Project VECTOR
Vaiable Envelope Compressor – Trial Optimation and Review

Project Code/Version No:
NGGTGN01_V2

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NGGTGN01_V2

Gas Network Innovation Competition Full Submission Pro-forma

Section 1: Project Summary

1.1 Project Title:
Variable Envelope Compressors: Trial, Optimisation and Review - 'VECTOR'

1.2 Funding Licensee:

National Grid Gas Plc (Transmission)

1.3 Project Summary:
The flow of gas on the Gas Transmission System is driven by a fleet of compressors. Because of the changing demands on the Gas Transmission System, many of these compressors are now operating outside their 'envelope', where they work most efficiently.

This problem is unique to networks that need to cope with significant variations from choices made by the supply market, and with demand changes from customers' evolving needs.

The VECTOR project will develop and demonstrate a solution that will enable compressors to operate stably and more efficiently over a wider range than is currently possible. This will provide increased operational flexibility on the Gas Transmission System that will be needed to support the Carbon Plan strategy.

Since most of the compressors were installed, new turbo engine technology has been developed by the car industry. This could help to resolve the problem by making the envelope on existing compressors larger.

None of the major international Original Equipment Manufacturers (OEMs) offer a solution that can be retrofitted onto an existing compressor.

Development and demonstration are needed to provide investment-level confidence that the technology can be used on a high-pressure natural gas network.

Overall, this solution will reduce fuel consumption, carbon emissions and fuel cost - and, above all, it will provide an additional option for increasing flexibility in the Gas Transmission System.

The project will start in April 2014 and finish in 2018.

1.4 Funding

1.4.2 NIC Funding Request (£k): 7,627.73

1.4.3 Network Licensee Contribution (£k): 0

1.4.4 External Funding - excluding from NIC/LCNF (£k): 321.60

1.4.5 Total Project cost (£k): 9,253.00

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Section 1: Project Summary continued

1.5 Cross industry ventures: If your Project is one part of a wider cross industry venture please complete the following section. A cross industry venture consists of two or more Projects which are interlinked with one Project requesting funding from the Gas Network Innovation Competition (NIC) and the other Project(s) applying for funding from the Electricity NIC and/or Low Carbon Networks (LCN) Fund.

1.5.1 Funding requested from the LCN Fund or Electricity NIC (£k, please state which other competition): None

1.5.2 Please confirm if the Gas NIC Project could proceed in absence of funding being awarded for the LCN Fund or Electricity NIC Project: N/A

☐ **YES – the Project would proceed in the absence of funding for the interlinked Project**

☐ **NO – the Project would not proceed in the absence of funding for the interlinked Project**

1.6 List of Project Partners, External Funders and Project Supporters:

Project Partners:
Rolls Royce is one of the worlds leading manufacturers of turbines and compressors and is the original equipment manufacturer for many of the compressors on the National Transmission System
The Carbon Trust is a widely recognised independent expert in carbon impact assessment and low carbon technologies.

External Funders:
The Carbon Trust has offered to provide financial support to this project by way of efficiency discount if National Grid is successful in securing funding for both its NIC projects.

1.7 Timescale

1.7.1 Project Start Date:	**1.7.2 Project End Date:**
April 2014	2018

1.8 Project Manager Contact Details

1.8.1 Contact Name & Job Title: Contact Name: Dominic Feenan Job Title: Specifications and Standards	**1.8.3 Contact Address:** National Grid House Warwick Technology Park Gallows Hill Warwick CV34 6DA
1.8.2 Email & Telephone Number: Email: Dominic.Feenan@nationalgrid.com Telephone: 01926 653894	

Glossary:

Entry Point –Locations where gas is injected into the Gas Transmission System, such as Liquefied Natural Gas terminals, interconnectors and connections to north sea gas fields.

Exit Point – Locations where regional distribution networks or directly connected customers such as power stations and large industrial sites remove gas from the Gas Transmission System.

Drive unit – The device that provides motive power to the compressor - either a gas turbine or an electric motor.

Compressor unit – A device that pumps gas by converts the motive power from the drive unit into higher gas pressure and/or higher gas flow rates in the gas pipelines. A compressor unit comprises a prime mover and a process gas compressor.

Surge line – the line on a compressor performance map beyond which the compressor can not physically operate; it marks the onset of destructive vibration known as surge

Choke line –the line on a compressor performance map beyond which the efficiency of a compressor rapidly decreases

Linepack – The extra gas that is held in the Gas Transmission Pipelines to provide an operational "buffer" above the minimum acceptable pressures.

Introduction

The flow of gas on the Gas Transmission System is facilitated by a fleet of 68 compressors at 24 compressor sites. Placed across the country, these compressors move the gas from entry points to exit points on the gas network - and ultimately to customers' homes and businesses.

Compressors enable onward transmission of gas. They are also used to boost gas pressure for delivery to distribution networks and other directly connected loads like gas fired power stations. Operation of compressors ensures that gas is delivered to regional gas distribution networks at a safe pressure for onward transportation to domestic consumers. Operation of gas compressors also facilitates entry of gas through terminals by quickly moving the gas away from terminals to other parts of the gas network. Compressors are operated in a variety of ways to cope with different duty requirements.

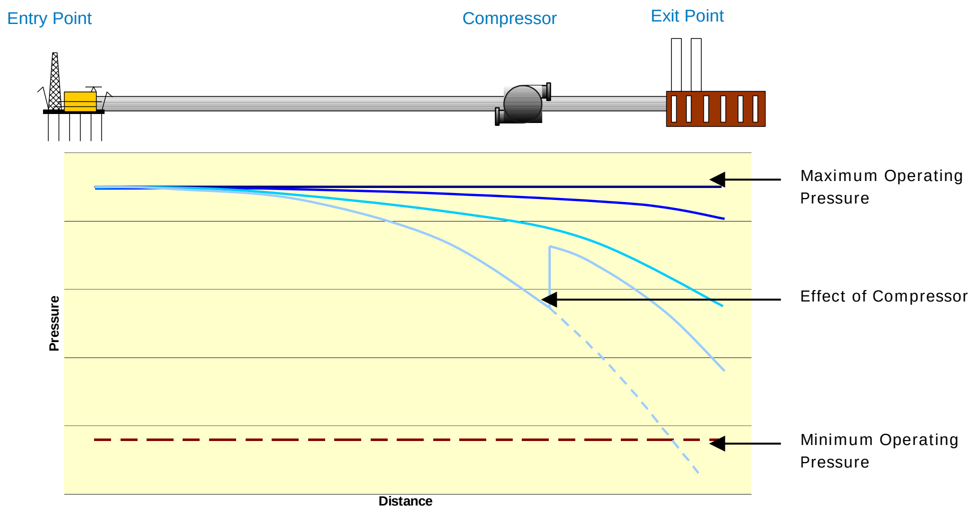

Figure 1: Role of compressors on the Gas Transmission System

Project Description continued

In 2012, compressor operations consumed 39.7 GWh of gas, with 235,741 tonnes of directly associated greenhouse gas (GHG) emissions. This is roughly the same as the emissions from 50,000 average UK households (2009 data).

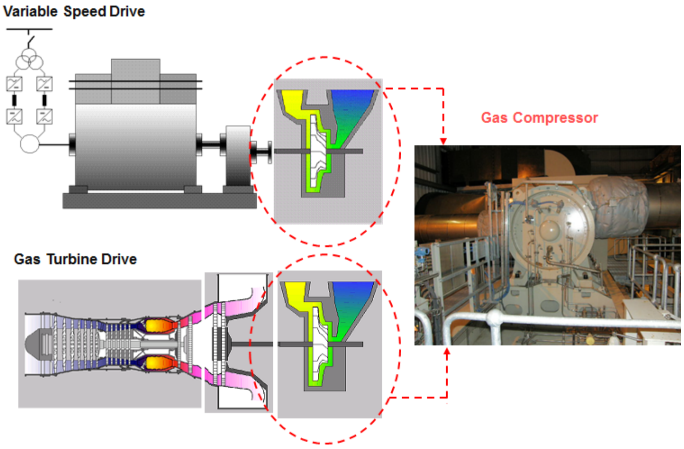

Figure 2: Compressor drive trains showing common compressor component

Each compressor has two main components: a drive unit and a gas compressor unit see figure 2. Most of the drive units on the Gas Transmission System are gas turbine engines that can deliver between 5 and 30 MW of power to the compressor. At the upper end of that scale they are as powerful as Boeing 747 jet engines. A few drive units are variable speed electric drives which can currently deliver up to 35 MW of power to the compressor.

The effect of a compressor is to increase gas pressure and gas flow through out the Gas Transmission System. The degree to which increased pressure is needed compared to increased flow depends on where gas is being injected into the network, and how quickly, and where gas is being taken off the network, and how quickly.

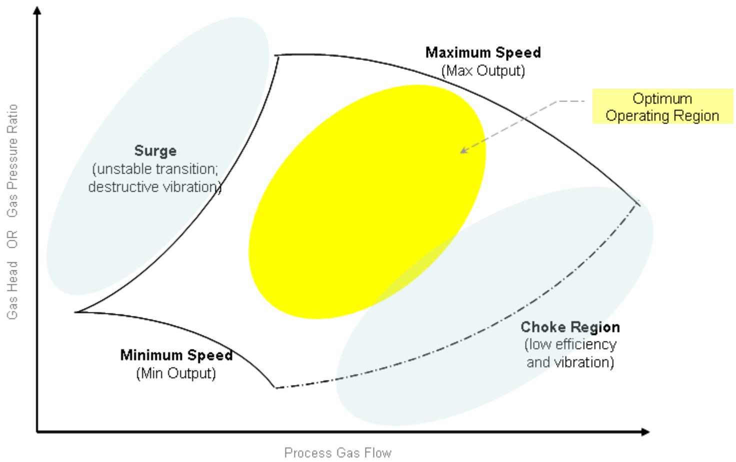

Figure 3: Typical speed controlled compressor envelope

The degree to which the compressor unit is providing pressure versus flow is varied by changing the speed at which they rotate. No compressor has infinite variability in operation. They are designed to operate within physical and efficiency limits which collectively define the 'envelope of operation' see figure 3. Operating outside this envelope either reduces efficiency, creates potentially destructive vibration, increases noise and emissions to air or reduces the life of the equipment or is simply beyond the capability of the unit to achieve.

When compressors are installed, their size and configuration are based on analysis of the network at that time using current and future gas supply and demand information received from the gas market. Inevitably, as the many factors involved in that analysis change, this means that what was appropriate during installation may not be ideal many years later.

The Gas Transmission System was originally designed for stable, 1 in 20 year forecast peak demand. Gas generally entered the Gas Transmission System from stable, predictable supplies like the UK Continental Shelf (UKCS commonly referred to as North Sea gas). Declining UKCS supplies in recent years coupled with continued gas demand has seen the introduction of new supplies located in more southerly areas of the system, such as Liquefied Natural Gas (LNG) import terminals, causing flow patterns to change significantly. Into the future, new storage sites are expected to be developed together with new interconnector routes between other European countries and the UK, and possibly new sources of gas within the UK, such as shale gas.

As North Sea gas sources contribute less, and LNG sources (importing in South Wales and the South East of England) contribute more, compressors which had previously experienced relatively stable operation are now experiencing frequent and significant changes in duty.

Supply diversity has had the beneficial effect of securing UK gas supply, see figure 4. It has also reduced the overall distance travelled by the gas from supply to demand points. The addition of new sources of gas has also had the beneficial effect of increasing market choice about which source of gas to use. As a result, compressors have generally been operating for fewer hours per year than in the past, when gas flow was generally from north to south.

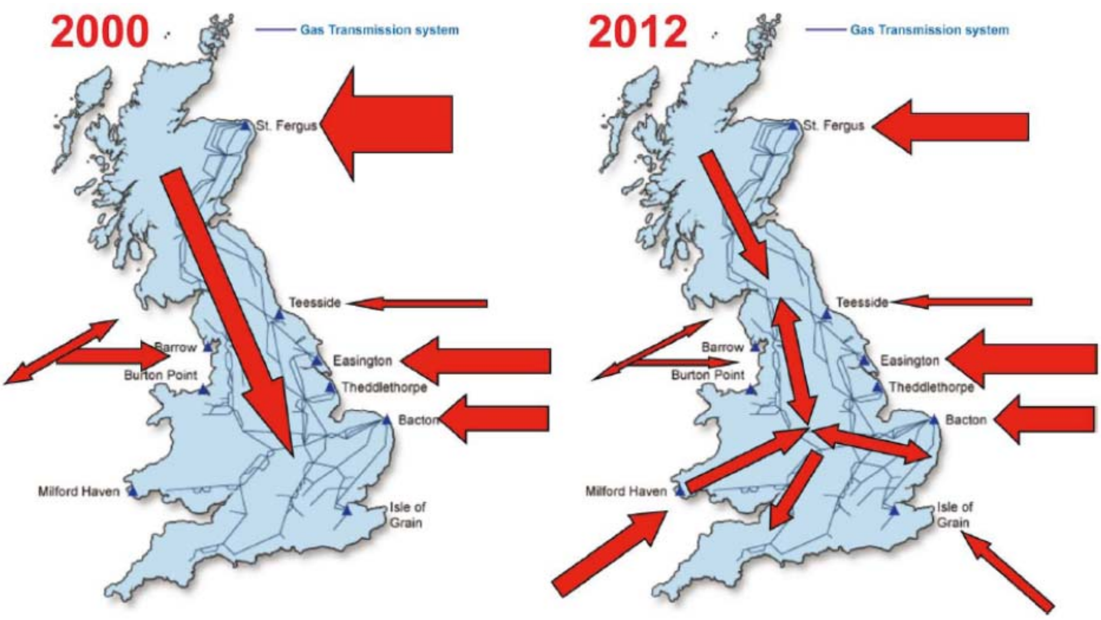

Figure 4: Changes in UK gas supply distribution

While overall utilisation of compression has reduced, Gas Transmission System compressors are becoming increasingly important for managing a wider range of gas flow requirements on the network for the following reasons:

Project Description continued

a) New supplies, see figure 5, are more heavily influenced by market volatility: for instance, LNG terminals and Interconnectors change flows into the network depending on price factors. So some compressors on the Gas Transmission System need to change from a "supply" position to "demand", in response to changes that can happen with little notice. These changes require increasing flexibility in compressor operation.

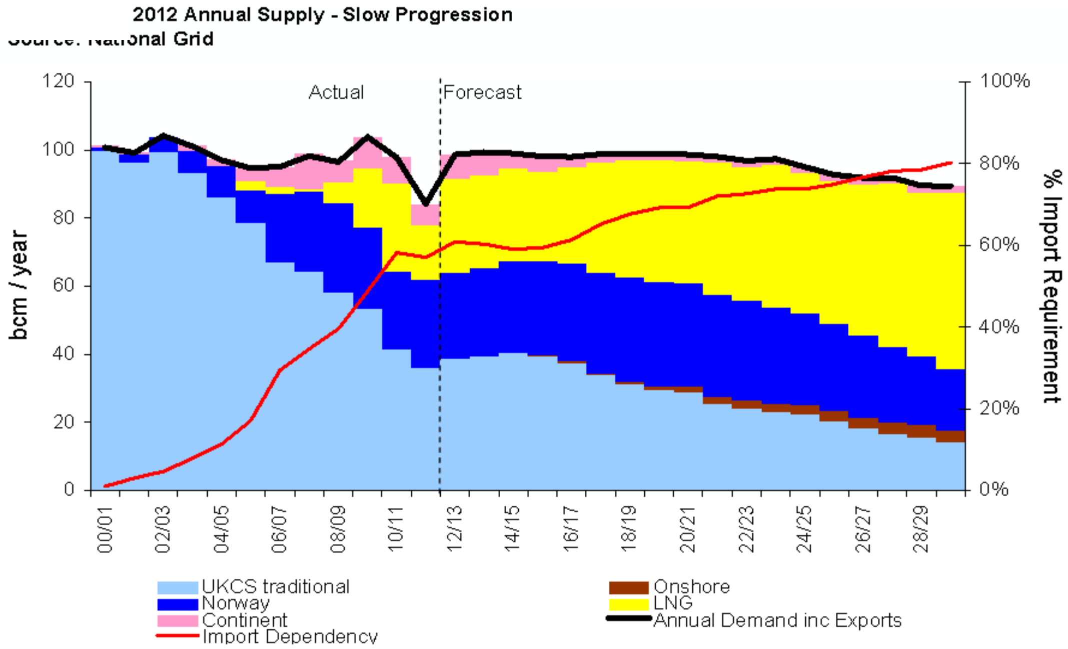

Figure 5: Annual Gas Supply – Slow Progression

b) There is a growing need for compressors to operate for short periods to manage short term flow volatility, caused by planned or unplanned changes in supply and / or demand in a local area of the Gas Transmission System over timeframes of a few hours. For example new storage sites are no longer designed as seasonal facilities but as flexible commercial ventures that exploit short term fluctuations in gas price; they may not fill just in the summer and empty in the winter, but instead may fill and empty a number of times in a relatively short timescale. This change from "supply" to "demand" means compressors have to quickly move gas to manage local supply deficits or enable gas injection.

c) With wind generation being highly dependent on weather conditions, fast response gas fired power stations are set to become the flexible generation source to cope with wind intermittency and peak demand. Fast electricity generation responses are likely to cause large, frequent and rapid fluctuations in gas demand, with these changes being met by diverse supplies connected to the Gas Transmission System. This will need fast configuration changes on the Gas Transmission System and an increasingly flexible compressor fleet capable of widely varying flow versus pressure capabilities.

