Future of Reactive Power
Market Analysis - Case Studies Workshop

11 November 2021

Agenda

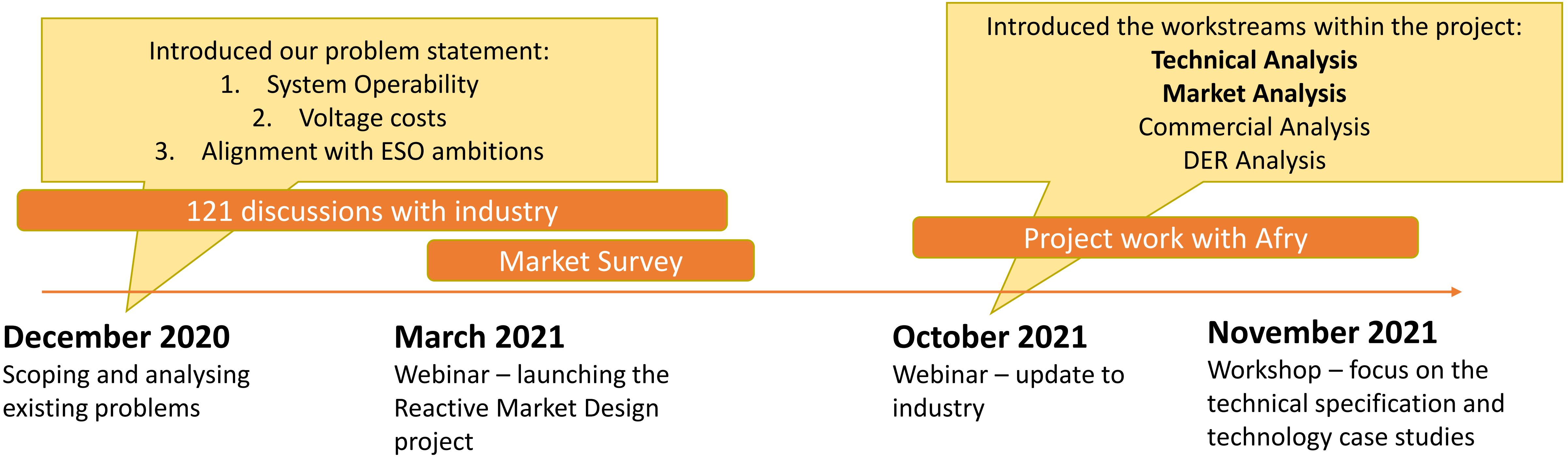
Welcome and Housekeeping	Vicci Page
Purpose of the Workshop	Eleanor Horn
Draft Technical Service Design Consideration	David Gregory
Case Studies: Review and Feedback	Afry: Simon Siöstedt & Jimmie Elek
Next Steps and Close	Vicci

Purpose of the Workshop

Eleanor

Purpose of the Workshop

- Test whether there are any thoughts or challenges with our **initial draft technical design**
- Share our **Technology Case Studies** with you and use this workshop to validate the information we have collected so far
- The workshop will also be an opportunity for us to fill up any gaps in knowledge on the case studies
- We'd like your feedback on the Case Studies:
    - Are they clear and understandable?
    - Have we missed anything?



Introduced our problem statement:
1. System Operability
2. Voltage costs
3. Alignment with ESO ambitions

121 discussions with industry

Market Survey

Introduced the workstreams within the project:
Technical Analysis
Market Analysis
Commercial Analysis
DER Analysis

Project work with Afry

December 2020
Scoping and analysing existing problems

March 2021
Webinar – launching the Reactive Market Design project

October 2021
Webinar – update to industry

November 2021
Workshop – focus on the technical specification and technology case studies

Technical Requirement Design Update

David Gregory

Draft Technical Service Design Consideration

Overall Technical Need

- To meet, or help meet the NETS SQSS voltage criteria (Chapter 6) in planning and/or operational timescales, depending on the market structure, covering:
  - Steady-state criteria
    - Both pre- and post-fault (SQSS terms this as following a *secured event*)
  - Step-change criteria (SQSS defines this as the difference in voltage between that immediately before a *secured event*, and that at the end of the *transient time phase* after the event – typically 5 seconds after the initiating event)
- Note that there are potential impacts on license conditions here, as currently both the ESO and TOs have the responsibility to ensure network compliance.

