Q-Flex

NIA Closedown Report

September 2022 - March 2023

nationalgrid

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Version Control

Issue	Date
D1.0	12/01/2024

Publication Control

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1. Executive Summary

The Q-Flex project was an Ofgem Network Innovation Allowance (NIA) project carried out between September 2022 and March 2023. This project had four main aims, which were to understand the technical and commercial feasibility of procuring flexible reactive power support at the distribution level, to run power system analysis studies to determine the technical potential for improving network operation through flexible reactive power support, to perform cost-benefit analyses (CBAs) to determine if reactive power is worth procuring, and to produce of an initial market design for the procurement of flexible reactive power at the distribution level. Power Systems Consultants were the main partner for the delivery of the project.

The need for this to be carried out comes as the volume of low-carbon technologies (LCTs), such as renewable generation, electric vehicles and heat pumps, being connected to distribution networks is forecast to increase significantly, and at an accelerating rate. This will lead to both voltage and thermal constraints on distribution networks, as well as increased losses. The traditional solution to network constraints is reinforcement, however this incurs financial and environmental costs. Increased losses increase the need for electricity generation, with marginal generation typically coming from combustion of natural-gas, bringing financial and environmental costs also.

The project sent technical reactive power questionnaires to and ran a series of commercial focussed workshops with potential providers of reactive power, summarising their responses to both in a Reactive Power Catalogue and Market Interest Summary Report respectively. PSSE studies of heavily constrained areas of 33kV network in the South West and South Wales showed the potential to reduce historical and future losses, and defer certain cases of future 33kV and 132kV reinforcement. The CBAs found no net benefits for reducing network losses in isolation, but did find cases of net benefit for reinforcement deferral, both with and without accompanying losses minimisation. An initial market design was developed based on the feedback in the Market Interest Summary Report and the CBAs.

2. Project Background

Achieving Net Zero requires an electricity system that can move energy from embedded generation to new loads through a network originally designed for centralised generation. NGED have already radically re-engineered our network to create capacity for 31 GW of distributed generation, with a network originally built for 14 GW of conventional demand[1].

However we need to go further, connecting an expected additional 1.5m Electric Vehicles (EVs) and 600,000 Heat Pumps by 2028. These changes will increase losses and create both voltage and thermal constraints on our network, with the traditional solution being network reinforcement. As such, our RIIO-ED2 business plan contains over £900m of load-related expenditure, which will be passed on to our customers through the Distribution Use of System (DUoS) component of household electricity bills.

Flexible reactive power support may represent an alternative solution; improving the power factors of cables, lines and transformers could increase the active power capacity of these assets and thus resolve thermal constraints, whilst also reducing losses associated with reactive power flows. Additionally, controlling reactive power to regulate network voltages may allow the resolution of both overvoltage and under-voltage constraints. Increasing voltages, within system limits, is also likely to reduce network losses further.

This project explored the potential environmental benefits of flexible reactive power support. These benefits can arise in two ways. Firstly, reducing network losses reduces the need for electricity generation. With marginal generation in the UK often being thermal generation using natural gas, reducing losses brings direct benefits to national greenhouse gas emissions. Secondly, deferring reinforcement allows the Scope 3 emissions associated with the production, transportation and installation of new network assets to be deferred too.

Both deferring reinforcement and minimising losses may bring financial benefits too. Savings in load-related expenditure from deferring reinforcement are split equally between NGED and our customers under the Total Expenditure (TOTEX) Incentive Scheme, whilst carbon pricing monetises the environmental value of deferred Scope 3 emissions and reduced marginal generation.

The project was carried out in five stages:

- Stage 1 – Researching Current & Emerging Technologies' Reactive Power Capabilities
- Stage 2 – Reactive Power Studies to Determine Network Benefits
- Stage 3 – Performing Cost-Benefit Analyses of Flexible Reactive Power Support
- Stage 4 – Reactive Power Flexibility Market Engagement & Development
- Stage 5 – Reporting on Outputs

[1] National Grid Electricity Distribution – investing in our network

3. Scope and Objectives

This project aims to solve the problem outlined above by demonstrating that the provision of flexible reactive power is technically possible, assessing whether flexible reactive power is a solution to forecasted network constraints, and understanding if participants are willing to provide reactive power as a flexibility service.