2.1 Aims and Objectives

New demands of flexibility are being placed on the network and these impacts are expected to increase over the next two or three decades as we progress further to a low carbon energy sector. There is an ever-increasing requirement for short duration reconfiguration of the Gas Transmission System. This is likely to lead to a growing number of compressors operating in inefficient areas of, or even outside, their design envelope for an increasing amount of time.

Much of this resilience requirement could be met by compressors that are more inherently flexible.

The aim of the VECTOR project is to develop and demonstrate a new option for increasing gas transmission compressor flexibility.

2.2 Technical Description of Solution

The most common way of changing the performance of gas compressors is to run it at different rotational speeds. The flexibility of a given compressor is limited by its envelope of operation. The envelope is limited at low flow by a 'surge' line, at high flow by 'choke' and by the maximum and minimum speed curves. The most efficient operating range is generally in the middle of this envelope (see figure 3).

Besides speed variation there are two other methods for varying the output of a gas compressor. These are:

- Variable Inlet Guide Vane control – effective but less efficient than speed control on its own; usually used for non-explosive gas processes;
- Suction throttle – effective but much less efficient than either speed control or Variable Inlet Guide Vane control

On its own, each technology is effective for varying the performance of the compressor. However, each solution is only effective within its "envelope of operation" and speed control offers the single most efficient method of varying performance.

Further variation of the compressor's performance has historically been achieved through an extensive and expensive redesign, which permanently changes aerodynamic performance.

Recently, there has been extensive research into ways of varying the performance of the compressor by combining two of the techniques.

Research into viable unconventional methods for varying the performance of centrifugal compressors has identified several options:

- **Variable Inlet Guide Vanes + Variable Speed** - varying the angle of the normally fixed inlet guide vane into the impeller during operation
- **Variable Diffuser Vanes + Variable Speed** – installing diffuser vanes and varying the angle during operation
- **Suction Throttle Control + Variable Speed** – varying the suction pressure of the gas flowing through the compressor using a small regulator, before gas reaches the impeller

The most promising technology and method identified is the use of Variable Inlet Guide Vanes (VIGV) in combination with variable speed control.

The car industry was facing a similar problem in the late 1980s. Limits around the 'envelope of operation' on car turbo units led to the development of variable vane turbo units.

Project Description continued

How VIGV + Speed Control Technology Works:

The compressor impeller receives gas from the suction side through the "eye", see figure 6. The gas is directed via inlet guide vanes located in the "eye" to the impeller blades; it then undergoes a change in direction and gains kinetic energy from the rotating impeller. The gas leaves the impeller and is channelled into the diffuser channel where it expands, slows down and undergoes pressure rise.

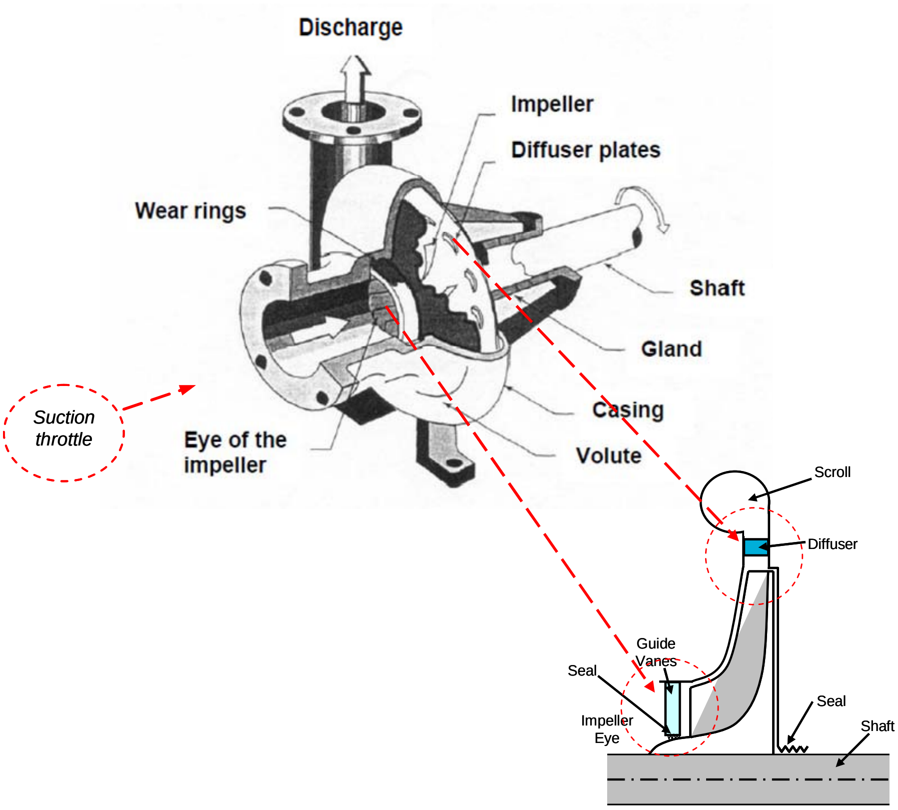

Figure 6: Cut-through a Centrifugal Compressor Showing Location of Guide Vanes (adapted from "Engineering Design Guidelines", KLM Technology Grp)

Vanes positioned upstream (eye/inlet) of the impeller ensure that the gas approaches the impeller at the optimum angle. Usually these vanes are fixed and provide either a positive or negative circumferential velocity component (prewhirl) to the gas entering the compressor.

- Positive prewhirl (produced by a positive vane angle) is in the direction of impeller rotation and this reduces the work done by the compressor on the gas;
- Negative prewhirl (produced by a negative vane angle) opposes the impeller rotation and this increases the work done on the gas.

Changing the angle of the guide vanes can vary the performance of the compressor, see figure 7. VIGVs have the potential to increase the flow range (turndown) of a speed controlled compressor by increasing the distance between the surge and choke regions as follows:

Project Description continued

- Surge: One potential cause of surge is due to the inlet gas flow stalling as it enters the impeller. In this case, VIGVs can be used to regulate the flow angle and delay the onset of surge. However, surge is a complex instability issue dependent on the system characteristics as well as those of the compressor. Whilst it is generally considered that VIGVs do shift the surge line to lower flows this is difficult to predict without detailed knowledge of the compressor geometry and system operating conditions;
- Choke: In theory, the onset of choke in the compressor is caused by relative velocity at the impeller eye reaching close to, or greater than the speed of sound. Applying a positive inlet guide vane angle reduces the relative Mach number and delays the onset of choke. Conversely, a negative angle increases it. In practice, choke in centrifugal gas compressors is manifested by a steep drop off in efficiency and manufacturers set the choke line at an efficiency level beyond which they consider operational efficiency unacceptable. Consequently, compressors can, and often do operate beyond the choke region but suffer a significant efficiency penalty when doing so.

A performance map which illustrates the effect of VIGV on a speed controlled compressor envelope is shown below.

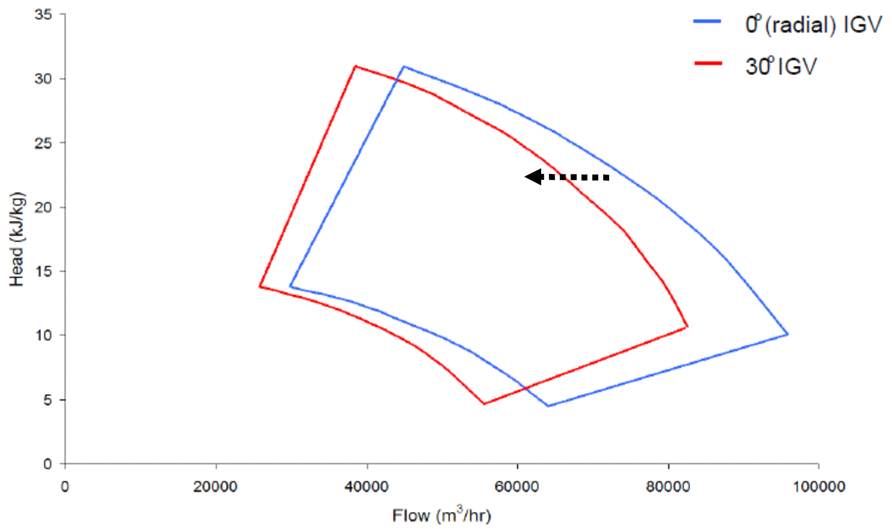

Figure 7: Example of a typical compressor envelope, where the blue curve is the original speed controlled envelope and the red curve shows the shift in capability realized by varying the VIGV by +30 degrees

This technology suggests possible flow variation in the region of 10%, increasing the flexibility of the compressor to respond to variable gas flow requirements. Theoretical efficiency improvements in the region of 2 – 5% are also possible.

A particular challenge that currently limits development of industrial-scale compressors with integrated VIGV + Speed Control technology ("variable envelope compressor") is the nature of the transport fluid – natural gas. VIGVs are located inside the compressor casing but are operated by a mechanism outside the casing. This introduces a potential leakage path could increase the risk of explosion. Also, instability of the gas flow as a result of changing the angle of the inlet vanes must be closely managed to prevent destructive vibration.

As a result, original equipment manufacturers (OEM) prefer only to use speed control for natural gas pipeline compressor applications.
None of the OEMs currently offer a variable envelope compressor solution that can be retrofitted to the existing compressors on the GB network. This means that major capital investment for replacing compressors across the network would be needed to give the flexibility that variable envelope compressors could provide.

2.3 Description of design of Trials

In order to adopt this technology into the GB gas network, four specific developments are needed:

Technology development & Risk evaluation.
There are two possible ways of introducing variable vane guides into an existing compressor; both have different risk and benefit profiles. In partnership with an OEM, the project team will evaluate the theoretical performance and risk issues for both options. At the end of the initial design phase the option with the greatest potential benefit will be taken forward to prototype manufacture and off line testing.

Demonstration.
As there are no examples of this solution being used elsewhere on the natural gas networks in the world that are comparable to the GB NTS, there is no information available to validate how much the operational envelope is increased in practice, and what set of flow and pressure requirements would justify its use from an economic perspective and what the practical installation issues could be. To generate this knowledge, to give an investment level of confidence to consider roll out across the network, we will undertake a full demonstration on one of the operational compressors.

Optimisation.
If successfully demonstrated, roll-out of the variable envelope technology across the Gas Transmission System fleet would inevitably be phased, so new systems and strategies that deal with a combination of fixed and variable vane compressors on the same site need to be developed, tested and optimised.

Successful rollout of this technology across key compressors on the gas transmission system will result in:

- Greater flexibility to deal with short term changes in gas transport requirement as a result of variation in gas supply and demand patterns.
- More effective resilience to manage fast ramp-up or ramp-down of network demands – e.g. CCGTs which need to provide fast response for wind generation.
- More efficient operation of compressors as a result of efficiency improvements when operating closer to optimum regions of the compressor envelope.

2.4 Changes since Initial Screening Process (ISP)

Only one change has been made to the VECTOR project since the ISP was submitted, this is associated with the date for completion. The end date for the project is now 2018 compared to 2017 from the original ISP. The reason for this change is to allow for contingency within the project plan for any unexpected delays in the production or commissioning phases.

To ensure that a compressor continues to operate efficiently and within its envelope, against a backdrop of changing supply and demand patterns, National Grid's adopts the following strategies:

1. **Changing the network conditions**. One tool that could be used, where a compressor supports export from a supply terminal, is the use of locational energy trades. Locational energy trades may be used to manage short term issues by increasing or reducing nominations at Entry and Exit Points by buying gas into, or selling gas out of, Gas Transmission System linepack. This impacts on customer behaviour and is an intervention in normal market operations.
2. **Reconfiguring the network.** Where possible, for example, using a nearby compressor station can reduce the requested duty on the affected one. This is usually only feasible with compressors that are not in line on the transmission network; and where this is possible, only a portion of one compressor station duty can usually be taken up by a different compressor station.
3. **Re-wheeling the Compressor.** This involves carrying out mechanical modifications to the compressor components in order to alter its capability.
4. **Introducing a new compressor train (i.e. a new compressor plus drive components).** This involves designing a new compressor train because the new throughput requirement of the compressor is associated with significantly different power requirements such that a new driver which is adequately matched to the new compressor is required.

These options are all used within the Gas Transmission System to manage network constraints depending on the severity, response time, cost versus risk, impact and resilience. The relative merits of each suggest that a solution which provides a low cost, low risk, and quick response is needed to manage changing system constraints. Using Variable Inlet Guide Vanes to vary compressor capability promises such a solution.

1. Operational - Change the network conditions.

This solution does not bring any security to manage future network changes and exposes shippers and National Grid to significant financial risk from locational exit and entry constraints and buyback.

Summary:
- Very quick response solution (~1 hour)
- No outage required
- Implementation cost = £0
- Least innovative and most reactive solution; retains ALL future risk.
- Impacts normal market operation and no guarantee of price or outcome.

2. Operational - Reconfigure local network to take up duty.

This is a relatively low cost solution since use is made of existing compression assets on other installations that may be operated less efficiently. It relies on the inbuilt flexibility of the network, plus availability of redundant compressors to cope with system constraints and future network flexibility requirements.

Also, this solution is of minimal benefit to the customer since where it is possible, only a portion of one compressor station duty can usually be taken up by a different compressor station, so nominated flows may still be curtailed.

It may also result in increased carbon emissions from less efficient use of other compressors around the network.

Summary:
- Quick response solution (~ 4 hours)
- No outage required
- Limited applicability
- Little or no innovation; reactive solution; retains ALL future risk.
- Implementation cost = £0 capital + unquantifiable £ opex due to: less efficient utilisation of other compressors, less efficient procurement of fuel gas.
- Starting and stopping additional compressors leads to increased venting of natural gas.

3. Investment - Compressor re-wheel

This is a medium-to-high cost, and low-to-medium impact solution. It needs long outages and equipment downtime as well as the cost of the re-wheel itself. However, this solution provides reasonable resilience to cope with foreseeable future events and provides opex benefits since a well-matched compressor wheel uses less fuel.

A re-wheel does not provide resilience to cover unforeseen transient events, but this may be mitigated by carrying out another re-wheel or keeping several wheels in storage to cope with probable duty variations.

To illustrate, Wormington compressor site located in the Southwest of the Gas Transmission System has been re-wheeled three times in the last 12 years for high and low flow.

Summary:
- Slow response solution – typically 12 to 18 months;
- ~1 month outage required
- Proactive solution; but retains an element of future risk.
- Implementation cost = [redacted]

4. Investment – Building a new compressor train

This is a very high cost solution. It would have a low-to-medium impact on customers dependant upon length of outage and overall time needed to deliver. It brings good resilience, especially if multiple units are installed with inbuilt flexibility to cope with expected network changes. Increased inbuilt flexibility comes at a cost that is not factored into the cost illustration below.

Summary:
- Slow response solution – 60 to 84 months typical
- ~12-18 month outage over 2 - 3 years typically required
- Proactive solution; potentially retains smallest future risk.
- Implementation cost = [redacted] (based on 15MW electric drive)

5. Use of Variable Inlet Guide Vanes +Variable Speed (PROPOSED)

This is an untried solution that promises to deliver inbuilt flexibility in the compressor, removing much of the requirement to re-wheel units. The risk involved in implementing the solution is reduced because of the ease of changing Inlet Guide Vane angles to move from one duty compressor envelope to another.

The range of operational and cost benefits offered by this technology in comparison to the other historically used methods, will be investigated through this demonstration project.