Requirements

- Current thinking is that the requirement will be defined as an effective MVAr value, with location, effectiveness and zoning of requirements being determined by the technical analysis workstream.
- Based on the *assumption* that effectiveness is the most appropriate way to quantify the locational nature of reactive power requirements, this is likely to be composed of two values (though this is subject further work and change):
  - $Eff_{Dx\text{-}Tx}$ – this is the effectiveness, in percent, of a distribution connected participant at the transmission GSP
  - Eff_{Tx} – this is the effectiveness, in percent, of a transmission connected participant at their location within a zone
- The overall effectiveness (Eff_{tot}), in percent, of a distribution connected participant connected to a GSP within a zone would therefore be given by:
  - $Eff_{tot} = Eff_{Dx\text{-}Tx} \times Eff_{Tx}$

Draft Technical Service design Consideration

Minimum size

- Minimum size for any solution is likely to be determined by various factors:
  - Dispatch system limitations
    - Size of minimum dispatch instruction
    - “Aggregation” of dispatch instructions – will there need to be numerous manual dispatch instructions, or a single instruction that can be sent to multiple parties?
  - Overall requirements size and economic viability of procuring/constructing multiple small assets to cover a large requirement
- Setting too restrictive minimum size could shut out smaller distribution connected providers, who could meet the overall requirement if aggregated together, demonstrating the potential benefits of aggregation at this level
- Any minimum size is likely to be based on the effective MVAr

Maximum size

- Maximum size of a reactive power provider is usually limited by technical considerations, such as voltage step change, and will be subject to technical analysis to ensure that the applicable standards can be met.
- Procurement strategy, such as contingency cover for unavailability, is a relevant consideration for maximum size as well. There will be a need to avoid non-optimal over-procurement, which would likely lead to a solution favouring multiple smaller and diverse sources of reactive power rather than a limited number of large providers.
- Any maximum size requirements placed on distribution participants will be determined by the arrangements implemented for distribution networks and will be subject to DNO technical assessments.

Draft Technical Service design Consideration

Location	• The location(s) will be determined by the requirements analysis, zonal definition and effectiveness which should indicate the most effective location(s).
Dispatch	• Dispatch requirements are not dealt with here. They will be driven by the overall market design and the timescales in which it operates • If dispatch is required for a short term market, then it is envisaged that there will be an electronic dispatch system able to dispatch reactive power requirements within the appropriate timescales. The Grid Code currently requires this to be within 2 minutes of an instruction being issued • Depending on the technology deployed, the instruction may be (though not limited to) to operate at a certain reactive power output, operate to a specified target voltage, arm an automatic system, etc. until instructed otherwise • Referring to the minimum size considerations, there may be a need to dispatch multiple assets with a single instruction

Draft Technical Service design Consideration

Reactive Power Control

- It is envisaged that two basic forms of reactive power control will be required:
  - A **constant reactive power mode**, where the reactive power output delivered by the provider will be fixed at a constant or near constant value (tolerances to be determined). This would normally be used to meet SQSS steady state requirements.
  - A **target voltage mode**, where the reactive power output delivered by the provider varies depending on the difference between the target voltage and the system voltage. This would normally be used to meet SQSS step change requirements, though with potential overlap on meeting stability requirements as well.

    For synchronous providers, this is likely to be similar to existing Grid Code requirements, with the machine terminal volts being held at a voltage by the AVR

    For non-synchronous providers, this is likely to be similar to the existing Grid Code requirements, with a setpoint voltage and slope characteristic determining the reactive power output)

    To satisfy the voltage step change criteria, the reactive power output will need to be delivered within 5 seconds of a step in voltage
- Whilst each control mode has been highlighted as being used for a specific requirement, there may be a need to use a combination of both to meet steady state requirements to provide voltage regulation, such that normal minute-by-minute changes in system conditions do not give rise to excessive voltage changes and therefore flicker
- Other control scenarios could be possible (could be considered as quasi-constant or quasi-target voltage):
  - Reactive power ramping on receipt of a signal or on detection of a voltage step or significant voltage change?
  - Automatic switching of reactive equipment on receipt of a signal or on detection of a voltage step or significant change in voltage?
  - Could these be interfaced with existing TO equipment (automatic reactive switching schemes, etc.)?
  - A **constant reactive power mode** that achieves this by adjusting the **target voltage** to achieve the target reactive power level, using a slow acting control loop. This will allow any fast acting control loops to adjust the reactive power output in the event there is a step change in system voltage, or other event on the system.

