is a unique project with an unparalleled consortium representing the transmission industry, the offshore wind industry and the supply chain, together with collaboration with Ofgem, DESNZ and NESO.

The project was conducted in three phases in three phases between 2022 and 2025:

- the Discovery Phase, which defined the problem and identified possible solutions;
- the Alpha Phase, which tested the technical, economic and regulatory feasibility of the solutions; and
- the Beta Phase, which addressed the barriers to deployment found in Alpha Phase feasibility studies. To do this, Beta Phase worked with three offshore wind farms currently in development in GB, using these as case studies for the technical, economic and regulatory innovation to enable a pathway to commercialisation of the solutions.

This report provides an executive summary of the project's findings.

[3] https://www.carbontrust.com/our-work-and-impact/guides-reports-and-tools/energy-storage-for-offshore-wind-with-innovative-converter-control

3. How can offshore wind contribute to grid stability?

3.1. Stability concepts: Inertia and system strength

As background, two areas of electrical stability are of key relevance to the INCENTIVE project.

Inertia

Inertia is the resistance of the power system to sudden changes in frequency; inertia keeps the grid steady when these changes occur and stop it from failing. Traditionally, power plants with large spinning masses have provided this inertia, which makes the grid more resilient to frequency fluctuations and associated potential blackouts.

INCENTIVE aimed to show that offshore wind, in conjunction with additional technologies such as energy storage, grid-forming devices and advanced control systems, can provide inertia to stabilise the grid in the absence of traditional inertia sources. The main responsibility for managing inertia in GB falls on the NESO, who has recently begun to procure inertia from the Stability Market to ensure reliable and resilient system operation.

System strength

System strength refers to the ability of the grid to maintain stable voltage levels and withstand disturbances. It is a measure of the sensitivity of the network to these disturbances. This concept is essential for evaluating the robustness of the electricity grid. Localised system strength can be an issue as specific regions may have weaker grid infrastructures, thereby increasing their vulnerability to instability. Offshore wind farms, for example, often face difficulties because they are far from onshore substations. The long cables used to transmit electricity to land can weaken the system, leading to voltage fluctuations.

INCENTIVE aimed to show that offshore wind farms can play a pivotal role in enhancing system strength by incorporating additional technologies that, in conjunction with the wind farm, contribute to voltage stability and reinforce grid resilience. Ensuring system strength is crucial for maintaining a stable and resilient power network, however, this is not individually procured by the NESO but is a characteristic of the network, which can impact the ability for renewables to export energy into the system.

3.2. INCENTIVE Solutions

INCENTIVE identified two emerging technologies of high maturity (i.e. high technology readiness level (TRL)) that could be integrated with future offshore wind farms in the near term to address stability issues. These are referred to as “INCENTIVE Solutions”:

INCENTIVE STATCOM

Grid following (GFL) offshore wind farm with a grid forming (GFM) static compensator (STATCOM) including supercapacitor energy storage as part of the onshore substation.

INCENTIVE BESS

GFL offshore wind farm with GFM battery energy storage systems (BESS) at or near the onshore substation.

The INCENTIVE STATCOM and INCENTIVE BESS have different capabilities; however, both can provide stability to the electricity system.

3.3. INCENTIVE Solution: INCENTIVE STATCOM

A STATCOM with GFM inverter and supercapacitor energy storage is an emerging advanced power electronics device that provides both voltage and frequency regulation, playing a crucial role in stabilising grids with low system strength. Unlike conventional STATCOMs, which only inject reactive power to support voltage, the GFM STATCOM with supercapacitor can contribute to inertia and system strength.

The GFM STATCOM with supercapacitor contributes to system inertia by rapidly injecting or absorbing active power to help stabilise the grid during frequency disturbances. This is achieved by the supercapacitors discharging a quick release of stored energy to slow the change of frequency of the network, thereby reducing the grid frequency change and maintaining stability.

The GFM STATCOM with supercapacitor energy storage additionally contributes to system strength by providing both active and reactive power support which helps to maintain voltage levels within the desired range and maintains a reliable robust grid.