Summary: - Very quick response solution (< 1 hour)
- No outage required
- Proactive solution; but retains an element of future risk.
- Implementation cost = [redacted] (estimated and to be determined through this project)

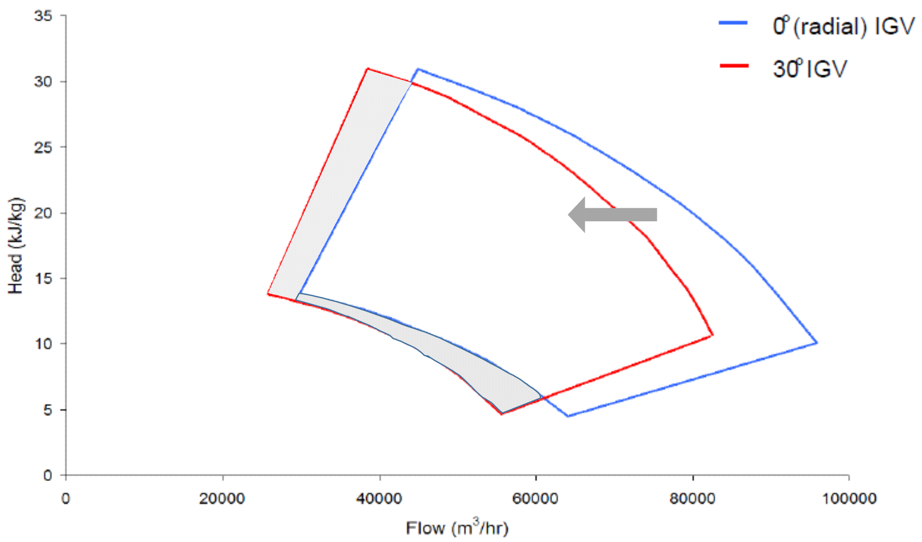

Fig. 8: VIGV + Speed Control Compressor Map showing additional [shaded] region which could be attained by changing VIGV angle by +30. Conversely returning the VIGV to its original setting would restore the compressor to its original envelope (blue border).

Capital Cost Savings & Resilience Benefits
To demonstrate the case for variable envelope compressors on the gas transmission network, a real design scenario is presented below.

Depending upon the network requirements the site in question typically operates one compressor on its own, or two in parallel. A new electric driven compressor unit has been installed to take up the bulk compression duty at the compressor site.

The new compressor design was based on anticipated duty up to nine years ahead using network analysis of the forecast gas supply/demand requirement supplied by the market (shown as large bubbles in figure 9) as well as historic operational hourly duty for 2006/07 (shown as crosses in figure 9).

Both data sets showed strong correlation (see oval red line); the new compressor envelope was designed on that basis. The design was finalized in 2008 ready for commissioning in 2011/12. The limits of the compressor envelope are shown superimposed on the data sets in figure 9. When design and production of the envelope was finalised, operating data from 2009/10 (from operation of the existing gas turbine units) was superimposed on it (see figure 10).

Project Business Case continued

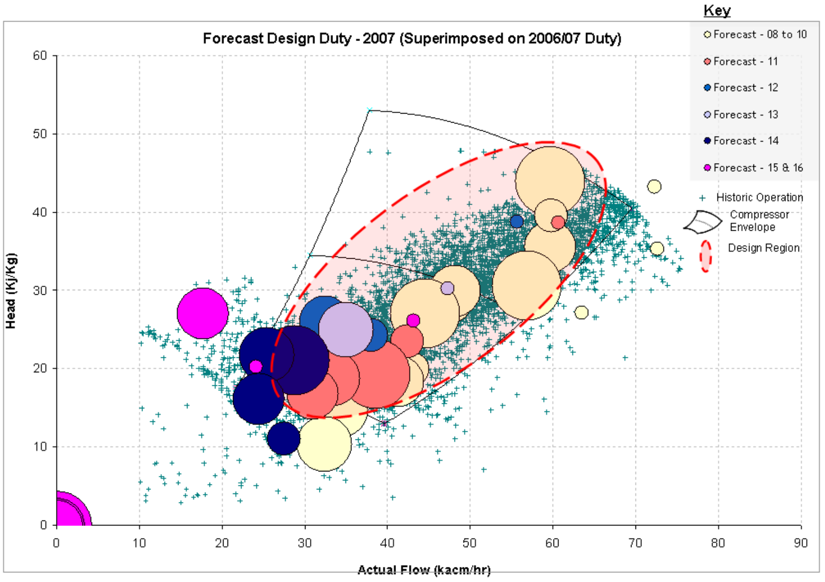

Figure 9: Forecast Design & Operating Data Superimposed on Design Envelope

A shift in required compression duty away from the 2006/7 design can be seen. This was due to unanticipated decline in entry point supplies far upstream as well as an increase in supplies from a nearer entry point reducing the requirement for high head (pressure) but increasing flow through the station.

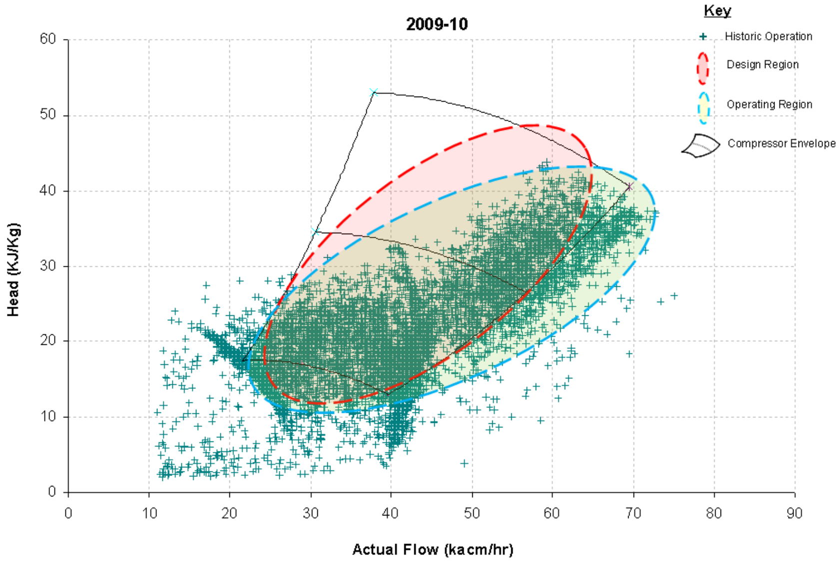

Figure 10: Forecast Operating Data (2009/10) Superimposed on Design Envelope

By 2011/12 the situation had changed again as the trend in flow from the different entry points continued. Figure 11 shows the shift away from the original 2006/07 design duty.

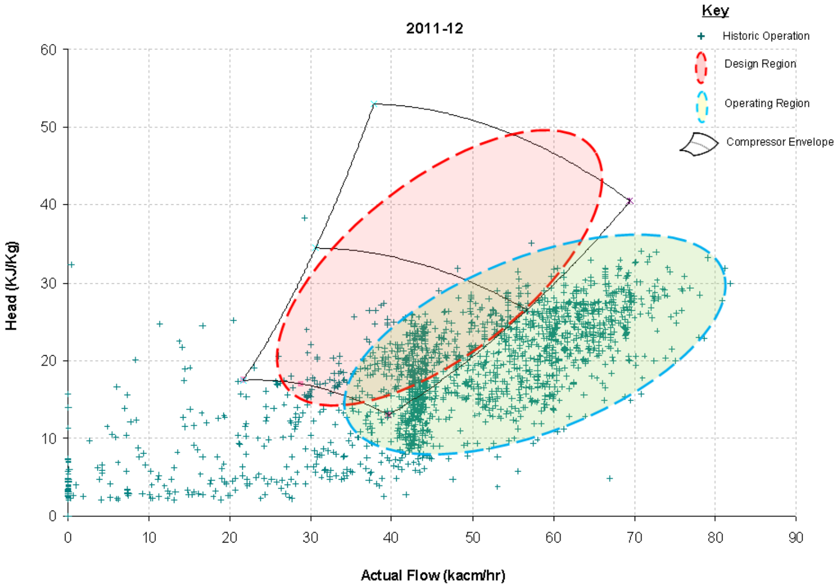

Figure 11: Forecast Operating Data (2011/12) Superimposed on Design Envelope

One possible solution to this problem would be a compressor re-wheel. This solution however would optimise the wheel around the current (2012/13) duty as well as the results of network analysis of future compression requirements. If the trend in the entry points continued or be reversed due to changes in market conditions, this would render the new envelope design obsolete, requiring yet another re-wheel.

The option to use variable envelope technology would reduce this risk by building the flexibility into the compressor to cope with changes of a similar magnitude.

Fuel Savings

Potential cost benefits of variable envelope technology include fuel savings from operating closer to higher efficiency regions of the compressor map. Figure 12 below shows the output of the Innovation Funding Incentive feasibility study which produced a variable compressor envelope model to evaluate the potential impacts, with operational data superimposed. Variable envelope technology is expected to increase the efficiency of operating in the choke region.

Considering a gas compressor installation with 1 x Electric Driven compressor plus 1 x gas turbine driven compressor the potential cost benefits of installing variable envelope technology can be illustrated as follows:

Using wholesale gas price of £20 per MWhr of gas, electricity price of £70.80 per MWhr of (standing and use of system charges not included) and utilisation of 3000 hours per year across the site, fuel costs could be reduced by approximately £0.8m per year if the compressors operated at their highest efficiency design point.

Due to the inherent variability of gas flows on the transmission system it is unlikely that all of this benefit could in practice be achieved. If variable envelope technology, which would allow efficient decentralised operation away from the design point, could be installed in the gas compressor, and assuming a conservative 3% efficiency gain results from higher frequency of operation within the compressor envelope, minimum likely fuel cost savings in the region of ~ £0.25m a year at this compressor installation could be realized

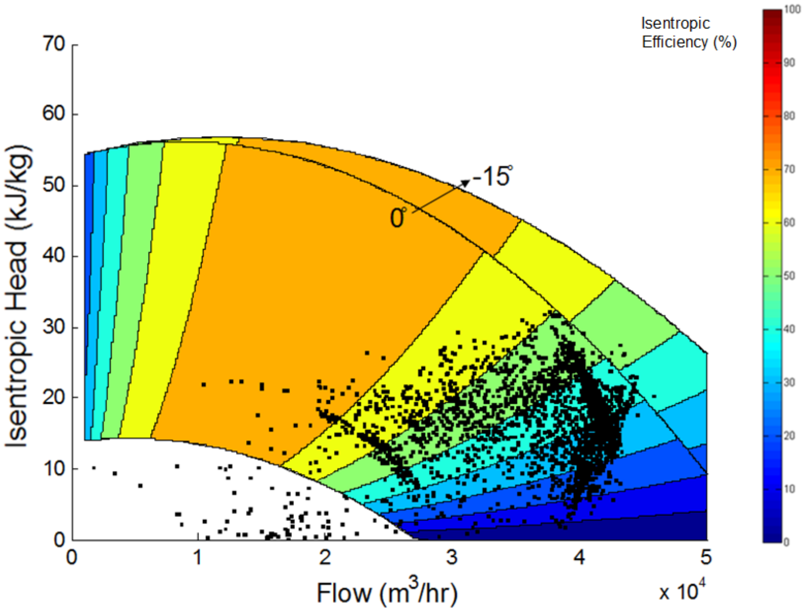

Fig. 12: Model prediction with 0° and -15° VIGV angle with site operational data (black markers)

Summary

At present there are two physical options for changing the capability of natural gas compressors on the Gas Transmission System:

1. Replace one fixed vane compressor wheel with another (re-wheeling). However, this is expensive and is impractical for managing daily or weekly or even annual variability.
2. Replace the existing compressors train with a new one which is very expensive and may require about 5 years to complete.

The proposed VECTOR project will develop an additional solution for changing compressor capability in time scales that existing solutions cannot achieve.

The demonstration project will measure the real achievable benefits and practical implications from retrofitting variable vane guide compressor technology.

4.1 Accelerating the development of a low carbon GB energy sector and delivering other environmental benefits

The Carbon Plan

The strategy set out in the Carbon Plan identifies the need for substantial changes to the way that and extent to which natural gas is used in Great Britain in the coming decades:

'As we look further ahead, the proportion of heat provided directly by natural gas will fall as we see increased use of low carbon technologies..' p39

'Towards 2030 government predicts a switch to more low carbon energy sources, such as bioenergy and electricity.' p62

These extracts illustrate the longer term changes in the way that gas in Great Britain is likely to be used.

Above all, through the Carbon Plan it is very clear that greater flexibility from gas fired power stations is needed to support the challenges of decarbonising the electricity sector in the short to medium term.

'The transition to low carbon power will not happen overnight. Over the next two decades, gas-fired power plants will provide the flexibility that we will need to meet peak demand and manage intermittent generation from some renewables, as well as baseload generation capacity' p72 The Carbon Plan

To do this gas fired power generation will need to respond quickly, which in turn will require increased flexibility in the gas transmission system that delivers the gas to these power stations, as illustrated in figure 13.

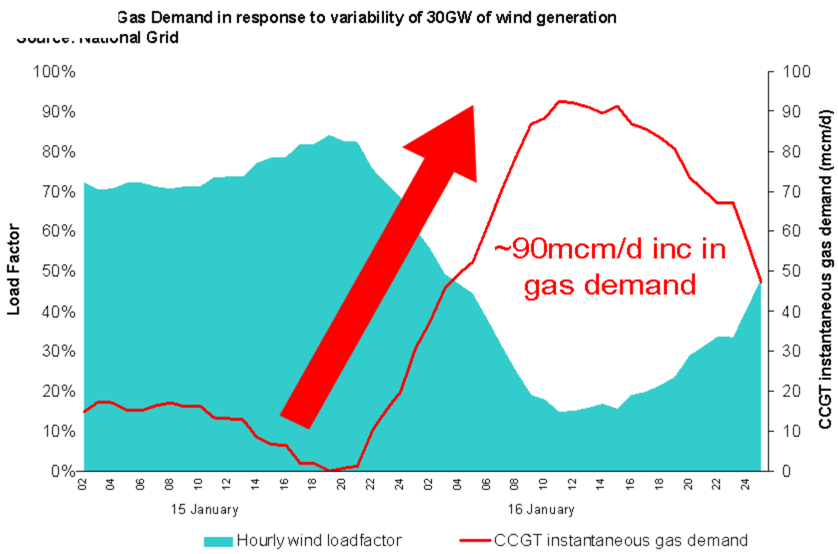

Figure 13: Wind generation demand response

Figure 13 above is taken from the July 2011 Transporting Britain's Energy (TBE) report and highlights a possible, extreme event in 2020/21 (based on extrapolated 2007 data) with total wind generation at 30 GW. Over a period of 15 hours, wind load factor decreases from

Evaluation Criteria continued

84% to 15%. If, as the Carbon Plan describes, the reduction in generation from wind is met by an upturn in CCGT generation, then this equates to an increase in within-day gas demand of ~90 million cubic meters/day. This previously unseen level of demand profiling on the Gas Transmission System would create challenges for the System Operator to manage the network and continue to meet pressure obligations.

Evidence from our compressor fleet, (examples are provided in section 3) shows that significant changes in the gas supply pattern are already occurring, and we expect more changes to occur in the future. These changes in supply and demand mean that the compressors will be increasingly required to operate in different areas of their envelope compared to their original design.

The current options for changing the operating range of compressors is described more fully in section 3. In summary:

- Re-wheeling on the existing network compressors currently takes between 12 and 18 months. Re-wheeling will remain the most appropriate option for some circumstances, however, this approach will never be a practical option for meeting timescales, illustrated in figure 13.
- Replacing existing compressors with multiple smaller units that can be switched in and out of service in series or in parallel provides the most flexible long term solution, but at high cost. At this stage, this level of investment is justifiably questioned. The Carbon Plan highlights that:

"The Government's aim is … to run a low carbon technology race between CCS, renewables and nuclear power". p 72 The Carbon Plan

Once there is greater clarity over the outcome of this race, this option may be the most appropriate for some compressor sites.

- Operational options offer solutions in the necessary timescales, but have significant draw backs in terms of cost, reduced efficiency and increased emissions.

The VECTOR project will develop and demonstrate a solution that will enable compressors to operate stably and more efficiently over a wider range than is currently possible. This will provide increased operational flexibility on the Gas Transmission System to support the Carbon Plan strategy. In addition we anticipate reduced compressor fuel consumption, fuel cost and carbon emissions directly associated with the operation of the network.

One of the main customers for National Grid Gas Transmission is Shippers. Shippers pay Capacity Charges for gas entering and exiting the Gas Transmission System. These are known as Entry and Exit capacity charges.

Network Capacity
VECTOR will develop a solution to provide flexibility in the capability of the gas transmission network that will be needed to manage the integration of intermittent renewables. VECTOR will not provide additional network capacity as capacity is a function of a combination of the diameter of the pipelines; the maximum operating pressure of the pipelines; or the power outlet of the compressor drive unit.

Evaluation Criteria continued

Financial Benefits

Supporting information for the evaluation of anticipated financial benefits is provided in Appendix 2.

It costs approximately [redacted] to re-wheel a compressor. So having to re-wheel each compressor three times costs [redacted] this is our "Base Case Costs".