Draft Technical Service design Consideration

Metering	• These requirements have not been determined at this stage, though metering will be required for settlements purposes, performance monitoring, and operational awareness.
Additional considerations	• To meet SQSS voltage step change requirements, providers will also need to remain connected to the system during and after a fault. Therefore, participants we be expected to be able to: • Meet the requirements set out in G99, where they are distribution connected • As a minimum, meet the existing Grid Code requirements for fault ride through • It is recognised that shunt reactors and capacitors will not necessarily meet fault ride through requirements, as their reactive power output will vary with their terminal voltage • Installation of shunt reactors and capacitors can give rise to onerous resonance conditions and other electromagnetic phenomena, that may limit where these types of technologies can be deployed, or place restrictions on their size • Harmonics impacts will also need to be considered • It is expected that providers will still need to meet all applicable requirements of the Grid Code and SO-TO Code

Case Studies: Review and Feedback

Simon and Jimmie

SUMMARY

There are a diverse range of technologies capable of providing reactive power output, but technical aspects vary widely – technical capability for converter connected equipment is evolving

Technologies investigated in depth have been rated based on their performance for each KPI

The Harvey Ball illustrate each technology's rating for each KPI based on the following scale:

○	Poor Performance
◔	Sufficient Performance
◑	Intermediate Performance
◕	Good Performance
●	Excellent Performance

Converter based *Synchronous*

Technologies		Reactive power Base[4]	Reactive power High[4]	MVAr output at 0MW	CAPEX[3]	OPEX[3]
Converter based	Onshore Wind	◔	◕	Yes	◔	◔
	Offshore Wind	◔	◕	Yes	◔	○
	Solar PV	◔	◕	Yes	◑	◑
	Battery Energy Storage System	◔	◕	Yes	◑	◑
	HVDC	◔	◕	Yes	◕	●
Synchronous	Pumped Hydro Energy Storage	◑	◑	Yes[1]	◔	●
	CCGT/OCGT	◑	◑	No[2]	◑	◔
	Nuclear	◑	◑	No	○	○
	Synchronous Condenser with Flywheel	●	●	Yes	●	◕

Note:[1]Commonly operates in a mode where turbine spins in air and provide reactive power [2]Can be designed to operate in synch-comp mode [3]Capex and Opex assessed on a per MVAr basis, we recognise that for most technologies this is a secondary consideration in terms of the business case. [4]Base equals NGESO grid codes and High equals ENTSO-E definition of maximum grid code capability for non-synchronous generators. NGESO grid codes for synchronous generators.

Assumptions for the deep dive per technology – Reactive power provision

- **High, Base and Low range/case**
  - The high, base and low range/case for the typical unit size, CAPEX, OPEX and capabilities are not linked to each other but rather presented per category to give an indication of the range
- **CAPEX and OPEX**
  - 2020 cost data where the cost per kW and kWh includes everything from the generator to the point of connection to the DNO/TSO grid
- **Reactive capability**
  - Base case: NGESOs grid codes requirement for the specific technology
  - High case: Higher grid code requirements equals ENTSO-E definition of maximum grid code capability for non-synchronous generators and NGESO grid codes for synchronous generators (same as base case)
  - Low case: Lower grid code requirements from other TSOs to produce reactive power
- **Grid codes - Additional capability beyond ORPS (MVAr/MW)**
  - Differentiation between High Case and Base case
- **Is MVAr output at 0MW generation possible?**
  - If a technology can/can't produce reactive power without producing active power
- **Availability dependences to provide reactive power**
  - What determines the reactive power provision per active power

In focus

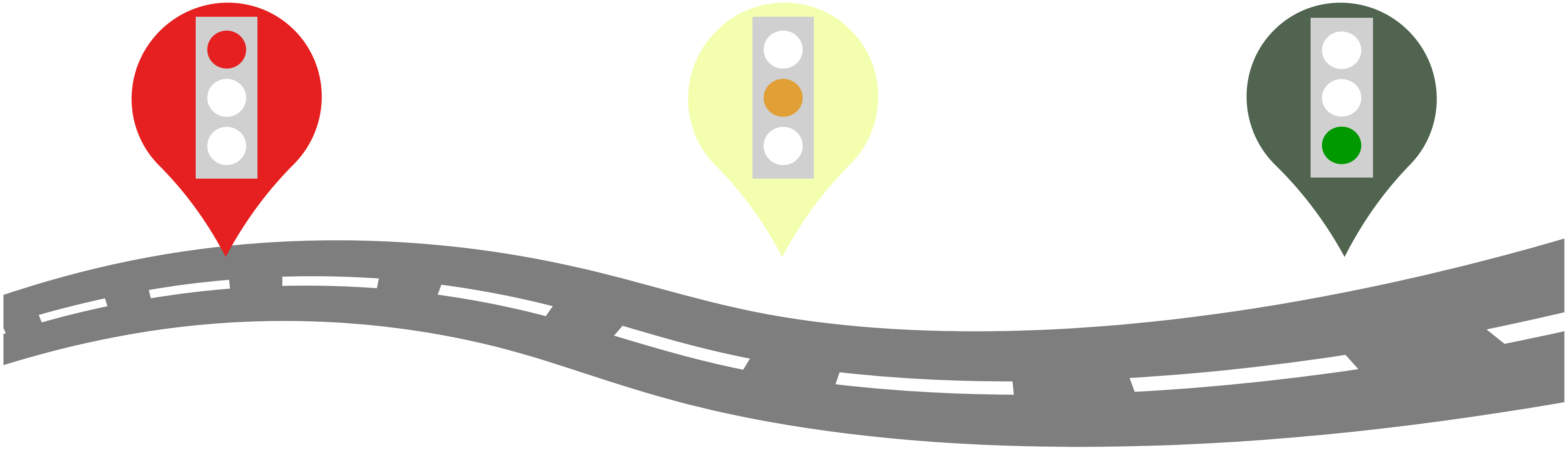
Example	**Base case**	**High range**	**Low range**
Typical unit size (MW)	100	200	50
Capex (£/kW)	500	1 000	250
Opex (£/kW/year)	40	50	30
Leading reactive capability (MVAr range per MW at full load)	0.33	0.50	0.30
Lagging reactive capability (MVAr range per MW at full load)	0.33	0.65	0.30
Grid codes - Additional capability beyond ORPS (MVAr/MW at full load)	Leading = **0.17** Lagging = **0.32**		
Is MVAr output at 0MW generation possible?	**Yes/No**		
Availability dependencies to provide reactive power	Can only provide reactive power when XXX		
Static only or dynamic? (Reactive Power)	Static and dynamic		
Facilities according to Heatmap	TBC		
Maturity (RAG) based on maximum MVAr capability	○ ● ○		