Table 3-1: Status of project objectives

Objective	Status
Demonstrate that the provision of flexible reactive power is technically possible.	✓
Assess whether flexible reactive power is a solution to forecasted network constraints.	✓
Understanding if participants are willing to provide reactive power as a flexibility service.	✓

4. Success Criteria

The project assessed a variety of technology providers which could participate in a reactive power flexibility market. After engagement with potential providers, a catalogue was produced which detailed the technical capabilities of assets connected to our network. We conducted power system studies across a variety of case studies to evaluate the overall performance of reactive power flexibility.

Table 4-1: Status of project success criteria

Success Criteria	Status
A catalogue of reactive power technology produced that has been developed using feedback and information from asset owners and operators.	✓
Power studies have been carried out on multiple case studies within the NGED network which have been selected and approved by NGED Network Strategy.	✓
Cost Benefit Analysis carried out to determine the financial and environmental costs/benefits of deferred network reinforcements and minimised losses achieved from the use of flexible reactive power.	✓
A concept design has been created for a reactive power flexibility marketplace.	✓

5. Details of the Work Carried Out

The Q-Flex project was carried out in four stages of work followed by overall reporting. The work carried out in each of these stages has been demonstrated in the following sections.

5.1 Researching Current & Emerging Technologies' Reactive Power Capabilities

Stage 1 of this project involved carrying out a literature review of potential providers of reactive power on NGED's network a producing a 'Reactive Power Catalogue' for future reference when considering reactive power as a flexibility service. Additionally, potential providers of reactive power were approached and asked to fill in questionnaires covering their assets' technical capabilities, and the resulting data was included in the Reactive Power Catalogue also. There were two questionnaires: one for incumbent assets already able to provide flexible reactive power and the other for assets not yet built or capable of providing flexible reactive power.

Reactive Power Questionnaires

The reactive power questionnaires covered the following:

- Asset class (e.g. Wind, Solar PV, BESS, conventional generation).
- Connection voltage and rated power, quantity of installations and installation date(s).
- Ability to provide reactive power to a distribution network, with a request for manuals and/or certification where applicable.
- Ability to provide reactive power at any time of day or night, limitations on duration.
- Presence of real power restrictions when generating or absorbing reactive power.
- Ability to provide both leading and lagging reactive power, or just one.
- Possible power factor range.
- Control system for changing the power factor.
- Control mode (voltage control, current control, power factor control, volt-VAr), and whether this can be changed.
- Ability to receive local and/or remote control signals/schedules to vary their reactive power output and the applicable response time and technology.
- Ability to provide reactive power whilst generating zero active power.
- P-Q generation curve.
- Presence of external static or dynamic devices such as a STATCOM or mechanically switched capacitors to keep the reactive power of plant within certain limits.
- Incumbent participation in any distribution-level flexibility services.

Additionally, NGED presented an overview of the Q-Flex project to Renewable UK's Wind Advisory Group in February 2023 and requested the opportunity to run workshops with the group's members to try and gather more technical data. This is not considered part of the Q-Flex project and so may continue beyond the end of March 2023.

Reactive Power Catalogue

Feedback from asset owners and operators was very productive and helped inform the development of the reactive power questionnaire, which was subsequently approved by NGED.

The technologies covered in the Reactive Power Catalogue are below:

- Conventional Generation Technology
- Solar Generation Technology
- Wind Generation Technology
- Battery Energy Storage Systems (BESS) Technology
- EV Charger Technology
- MVDC Link Technology
- Soft Open Points Technology
- Domestic Heat Pumps Technology
- Communications Technology and Infrastructure

5.2 Reactive Power Studies to Determine Network Benefits

It was decided to model the effectiveness of flexible reactive power support on three distinct network scenarios. These were:

- Historical Losses Minimisation
- Future Losses Minimisation
- Reinforcement Deferral

An overview of the sensitivity studies performed and their implications will be given.

Historical Losses Minimisation

The 33 kV network around Barnstaple BSP was used for this study. Half-hourly load and generation data for 2018 was used, although computations were done on a 60-minute basis to reduce processing time. Barnstaple BSP was used as it represents a constrained section of network and PSC had the load and generation data from NGED's NIA Virtual STATCOM project.

The aim of performing the historical losses minimisation studies was to quantify the reduction of losses which would have been in 2018 if the reactive power flexibility had been available by that time, compared to the case in which no reactive power flexibility been used (i.e. all DGs are operating using a fixed power factor).

It is important to note that the PSS/E model used for this study for Barnstaple BSP was not the newer switch-level type used by NGED. However, the network is fundamentally the same as the one used in the future loss studies except for new network additions.

The Q-Flex algorithm's operation resulted in an estimated reduction in losses of 11.17% for the year, from 3251.97 MWh to 2888.83 MWh.