The cost for implementing the VECTOR technology is assumed to be approximately [redacted] per retrofit unit (to be confirmed as part of the VECTOR project deliverables). Adding on the requirement to conduct one re-wheel per compressor, gives a "Method Cost" of [redacted]

The difference between "Total Base Costs" and the "Total Method Costs" is £2.4 million and this is the estimate financial benefit of the project. This is the main direct financial benefit of the VECTOR project.

Nine compressor sites are located in close proximity to the supply points and/or anticipated gas fired power station clusters; these are the sites that are most likely to benefit from variable envelope technology to increase their ability to respond to transient within-day fluctuations. It is reasonable at this stage to assume that the VECTOR solution would only be applied to the main duty compressors and not backup compressors, so it is foreseeable that it would be useful for 15 compressor units. It is also reasonable to assume that it will not be the most effective solution in all cases. Assuming that it is for between a quarter (4) and a half (8) of them, over their operational lifetime the savings from avoiding repeated re-wheeling could be in the order of £9m to £19m.

In addition, for those sites where it is deployed annual fuel saving from of up to £0.25m (at 2012 prices) has been estimated (appendix 2) per site.

The benefits gained as a result of this project will be wholly attributed to the Gas Transmission Network as it is the only Network Licensee that operates compression for the purposes of gas transportation.

4.2 Delivering VECTOR at Competitive Cost

The concept for VECTOR emerged from an IFI funded research project, the objective of which was

- to identify, and evaluate, ways in which to increase the operating envelope of compressors on the NTS,
- develop a model to understand, at a theoretical level, how and why the most attractive variable envelope technologies perform, and
- establish the level of technology maturity of the options through bilateral meetings with all six manufacturers who have built the existing NTS compressor fleet.

Following this, further bilateral discussions were held with the manufacturers that had experience of and expressed interest in variable inlet guide vane approaches to establish their appetite for partnering on the VECTOR development and demonstration project.

It is the intention of the VECTOR project to have two original equipment manufacturers participating in the initial design stage to enable a competitive element including price, likely whole life cost (capital and opex), modelled efficiency gain and modelled envelope increase, to form the basis of its selection criteria.
The VECTOR project will also be undertaking a competitive tender exercise to find a suitable

independent consultant to evaluate the design solution and results from the performance testing.

To ensure value for money the VECTOR project has:

- Appointed an experienced project manager, with over seven year's experience of dealing with contractors and delivering projects effectively.
- Secured the services of a buyer from its procurement department, to ensure that adequate terms and conditions are put in place with any suppliers to meet the criteria under the NIC governance document and ensure the project is getting the best possible value for money from its suppliers
- A functional design specification will be prepared by the Compressor Engineer to ensure that the designs and prices submitted by the original equipment manufacturers at the initial design phases are accurate.
- Established a governance process within the Project Steering Committee that will ensure that the project continues to deliver value for money to customers through to its conclusion.

Protection from Incentives

The VECTOR project is being planned to reduce the risk of exposure to any availability and reliability incentives to the minimum acceptable, as such the VECTOR project team is not requesting any protection from its incentives.

The VECTOR project plan includes provision for overhauling the standby compression on site to ensure reliability and availability levels are maintained. Also the project installation, commissioning and performance trial periods are being planned in the normal summer outage period for compression.

4.3 New knowledge from VECTOR

Four main areas of learning are expected to be delivered by this project:

- A functional design for a retrofit variable guide vane wheel for the demonstration compressor, and for similar units on the Gas Transmission System.
- The design issues and philosophy for a retrofit solution that will be suitable for other compressor types and for other OEM compressors on the Gas Transmission System.
- The requirements of, and interactions between, control systems in order to manage compressors with both variable vane and rotation speed control, and those with just rotation speed control.
- The costs and benefits of rolling out the technology across the GB fleet of Gas Transmission System compressors, to establish where and under what circumstances it is viable and beneficial.

This learning will provide National Grid Gas Transmission with another valuable option for its compression fleet, helping to deal with the challenges that it faces in the upcoming years with the predicted changes in the Gas Transmission System flow patterns.

The project team will happily share all relevant knowledge with interested parties. From a GB licensee perspective, it is envisaged that the benefit of the knowledge sharing will be relevant to National Grid Gas Transmission, as it is the only UK Gas Transporter Licensee that operates compressors for gas transportation purposes.

Evaluation Criteria continued

4.4 VECTOR is an Innovative Solution with associated risks for the Natural Gas network.

An independent consultant acting for National Grid has interviewed six major international compressor equipment manufacturers to establish the maturity of the technology. This review, confirmed that:

- Most of the global compressor market meets the needs of industrial processes that do not have the variable operational requirement and complexity of the GB transmission network.
- None of the OEMs have either new natural gas compressors or retrofit solutions with this technology that can be currently used on the GB Gas Transmission System.
- It is clear that due to the niche nature of the market for a retrofit solution, particularly one that could be applicable to compressors from multiple vendors, this solution will not be developed without funding support.

The potential benefits from a retrofit solution are clearly understood from the aerodynamic performance of new compressors for non-explosive gases. However, full-scale demonstration on the GB natural gas network is needed to:

- establish the technical feasibility of a retrofit solution on existing compressors from various OEMs, of various sizes, configurations and ages;
- to test the risks from their use with explosive gases and the knock-on costs to maintain safe operations;
- to validate the actual operational benefits and the circumstances in which it is a cost-effective solution for the GB network.

4.5 Involvement of other partners and external funding

The VECTOR project will be delivered with the assistance of three partners.
The first, the Carbon Trust was identified early in the process as holding a unique position to support National Grid's NIC projects as widely recognised and trusted independent experts in the field of low carbon technologies and carbon impact evaluation.

The second will be one of the compressor original equipment manufacturers from the existing National Grid Compressor Fleet who will design, manufacturer, install and then assist in the commissioning of the VECTOR technology.

The third will be an independent technical specialist partner with specific expertise in compressor design and fluid dynamics.

An agreement in principle has been reached with one of our OEM partners that they will provide in kind funding to cover the costs for the initial design and detailed design phases of the project.

National Grid's Approach to NIC projects & VECTOR

Throughout 2012 National Grid's Innovation team together with technology leaders in Gas Transmission, organised a number of workshops and bilateral discussions with: the teams within National Grid assessing the challenges likely to be faced in the RIIO-T1 period and beyond, suppliers and existing and potential new collaboration partners. From this process a long list of challenges and innovative ideas was collated.

Awareness of the NIC and NIA was raised with all parties and links to the relevant parts of Ofgem's website provided as a source of further information.

In the autumn of 2012 the Innovation Team screened 43 proposals (across Gas and

Electricity Transmission) to remove any that were deemed unnecessary duplication of work known to have been done already. The remaining projects were evaluated by a selection of technical and business leads to assess their priority in terms of potential to deliver value and their relevance to the timing of the challenges. Two Gas Transmission projects that met the criteria for NIC were shortlisted and finally one, VECTOR, approved for development for the 2013 Gas NIC.
The concept for VECTOR was further developed through an IFI funded research project, the objective of which was to:

- identify, and evaluate, ways in which to increase the operating envelope of compressors on the NTS,
- develop a model to understand, at a theoretical level, how and why the most attractive variable envelope technologies perform, and
- establish the level of technology maturity of the options through bilateral meetings with the six manufacturers who have built the existing Gas Transmission compressor fleet.

The project indicated that the promising option was VIGV in conjunction with speed control. Further bilateral discussions were held with the manufacturers that had experience of, and expressed interest in, VIGV approaches to establish their appetite for partnering on the VECTOR development and demonstration project.

VECTOR Partners
The Carbon Trust
The Carbon Trust is a world-leading organisation helping businesses, governments and the public sector to accelerate the move to a low-carbon economy through carbon reduction, energy-saving strategies and commercialising low-carbon technologies. Their mission is to tackle climate change by creating a vibrant low-carbon economy that delivers jobs and wealth. They can help organisations put sustainability at the heart of their business strategy and gain a competitive advantage in the market.

The Carbon Trust brings value to each of the three specific roles it has in the VECTOR project:

- Assessment of CO_2 impact,
- Dissemination of knowledge,
- Independent representative on the Project Steering Committee.

Created in 2001, they have developed into a world-leading and trusted expert in low-carbon issues and strategies, carbon footprinting and low-carbon technology development and deployment. They offer more than 10 years of unparalleled experience in the low-carbon sector.

Since its inception, the Carbon Trust's core mission has been to help public and private sector to reduce their CO_2 emissions and so it has unrivalled experience in helping companies achieve this goal. As a means to maximise CO_2 reduction, Carbon Trust has carried out extensive dissemination of knowledge to a variety of audiences. This has included events, reports, case studies and webinars. Many of these are viewable on their website.

Given its status as a not for profit organisation, Carbon Trust will not be in a position to make a financial contribution to the project.

Original Equipment Manufacturers
The original equipment manufacturers bring with them expert knowledge on the fluid and

machinery characteristics that will be experienced when the VECTOR technology is introduced, which will be essential to identify and deal with any issues that may occur or be unforeseen to the Project Team. They also bring with them their knowledge and expertise on the equipment that National Grid has installed.
It is the intention of the VECTOR Project Team to engage two original equipment manufacturers at the initial design stage to try and ensure that there is competition in terms of cost and technology.

One of National Grid's original equipment manufacturers, Rolls Royce, has already confirmed that they are interested in working with us to deliver a solution that meets our project scope. The VECTOR Project Team are continuing to seek another one of our original equipment manufacturers willing to participate in this project.

The original equipment manufacturers will be engaged on a collaboration basis. One OEM has already agreed to make a contribution to funding the project, and it is envisaged that the second will be engaged on a similar basis. As a result the OEM appointments will be as collaboration partners.

Technical Partner

To mitigate the risk of unsuccessful implementation of the demonstration project, National Grid's strategy is to retain the services of a technical partner. The technical partner will support National Grid in developing functional design specifications for the new variable compressor design, developing and carrying out baseline and comparator tests on selected compressor installations for the demonstration project. The technical partner may be selected via a competitive process or single source option depending on the availability of specific skill set required to deliver an innovative gas compressor project.

4.6 Relevance and timing

As previously indicated the Gas Transmission System is already facing significant challenges, at present dominated by increasing variation on the supply side. This variability is forecast to increase as new sources of supply are considered and demand patterns change to support intermittent renewable electricity generation.

The VECTOR Project aims to develop and demonstrate an additional innovative and unproven means of dealing with these changes by 2018. This is realistic and appropriate timing for it to become a business as usual option for deployment in the 2020's.

If the VECTOR technology proves successful, the ability to be able to vary the envelope of the compressor will be added to the specification that National Grid has for constructing new Compressor stations and overhauling existing ones.

Depending upon a number of other factors, to be investigated as part of this project, VECTOR technology could also be deemed "Best Available Technology" for selecting compressor technology to be employed on the Gas Transmission System.

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Section 5: Knowledge dissemination

☐ Please cross the box if the Network Licensee does not intend to conform to the default IPR requirements.

The VECTOR project will generate significant new knowledge that will be of interest and benefit to a diverse set of audiences. We will ensure that all relevant stakeholders are reached by well structured dissemination activities that are tailored to meet the needs of the different interest groups.

New Learning

VECTOR has four focussed learning objectives:

- A functional design for a retrofit variable guide vane wheel for the demonstration compressor, and for similar units to it on the Gas Transmission System.
- The safety, installation, operational and maintenance issues and philosophy for a retrofit solution that will be suitable for other compressor types on the Gas Transmission System.
- The requirements of, and interactions between, control systems in order to optimally manage compressors with both variable vane and rotation speed control alongside those with just rotation speed control.
- The costs and benefits of rolling out the technology across the GB fleet of Gas Transmission System compressors, to establish where and under what circumstances it is viable and beneficial.

Key Audiences for VECTOR

Customers: Our direct customers are those parties that pay NTS charges: shippers and connected networks (gas distribution and independent gas transporters). Our customers will have an interest in ensuring that NIC funding is well managed and that the projects funded have the greatest potential to deliver lower-cost options for the future that can ultimately be passed through to gas consumers. Stakeholder feedback during engagement activities leading up to RIIO-T1 was clear that safety and reliability are high priorities for customers, so it can be expected that they will have a keen interest in ensuring that our high standards in these areas are maintained in the development of the new technology.

Technology Vendors and Original Equipment Manufacturers (OEMs) will be interested in the learning that VECTOR develops around the ability to achieve greater operational flexibility through the use of inlet guide vanes. VECTOR seeks to demonstrate this technology by retrofitting it on an existing compressor, but the project team recognises the potential for this technology to be specified on future new compressor purchases, as well as retrofitting to others on the network.

Consumers: gas consumers are one step removed from the Gas Transmission network as their day to day dealings with Gas Transmission are with suppliers and Gas Distribution Networks. However, the costs of running the network and funding the NIC are ultimately passed through to consumers, so they will have an interest in knowing that this money is being well spent on projects that have a realistic prospect of leading to lower costs than a 'business-as-usual' approach.

Industry Groups: National Grid is involved with a wide range of National and International industry groups such as ENTSO-G, Institute of Gas Engineers, Pipeline Research Council International, Gas European Research Group, as well as having a network of International bilateral information sharing and collaboration partnerships with Transmission Network

Knowledge dissemination continued

owners and operators in various parts of the world. The technology being developed and trialled by the VECTOR project will be of interest to others in the international industry, particularly for networks where greater volatility of gas flow is foreseen.

Academic Institutions & Schools: information and knowledge developed through VECTOR will be relevant to the education sector at all levels from Primary up to Universities and Higher Education Institutions. National Grid has an active programme to provide engaging and informative material relevant to the National Curriculum through our School Power initiative. We will use this to raise awareness of the challenges that we face with our future energy networks, and some of the possible solutions that, in combination, will be deployed to solve them. We have close contact with a wide range of Academic Institutions through our framework agreements with several universities and they, and others, will have an interest in access to the data generated by the project and the lessons learned from it.

Government Departments and Regulator: DECC, Ofgem, HSE and Environment Agency will have an interest in the outcomes of the project as it could have implications for what is determined to be Best Available Technique for compressors.

Our Approach to Dissemination.
We will use a range of opportunities and activities designed to meet the needs of each of the different audiences to maximise their awareness of the problem and the learning derived from trialling the proposed method to develop a practical and usable solution.

The VECTOR team recognises the importance of two-way engagement with several audiences. This will enable the Steering Committee to ensure the VECTOR project is responsive to inputs from key stakeholders. Our approach will include the following:

- *VECTOR Website:* This will be the central point for all our dissemination activities. It will be updated with progress reports and results, and provide information about other dissemination events with relevant links to them. The link to the VECTOR website will be identified prominently on the National Grid Innovation website www.nationalgrid.com/innovation and we will ask that our peers share the link on their websites, for example the Ellen MacArthur Foundation and the Science Museum.
- *Lectures, Conferences and Webinars:* we are proposing to hold six formal dissemination events throughout the life of the project. These will include the NIC conferences in years 2 and 3. In addition we will use managed webinars once a year. This will give interested parties the opportunity to engage with the project team and to ask questions; it will also enable the project team to understand the key issues for stakeholders.
- *Podcasts, social media and press releases:* We will be proactive. The National Grid communications team will manage a series of podcasts outlining in clear terms the nature of the problem, the potential solution and what the VECTOR project is trialling to test the solution. We will use social media channels to provide regular updates and specific platforms will be created, for example on Twitter, so that interested parties can get involved in the conversation. Our aim is to create a virtual community where ideas can be shared and discussed. The National Grid press office will release a series of articles about the VECTOR project to the press, targeting a variety of audiences, both mainstream and specific, including trade, environmental and scientific coverage.
- *Journal Articles and Industry Conferences*: National Grid are members of specialist associations and we will use our representatives as ambassadors for the project, inviting their members to lectures and demonstrations. In addition, the project team will prepare trade journal articles for relevant industry publications.

Knowledge dissemination continued

- *STEM education programme:* National Grid has a range of engagement programmes to enable a younger audience to understand the practical applications of science and engineering in the workplace. The VECTOR project will be incorporated into our work on the importance of innovation to tackle key issues such as climate change and the responsible use of resources.
- *Six Monthly Progress Reports and Close Out Report*: the reports required under the NIC governance provide a valuable source of information during and at the conclusion of the project. These will be published on the VECTOR website as well as being submitted as required to Ofgem as well as published on the portal currently hosted by the Energy Networks Association (ENA).

Communications timeline

- Social media activities will be ongoing, although activities will increase as the project continues and a community is established.
- Press releases will be issued at regular intervals to coincide with six monthly progress reports.
- Key journalists will be contacted for a briefing once the project is underway and given updates at the key stages of the project.
- Footage and time lapse photography will also be used to document progress to be used at the end of the project to show what has been achieved.

Intellectual Property Rights (IPR)

Careful consideration has been given to IPR in the preparation of this proposal.