Red, yellow and green traffic lights indicate maturity of the MVAr capability of the technology (rather than maturity of the MW capability)

- Red light indicate **low technical readiness level** and immature technology
- **Fundamental or applied research conducted** of technology. Proof of concept has been established

- Yellow light indicate **medium technical readiness level** and a maturing technology
- **Laboratory testing of components and full system conducted**. Prototype of technology deployed

- Green light indicate **high technical readiness level**
- Operational pilot system demonstrated, technology incorporated in commercial design or **full-scale deployment of technology**



CASE STUDIES

Onshore Wind

Characteristics

- Reactive capability for onshore wind has the potential to be much higher than the Base case and High range which is reflected in if MVAr can be produced at 0MW.
- Wind power generators (WPG) can be classified into two main types: fixed speed and variable speed where variable speed configurations are the most common today. Variable speed turbines are fully or partly connected via a converter between the grid and the generator and has the potential to regulate the voltage.
- The data for onshore wind are focussed on variable speed turbines and especially type 3 (DFIG) and type 4 (full power converter).
- Each wind farm consist of multiple individual wind turbines with a power ranging between generally 1 MW to 5-6 MW per turbine. Each wind turbine is then connected by a cable which forms the internal grid of the wind farm which is connected to the main substation of the grid.

	Base case	High range	Low range
Typical unit size (MW)[1]	150	450	~1-5
Capex (£/kW)[2]	1 113	1 260	966
Opex (£/kW/year)	44	50	38
Leading reactive capability (MVAr range per MW at full load)	0.33	0.50[3]	0.33
Lagging reactive capability (MVAr range per MW at full load)	0.33	0.65[3]	0.33
Grid codes - Additional capability beyond ORPS (MVAr/MW at full load)	Leading = **0.17** Lagging = **0.32**		
Is MVAr output at 0MW generation possible?	**Yes**		
Availability dependencies to provide reactive power	Can only provide reactive power when wind is blowing (unless withdrawing active power from the grid). Accessible absolute MVAr output lower at lower wind levels.		
Static only or dynamic? (Reactive Power)	Static and dynamic, converter-based		
Facilities according to Heatmap	TBC		
Maturity (RAG) based on maximum MVAr capability	○ ● ○		

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[1] Per wind farm. [2] Include cost of turbines, grid asset and grid connection cost. [3] ENTSO-E definition of maximum grid code capability for non-synchronous generators

CASE STUDIES

Barriers & Enablers for Onshore Wind

	Barriers			Enablers		
Reactive power	– Existing grid codes and compliance needs limit capabilities	❯	– Manufacturers follow existing market arrangements for converters and control loops, which may limit functionality	– Not fully utilised reactive power capability (potential)	❯	– The reactive capability of the WTG has been determined by the grid codes rather than the WTG capability
	– Converters are not dimensioned to provide high reactive power per active power	❯	– Higher reactive power per active power could limit the life time of the converters	– Generate or consume reactive power (leading/lagging)	❯	– Potential to be a very flexible source for reactive power
	– Reactive power provision generally linked to available active power	❯	– Low wind periods could lead to low production of reactive power	– Advantageous to combine with storage solutions	❯	– In order to capture more value wind can easily be combined with e.g. batteries to provide services during more hours of the day
	– Higher losses when producing reactive power	❯	– Higher losses when operating at power factors deviating significantly from a power factor close to 1	– Reactive power provision when no wind possible	❯	– Possible to provide reactive power by drawing power from other sources (such as the grid[1])