3.4. INCENTIVE Solution: INCENTIVE BESS

A BESS with a GFM inverter is a significant advancement in energy storage technology, allowing power grids to function more reliably in a future driven by renewable energy. Unlike traditional GFL BESS storage, which merely responds to existing grid conditions, GFM BESS actively shapes and stabilises grid voltage and frequency. This capability makes it an attractive solution for grids with low inertia and low system strength.

GFM solutions in general have seen a large increase in popularity globally in the past decade. Specifically in GB, as part of the Stability Pathfinder, five new GFM BESS installations were awarded contracts in Scotland. In places such as Australia, several GFM BESS devices are already operational at both distribution and transmission levels, with more planned in the next few years.

The GFM BESS contributes to system inertia by rapidly injecting active power into the grid to counteract a fluctuation in frequency, effectively slowing the change of frequency of the network. This rapid response helps maintain grid frequency within safe limits, preventing potential system failures.

The GFM BESS can also contribute to system strength by providing voltage support, it achieves this through injecting or absorbing reactive power during disturbances, helping to stabilise local voltage levels.

3.5. Counterfactual solution: Synchronous condenser

Synchronous condensers are part of the FACTS (Flexible AC Transmission Systems) group of devices. They have a long history of use in the electrical system. The synchronous condenser operates similarly to a synchronous machine but is specifically targeted for reactive power response. They are spinning electrical machines connected to the network, designed to exchange minimal active power with the network under normal operating conditions. Its primary function is to exchange reactive power to provide voltage stability.

Synchronous condensers contribute to system inertia by being a physically spinning electrical machine directly connected to the grid. It is also possible to incorporate additional mass through a flywheel to enhance the inertia provided.

Synchronous condensers contribute to system strength by providing a large fault current in case of a short circuit in the system.

It is included in INCENTIVE's analysis as a counterfactual. It is a well-established technology that could be included at the onshore substation of an offshore wind farm. It can provide both inertia and system strength. However, it has drawbacks as it is expensive, particularly due to its ongoing cost of operation (as it is physically spinning at 50 Hz, it consumes energy and requires more maintenance than static devices like BESS or STATCOM)), and it is inefficient in providing inertia as a percentage of the installed capacity (only a small percentage of the installed inertia capacity can be utilised by the power grid, whereas the STATCOM can utilise nearly all of the installed inertia capacity).

4. INCENTIVE Solutions technical testing

4.1.1. Aims of technical testing

The technical testing undertaken in the INCENTIVE project aimed to answer these four questions:

1. Do INCENTIVE Solutions provide inertia and system strength in accordance with Grid Code requirements?
2. Are the Grid Code requirements appropriate for the technical rating of the INCENTIVE Solutions?
3. How can the technical specifications of INCENTIVE Solutions be optimised to maximise their benefit to the system, whilst minimising the cost?
4. Is there a benefit to co-locating INCENTIVE Solutions with offshore wind farms, rather than elsewhere on the system?

4.1.2. INCENTIVE Solutions testing set-up

The testing of the INCENTIVE Solutions was performed using the PSCAD simulation environment, with the test rig configured as illustrated in Figure 2. The Great Britain Grid Forming Best Practice Guide[4] was utilised to define the detailed test plan. The tests were divided into two areas: grid code compliance testing and frequency sweeping. The grid code compliance tests included frequency events, fault events, and angle events. The frequency and voltage phase angle events were applied by modulating the controllable voltage source of the AC Grid, while the fault scenarios were implemented by applying a solid fault at the Grid Connection Point. Two frequency scanning tools were used for small-signal frequency sweeping tests: the Network Frequency Perturbation (NFP) Scanning tool and the HVDC Centre's in-house Impedance Scanning tool.