<u>Aspects for which IPR is not expected to be an issue.</u>

The results of the analysis of system wide carbon benefits and the roll out requirements and assessment of system wide cost and benefits from doing so are not expected to result in the generation of foreground IPR.

<u>Background and Commercial IPR</u>

The technology and know-how needed to develop a VIGV solution to be retrofitted onto a GB Gas Transmission System compressor have already been developed by manufacturers for use in non-explosive environments, and they already own the Intellectual Property Rights associated with it.

The compressor industry is highly competitive and IPR is closely protected by Manufacturers. It is therefore important that sensitive information does not become disclosed to VECTOR partners' competitors.

In order to meet the needs of both the NIC governance and the project partners, an agreement in principle has been reached with one of our OEM partners that they will provide in kind funding to cover the costs for the initial design and detailed design phases of the project. The foreground IPR from the initial and detailed design phases will be owned by the OEM.

Gas Network Innovation Competition Full Submission Pro-forma

Knowledge dissemination continued

The valuable and relevant learning for GB Gas Networks with compressors will come from:

- The results from the performance trials.
- The lessons from any installation and operating challenges.
- Any necessary procedural changes.
- The circumstance which would render this option technically unsuitable for roll out.
- Information cost and benefits to inform roll out where it is technically suitable.

Learning of this kind will be made openly available to the different audiences.

Section 6: Project Readiness

Requested level of protection require against cost over-runs (%):
[redacted]%

Requested level of protection against Direct Benefits that they wish to apply for (%):
0%

The following additional information is appended in support of this section of the VECTOR proforma:

- Cost Spreadsheet, Appendix 1
- Project Programme, Appendix 3
- Risk Register, Appendix 4
- Contingency plan, Appendix 5
- Organogram, Appendix 6
- VECTOR Governance Terms of Reference, Appendix 7
- Extract of initial Research Report: "*Research into Variable Envelope Compressors*", Appendix 8

Technology Readiness
The VECTOR project aims to demonstrate the feasibility of variable gas compressor technology as well as to optimise the technology for application on the gas transmission network.

National Grid has carried out initial research – "*Research into Variable Envelope Compressors*" – through the Innovation Funding Incentive to investigate various theoretically feasible methods for varying compressor performance and identify the most promising method for demonstration and optimisation.

The study covered:

- Technical literature review of technologies for extending the range of gas pipeline centrifugal compressors.
- Engagement with compressor OEMs through stakeholder interviews to understand their views on the proposed methods as well as understanding more generally their R&D strategy for centrifugal gas compressor development.
- Independent quantitative analytical modelling to predict the potential benefits in range extension and efficiency using existing operational data from National Grid compressor stations.
- Engineering Risk Analysis which summarised previous development and commercial experience of the OEMs and a Technology Readiness Level (TRL) assessment. It also considered the engineering risks of deploying such as system.

A copy of the research report is attached to this proforma.

This initial research was carried out with a technical partner – Frazer Nash Consultancy. The research included a survey of the state of technology readiness as well as appetite, of each OEM to facilitate a demonstration project on the Gas Transmission System.

Resource Readiness
Two compressor OEMs initially demonstrated an acceptable level of technology readiness and expressed willingness to carry out a demonstration project. National Grid has formally

Project Readiness continued

approached both OEMs and requested expressions of interest in supporting a demonstration project. National Grid's strategy is to engage at least one compressor OEM as a key partner in delivering the VECTOR project. Rolls Royce have already confirmed their interest in participating in this project. At the time of submission final cost estimation from Rolls Royce is still pending. In parallel with the project funding competition the project team is pursuing the engagement of the second OEM.

A selection exercise will be undertaken to identify the technical partner in the period between funding decision and project commencement in April 2014.

Resources within National Grid have already been identified for the roles of project manager, compressor engineer, corporate communications and Network Innovation Competition Manager.

Project Programme
The VECTOR project programme is a combination of the compressor OEM's programme, the technical partner's programme and National Grid's programme.

It has been drawn up based on a "best view" provided by both sets of project partners as well as National Grid's extensive experience of lead times and schedule associated with compressor retrofit projects.

Key stages in the programme which mark milestones in VECTOR project delivery post NIC award are:

1. Design & Testing Phase: ~ 12 months
2. Build & Testing Phase: ~ 14 months
3. Commissioning & Operational Testing Phase: ~ 15 months
4. Final Report & Closeout: ~ 5 months

A key programme risk is the manufacture and offline testing of the technology by the OEM. Since this will be strongly influenced by shop floor schedules, there is a risk of slippage. However a contingency is in place to mitigate the risk of slippage on the overall project.

Project Management / Control
A National Grid project manager has been appointed with direct control of the project programme. Control of the project programme and deliverables will be managed as follows:

1. Weekly by the project manager through team meetings and work package management.
2. Quarterly project steering committee meetings of National Grid and project partners.
3. Semi-annual project reports to Ofgem and National Grid's internal Project Management Group.
4. Annual updates at NIC conference.

National Grid projects must follow international accounting guidelines as well as internal project management procedures, under which require the project has to be reviewed at the appropriate governance level if any of the key delivery parameters – time, cost and scope – are likely to be exceeded. An annual financial audit of the project, independent of the VECTOR project delivery team will be carried out to ensure the spend remains in line with the project plan.

Project Readiness continued

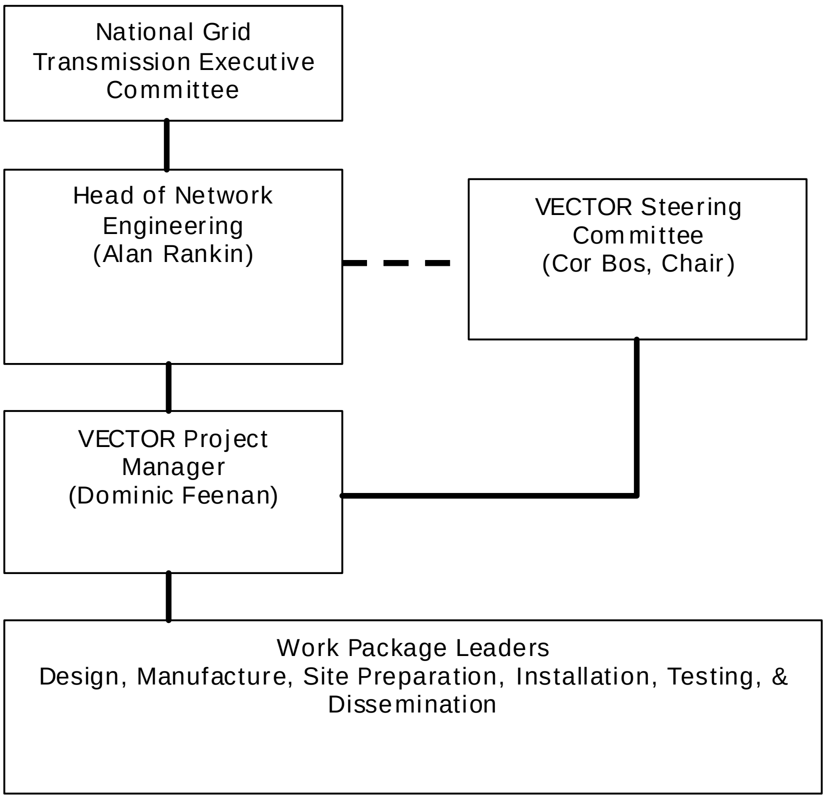

Figure 14: VECTOR Project Management Organogram

Risk Management (inc. failsafe)

A project risk register is in place to monitor project and programme risks concerning:

- Realising project benefits
- Project continuity
- Design / implementation
- Timely completion
- Controlling project costs

A detailed risk register is included in the appendix 4. Individual risks will be managed at appropriate levels within the project delivery structure shown in figure 14 above and as described in the risk register.

As part of the project control system, if there is a risk that there could be a change in the scope, benefits or cost range of the project, it would be escalated to the appropriate delegated authority (as shown in the project management structure). The Terms of Reference for the steering committee require that any such changes be reviewed every three months and a proactive decision made to the continuation of the project.

Management of Modification

National Grid's management procedures must be applied for new installations or modifications to existing assets on its operational sites. These procedures incorporate the philosophy outlined in the Institution of Gas Engineers & Managers (IGEM) guidance document IGE/GL/5 (*Plant Modification Procedures*).

Project Readiness continued

The aim of the process is to ensure that:

- A system of design appraisal is in place prior to implementation.
- A system of documentation is in place to record any change
- Adequate training is in place to ensure all relevant personnel have the skills, training, experience and personal qualities necessary for the exercise of professional judgement.

The scope of the proposed VECTOR project currently suggests that it falls within the category of a "**high risk project**" within the above procedure and so will be subject to an independent formal design appraisal carried out by approved appraisers registered on National Grid's appraiser database.

Management of Environmental Risk
When modifying or installing new gas transmission equipment, Formal Environmental Assessments (FEA) activities must be carried out.

These activities assess the interaction between the new and existing equipment and operations, in line with National Grid's management procedures. It is essential to apply FEA techniques at the design and delivery stages of new projects and, as required, during normal operations, to ensure that potential environmental impacts are minimised and also that National Grid Gas remains fully legally compliant with environmental legislation.

Examples of FEA activities which may be required for the VECTOR project include:

- Noise assessment
- Air quality assessment
- Geotechnical risk assessment
- Environment permits review
- Planning conditions review

Management of Safety Risk
Applying Formal Process Safety Assessment (FPSA) techniques is essential at the design stage of new projects with major hazard potential because it ensures appropriate levels of process safety. The techniques are equally applicable during modifications.

This process is implemented through National Grid's management procedures and ensures that all potential significant hazards are identified at design stage for new projects or modifications to enable appropriate control and mitigation measures to be put in place.

Examples of FPSA activities which may be required for the VECTOR project include:

- HAZID (hazard identification study)
- HAZOP (hazard & operability study)
- HAZCON (construction hazard assessment)
- DSEAR Assessment (explosive atmosphere risk assessment)
- Safe Working Design Study
- Human Factors Assessment

Cost & Quality Control
National Grid's suite of policies and specifications for design, construction, commissioning and modifying compressor installations will be used to develop the Functional Design Specification as well as design and commissioning of the new equipment.

Project Readiness continued

A quality control system is currently in place within National Grid's Capital Delivery department which specifies the following activities during the design, installation and commissioning process:

- Cross-functional engineering design review
- Management challenge and review
- Compliance statements
- Design change control

All of these activities have been included within the project plan and project costs. Reasonable estimates of programme contingency have been made within the project programme to allow appropriate remedial action to be taken to manage design, construction or operational issues identified through these processes.

Project cost have been developed using a combination of the following:

1. OEM provisional cost estimates for related scope of works.
2. National Grid's historical material and equipment costs for managing machine modifications of similar scope.
3. National Grid labour rates.
4. A provisional sum to cater for a replacement compressor in the event that the technology is unsuccessful.

VECTOR project costs will be managed at both the project manager and project steering committee levels. The management of project cost changes will be as follows:

Cost Change Driver	**Delegated Authority to Approve** *(depending on magnitude of change)*
Scope Change	VECTOR Steering Committee, with agreement with Ofgem.
OEM (or other Partner) Material / Delivery Cost Change	VECTOR Steering Committee VECTOR Project Manager
Time Increase	VECTOR Steering Committee VECTOR Project Manager

Project Code/Version No: NGGTGN01_V2

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Section 7: Regulatory issues

☐ Please cross the box if the Project may require any derogations, consents or changes to the regulatory arrangements.

The VECTOR Project Team has consulted with the National Grid Regulation Department and does not expect that the VECTOR Project will require any derogation, licence consent or licence exemption.

The VECTOR project explores increasing the flexibility of the existing network assets and aims to trial new techniques for the active management of the Gas Transmission network into the future.

As stated previously, we will not request any variation to our commercial regime and associated incentives as part of delivering this project. This project also does not replace any existing investments included in our baseline funding for the RIIO-T1 period.

Section 8: Customer impacts

Customer Interaction and Engagement

Due to the nature of the VECTOR project, the works will be conducted on a compressor station and as such there should be no need for direct interaction with customers. There will probably not be any need to enter customer's premises as a result of this project. If these assumptions are likely to change the VECTOR Project Manager will notify OFGEM, via email, and detail:

- The reasons for the interaction
- An overview of the anticipated interaction
- The measures that will be put in place to protect any customer information required and obtained, including disposal.

The VECTOR project does plan to engage with the Gas Transmission Customers that it will likely impact upon (mainly shippers). This will take the format of presentations and drop in Question and Answer sessions, at existing forums that National Grid facilitates. These sessions will be designed to inform customers on:

- What the project entails.
- The potential benefit(s) to them.
- The potential benefit(s) to the environment.
- The potential benefit(s) to National Grid.
- How it supports the Carbon Plan

The VECTOR Website, Twitter and Facebook pages will also be promoted at these sessions to allow the customers the option of keeping track on project progress. Customers will also be given the opportunity to request attendance of the VECTOR Project Team, to future forums to provide updates on the progress of the project.

Customer Contracts and Charging

Through out the delivery phases of the VECTOR project there will be no need to change any of the contractual or charging arrangements that exist between National Grid Gas Transmission and its customers. As previously noted, there may be an opportunity to reduce the charges to customers in the future – that depends upon the successful outcome of the project and realising the potential savings anticipated.

Interruption of Customers' Supplies

The VECTOR project has been planned in such a way as to try and ensure that there is no interruption of customers' gas supply. During the VECTOR project it is envisaged that the only time when the gas supply will be at an increased risk is during the installation and performance trial periods. This risk will be minimised by conducting the installation during the National Grid's normal outage period which is typically over the summer.

National Grid designs its compressor stations so that there is typically 100% standby compression available on site, this is provided by another unit or units. To minimise the possible risk of interruption to customers' gas supplies as a result of an unforeseen event or problem during the installation, performance trials or the period after the VECTOR project has been closed out, the standby compression will undergo extensive pre-emptive maintenance and overhaul.

This will be above and beyond the normal maintenance conducted by National Grid on its compressor fleet. This is to ensure that that the standby compression will be in a position to run reliably for a period of up to two years with minimal down time.
This two year period has been developed on the worst case assumption that the

Customer impacts continued

compressor, the VECTOR technology is being installed on, requires a complete replacement as a result of the casing being damaged beyond economic repair.

The two year timescale assumes:

- The standby compressor is run for two months during the installation of the VECTOR technology.
- The damage is found during the commissioning phase
- A 14-16 month delivery time for a new compressor
- Installation time of two months for the new compressor.

Despite all the measures described above there is still a very small risk that an unplanned interruption of gas supply to customers may occur if all compression on the site was unavailable for an extended period of time (more than two months). If this happened, the impact on customers' supplies cannot be quantified due to a number of factors that are unknown to the VECTOR Project Team. These include:

- Nature of the failure(s)
- Time and duration of failure(s)
- Supply flows during this period
- Demand requirements during this period.
- Availability/unavailability of other equipment on the Gas Transmission System.

In the event that all compression is lost from the site, for an extended period, the VECTOR project team will work with Gas Transmission Asset Management to reinstate compression to the site as soon as possible. This may involve looking at the status of the VECTOR technology installation programme and making an informed decision around whether it is viable to go back to the original design or accelerate the installation phase. Once again this will minimise the risk of gas supply interruptions to customers.

Protection from Incentive Penalties

As the degree of impact cannot be reasonably estimated at this stage and the likelihood of customers experiencing impact is very low, the Vector Project is not requesting any protection from any incentive penalties.

Alternative Ways to Implement the Project

The VECTOR Project Team has examined the methods of delivering the installing the technology and it firmly believes that there will be a need to make a compressor unavailable for an extended period while the VECTOR technology is installed and commissioned.

To reduce the risk of gas supply interruption as much as is feasibly possible, during these phases, the Project Team believes that extensive maintenance and overhaul of the standby compression is essential.

The only alternative identified was to continue with the normal maintenance that National Grid conduct on the rest of its compressor fleet. This was discounted because the VECTOR project may involve creating an opening in the compressor casing. This is not a normal operation is and brings with it an increased risk that the compressor casing becomes compromised.

Section 9: Successful Delivery Reward Criteria

Criterion (9.1)

Initial Design Evaluation and Selection of Preferred Solution

1. National Grid prepares a functional specification and submits it to the OEMs
2. OEM initial designs are submitted to the National Grid Project Team for evaluation
3. National Grid selects a preferred solution for further design and prototype build.