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[1] Cost of energy draw must be considered

AFRY
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CASE STUDIES

Offshore Wind

Characteristics

- Reactive capability for offshore wind has the potential to be much higher than the Base case and High range which is reflected in if MVAr can be produced at 0MW.
- Wind power generators (WPG) can be classified into two main types: fixed speed and variable speed where variable speed configurations are the most common today. Variable speed turbines are fully or partly connected via a converter between the grid and the generator and has the potential to regulate the voltage.
- Offshore wind connected by HVAC theoretically has the same characteristics as onshore wind with the differences that the connection to the main grid generally are longer than onshore wind and that that electricity needs to be transformed more than one time from the turbine to the main grid.
  - It should be noted that whilst technical characteristics are similar, GB arrangements mean a wide array of solutions are employed to meet connection requirements.

	Base case	High range	Low range
Typical unit size (MW)[1]	750	1 000	500
Capex (£/kW)[2]	1 900	2 117	1 680
Opex (£/kW/year)	91	105	76
Leading reactive capability (MVAr range per MW)	0.33	0.50[3]	0.33
Lagging reactive capability (MVAr range per MW)	0.33	0.65[3]	0.33
Grid codes - Additional capability beyond ORPS (MVAr/MW at full load)	Leading = **0.17** Lagging = **0.32**		
Is MVAr output at 0MW generation possible?	**Yes**		
Availability dependencies to provide reactive power	Can only provide reactive power when wind is blowing (unless withdrawing active power from the grid). Accessible absolute MVAr output lower at lower wind levels.		
Static only or dynamic? (Reactive Power)	Static and dynamic, converter-based		
Facilities according to Heatmap	TBC		
Maturity (RAG) based on maximum MVAr capability	○ ● ○		

[1] Per wind farm. [2] Include cost of turbines, grid asset and grid connection cost. [3] ENTSO-E definition of maximum grid code capability for non-synchronous generators.

CASE STUDIES

Barriers & Enablers for Offshore Wind

Reactive power

Barriers

Existing grid codes and compliance needs limit capabilities	Manufacturers follow existing market arrangements for converters and control loops, which may limit functionality
Converters are not dimensioned to provide high reactive power per active power	Higher reactive power per active power could limit the life time of the converters
Reactive power provision generally linked to available active power	Low wind periods could lead to low production of reactive power
Long distance to the point of interconnection (POI) to the main grid	Uncertain of how the reactive capability of the converters will affect at the POI as cables and several voltage transformations is in between
Higher losses when producing reactive power	Higher losses when operating at power factors deviating significantly from a power factor close to 1

Enablers

Not fully utilised reactive power capability	The reactive capability of the WTG has been determined by the grid codes rather than the WTG capability
Generate or consume reactive power (leading/lagging)	Potential to be a very flexible source for reactive power
Advantageous to combine with storage solutions	In order to capture more value wind can easily be combined with e.g. batteries to provide services during more hours of the day
Reactive power provision when no wind possible	Possible to provide reactive power by drawing power from other sources (such as the grid[1])

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[1] Cost of energy draw must be considered

CASE STUDIES

Solar PV

Characteristics

- Reactive capability for solar PV has the potential to be much higher than the Base case and High range which is reflected in if MVAr can be produced at 0MW.
- Solar PV generation utilises solar power to convert to electricity using photovoltaics. The direct current produced is converted to alternating current via a converter which can be further used for control of active and reactive power flow.
- Rapidly decreasing prices and matured technology over the past few years, enabling both small- and large-scale PV installations.
- Reactive power provision usually requires availability of active power → no reactive power provision during night; new technologies enable operation in VAR compensation mode in which power is drawn from the grid, regulate the DC bus, and inject the desired level of reactive power (e.g., Q at Night, SMA).