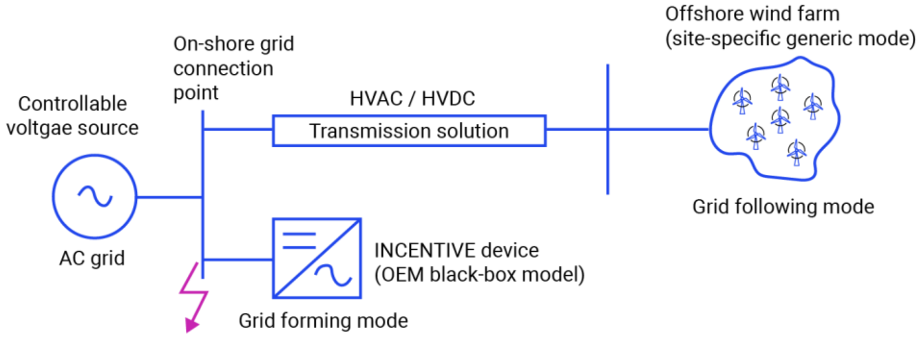

Figure 2: Configuration of the test environment implemented in PSCAD simulator

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[4] The Great Britain Grid Forming Best Practice Guide, published in April 2023, provides detailed guidance for stakeholders, including developers and manufacturers, on implementing grid-forming technology within the UK. This guide explains the requirements outlined in the Grid Code, particularly after the approval of Grid Code Modification GC0137 in early 2022, which introduced grid-forming capabilities as an optional standard. This guide was used as a baseline for the INCENTIVE testing. How Grid Forming Technology is changing, NESO, https://www.neso.energy/news/how-grid-forming-technology-changing

4.1.3. Observations from testing

With regard to the four key aims mentioned above, the following was observed:

5. Based on the outcome of testing, the INCENTIVE STATCOM and INCENTIVE BESS both demonstrated the expected grid-forming behaviour and were able to provide inertia-type active power response during a frequency event, which was confirmed by the result from the NFP scan. Additionally, from the impedance frequency scanning test, no identified resonance between the wind farm and the INCENTIVE Solution was found.
6. The testing of the INCENTIVE Solutions against Grid Code requirements demonstrated that the Grid Code best practices do not give a full picture of all the system strength benefits provided by the INCENTIVE STATCOM, with the tests more highly rating other technologies despite the same end performance.
7. To ensure stability, GFM solutions should be tested in networks where frequency variations are considered. Additionally, as response and reserve markets evolve, the interaction between inertia and frequency response must be optimized to prevent negative effects and improve efficiency. In relation to the INCENTIVE project, integrating the new dynamic containment service (DyC)[5]with GFM STATCOMs could reduce energy storage needs, making them a more cost-effective solution for the GB system.
8. The testing showed that there is a benefit in co-locating INCENTIVE solutions with offshore wind farms due to the presence of a large energy source, which is capable of slower frequency response to hand over to.

[5] NESO, "Dynamic Response Services Provider Guidance v.9," NESO, 10 2024. [Online]. Available: https://www.neso.energy/document/276606/download

5. Business models for INCENTIVE Solutions

The INCENTIVE project created business models for INCENTIVE Solutions, including who should own the assets, how the costs of the assets can be recouped by the owner to justify the added investment in the assets, and what market and regulations need to be considered.

5.1.1. Summary of business model for INCENTIVE STATCOM

There are two business model options for the INCENTIVE STATCOM.

1. Option 1: The offshore wind farm operator (i.e. a generator licence holder) owns the GFM STATCOM with supercapacitor asset at the onshore substation, with the OFTO owning the remainder of the onshore substation.
2. Option 2: The OFTO (i.e. a transmission licence holder) owns the GFM STATCOM with supercapacitor asset at the onshore substation, along with the remainder of the onshore substation

As a guiding principle, where the business case relies on revenue from the Stability Market, Option 1 must be selected. Where the business case is based upon local system strength (or by being mandated in future), Option 2 may be preferred.

To support this guiding principle, various considerations are set out below.