Evidence (9.1)

Initial Design Evaluation and Selection of Preferred Solution

1. A functional Specification will be delivered to the OEMs by the end of April 2014. A summary will be published on the National Grid VECTOR Innovation Website and a copy of the full specification can be provided to Ofgem at the same time if requested. An announcement to be made on the National Grid VECTOR Twitter/Facebook accounts that the functional specification has been submitted to the OEMs.
2. Monthly progress meetings between National Grid and the OEMs' design teams will be held, with minutes of the meetings available for OFGEM, if requested. The OEMs initial designs will be submitted to National Grid by October 2014. An announcement will be made on the National Grid VECTOR Twitter/Facebook accounts that OEMs' initial designs have been received and are going to be evaluated.
3. National Grid will announce its preferred solution and justification for its decision, including its selection criteria, by the end of December 2014. An overview of the selection process and outcome will be provided in the next six-monthly project report. An announcement will be made on the National Grid VECTOR Twitter / Facebook accounts that the OEMs' initial designs have been evaluated and the preferred supplier for the prototype build and trial has been decided. A summary of the initial designs and the specification will be published on the National Grid VECTOR Innovation website. An overview video of the proposed design, and an introduction on how it works, will be published on the National Grid YouTube Channel by April 2015. A link to the video will be placed on the National Grid VECTOR Innovation website and on the Twitter / Facebook pages.

Criterion (9.2)

Detailed Design and Prototype build and Offline Trial

1. The trial site is finalised and detailed design of the Prototype starts.
2. Manufacturing of the prototype compressor wheel starts.
3. The offline trial of the prototype starts.

Evidence (9.2)

Detailed Design and Prototype build and Offline Trial

1. Agreement will be reached with all relevant parties within National Grid (Gas Network Control Centre, Site Operations, Compressor Fleet Management and VECTOR project team) and with the successful OEM on which compressor unit will be used for the VECTOR installation by April 2015. All available detailed drawings and specifications of the compressor casing, wheel, shaft and power train will be shared

Successful Delivery Reward Criteria continued

with the successful OEM. Trial site details will be published on the National Grid VECTOR Innovation website. An announcement will be made on the National Grid Twitter / Facebook accounts and Innovation website that the site has been decided.

2. Monthly progress meetings will be held between National Grid and the OEM design and manufacturing teams. Minutes of the meetings will be available for Ofgem, if requested. An offline testing programme will be agreed with the OEM, including: functional operation testing, leakage proof testing, telemetry interaction testing, etc. An announcement will be made on the National Grid VECTOR Twitter / Facebook accounts that the OEM prototype is being produced and will be evaluated.
3. By June 2016 the agreed offline testing will be completed. If permitted (subject to testing facility rules and regulations), a video of the offline trials will be published on the National Grid YouTube channel. A link to the video and announcement will be placed on the National Grid VECTOR Innovation website as well as on the Twitter / Facebook pages. An announcement as to whether or not testing has been successful will be published on the National Grid VECTOR Innovation website. The outcome of the offline trials will be included as part of the next six-monthly project report and presented at the next NIC conference.

Criterion (9.3)

Preparation for and actual Installation of the VECTOR Technology on Live System.

1. A major overhaul is carried out and extensive maintenance is conducted on the standby compression.
2. Baseline envelope tests are performed on the existing compressor train.
3. Outage requests are submitted and the project delivery team is assembled for installation and the performance test period.
4. The VECTOR technology is installed

Evidence (9.3)

Preparation for and actual Installation of the VECTOR Technology on Live System.

1. The team develops and agrees equipment on the standby compression that needs an overhaul and intensive maintenance to ensure it can run for a period of up to two years with minimal downtime. The overhaul and intensive maintenance is carried out from June 2016 to October 2016. Essential annual maintenance on the standby compression is carried out in April 2017.
2. Compressor train base line checks are performed during 2016 to establish the efficient operating speed for the drive unit and the emissions experienced. Compressor envelope ‘mapping’ is conducted to establish the benchmark information of the existing compressor wheel and casing.
3. In the event of successful offline tests, an outage request form will be submitted for May 2017 to September 2017 to allow for the installation of the VECTOR technology and performance trials. In early 2016 the project delivery team will be established to ensure that the project is delivered in an efficient and compliant way (including CDM regulations).
4. From May 2017 to September 2017, the VECTOR technology will be installed. A video will be established, showing a time lapse of the installation process and the technology. This will be published on the National Grid YouTube channel. A link to the video will be placed on National Grid’s VECTOR Innovation website as well as on

Successful Delivery Reward Criteria continued

the Twitter / Facebook pages. An announcement that installation has been completed will be made on the National Grid VECTOR Innovation website as well as on the Twitter / Facebook pages.

Criterion (9.4)

Performance Trials and Benchmarking.

1. A new compressor map will be established, with the VECTOR technology not engaged and not influencing the gas flow path.
2. The compressor flow characteristics will be mapped, with the VECTOR technology fully engaged and fully influencing the gas flow path.
3. The compressor flow characteristics will be mapped, with the VECTOR technology engaged at its various intermediate stages and influencing the gas flow path accordingly.
4. The results of the project will be benchmarked against the baseline.

Evidence (9.4)

Performance Trials and Bench Marking.

1. In September 2017 the retrofitted compressor will be online and, using any test loop that may be available, a mapping exercise will be performed – without any VECTOR technology influencing the gas flow path, noting the flow rates and generated head across the maps. The most efficient area for running the compressor and the train will be established.
2. By the end of December 2017, utilising any test loop that may be available, a mapping exercise of the compressor will be performed – with the VECTOR technology fully engaged and fully influencing the gas flow path, noting the flow rates and generated head. An education visit will be held for interested parties to visit the site and view the installed technology – this will be extended to Ofgem as well. A training visit programme will be set up for National Grid staff who may be affected by this technology (this may include the control centre staff and engineers from other compressor sites).
3. During September to December 2017 continue with the mapping exercise of the compressor using the various intermediate stages of engagement of the VECTOR technology. Continue with educational and training visits.
4. In January 2018, once all performance tests have been completed, a benchmarking exercise on the extent of the extra variation will be completed and improvements expressed as a percentage of the compressor map that can be utilised as a result of the VECTOR technology. The result of this benchmarking will be published on the National Grid VECTOR Innovation website and on the Twitter / Facebook pages.

Successful Delivery Reward Criteria continued

Criterion (9.5)

Verification of Results from Trials, Knowledge Dissemination and Project Close Out.

1. The results from the testing programme will be verified.
2. The knowledge from the trial will be disseminated.
3. The VECTOR project will be closed out.

Evidence (9.5)

Verification of Results from Trials, Knowledge Dissemination and Project Close Out.

1. During the period from January to March 2018 the results of the testing programme will be independently verified. An estimate of the carbon savings that will potentially be achieved by running the compressor train and compressor in the most efficient area of the map will be verified by the Carbon Trust. The potential savings to customers will be re-evaluated based on the outcomes of the testing programme. National Grid will also conduct a final assessment on how widely the VECTOR technology can be rolled out across the compressor fleet.
2. By March 2018 a technical paper will be prepared. This will be submitted for publication in at least two of the following institution journals – Gas Engineers and Managers, Chemical Engineers, Mechanical Engineers. By February 2018 a summary paper of the findings will be prepared and published on the National Grid VECTOR Innovation website; a link to the report will be published on the VECTOR Facebook / Twitter pages. The outcomes of the project will also be shared with National Grid Gas Transmission customers at the next available forum. When the VECTOR project has been completed successfully, it will be put forward for presentation at the National Grid Shareholders' Annual General Meeting, as well as inclusion in National Grid's Annual Performance Report. The project team will produce an overview video presentation on the VECTOR project and its benefits, and the video will be published on the National Grid YouTube channel. A link to the video will be placed on the National Grid VECTOR Innovation website as well as on the Twitter / Facebook pages. If successful, the National Grid specification for new compressors will be updated to ensure that this technology is routinely considered as a design option.
3. By April 2018 the final six-monthly report will be produced, providing an overview of the project in its entirety, its successes and delivery against its initial goals. The project finances will be finalised. The project team will present the findings from the VECTOR project at the next available NIC conference.

Section 10: List of Appendices

This submission is supported by the following appendixes:

Appendix	Title	Description
1	Full Submission Cost Spreadsheet	Provides a breakdown of development and delivery cost and spend phasing of the VECTOR project
2	Cost Assumptions	Provides details of the material and resource assumptions which underpin the VECTOR cost build-up (including fuel savings calculations)
3	VECTOR Project Programme	Detailed project programme including contingency
4	VECTOR Project Risk Register	Risks associated with VECTOR delivery and controls in place
5	VECTOR Contingency Plan	Contingency plans for the VECTOR project
6	VECTOR Organogram	Schematic overview of team structure during initial and final design and build phases
7	VECTOR Governance Terms of Reference	Description of VECTOR project governance including organogram
8	Extract of initial Feasibility Report: "*Research into Variable Envelope Compressors*"	Extract of NIA-funded research into Variable Envelope Compressor Technology and application to gas pipeline compressors
9	Future Gas Network Resilience	Addendum to Sections 2 & 3
10	Maps & Network Diagrams	NTS Map with Compressor stations identified
11	Glossary	Glossary of terms used within the proforma and the appendices
12	Project Partners Support Statements	Email and letters received from Project Partners showing their support for the VECTOR Project.
13	Additional Info	Clarification of points raised during the Expert Panel process
14	Addendum	Register of changes made between original submission and final submission

Appendix 1
Full Submission Cost Spreadsheet

Project VECTOR

Project Code/Version No:
NGGTGN01_V2

Gas Network Innovation Competition Full Submission Spreadsheet

(version 2.0)

Appendix A

Licensee Name: **National Grid Gas Transmission**

Submission Date: **10/10/2013**

	Input cells
	Totals cells (of formula within worksheet)
	Referencing to other worksheets
	Check cells
	No Input
	Descriptions and pack data
	Ofgem Input cells

	A	B	C	D	E	F	G	H	I	J	K	L
1	**NIC Funding Request**											
2			2013/14	2014/15	2015/16	2016/17	2017/18	2018/19	**Total**			
3	**Cost**	*From Project Cost Summary sheet*										
4		Labour	93.00	177.00	215.00	345.00	385.00	-	1,215.00			
5		Equipment	2.00	2.00	1,152.00	1,403.00	103.00	-	2,662.00			
6		Contractors	-	305.00	295.00	635.00	1,150.00	-	2,385.00			
7		IT	3.00	5.00	-	-	-	-	8.00			
8		IPR Costs	-	-	-	-	-	-	-			
9		Travel & Expenses	2.00	9.00	-	-	32.00	-	43.00			
10	Payments to users & Contigency		5.00	30.00	150.00	250.00	2,505.00	-	2,940.00			
11		Decommissioning	-	-	-	-	-	-	-			
12		Other	-	-	-	-	-	-	-			
13		**Total**	105.00	528.00	1,812.00	2,633.00	4,175.00	-	9,253.00			
14												
15	**External funding**	*Any funding that will be received from Project Partners and/or External Funders - from Project Cost Summary sheet*										
16		Labour	-	18.00	36.00	-	-	-	54.00			
17		Equipment	-	-	-	-	-	-	-			
18		Contractors	-	180.00	60.00	-	-	-	240.00			
19		IT	-	-	-	-	-	-	-			
20		IPR Costs	-	-	-	-	-	-	-			
21		Travel & Expenses	-	3.60	-	-	-	-	3.60			
22	Payments to users & Contigency		-	18.00	6.00	-	-	-	24.00			
23		Decommissioning	-	-	-	-	-	-	-			
24		Other	-	-	-	-	-	-	-			
25		**Total**	-	219.60	102.00	-	-	-	321.60			
26												
27	**Licensee extra contribution**	*Any funding from the Licensee which is in excess of the Licensee Compulsory Contribution - from Project Cost Summary sheet*										
28		Labour	-	-	-	-	-	-	-			
29		Equipment	-	-	-	-	-	-	-			
30		Contractors	-	-	-	-	-	-	-			
31		IT	-	-	-	-	-	-	-			
32		IPR Costs	-	-	-	-	-	-	-			
33		Travel & Expenses	-	-	-	-	-	-	-			
34	Payments to users & Contigency		-	-	-	-	-	-	-			
35		Decommissioning	-	-	-	-	-	-	-			
36		Other	-	-	-	-	-	-	-			
37		**Total**	-	-	-	-	-	-	-			
38												
39	**Initial Net Funding Required**		*calculated from the tables above*									
40		Labour	93.00	159.00	179.00	345.00	385.00	-	1,161.00			
41		Equipment	2.00	2.00	1,152.00	1,403.00	103.00	-	2,662.00			
42		Contractors	-	125.00	235.00	635.00	1,150.00	-	2,145.00			
43		IT	3.00	5.00	-	-	-	-	8.00			
44		IPR Costs	-	-	-	-	-	-	-			
45		Travel & Expenses	2.00	5.40	-	-	32.00	-	39.40			
46	Payments to users & Contigency		5.00	12.00	144.00	250.00	2,505.00	-	2,916.00			
47		Decommissioning	-	-	-	-	-	-	-	Check Total = to Initial Net Funding request		
48		Other	-	-	-	-	-	-	-	in Project Cost Summary		
49		**Total**	105.00	308.40	1,710.00	2,633.00	4,175.00	-	8,931.40	**OK**		
50												
51	**Direct Benefits**	*from Direct Benefits sheet*										
52		Total	-	-	-	-	-	-	-			
53												
54												
55												
56	**Licensee Compulsory Contribution / Direct Benefits**			*from Project Cost Summary sheet*								
57		Labour	9.30	15.90	17.90	34.50	38.50	-	116.10			
58		Equipment	0.20	0.20	115.20	140.30	10.30	-	266.20			
59		Contractors	-	12.50	23.50	63.50	115.00	-	214.50			
60		IT	0.30	0.50	-	-	-	-	0.80			
61		IPR Costs	-	-	-	-	-	-	-			
62		Travel & Expenses	0.20	0.54	-	-	3.20	-	3.94			
63	Payments to users & Contigency		0.50	1.20	14.40	25.00	250.50	-	291.60			
64		Decommissioning	-	-	-	-	-	-	-	of Total Initial Net Funding Required		
65		Other	-	-	-	-	-	-	-	**OK**		
66		**Total**	10.50	30.84	171.00	263.30	417.50	-	893.14	Check that **Total** is = or > than		
67										Total Direct Benefits		
68										**OK**		
69	**Outstanding Funding required**		*calculated from the tables above*									
70		Labour	83.70	143.10	161.10	310.50	346.50	-	1,044.90			
71		Equipment	1.80	1.80	1,036.80	1,262.70	92.70	-	2,395.80			
72		Contractors	-	112.50	211.50	571.50	1,035.00	-	1,930.50			
73		IT	2.70	4.50	-	-	-	-	7.20			
74		IPR Costs	-	-	-	-	-	-	-			
75		Travel & Expenses	1.80	4.86	-	-	28.80	-	35.46			
76	Payments to users & Contigency		4.50	10.80	129.60	225.00	2,254.50	-	2,624.40			
77		Decommissioning	-	-	-	-	-	-	-	Check that Total is =to		
78		Other	-	-	-	-	-	-	-	Total Outstanding Funding required		
79		**Total**	94.50	277.56	1,539.00	2,369.70	3,757.50	-	8,038.26	**OK**		
80												
81	balance	7,627.73	0.00	7,255.67	5,865.50	3,627.01	(35.56)	0.35	7,627.73			
82	interest		0.00	148.83	131.21	94.93	35.91	(0.35)	410.53			
83									8,038.26	-	click this button to calculate the NIC funding request	
84												
85	Bank of England interest rate			0.5%		**NIC FUNDING REQUEST £**			**7,627.73**			
86	interest rate used in calculation			2.0%								
87		RPI adjustment	2013/14	2014/15	2015/16	2016/17	2017/18	2018/19	2019/20	2020/2021	2022/2023	
88		Index	252.02	260.33	269.12	275.85	282.74	289.81	297.06	304.48	312.09	
89		Annual inflation	3.00%	3.30%	3.40%	2.50%	2.50%	2.50%	2.50%	2.50%	2.50%	
90	*n.b the Second Tier Funding Request calculation should use the Bank of England Base rate plus 1.5% on 31 June of the year in which the Full Submission is made.*											

Direct Benefits

Direct Benefit: Any benefits of the Project accruing to the Licensee during the Project Implementation, comprising any expenditure included within the Network Lincesee Business plan for RIIO-T1 or GD1 that will be saved as a result of undertaking the project

Description of Direct Benefit	2013/14	2014/15	2015/16	2016/17	2017/18	2018/19	Total
							-
							-
Total Direct Benefits	**-**	**-**	**-**	**-**	**-**	**-**	**-**

n.b. These are Direct Benefits associated with the Project itself, not the wider deployment of the Solution and therefore should not exceed beyond the project or the DPCR5 period

Appendix 2
Cost Assumptions

Project VECTOR

Project Code/Version No:
NGGTGN01_V2

Cost Assumptions
This appendix is broken down into two parts:

The first details the assumptions that where made to build up the "base costs" and "method cost" assumptions to arrive at the financial benefit detailed in Section 4 – Evaluation Criteria, as well as those stated in Appendix 1 – Full Submission Cost Spreadsheet "Net Benefits" tab.