	Base case	High range	Low range
Typical unit size (MW)	10-30	70	1
Capex (£/kW)[1]	535	588	483
Opex (£/kW/year)	26	30	22
Leading reactive capability (MVAr range per MW)	0.33	0.50[2]	0.33
Lagging reactive capability (MVAr range per MW)	0.33	0.65[2]	0.33
Grid codes - Additional capability beyond ORPS (MVAr/MW at full load)	Leading = **0.17** Lagging = **0.32**		
Is MVAr output at 0MW generation possible?	**Yes**		
Availability dependencies to provide reactive power	Can only provide reactive power when sun is shining without withdrawing active power from the grid. Lower solar irradiation results in lower accessible absolute MVAr range.		
Static only or dynamic? (Reactive Power)	Static and dynamic, converter-based		
Facilities according to Heatmap	TBC		
Maturity (RAG) based on maximum MVAr capability	○ ● ○		

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[1] Include cost of PV-cells, converter, grid asset and grid connection cost [2] ENTSO-E definition of maximum grid code capability for non-synchronous generators

CASE STUDIES

Barriers & Enablers for Solar PV

Reactive power

Barriers	
– Low capacity installations	– Lower scalability than other technologies, often quite small installations
– Existing grid codes and compliance needs limit capabilities	– Manufacturers follow existing market arrangements for converters and control loops, which may limit reactive power provision
– Generally connected to the distribution grid instead of the transmission grid	– The service will provided to the DNO grid, an intermediate step to reach the Transmission network
– Reactive power provision linked to available active power	– Periods without sun could lead to low production of reactive power
– Converters are not dimensioned to provide high reactive power per active power	– Higher reactive power per active power could limit the life time of the converters

Enablers	
– Implementation of VAR compensation mode possible	– Increases suitability for reactive power provision, enabling provision during the night time
– Generate or consume reactive power (leading/lagging)	– Potential to be a very flexible source for reactive power
– Advantageous to combine with storage solutions	– In order to capture more value solar PV can easily be combined with e.g. batteries to provide services during more hours of the day
– Not fully utilised reactive power capability	– The reactive capability of the PV has been determined by the grid codes rather than the PV converter capability

CASE STUDIES

Battery Energy Storage System (BESS)

Characteristics

- Reactive capability for BESS has the potential to be much higher than the Base case and High range which is reflected in if MVAr can be produced at 0MW and the flexible and potential high availability.
- Battery Energy Storage System (BESS) is a flexible technology with good reactive capability.
- BESS could be dimensioned in a modular setting, where many battery cells could be compiled to meet unit size request.

	Base case	High range	Low range
Typical unit size (MW)[1]	50	200	10
Capex (£/kW)[2]	572	622	521
Opex (£/kW/year)[2]	25	29	21
Leading reactive capability (MVAr range per MW)	0.33	0.50[3]	0.33
Lagging reactive capability (MVAr range per MW)	0.33	0.65[3]	0.33
Grid codes - Additional capability beyond ORPS (MVAr/MW)	Leading = **0.17** Lagging = **0.32**		
Is MVAr output at 0MW generation possible?	**Yes**		
Availability dependencies to provide reactive power	Can provide reactive power independently but storage level of cells will be depleted.		
Static only or dynamic? (Reactive Power)	Static and dynamic, converter-based		
Facilities according to Heatmap			
Maturity (RAG) based on maximum MVAr capability	● ○ ○		

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[1] Refers to the size of the converter and not storage potential (MWh). [2] 2hr Li-ion battery, 100 MWh, Includes cost of battery, inverters, various electronic control systems, grid connection, EPC, land, permitting; [3]ENTSO-E definition of maximum grid code capability for non-synchronous generators

CASE STUDIES

Barriers & Enablers for Battery Energy Storage System (BESS)

Reactive power

Barriers

Existing grid codes and compliance needs limit capabilities	❯	Manufacturers follow existing market arrangements for converters and control loops, which may limit functionality
Generally connected to the distribution grid instead of the transmission grid	❯	The service will provided to the DNO grid, an intermediate step to reach the Transmission network
Converters are not dimensioned to provide high reactive power per active power	❯	Higher reactive power per active power could limit the life time of the converters

Enablers

Excellent reactive power provision	❯	Can balance grids with drain/supply of active and reactive power
Plannable provider of reactive power	❯	BESS could provide reactive power fast and when the demand for reactive power services is high
Reactive power provision independent from active power	❯	Could deliver reactive power without producing any active power
Provide reactive power while charging	❯	BESS can provide reactive power to the grid when charging resulting in high availability
Not fully utilised reactive power capability	❯	The reactive capability of the BESS has been determined by the grid codes rather than the BESS capability

CASE STUDIES

HVDC Voltage Source Converter

Characteristics

- Reactive capability for HVDC VSC has the potential to be much higher than the Base case and High range which is reflected in if MVAr can be produced at 0MW.
- Multi-terminal system ability, can also be used with LCC links (Hybrid) but mainly focus on HVDC VSC for this case study.
- High Voltage Direct Current (HVDC) Voltage Source Converter (VSC) is suited for long-distance interconnection, e.g., offshore wind or country interconnections.
- Costs: Capex/MW declines non-linearly for larger units, opex/MW declines almost linearly for larger units.
- Not economical for short cable lengths.