Future Losses Minimisation

These studies used the Distributed Future Energy Scenarios (DFESs), generated by the Forecasting Team in Network Strategy to model estimated network conditions in 2025, 2028 and 2032, with a baseline of 2022 being used also.

Each of the four representative days in the DFES were modelled without the Q-Flex algorithm initially, to determine the predicted network losses. The studies were then run again with the algorithm and the differences quantified.

There were three network areas studied in intact condition:

- Ryeford BSP (33kV)
- Abergavenny BSP (66kV)

- Barnstaple BSP (33kV)

Ryeford showed reductions in losses of generally less than 1%, with Summer Generation being the best case in the 2-3% range, and Summer Demand being the worst case with reductions of ~0.5%. This is likely due to some voltage headroom in the summer being exploitable when generation is high relative to demand, and to a lack of generator capacity when summer demand is high.

Abergavenny saw reductions in losses of a few percent in the Intermediate Warm and Winter Demand cases, due to the ability to increase network voltage. Summer Generation saw increased losses, due to overvoltage constraints being resolved by the algorithm preferentially to reducing losses.

Barnstaple also saw reductions of a few percent in all cases except Summer Generation, which increased network losses in 2025 and 2032. This is due to the algorithm resolving overvoltage constraints too.

Reinforcement Deferral

This analysis simulated future voltage and thermal constraints on the network under outage conditions, again using estimates from the DFES. Voltage constraints were defined as below 0.94 p.u. or above 1.06 p.u, and thermal violations were defined as loading above the rated value of circuits and/or transformers. Studies were again run both without and then with the Q-Flex algorithm.

Additionally, the potential to reduce reactive power flows on the 132kV network was studied to determine if assets connected at 11kV and 33kV had the potential to reduce loading on the 132kV network and thus enable 132kV reinforcement deferral.

Four network areas were studied in this analysis:

- Golden Hill and Haverfordwest BSP (33kV – Golden Hill to St. Florence fault).
    - This showed under-voltage violations in the Winter Demand case only from 2022 onwards, however the algorithm was able to resolve them in all years studied. Thermal constraints were found in Winter Demand only from 2028, and the algorithm failed to resolve these. Therefore, reinforcement could possibly be deferred to 2025 only.
    - For 2032, the net reactive power flowing from the 132kV network into the 33kV network was found to be reduced by 27.6% by the operation of the algorithm, and the apparent power by 2%.
- Ryeford BSP (33kV – Ryeford Loss of Circuit).
    - This showed under-voltage violations in the Winter Demand case only from 2022 onwards, with the algorithm able to resolve them out to 2028. No thermal violations were found in any year, meaning reinforcement may be deferrable to 2028.
    - For 2028, the net reactive power flowing from the 132kV network into the 33kV network was found to be reduced by 28.4% by the operation of the algorithm, however the total apparent power was found to have increased by 4%, due to increases in the magnitudes of both export and import of reactive power at different transformers
- Abergavenny BSP Northern (66kV – Loss of Busbar 1).
    - This showed voltage violations in the Intermediate Warm, Summer Demand and Winter Demand cases from 2022 onwards. The algorithm could resolve these for 2022 only. Thermal violations were found from 2025 in the Winter Demand case. It does not appear possible to defer reinforcement beyond 2022.
    - For 2025, the net reactive power flowing from the 132kV network into the 33kV network was found to be reduced by 53.6% by the operation of the algorithm, and the apparent power by 2.5%.
- Abergavenny BSP Southern (66kV – Abergavenny to Blae outage and loss of Panteg GT3).
    - This showed voltage violations in the Intermediate Warm, Summer Demand and Winter Demand cases from 2022 onwards, with the algorithm failing to fully

resolve these even for 2022. Unresolvable thermal constraints were found from 2022 for the Winter Demand case also. Under this outage scenario, even with the algorithm operating in 2022, there would be unresolved constraints on the network.

- For 2028, the net reactive power flowing from the 132kV network into the 33kV network was found to be reduced by 60.8% by the operation of the algorithm, and the apparent power by 3.5%.

To summarise the above, it appears possible to defer reinforcement at Golden Hill and Haverfordwest BSP to 2025 and Ryeford BSP to 2028, but not at Abergavenny BSP. The Q-Flex algorithm showed a capability to reduce reactive power import from the 132kV network in all cases, and lowered apparent power import at Golden Hill and Haverfordwest BSP and Abergavenny BSP. It therefore appears possible to assume that there may be potential to defer network reinforcement at 33kV, 66kV and 132kV, all using assets connected at 11kV and 33kV.