The second shows the calculations and assumptions used to calculate the fuel saving figures quoted in Section 4 – Evaluation Criteria.

Method and Base Cost assumptions
Section 4 assumptions
The following assumptions have been made for the calculation of the "Base Costs" and the "Method Costs" in section 4:

- It costs approximately [redacted] to re-wheel a compressor.
- The VECTOR technology will cost [redacted] per installation (to be confirmed as part of the project)
- There are two units on the compressor station.
- Over the life of the compressor station the change in flow patterns results in having to re-wheel each of the compressors three times.
- Each of the re-wheels involves having to purchase a new wheel
- For the "Method Costs" each of the units is fitted with the VECTOR technology
- As a result of the installation of the VECTOR technology there is a reduction in the requirement to re-wheel each compressor to only once.
- There is no need to install new VECTOR technology as a result of the re-wheel.

The table below shows how the costs in section 4 have been calculated.

Item	**Base Costs (£M)**	**Method Costs (£M)**
Cost for single re-wheel		[redacted]
Cost for installation of VECTOR Technology		[redacted]
Cost for three re-wheels	[redacted]	
Total per unit	[redacted]	[redacted]
Total per station	[redacted]	[redacted]

Financial Benefit = Base Costs - Method Costs	**2.4**

Full Submission Cost Spreadsheet "Net Benefits" tab assumptions
The assumptions that have been made in this spreadsheet are the same as in section 4 however it has been cost out, on one unit, in this instance.

Fuel Cost assumptions

This section covers the assumptions that have been made in calculating the fuel savings that could be associated with the utilisation of the VECTOR technology.

The assumptions in this section are:

- We use a site which has two compressors.
- One electric drive variable speed drive (VSD) and the other a gas turbine (GT) drive.
- The site is utilised for 3000 hours per year.
- Both units are fitted with the VECTOR technology

The table, on the next page, shows how the fuel savings costs have been calculated. Some of the lines have been colour coded so that the calculations can be easily followed based upon whether it is based upon the current, target or ideal efficiency.

Compressor Fuel Cost Savings Sample

	VSD	GT	
Wholesale Gas Cost (£/MWhr)		20	*Based on 2p / kWhr*
Electricity Commodity Cost (£/MWhr)	70.8		*Based on: (3 x Wholesale Gas Price + 18 % Retail uplift)*
Required Engine Power (MW)	25	12	*Average Shaft Power across range of duty*
Annual Utilisation (Hours)	2250	750	*Assuming 25% of 3000 hours total station utilisation is taken up by gas turbine and 75% by electric drive*
Engine (Driver) Efficiency (%)	90	26	*Based on average shaft powers*
Compressor Efficiency Current (%)	76	70	*Based on 2010/11 operation (conservative)*
Compressor VIGV Efficiency Target (%)	**79**	**73**	***Assume net gain of 3% efficiency after losses***
Compressor Efficiency Ideal (%)	86	80	*Assumes only 2% deviation from Max Efficiency (88% and 82% respectively) due to system losses and age degradation*
Combined (Compressor + Driver) Efficiency Current (%)	68.4	18.2	
Combined (Compressor + Driver) Efficiency VIGV Target (%)	**71.1**	**18.98**	
Combined (Compressor + Driver) Efficiency VIGV Ideal (%)	77.4	20.8	

			Total Cost/yr (£'000s)
Yearly Cost Current (£'000s)*	**5,822**	**989**	**6,811**
Yearly Cost Target (£'000s)*	5,601	948	**6,550**
Year Cost Ideal (£'000s)*	5,145	865	6,011

Target Saving pa (£) (Current minus Target)	261,747	Used £250,000 in Section 4
Maximum Saving pa based on Ideal (£) (Current minus Ideal)	800,646	Used £800,000 in Section 4

* The yearly cost for fuel is calculated using the following calculation:

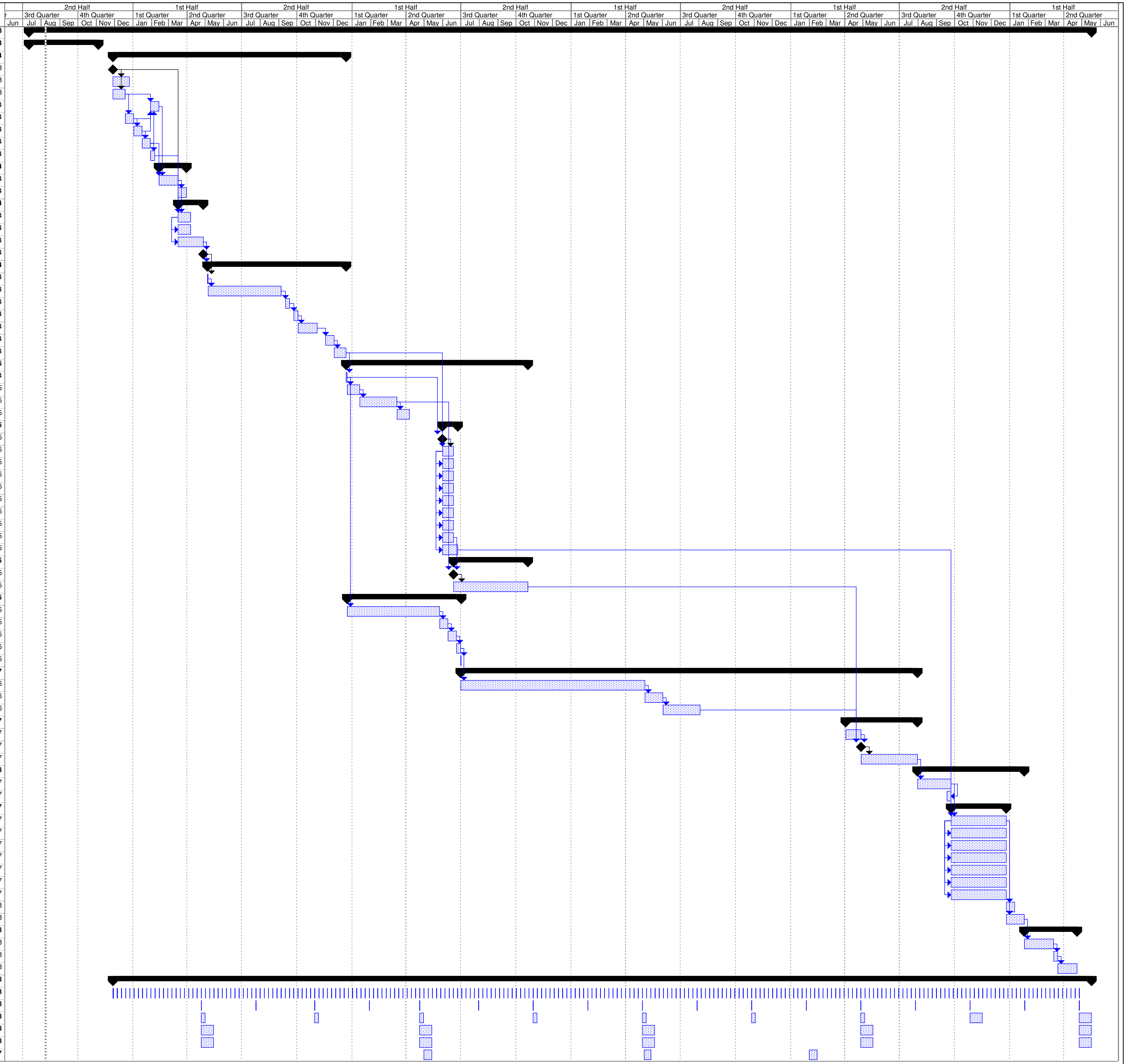
Cost of Fuel x Annual Utilisation x Required engine power x appropriate efficiency

Appendix 3
VECTOR
Project Programme

Project VECTOR

Project Code/Version No:
NGGTGN01_V2

ID	Task Name	Start	Finish
1	**VARIABLE ENVELOPE COMPRESSOR TRIAL OPTIMISATION & REVIEW (VECT**	**Fri 12 Jul '13**	**Thu 17 May '18**
2	**VECTOR NIC BID**	**Fri 12 Jul '13**	**Mon 04 Nov '13**
10	**VECTOR DESIGN PHASE**	**Fri 29 Nov '13**	**Mon 22 Dec '14**
11	VECTOR NIC Award (First Indication)	Fri 29 Nov '13	Fri 29 Nov '13
12	NGGT License Variation for VECTOR	Fri 29 Nov '13	Thu 26 Dec '13
13	Negitiate and Agree OEM & Partner Ts & Cs	Fri 29 Nov '13	Thu 19 Dec '13
14	Internal (NG) Governance / Approval for Design, Manufacture & Build	Thu 30 Jan '14	Thu 13 Feb '14
15	Integrate Project Plans (OEM & NGGT)	Thu 19 Dec '13	Thu 02 Jan '14
16	Select Trial Compressor Locations (up to 2x)	Thu 02 Jan '14	Thu 16 Jan '14
17	Identify Test Loops	Thu 16 Jan '14	Thu 30 Jan '14
18	Identify & Schedule FEA and FPSA Activities	Thu 30 Jan '14	Thu 06 Feb '14
19	**Selection of Technical Partner**	**Thu 13 Feb '14**	**Mon 31 Mar '14**
20	Contract Technical Partner for Baseline Tasks & Project Tech Suppc	Thu 13 Feb '14	Mon 17 Mar '14
21	Negotiate Provisional Outage for Baseline Work	Mon 17 Mar '14	Mon 31 Mar '14
22	**Develop Basis of Design Specifications (FDS)**	**Mon 17 Mar '14**	**Mon 28 Apr '14**
23	Write Functional Design Specifications	Mon 17 Mar '14	Mon 07 Apr '14
24	Analytical Assessment of Station/Unit Operation	Mon 17 Mar '14	Mon 07 Apr '14
25	Develop Integrated Basis of Design Document (BoDD)	Mon 17 Mar '14	Mon 28 Apr '14
26	Approve & Issue BoDD	Mon 28 Apr '14	Mon 28 Apr '14
27	**OEM Designs (2x in Parallel)**	**Mon 05 May '14**	**Mon 22 Dec '14**
28	OEMs BoDD Clarification Meeting	Mon 05 May '14	Tue 06 May '14
29	Deliver Initial Designs	Tue 06 May '14	Fri 05 Sep '14
30	Stakeholder Design Review of Initial Designs	Fri 12 Sep '14	Fri 19 Sep '14
31	Stakeholder HAZOP of Initial Designs	Fri 26 Sep '14	Fri 03 Oct '14
32	Deliver Final Designs	Fri 03 Oct '14	Tue 04 Nov '14
33	Stakeholder Review & Selection of Final Design	Tue 18 Nov '14	Tue 02 Dec '14
34	Release Results of Design Competition	Tue 02 Dec '14	Mon 22 Dec '14
35	**VECTOR DETAIL DESIGN, PROTOYPING & FINAL BUILD PHASE**	**Mon 22 Dec '14**	**Wed 21 Oct '15**
36	Final Site Selection Start	Mon 22 Dec '14	Wed 24 Dec '14
37	Identify Schedule of Activities for Overhaul of Backup Compression	Wed 24 Dec '14	Wed 14 Jan '15
38	Negotiate Contract for Overhaul of Backup Compression	Wed 14 Jan '15	Tue 17 Mar '15
39	Negotiate Programme for Overhaul with Internal Stakeholders	Tue 17 Mar '15	Tue 07 Apr '15
40	**Baseline Compressor Design & Performance**	**Mon 01 Jun '15**	**Fri 26 Jun '15**
41	Outage #1 for Baseline Work (between May - September) 01 June P	Mon 01 Jun '15	Mon 01 Jun '15
42	Physical Dimensions (Longitudinal & Axial Dim & Weight)	Mon 01 Jun '15	Fri 19 Jun '15
43	Performance Envelope	Mon 01 Jun '15	Fri 19 Jun '15
44	Vibration	Mon 01 Jun '15	Fri 19 Jun '15
45	Operating Philosophy	Mon 01 Jun '15	Fri 19 Jun '15
46	Gas Leakage Rates, Venting	Mon 01 Jun '15	Fri 19 Jun '15
47	SCADA / Instrumentation & Control Accuracy / Responsiveness	Mon 01 Jun '15	Fri 19 Jun '15
48	Noise	Mon 01 Jun '15	Fri 19 Jun '15
49	Emissions (e.g. CO2)	Mon 01 Jun '15	Fri 19 Jun '15
50	Develop and Issue Results of Baseline Testing	Mon 01 Jun '15	Fri 26 Jun '15
51	**Outage #2 for Overhaul of Backup Compressor**	**Fri 19 Jun '15**	**Wed 21 Oct '15**
52	Outage Start for Overhaul of Backup Compression	Fri 19 Jun '15	Fri 19 Jun '15
53	Overhaul of Backup Compressor	Fri 19 Jun '15	Wed 21 Oct '15
54	**OEM Prototype (1 x)**	**Wed 24 Dec '14**	**Thu 02 Jul '15**
55	Manufacture Prototype	Wed 24 Dec '14	Wed 27 May '15
56	Offline Testing of prototype	Wed 27 May '15	Wed 10 Jun '15
57	Evaluate Results from testing	Wed 10 Jun '15	Wed 24 Jun '15
58	Review and re-issue Functional Design Specification as Appropriate	Wed 24 Jun '15	Wed 01 Jul '15
59	Request Provisional Outages #3 for Overhaul and Build	Wed 01 Jul '15	Thu 02 Jul '15
60	**OEM Manufacture of Components for Final Build**	**Wed 01 Jul '15**	**Mon 31 Jul '17**
61	Manufacture Final Design	Wed 01 Jul '15	Tue 03 May '16
62	Offline Factory Acceptance Testing of Final Design Components	Tue 03 May '16	Thu 02 Jun '16
63	National Grid Modifications Process (G35)	Thu 02 Jun '16	Wed 03 Aug '16
64	**Outage #2 for Installation of VIGV Compressor**	**Mon 03 Apr '17**	**Mon 31 Jul '17**
65	Extensive Annual Maintenace on Backup Compression	Mon 03 Apr '17	Fri 28 Apr '17
66	Outage #3 Start for Installation / Build	Fri 28 Apr '17	Fri 28 Apr '17
67	On-Site Installation of VIGV Compressor	Fri 28 Apr '17	Mon 31 Jul '17
68	**VECTOR COMMISSIONING PHASE**	**Mon 31 Jul '17**	**Thu 25 Jan '18**
69	Commission Installation & Performance Trials	Mon 31 Jul '17	Mon 25 Sep '17
70	Develop Operating Philosophy	Mon 18 Sep '17	Mon 25 Sep '17
71	**Online Testing of VECTOR**	**Mon 25 Sep '17**	**Tue 26 Dec '17**
72	Performance Envelope	Mon 25 Sep '17	Tue 26 Dec '17
73	Vibration	Mon 25 Sep '17	Tue 26 Dec '17
74	Operating Philosophy	Mon 25 Sep '17	Tue 26 Dec '17
75	Gas Leakage Rates, Venting	Mon 25 Sep '17	Tue 26 Dec '17
76	SCADA / Instrumentation & Control Accuracy / Responsiveness	Mon 25 Sep '17	Tue 26 Dec '17
77	Noise	Mon 25 Sep '17	Tue 26 Dec '17
78	Emissions (CO2)	Mon 25 Sep '17	Tue 26 Dec '17
79	Refine Operating Philosophy	Tue 26 Dec '17	Tue 09 Jan '18
80	Benchmarking Exercise & Knowledge Dissemination	Tue 26 Dec '17	Thu 25 Jan '18
81	**VECTOR CLOSE-OUT**	**Thu 25 Jan '18**	**Mon 23 Apr '18**
82	Carbon Trust (Concluding) Independent Evaluation of VECTOR	Thu 25 Jan '18	Thu 15 Mar '18
83	Internal Approval / Governance of Closure Report	Thu 15 Mar '18	Thu 22 Mar '18
84	Prepare Final Project Closure Report to Ofgem	Thu 22 Mar '18	Mon 23 Apr '18
85	**PROJECT COMMUNICATION / MANAGEMENT**	**Fri 29 Nov '13**	**Thu 17 May '18**
86	**Weekly Progress Meeting (Project Delivery)**	**Fri 29 Nov '13**	**Fri 27 Apr '18**
338	**Quarterly Project Steering Group Meeting**	**Fri 25 Apr '14**	**Fri 27 Apr '18**
356	**Six monthly Progress Reports**	**Fri 25 Apr '14**	**Thu 17 May '18**
366	**Annual Statement on Funding and Progress (NG Corporate)**	**Fri 25 Apr '14**	**Thu 17 May '18**
372	**Updates at Annual NIC Conference**	**Fri 25 Apr '14**	**Thu 17 May '18**
378	**Annual Finance Audit**	**Fri 01 May '15**	**Tue 14 Feb '17**