Revenue

- **Option 1: market access**. INCENTIVE STATCOMs can earn revenue by providing stability and reactive compensation services. Under current GB licence conditions, to earn revenue for the stability services the STATCOM provides, the asset owner must have access to the Stability Market (for inertia provision) and Obligatory Reactive Power Service (ORPS) for reactive power compensation. A generator can participate in those markets and hence use these markets to generate revenue. See section 5.2 for more details.
- **Option 2: regulated return.** A transmission licence holder cannot access the market revenue mentioned above. Rather, the revenue would come from regulated revenue called the transmission network use of system (TNUoS) charge. This could be paid by the offshore wind developer (standard approach) or socialised amongst all network users (as has been proposed in the code modification CMP 418[1]).
- **Option 1 and 2: increased wind farm output**. Especially in areas of low system strength, the INCENTIVE STATCOM has the ability to increase the local system strength which could allow the offshore wind farm to export more power. This would increase offshore wind farm output and hence increase the revenue of the generator.

Asset ownership regulations

- **Option 1.** This is a novel arrangement that will require a sandbox application to Ofgem, as in business-as-usual, the STATCOM would be owned the OFTO. However, work done in INCENTIVE has made significant headway to de-risking Option 1. If any readers wish to know more details, please contact the Carbon Trust.
- **Option 2.** This is the standard ownership arrangement and so may have fewer regulatory issues. However, the OFTO regime's cost assessment process may, which demands offshore wind developers to minimise costs of the onshore substation, may create issues for developers to build and then divest GFM STATCOM with supercapacitors instead of standard STATCOMs. Ofgem carefully scrutinises developers' capital expenditure to ensure unnecessary assets are not transferred to the OFTO, and that substation equipment is not specified past what is required to facilitate the transfer of power from the wind farm to the onshore system. The developer would therefore need to show that the GFM STATCOM with supercapacitors is necessary for the transfer of power from the wind farm to the onshore system.

5.1.2. Summary of business model for INCENTIVE BESS

There is only one option for the business model for the INCENTIVE BESS: offshore wind farm operator (i.e. a generator licence holder) owns the onshore GFM BESS asset, with the OFTO owning the onshore substation.

Revenue

- GFL BESS can earn revenue by providing a range of active and reactive power services. INCENTIVE focussed on the additional revenue that a GFM BESS can generate due to its ability to provide stability services. Under current GB licence conditions, to earn revenue from stability services, the GFM BESS must have access to the Stability Market. Being owned by a generator allows the GFM BESS to access the Stability Market.
- In areas of low system strength, the INCENTIVE BESS has the ability to increase the local system strength which could allow the offshore wind farm to export more power. This would increase offshore wind farm output and hence increase the revenue of the generator.

Asset ownership

- Transmission licence holders are barred from participating in energy markets, the asset cannot be owned and operated by a transmission licence holder. No alterations to codes or energy licences are needed to facilitate generator ownership of the GFM BESS.

5.1.3. Business model considerations

From the above, INCENTIVE has devised two potential business models. However, fundamentally, when designing and building the onshore substation, an offshore wind developer must have a reason to include an INCENTIVE Solution. GFM STATCOM with supercapacitors is more expensive than a business-as-usual GFL STATCOM. A GFM BESS is more expensive than a GFL BESS. For a successful business model, the offshore wind developer must see benefits to these additional costs. There are three possible reasons:

- **Market pull**
  - The offshore wind developer envisages sufficient from revenue generated by the asset in the Stability Market. Section 5.2 below shows the potential for an incentivised market pull; however, section 1.3.4 discusses issues with this approach.
- **Benefit to wind farm**
  - Particularly in locations of low system strength, the INCENTIVE Solution may strengthen the local grid, which will then allow more energy export from the offshore wind farm. Section 5.3 below discusses this in more detail; however, section 1.3.3 sets out necessary changes to enable this.
- **Mandating**
  - This is not currently the case; but there are ongoing discussions in GB about requiring renewable generators to provide stability capabilities. INCENTIVE Solutions could be a way of meeting any such requirement. Section 1.3.4 discuss this in more detail.

5.2. Cost-benefit analysis for INCENTIVE Solutions Inertia: Benefit analysis results

Both the INCENTIVE STATCOM and INCENTIVE BESS can provide cost-competitive inertia to the system, which can reduce the cost of system operation and increase revenues for offshore wind developers.

Regarding the method, the Stability Market is an emerging national inertia market, making it possible to assess the price of inertia, and hence to assess if INCENTIVE Solutions can provide inertia and lower cost than the current inertia price (and hence add benefit to the system and to the INCENTIVE Solution owners)[6].