Sensitivity Studies

The results outlined above are dependent on a number of assumptions. These were subject stress-tests and sensitivity analyses as appropriate

Firstly, it was checked that the amount of reactive power that the Q-Flex algorithm decided to dispatch did not exceed the reactive power capability available. Ryeford BSP in both intact and outage conditions was studied for 2022 through to 2032, and the reactive power capability available was found to be sufficient in each year.

Secondly, the effect of reducing the capacity of the generator providing the largest amount of reactive power was studied. For the historical losses case at Barnstaple in 2018, reducing the largest generator’s capacity by 90%, lowered network losses reduction from 11.61% to 9.05%. For the Ryeford BSP N-1 case in 2022, reducing the largest generator’s capacity by 98% meant that rather than the algorithm resolving all constraints, it resolved none of them. These results suggest that reactive power support is highly location-dependent and that generators are non-interchangeable.

Thirdly, the effect of reducing the capacities of the generators providing the least reactive power was explored. Here the Ryeford BSP N-1 case in 2028 was used, as this represented the limit of when reinforcement could be deferred to. It was possible to reduce the number of generators required from 26 to 23, which represents little improvement. It is possible that deferring reinforcement to 2028 was a marginal result, or it may be that some of the generators providing the least reactive power were in highly strategic positions. Thus, being able to rank generators based on their ‘usefulness’ appears challenging.

Exploring this point further, the conventional approach to this issue in the case of one constraint would be to rank generators based on their sensitivity factors. However, if there is more than one constraint, generators’ sensitivity factors will differ between constraints in different locations. With some studies showing in excess of 40 constraints, ranking becomes highly complex. The Q-Flex algorithm is a Particle Swarm Optimisation algorithm for precisely this purpose. With an objective function defined by a combination of the number and magnitude of voltage and thermal violations for a given range of power factor setpoints (one for each generator), the algorithm searches for the global minimum of this objective function by varying the power factor setpoint for all generators. What this means is that if 30 generators are present, the algorithm is trying to solve a 30-dimensional problem by varying 30 setpoints simultaneously.

It is apparent that this requires numerical computation, and thus attempting to reduce the number of generators required and/or the volumes of reactive power procurement needed to resolve all constraints, must be built into the objective function that the Q-Flex algorithm seeks to minimise.

5.3 Performing Cost-Benefit Analyses of Flexible Reactive Power Support

Having modelled the technical potential for flexible reactive power support to minimise network losses and defer network reinforcement and finding likely opportunities for both, the next step was to determine if it was economically and environmentally beneficial to do so using a modified version of Ofgem’s Common Evaluation Methodology (CEM)

Environmental benefits from reduced need for marginal generation and deferred Scope 3 emissions for new equipment were estimated for each case, and ‘converted’ into economic benefits using carbon pricing. These savings were added to the financial benefits of deferring investment in reinforcement and reduced losses, with the latter captured using a conversion factor in the CEM tool. All these values were then considered, along with estimated costs for flexible reactive power support, to give an estimated Net Present Value (NPV) for each area.

The benefits were modelled for three scenarios:

- Reinforcement Deferral Only
- Losses Minimisation Only
- Reinforcement Deferral and Losses Minimisation

Reinforcement Deferral Only

As outlined in Section 5.2, it was found impossible to defer reinforcement using the Q-Flex algorithm for both Abergavenny cases, but possibly to 2025 in the Golden Hill & Haverfordwest BSP area and to 2028 in the Ryeford BSP area.

The NPV for the Golden Hill & Haverfordwest BSP area case was found to be £29.4k, with Ryeford BSP having an NPV of £1.04m. The availability breakeven prices were found to be £0.41/MVAr/h and £5.40/MVAr/h, respectively. The apparently superior business case for Ryeford BSP is likely due to the higher reinforcement cost and the longer timescale for reinforcement deferral.

There are two crucial caveats to these business cases. The first is that this assumes that all generators that are invited to participate elect to do so, and fulfil their contracted requirements perfectly. The second is an assumption that reactive power procurement can be done sufficiently far in advance to render its consideration possible. The further into the future the Earliest Possible Reinforcement Completion (EPRC) and corresponding time for planning, wayleaves, and building etc., the further ahead flexible reactive power must be procured.

Losses Minimisation Only

These results are summarised below. All values are negative, thus representing net costs.