	Base case	High range	Low range
Typical unit size (MW)	1 000	2 000	500
Capex (£/kW)[1]	252	210	294
Opex (£/kW/year)	1.4	1.7	1.2
Leading reactive capability (MVAr range per MW)	0.33	0.50[2]	0.33
Lagging reactive capability (MVAr range per MW)	0.33	0.65[2]	0.33
Grid codes - Additional capability beyond ORPS (MVAr/MW)	Leading = **0.17** Lagging = **0.32**		
Is MVAr output at 0MW generation possible?	**Yes**		
Availability dependencies to provide reactive power	Can only provide reactive power when the HVDC link is in operation, otherwise disconnected from the grid		
Static only or dynamic? (Reactive Power)	Static and dynamic, converter-based		
Facilities according to Heatmap			
Maturity (RAG) based on maximum MVAr capability	○ ● ○		

[1] Include cost of the complete system with inverter, grid assets and transformers (excl. cable). [2] ENTSO-E definition of maximum grid code capability for HVDC converter stations

CASE STUDIES

Barriers & Enablers for HVDC

Reactive power

Barriers

Existing grid codes and compliance needs limit capabilities	Manufacturers follow existing market arrangements for converters and control loops, which may limit functionality
Reactive power provision	Can only provide reactive power when the HVDC link is in operation, otherwise disconnected from the grid
Converters are not dimensioned to provide high reactive power per active power	Higher reactive power per active power could limit the life time of the converters

Enablers

Generate or consume reactive power (leading/lagging)	Potential to be a very flexible source for reactive power
Reactive power capability can be independent to active power	Could deliver reactive power without producing any active power
Not fully utilised reactive power capability	The reactive capability of the HVDC VSC has been determined by the grid codes rather than the HVDC VSC capability

CASE STUDIES

Pumped Hydro Energy Storage

Characteristics

- Pumped Hydro Energy Storage (PHES) is a flexible energy technology able to provide system services. PHES is utilising water reservoirs at different altitudes and a pump/turbine.
- Pumped hydro is a relatively established technology, however no new projects have become operational in recent years (albeit a reasonable pipeline currently exists in GB).
- The location of Pumped Hydro Energy Storage is highly restricted by geography which in many cases will not correspond with areas of the system where the need for additional reactive power service provision is acute.

	Base case	High range	Low range
Typical unit size (MW)	335	3 000	10
Capex (£/kW)	1 007	1 854	400
Opex (£/kW/year)	5	9	2
Leading reactive capability (MVAr range per MW)	0.33	0.33	0.33
Lagging reactive capability (MVAr range per MW)	0.62	0.62	0.62
Grid codes - Additional capability beyond ORPS (MVAr/MW at full load)	-		
Is MVAr output at 0MW generation possible?	**Yes**		
Availability dependencies to provide reactive power	Can provide reactive power whilst spinning in air (requires power draw from the grid) and whilst dispatching		
Static only or dynamic? (Reactive Power)	Static and dynamic		
Facilities according to Heatmap	TBC		
Maturity (RAG) based on maximum MVAr capability	● ○ ○		

CASE STUDIES

Barriers & Enablers for Pumped Hydro Energy Storage

	Barriers		Enablers	
Reactive power	– Plannable provider of reactive power with high availability	– Pumped hydro could provide reactive power fast and when the demand for reactive power is high	– Plannable provider of reactive power with high availability	– Pumped hydro could provide reactive power fast and when the demand for reactive power is high
	– Geographical constraints	– Geological formations as old mines, caves or mountainous areas restricts the locations of pumped hydro	– Reactive power provision independent from active power	– Could deliver reactive power without producing any active power by spinning the turbine in air

CASE STUDIES

CCGT

Characteristics

- Thermal generation technology, utilising energy from combustion and steam/gas turbines to produce electrical energy to the power grid at synchronous speed.
- Widespread today in GB, but number/capacity of installations are in decline.

	Base case	High range	Low range
Typical unit size (MW)	450	500	400
Capex (£/kW)	683	714	651
Opex (£/kW/year)	29-64	64	29
Leading reactive capability (MVAr range per MW)	0.33	0.33	0.33
Lagging reactive capability (MVAr range per MW)	0.62	0.62	0.62
Grid codes - Additional capability beyond ORPS (MVAr/MW at full load)	-		
Is MVAr output at 0MW generation possible?	**No**[1]		
Availability dependencies to provide reactive power	Generators need to be spinning to provide services, ramping affects how fast it can respond to changes in demand		
Static only or dynamic? (Reactive Power)	Static and dynamic		
Facilities according to Heatmap	TBC		
Maturity (RAG) based on maximum MVAr capability	● ○ ○		