Table 1 presents a high-level overview of the CBA results, for the whole system assessment, the assessment period is 25 years, with a hurdle rate of 3.5%. For the developer-owned assessment, the assessment period is 10 years, with a hurdle rate of 8%. The key metric shown is the "calculated cost of inertia" from the different technologies and assessment perspectives. This effectively is a switching value (where net present value is zero), which gives an indicative inertia price that an asset would need to achieve through tendering to cover its costs. It should be noted that the GFM BESS and GFM STATCOM with supercapacitors are emerging technologies; we expect costs will decrease over time, leading to increased competitiveness.

Table 1: Calculated inertia cost for different technology options and assessment perspectives

Technology option	CBA perspective	Calculated inertia cost range (£/GWs/hr)	Market comparison
INCENTIVE STATCOM	Whole system / economic	230 - 270	This is lower than over 50% of the tenders in the Stability Pathfinder
	Developer	680 - 750	Lower price than around 25% of the Stability Pathfinder tenders.
INCENTIVE BESS	Whole system / economic	110 - 200	Less than almost all Stability Pathfinder tenders
	Developer	140 -230	

[6] The Stability Market owners, NESO, have not been part of the CBA analysis process.

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5.2.1. INCENTIVE STATCOM inertia cost-benefit

This shows that the INCENTIVE STATCOM is an economically feasible alternative to current business-as-usual inertia-providing technologies. With current technology costs, it has the potential to offer inertia at prices comparable with existing options bidding into long-term tenders.

However, the INCENTIVE STATCOM challenges the current regulatory and ownership model for equipment that provides reactive power and inertia (see section 5.1.1 above). This poses two significant challenges:

1. Where the INCENTIVE STATCOM ownership remains with the developer: this can lead to a higher inertia price, probable developer benefits, but an uncertain level of benefit for the consumer.
2. Where INCENTIVE STATCOM is ownership is transferred to the OFTO: this provides significant benefit to the system through a reduced cost in system services, but provides little motivation to the developer for installation (for inertia alone, although see section 5.3 for other motivations to install the INCENTIVE STATCOM); it brings additional, unfamiliar responsibilities to the OFTO and potentially disrupts the new Stability Market arrangements.

5.2.2. INCENTIVE BESS inertia cost-benefit

The INCENTIVE BESS has a low incremental cost compared to a business-as-usual BESS and can deliver inertia at a price that is competitive with historical prices. This option would see the system receive benefits in line with the reduction in the price that it pays for the inertia from the INCENTIVE BESS and the ability to add inertia payments to a typical BESS revenue stack could be attractive to developers. The potential to switch between revenue streams, coupled with the low incremental cost of this option suggests that it would be best suited to operation within the mid-term and day-ahead Stability Markets.

5.3. Local system strength: Benefit analysis results

System strength can impact on the speed and volume of the roll-out of offshore wind. When connecting to areas of the electricity network with low system strength (such as the North of Scotland), it may be necessary to make interventions to improve system strength (either on the network or at the OWF point of connection) to make the connection viable or prevent excessive stability-related curtailment occurring.

The specific impact on an offshore wind farm developer from addressing system strength issues at their point of connection was assessed. Current metrics for measuring system strength were used and system ratings and costs were adjusted accordingly. The results highlight that to correct system strength issues (at least from a short circuit level perspective) , the synchronous condensers will likely be the cheapest solution, although it is noted that running costs are significant and subject to uncertainty over time. However, where inertia payments are applied then the return from the INCENTIVE STATCOM is substantial and overall presents a more economical solution. Further, if alternative system strength metrics are used, this may further increase the case for the INCENTIVE STATCOM (see section 1.3.3).

Analysis of the BESS presents a relatively low return in comparison to the other technologies. Returns in this case are highly sensitive to the assumed BESS revenue benchmark, which has declined from previous analysis within the Alpha phase of this project. Previous conclusions around the benefits of inverter overrating are still valid despite this finding. A reduction in future BESS storage costs will also improve returns.

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