Table 1: NPV results from losses minimisation only

Network Area	Net Present Value
Historic Losses (Barnstaple BSP)	-£147.37k
Future Losses (Barnstaple BSP)	-£562.35k
Future Losses (Abergavenny BSP)	-£737.66k
Future Losses (Ryeford BSP)	-£510.26k

The factors that drive these net costs are the low monetary values of losses and the costs of setting up and running a flexible reactive power market. The historical case is significantly better due to the superior reduction in losses seen in that case relative to the others.

It appears possible to conclude that losses minimisation only does not have a business case on that areas of network studied. As they were selected as more suitable areas of network to benefit from reductions in losses via flexible reactive power support, it seems unlikely that a business case for this will be found across NGED’s broader network for this in isolation.

Combined Reinforcement Deferral and Losses Minimisation

Only Ryeford BSP and Abergavenny BSP network areas were modelled for both reinforcement deferral and losses minimisation. Ryeford BSP had a NPV of £1.47m and Abergavenny BSP had an NPV of -£737.66k.

Ryeford had a positive NPV due to the benefits of reducing losses stacking with the benefits for deferring reinforcement, without incurring the upfront and ongoing costs twice. For this network area, there appears to be a good business case for using flexible reactive power support to accomplish both of these goals together.

Abergavenny BSP did not show any potential for reinforcement deferral, so the result here is the same as for the minimisation of losses only study.

It should be noted that the NPVs have been computed from the perspective of a single private party to the electricity system, i.e., NGED, rather than the electricity system as a whole. NPV calculations from the whole system's perspective are outside the scope of the Q-flex project.

Inputs and Assumptions

As the viability of a CBA is highly dependent on the values of both the costs and the benefits, it is important to detail the inputs and their underlying assumptions and shortcomings where present.

The assumptions regarding benefits are detailed in the CBA Methodology Report and stem from ENA’s CEM tool, however the assumptions of cost have been determined in the course of this project.

Two parties stand to bear costs in a reactive power market, the entity running the market and the entity participating in the market. Estimates of costs for market participants were produced by NERA Economic Consulting as a breakeven price for availability payments.

Estimates for the upfront and ongoing costs of setting up and operating a reactive power market were estimated by PSC and the Flexibility Team within NGED’s Network Strategy Team as £140,000 and £9000 per generator per year, respectively. The former represents web interface development, testing and training costs, and the latter the costs of personnel to run a market.

An upfront £10,000 per generator for market qualification testing and power factor metering is assumed to be passed on to the generators.

Sensitivity analysis showed that the different carbon price scenarios and cost of losses calculation methods produce similar results to those obtained in the central scenarios. The availability and utilisation costs were the most sensitive variables. To establish the breakeven point for availability and utilisation payments, the utilisation price was set at £0 and the availability cost was incremented accordingly. Since the types of generation being considered had a low marginal fuel cost, the burden was on the availability payment.

5.4 Reactive Power Flexibility Market Engagement & Development

This section of the project had two parts. The first concerned engaging with the same potential providers of reactive power who were sent the questionnaires outlined in Section 5.1 regarding their commercial perspectives on a potential marketplace for the provision of flexible reactive power support and summarising these in a Market Interest Summary Report. The second part involved taking the outputs from the modelling and CBAs in Sections 5.2 and 5.3 respectively, and blending these with the feedback in the Market Interest Summary Report to produce an initial Market Design.

Engagement with potential providers

This consisted of a series of workshops asking questions about the following topics:

Market Entry	Functional Performance	Market Structure &	Operation
•Opportunity costs for reactive power provision •Lead time for market participation •Minimum kit and investment needed for market participation •Potential barriers to entry	•Percentage of capacity available for reactive power support •Presence of economies of scale for reactive power provision	•Long-term vs short-term contracts •Availability vs utilisation payments •Ad-hoc vs regular procurement •Openness vs minimising lead time by using already-proven providers only •Bundling of services (leading and lagging)	•Ideal bidding frequency •Main operating costs for reactive power provision (including as a proportion of total operating costs) •Main fixed costs for reactive power provision •Willingness to offer a discount for long-term contracts

The main finding was a very strong need for revenue certainty to justify investments in assets and systems to be able to provide reactive power for those that did not already have this capability. By contrast, those with incumbent capable assets and systems favoured more flexible solutions.

Generally, older Solar PV and Wind assets fell into the former camp, and favoured long-term, availability-based, regularly scheduled, open markets with leading and lagging bundled together. Meanwhile more modern Solar PV and Wind and BESS owners and operators favoured shorter-term contracts. However, these providers still preferred availability payments with regular procurement and bundled services, and argued that the market should be kept open to all.