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[1] Can be designed to operate in synch-comp mode

CASE STUDIES

Barriers & Enablers for CCGT

	Barriers		Enablers	
Reactive power	– Slow ramp up/down	– Ramping makes CCGT less dynamic for bigger changes in reactive power stabilization	– Technically configured to provide reactive power today	– CCGT is a well established source of reactive power provision today
	– Reactive power capability linked to active power	– Need to produce active power to provide reactive power	– Flexible thermal generator	– CCGT are one of the most dynamic and flexible thermal generators to provide reactive power
	– Wear on the equipment operating at power factors far from unity	– Wear on equipment and losses increase as power factor deviates		

CASE STUDIES

Nuclear

Characteristics

- Nuclear power utilise fission to drive steam turbines for the production of electrical energy and its injection into the power grid at synchronous speed.
- There are still a large number of nuclear installations in Great Britain, however the vast majority of these are scheduled to close in the coming years with limited new entrant pipeline to replace existing facilities.

	Base case	High range	Low range
Typical unit size (MW)	1 600	1 600	600
Capex (£/kW)	4 340	10 000	3 431
Opex (£/kW/year)	73	109	66
Leading reactive capability (MVAr range per MW)	0.33	0.33	0.33
Lagging reactive capability (MVAr range per MW)	0.62	0.62	0.62
Grid codes - Additional capability beyond ORPS (MVAr/MW at full load)	-		
Is MVAr output at 0MW generation possible?	**No**		
Availability dependencies to provide reactive power	Generator needs to be spinning to provide reactive power		
Static only or dynamic? (Reactive Power)	Static but potential to be dynamic depending on operation mode		
Facilities according to Heatmap	TBC		
Maturity (RAG) based on maximum MVAr capability	● ○ ○		

CASE STUDIES

Barriers & Enablers for Nuclear

	Barriers		Enablers	
Reactive power	– Slow ramp up/down	– Static behaviour rather than dynamic why not ideal for reactive power market as for today	– Stable reactive power provision	– Potential to be dynamic and deliver stable reactive power, high load factors result in availability
	– Reactive power capability linked to active power	– Need to produce active power to provide reactive power	– Large source of reactive power provision	– Large generators with a capability to provide bulk source of reactive power to the transmission grid in areas

CASE STUDIES

Synchronous Condenser with Flywheel

Characteristics

- A synchronous condenser (SC) is an AC-driven synchronous motor able to spin freely without load, and can provide system-critical services including reactive power (and other) services.
- A well established technology that has been applied to many other grids across the world to provide critical services.

	Base case	High range	Low range
Typical unit size (MVAr)	125	200	50
Capex (£/kVAr)	208	269	147
Opex (£/kVAr/year)	12	18	6
Leading reactive capability (MVAr range per MW)	Only MVAr	Only MVAr	Only MVAr
Lagging reactive capability (MVAr range per MW)	Only MVAr	Only MVAr	Only MVAr
Grid codes - Additional capability beyond ORPS (MVAr/MW)	-		
Is MVAr output at 0MW generation possible?	**Yes**		
Availability dependencies to provide reactive power	Needs to draw power to provide reactive power services		
Static only or dynamic? (Reactive Power)	Static and dynamic		
Facilities according to Heatmap	TBC		
Maturity (RAG) based on maximum MVAr capability	● ○ ○		

CASE STUDIES

Barriers & Enablers for Synchronous Condenser with Flywheel

	Barriers		Enablers	
Reactive power	– Losses and mechanical wear, occupies large space	– Relatively high losses and mechanical wear, and facilities require quite large space	– Mature technology	– Tried and tested technology for providing reactive power
			– Dynamically controlled reactive power provision	– Manufactured in considerable sizes with the ability to continuously adjust reactive power output
			– No active power	– Shaft spinning freely so SC's can provide reactive power without active power
			– Easy to deploy	– Easy to deploy in relation to a substation where the reactive demand is high

Next Steps and Close

Vicci

Next Steps

- **Mural board** open till 18 November for further feedback so please continue to add to it
- Follow up 1-1's as required to fill up gaps in knowledge and areas where we need more feedback
- Will publish **workshop slides** and **summary output** from mural board on website
- Case studies will feed into Commercial Analysis workstream
- Will iterate case studies and re-share
- Once finalised they will be published on the Reactive Power Reactive Reform pages of the website
- We'd love to get your feedback on the workshop - feedback form Your feedback helps shape future events
- **Any further comments** please send to box.futureofbalancingservices@nationalgrideso.com
- Plan further playback to industry on project progress prior to Christmas

Thank you for joining today's workshop and for your input