Table 2: Summary of Reactive Power Market preferences

	Scenario 1	Scenario 2
Types of Generation	Modern Solar PV, Wind, and Battery Energy Storage	Older Solar PV and Wind
Installed Grid Forming Equipment	Yes	No
Contract duration preference	Shorter-term contracts	Longer-term contracts
Payment structure preference	Availability based	Availability Based

Development of conceptual framework

To begin the market design process, NERA developed a conceptual framework to break down the market design process into key decision blocks. The framework was based on five key trade-offs involved in reactive power market design, and four possible procurement situations. Using this, NERA proposed market design strawmen that balanced the five trade-offs based on the demand and supply conditions at given locations.

The five trade-offs were:

1. When to use long-term vs short term procurement (or a combination of the two)?
2. When to pay based on availability vs utilisation?
3. When to run ad hoc procurement vs regularly scheduled procurement?
4. Should the market be open to all producers, new entrants only, or proven providers only?
5. Should procurement be bundled/linked across services or kept separate?

Each was used to motivate the high-level strawmen for reactive power market design.

The four possible procurement situations assessed when considering whether DNO's demand for reactive power flexibility or whether a providers ability to supply reactive power influences overall procurement conditions.

Assessment of market interest

Building on the above conceptual framework, sessions were conducted to survey the interests, concerns, and technical capabilities of potential providers of reactive power. Stakeholders were identified with the aid of the Reactive Power Technology Catalogue from WP1. The questionnaires in WP1 were used to guide the stakeholder engagement sessions.

Some key lessons were learned about potential providers' capabilities and preferences, which were later incorporated by updating the conceptual market design framework.

The first set of lessons relates to providers' technical capabilities. All the asset-operating stakeholders interviewed could already provide leading and lagging reactive power. Only generators belonging to certain technology groups may require additional investment in equipment to enhance their reactive power capabilities. For example, older windfarms (from around 2017 or older) will likely require additional equipment to provide reactive power at zero-wind conditions. This translates into different technologies being more suited to different market designs, depending on whether they require revenue certainty to reduce the risk they are exposed to through their initial investment.

The second set of lessons learned relates to providers' preferred market structure and input from NGED's DSO Team. Stakeholders desired certainty around their legal obligations to grid connection agreements and how these would interact with legal obligations under reactive power supply agreements. It was understood from this that setting up a reactive power market subject to the existing connection agreements would likely expedite market implementation and reduce complexity for stakeholders. Moreover, respondents generally preferred alignment between the reactive power market and existing active power flexibility markets, suggesting implementation into NGED's existing Flexible Power platform. Potential RPPs generally favoured a predictable market with availability contracts and bundled products.

These key findings and the process through which the stakeholder engagement process was organised are summarised in the Market Interest Summary Report.

Development of market design

Building on the findings of the stakeholder engagement and the results from PSC's simulations, a high-level market design for reactive power was proposed. NERA advised that NGED procures reactive power for loss minimisation and the deferred reinforcement use cases in a bundled product to reduce confusion and encourage participation in the market.

The findings from PSC's analysis and the stakeholder engagement process were incorporated into the conceptual framework by adding a sixth and seventh to the previous five trade-offs for market design:

- Pay-as-bid or pay-as-clear market: this is relevant due to the issue of suppliers potentially being local monopolists. The N-2 Liquidity Test used by NGED within the Flexible Power Platform for each Constraint Management Zone could be adapted for this decision.

- The commitment horizon for NGED: a long commitment horizon could allow NGED the possibility to provide revenue certainty over a longer horizon whilst maintaining short-term contracts which are aligned with active power flexibility service timelines.

With the refined list of trade-offs, the final market design was proposed. This had a lead time of 12 to 24 months to ensure that NGED can opt for network reinforcement if needed. In line with NGED's active power flexibility services market, the proposed design consisted of a "Service Requirements" stage and an "Availability Market" stage before NGED makes and dispatches utilisation decisions.

The market design approach and the proposed designs are described in the Market Design Report. The WP4 Report combines the Market Interest Summary Report and Market Design Report.

6. Performance Compared to Original Aims, Objectives and Success Criteria

This project satisfied all of the objectives and success criteria set out at the beginning of the project.

Table 6-1: Performance compared to project objectives

Objective	Status	Performance
Demonstrate that the provision of flexible reactive power is technically possible.	✓	Asset owners and operators have been found to have the capability to provide flexible reactive power at the distribution level.
Assess whether flexible reactive power is a solution to forecasted network constraints.	✓	Modelling has suggested that there are certain network areas where flexible reactive power support could effectively defer network reinforcement.
Understanding if participants are willing to provide reactive power as a flexibility service.	✓	Asset owners and operators have been found to be willing to provide flexible reactive power at the distribution level, subject to the existence of a satisfactory market.

Table 6-2: Status of project success criteria

Success Criteria	Achieved	Performance
A catalogue of reactive power technology produced that has been developed using feedback and information from asset owners and operators.	✓	This has been produced and includes thermal generation, wind and solar PV, electric vehicle, heat pump, battery energy storage, medium-voltage direct current links, and soft open-points.
Power studies have been carried out on multiple case studies within the NGED network which have been selected and approved by NGED Network Strategy.	✓	These have been performed to show benefits on the 33kV and 132kV networks, represented by reduced losses and deferred reinforcement. The potential to reduce losses was found in all areas studied and reinforcement deferral was found possible in two areas studied.
Cost Benefit Analysis carried out to determine the financial and environmental costs/benefits of deferred network reinforcements and minimised losses achieved from the use of flexible reactive power.	✓	Work Package 3 reports demonstrated the financial and environmental benefits of deferred network reinforcement and minimised losses. We found strong performance for the deferral of reinforcement, but weaker performance when addressing network losses.
A concept design has been created for a reactive power flexibility marketplace.	✓	Market structures have been prepared as a part of Work Package 4 that explain how a reactive power flexibility marketplace would interplay with existing Flexible Power exist.

7. Required Modifications to the Planned Approach during the Course of the Project

None.

8. Project Costs

Table 8-1: Project Spend

	Budget (£)	Actual (£)	Variance(£)
NGED Internal Costs Total	26,296.00	27,773.81	1,478
Stage 1 – Researching Current & Emerging Technologies' Reactive Power Capabilities	51,551.00	51,551.00	-
Stage 2 – Reactive Power Studies to Determine Network Benefits	102,320.00	102,320.00	-
Stage 3 – Performing Cost-Benefit Analyses of Flexible Reactive Power Support	62,660.00	62,660.00	-
Stage 4 – Reactive Power Flexibility Market Engagement & Development	220,093.00	220,093.00	-
Stage 5 – Reporting on Outputs	26,417.00	26,417.00	-
	489,337	**490,815**	1,478

9. Lessons Learnt for Future Projects and outcomes

Table 3: Project Learning

Work Package	Learning Detail
WP1 - Current & Emerging Technologies Reactive Power Capability:	• The Reactive Power Technology Catalogue summarised the reactive power capabilities of different existing and emerging technologies connected to the network, the P-Q capability plots of the existing and emerging technologies and the common reactive power control methods of the existing and emerging technologies. • The use of flexible reactive power dispatch could provide one means to operate the existing network more efficiently. However, new services and optimisation in this area are needed to release the capacity for accelerated LCT connections. • Market engagement found that many potential RPPs, particularly solar PV and wind energy, could provide significant reactive power support with negligible opportunity costs when operating below full active power export during darker and less windy periods, respectively. • With suitable control systems, modern grid-forming inverter-based Distributed Energy Resources (DERs) can vary their reactive power production, impacting voltage and reactive power flows at the point of common coupling. If this function is enabled, DERs can potentially act as sources and sinks of reactive power with significantly better variability than fixed capacitor banks or reactor at the distribution level.
WP2 - Q-Flex Reactive Power Studies:	• The optimisation algorithm from the Virtual STATCOM project was successfully updated to optimise power factor correction on voltages from 11kV to 132kV, with the primary goal of resolving network constraints and the secondary goal of reducing network losses. • It may be possible to resolve network constraints and defer future network reinforcements in certain cases, with estimated reductions in thermal loadings of up to 5%. These represent up to 6 years of reinforcement deferral and apply at voltage levels from 33kV to 132kV. • It may be possible to reduce the power losses of the electricity network, although this was more effective for the historic study than for the studies of future years based on the DFES. • It was found that many generators were limited by a 3% rapid voltage change limit rather than a reactive power capability limit (the voltage step constraints are given in the Distribution Planning and Connection Code and Engineering Recommendation P28/2). • Sensitivity studies showed the ability to resolve constraints and reduce network power losses to be highly dependent on nodal effectiveness, making certain generators strategic.
WP3 - Q-Flex Cost Benefit Analysis Studies:	• Cost-benefit analyses were successfully performed using the CEM tool developed by Baringa to assess flexibility procurement. These produced NPVs for all study cases, and where these were positive,

	ceiling prices for availability payments where the cost would be equal to network reinforcement were calculated. • There are significant estimated net financial benefits for deferring network reinforcement, varying with the CAPEX to be deferred, the timescale of deferral and the Weighted Average Cost of Capital (WACC). • There were no estimated net financial benefits for minimising losses in the network unless these were coupled with the deferment of network reinforcement. • Ensuring reactive power procurement is beneficial for us and our customers depends on the required volumes of reactive power, which depend on the network topology and the cost of deferrable network reinforcements. However, the most important factor is the presence of suitable and willing potential RPPs in the relevant Constraint Management Zone to provide reactive power support, which may depend on their market-entry upfront and opportunity costs.
WP4 - Reactive Power Flexibility Market Engagement & Development:	• Potential RPPs interviewed as part of NERA's stakeholder engagement process generally expressed a preference for alignment between the reactive power market and existing active power flexibility markets. • Potential providers have differing needs for revenue certainty depending on their technology type; in particular, older windfarms and solar plants may require upfront investment to enable reactive power capabilities. • Since suppliers will initially likely be monopolists over demand for their reactive power, a pay-as-bid market design has been developed initially. This allows NGED to compare bids against the cost of network reinforcement at the Service Requirement stage. Moreover, the prices RPPs can submit at the Availability Market stage are capped at the prices submitted in the Service Requirement stage. • We may wish to transition to a pay-as-clear market design in the future if the interchangeability of supply arises in the reactive power market, as defined by an N-2 Liquidity Test for each Constraint Management Zone.

10. The Outcomes of the Project

The outcomes of the project are as follows:

Work Package	Title	Outcome
WP1	**Current & Emerging Technologies Reactive Power Capability**	• Gathered literature on existing and emerging technologies' reactive capabilities/controllability, trial results, control systems, etc. • Developed and issued questionnaires to asset owners/operators. • Produced a Reactive Power Technology Catalogue.
WP2	**Q-Flex Reactive Power Studies**	• Identified constraint case studies using the Distribution Networks Options Assessment (DNOA) and Shaping Sub-transmission Reports. These were modelled in PSS/E. • Updated the optimisation algorithm developed in the Virtual STATCOM NIA project. • Undertook Q-Flex reinforcement deferral studies for networks at voltage levels 33kV, 66kV and 132kV. • Undertook Q-Flex loss minimisation studies. • Undertook Q-Flex operational studies. • Undertook Q-Flex sensitivity studies.
WP3	**Q-Flex Cost Benefit Analysis**	• Developed costs and benefits assumptions to feed into the Common Evaluation Methodology (CEM) tool developed by Baringa. • Undertook cost-benefit analyses (CBAs) for flexible reactive power dispatch.
WP4	**Reactive Power Flexibility Market Engagement & Development**	• Assessed flexible reactive power market interest. • Developed initial flexible reactive power market design.
WP5	**Q-Flex Project Report**	• Produced this report summarising the work done, learnings, conclusions, and recommendations from the project.

11.Data Access Details

All reports and supporting work are published on the National Grid – Q-Flex project page. Additional data can be requested by contacting us directly.

NGED data can be requested via the National Grid Connected Data Portal (https://connecteddata.nationalgrid.co.uk/).

(/www.nationalgrid.co.uk/innovation/contact-us-and-more)

12. Foreground IPR

New foreground IPR has been created in the project reports. These are published and freely available on the NGED Innovation website. This includes an update to the V-STATCOM algorithm which is available on our website.

13. Contact

Further details on this project can be made available from the following points of contact:

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14. Glossary

Abbreviation	Term
BESS	Battery Energy Storage System
BSP	Bulk Supply Point
CAPEX	Capital Expenditure
CBA	Cost Benefit Analysis
CEM	Common Evaluation Methodology
CMZ	Constraint Managed Zone
DER	Distributed Energy Resources
DFES	Distribution Future Energy Scenario
DSO	Distribution System Operator
DUoS	Distribution Use of System
ENA	Energy Network Association
EPRC	Earliest Possible Reinforcement Completion
GSP	Grid Supply Point
LCT	Low Carbon Technology (i.e. Electric Car, Heat Pump, PV)
MVDC	Medium Voltage Direct Current
NGED	National Grid Electricity Distribution
NIA	Network Innovation Allowance
NPV	Net Present Value
RIIO - ED2	Revenue = Incentives + Innovation + Output Electricity Distribution 2
RPP	Reactive Power Provider
STATCOM	STATic synchronous COMpensator
TOTEX	Total Expenditure
WACC	Weighted Average Cost of Capital
WP#	Work Package

15. Appendices

Not applicable

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