Appendix 4
VECTOR Project
Risk Register

Project VECTOR

Project Code/Version No:
NGGTGN01_V2

Appendix 4 – VECTOR Project Risk Register

N0.	Risk	Mitigation/control measure	Risk level L/M/H	Delegated Authority at Which Risk is Managed	VECTOR Phase Impacted
1	There is a risk that one or both of the OEMs identified as potential partners do not want to be part of the project	Liaison has already begun with the OEMs and we have one OEM who has registered their interest (subject to adequate Intellectual Property agreements being put in place) in helping deliver the project. If both OEMs pull out of the project the National Grid Project team will evaluate any alternative options for delivering the project, but may ultimately decide to stop the project.	L	VECTOR Steering Committee	NIC Bid Phase / Design Phase
2	There is a risk that the default IPR associated with the NIC rules and regulations prevents OEMs participating in the project	Default IPR has been shared with OEMs for comment. One OEM has already indicated that they are willing to agree to the default IPR arrangements and it is envisaged that the second OEM will follow suit. Contract negotiations will take place with the OEMS Application for non-default IPR arrangements if required.	L	VECTOR Steering Committee	NIC Bid Phase
3	There is a risk that the technology will not be able to be fully rolled out across the compressor fleet due to the different types and manufacturers, etc.	This is very dependant upon the technology developed and selected for bringing forward to the prototype and manufacturing stages. The versatility of the technology across the fleet will form part of the selection criteria used by the project team.	M	VECTOR Project Manager	NIC Bid Phase / Design Phase
4	There is a risk that the technology cannot be utilised on a gas transmission site due to safety concerns	Some of these variable compressors have been utilised successfully in other industries. Prototype and offline trials have been planned for as part of the project	L	VECTOR Project Manager	Design Phase

N0.	Risk	Mitigation/control measure	Risk level L/M/H	Delegated Authority at Which Risk is Managed	VECTOR Phase Impacted
		Safety design for natural gas purposes will be expressed to the OEMs at the start of the project and through out at key stages and reviewed by National Grid during each of the project liaison meetings with the contractor.			
5	There is a risk that the compressor unit identified for the trial will not be available due to changes in gas flow, availability of standby compressor, etc. resulting in delays to the project and increased costs	Extensive overhaul and maintenance of the standby unit has been planned in and budgeted for in the project to try and maximise the availability and reliability of the standby compressor. Liaison with the fleet management, Gas National Control Centre and site operations will take place to ensure that site selection is the best for all parties and any changes to the planned outage on the compressor unit is identified as soon as possible.	L	VECTOR Project Manager	Build Phase / Commissionin g Phase
6	There is a risk that key staff involved in the project are not available for the duration of the project.	Succession planning for key staff will take place. The project team will be capable of stepping up and covering staff that may leave or be on long term sick until a suitable alternative can be found. Compressor Engineer resource from the existing Network Engineering pool could be utilised. In the event that the project manager is not available a project manager from Capital Delivery could be utilised.	L	VECTOR Steering Committee	Whole VECTOR Project
7	There is a risk that OEM costs could escalate due to unforeseen work in	Adequate contingency funds to be included in the project submission.	L	VECTOR Steering Committee	Design Phase / Build Phase / Commissionin

N0.	Risk	Mitigation/control measure	Risk level L/M/H	Delegated Authority at Which Risk is Managed	VECTOR Phase Impacted
	either the design or installation phases.	A substantial functional specification will be prepared at the very start of the project that will be shared with the OEMs. The prototype and final manufacturing designs will actively involve the OEM. All relevant and available drawings and designs will be shared with the OEM. Contraction negotiations will take place in the event of any claims from the OEM.			g Phase
8	There is a risk that the project does not succeed or deliver full benefits stated in business case	Unfortunately this is the nature of a research project, however some of these variable compressors have been utilised successfully in other industries. A number of key milestones have been identified in the project plan to track success criteria and measure the success of the project. If it is likely that the project will not succeed, the project team will stop all works at the earliest moment to prevent any excessive costs being incurred.	H	VECTOR Steering Committee	Whole VECTOR Project
9	There is a risk that the project dissemination is not fully effective resulting in the technology not being utilised to its maximum potential	A well thought through internal dissemination plan with appropriate updates to the various parts of National Grid including Network Engineering, System Operation (including the Gas National Control Centre) and Site Operations to spread awareness of the project and results.	L	VECTOR Project Manager / VECTOR Steering Committee	Whole VECTOR Project

N0.	Risk	Mitigation/control measure	Risk level L/M/H	Delegated Authority at Which Risk is Managed	VECTOR Phase Impacted
		Plans in place to develop technical specs and vary policy documents to ensure greatest beneficial use of learning from the project in remainder of RIIO T1 and in future regulatory periods.			
10	This is a risk that the compressor casing could be compromised due to a catastrophic failure during the installation or commissioning phases	Overhaul of standby Compression to ensure reliability of supply to customers Contingency funding included in submission for replacement Compressor Design appraisal process in place. Method statements and Risk assessments during installation phase to be robust and followed.	L	VECTOR Project Manager / VECTOR Steering Committee	Design/Installation/Commissioning Phases

Appendix 5
VECTOR
Contingency Plan

Project VECTOR

Project Code/Version No:
NGGTGN01_V2

VECTOR Contingency Plans:

Two credible contingency scenarios have been identified that may occur during the VECTOR project, that require a contingency plan.

The first is that during the commissioning phase of the VECTOR project that the design and off line trial processes have failed to identify an issue that causes a catastrophic failure of the compressor. The compressor would be unable to return to normal service as it is likely to have a significant sized hole drilled in the casing.

Contingency Plan:
Primarily we have made contingency in our submission for purchasing a new compressor, should this unlikely eventuality occur. We also plan to conduct extensive maintenance and overhaul on the standby compression on site to ensure availability of compression on the Gas Transmission System whilst the repair is undertaken.

The second scenario is that during any of the initial design, prototype build or final design stages it is identified that the only means of installing the mechanism required for the VECTOR project is through purchasing a brand new compressor.

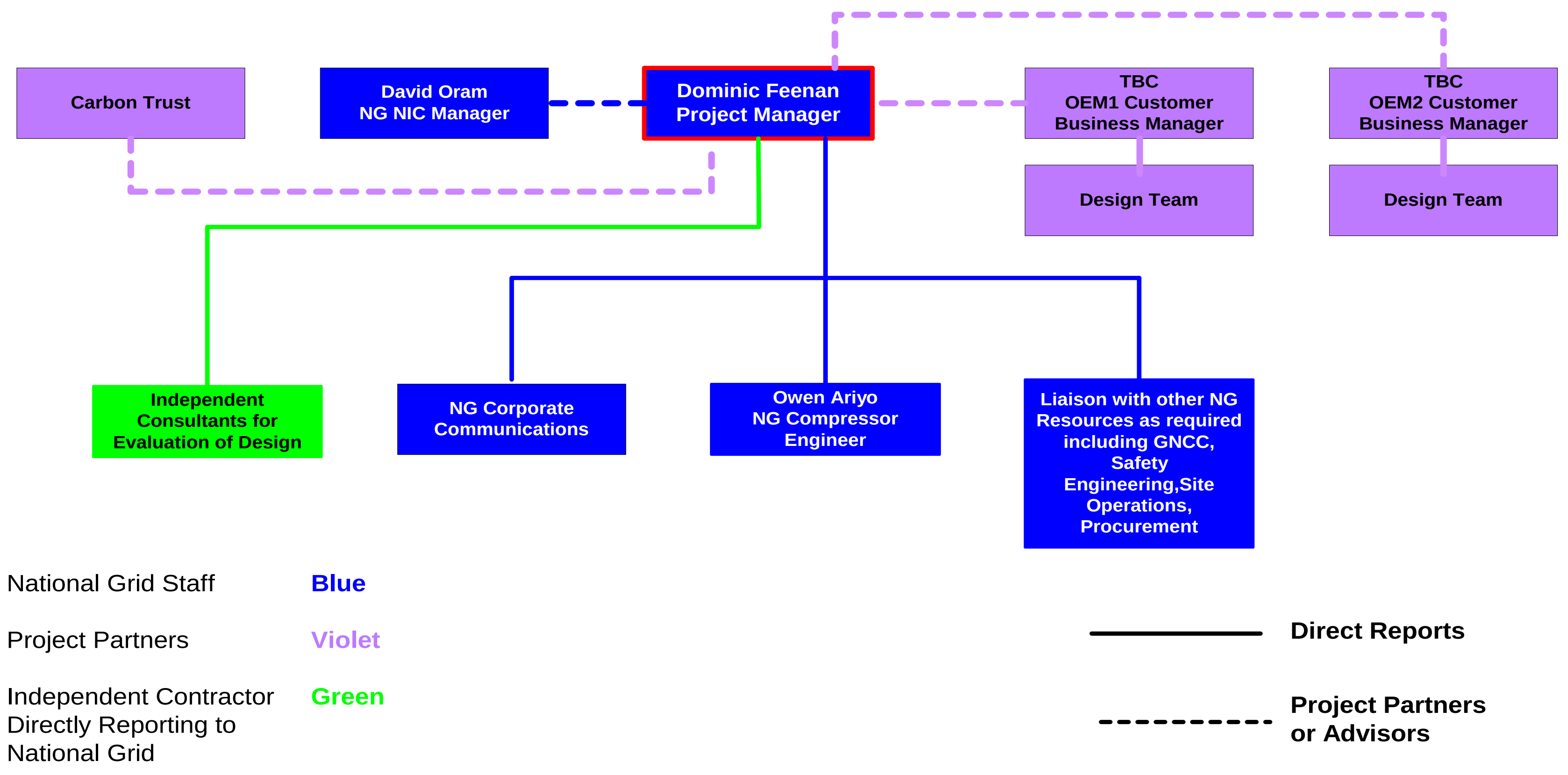
Contingency Plan:
This would constitute a significant change in project scope and as such an ad-hoc steering committee meeting would be called to discuss the options available to the project team. These options could include stopping the project completely, or pausing whilst OFGEM is consulted on a potential new project direction.

Appendix 6
VECTOR Organogram

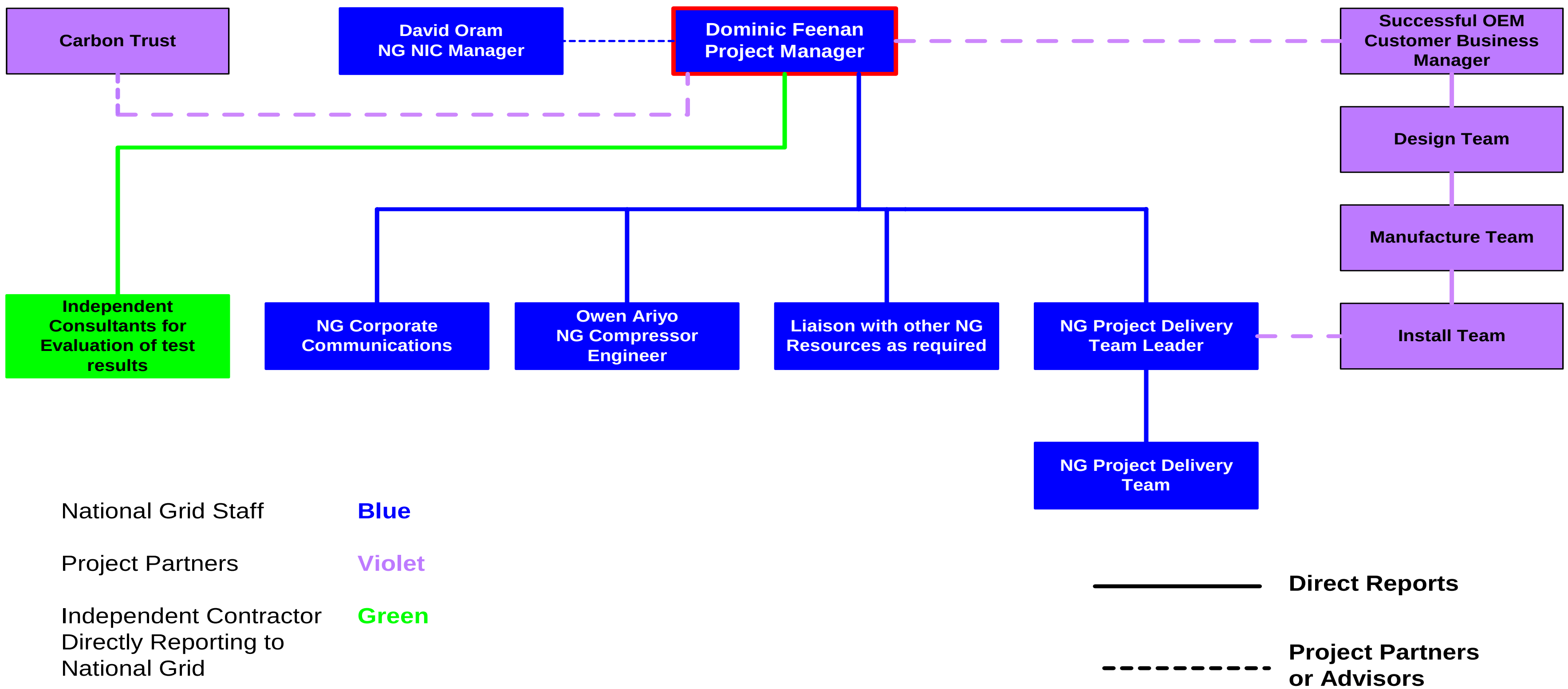
Project VECTOR

Project Code/Version No:
NGGTGN01_V2

Vector Organogram - Initial Design Stage



Vector Organogram - Final Design and Build Phase



Appendix 7
VECTOR Governance Terms of Reference

Project VECTOR

Project Code/Version No:
NGGTGN01_V2

VECTOR Project Steering Committee

Terms of Reference

Version 1.1 – 1st August 2013

1. Context

National Grid Gas is accountable to Ofgem for undertaking the VECTOR demonstration project which is part funded through the Network Innovation Competition (NIC). NIC funding is subject to the requirements set out in Ofgem's Gas Network Innovation Competition Governance Document and the VECTOR Project Direction.

Reference to the "Committee" shall mean the VECTOR Project Steering Committee

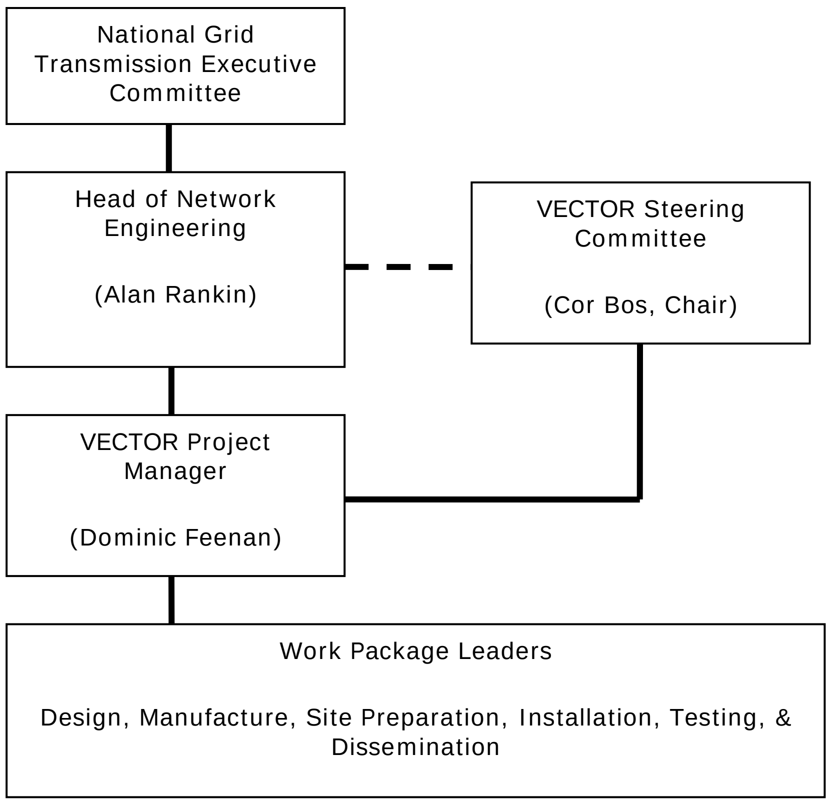
Reference to "Governance Document" shall mean the Gas Network Innovation Competition Governance Document

2. Purpose of the Committee

The purpose of the Committee is to provide assurance that the requirements set out in the Governance Document and the Project Direction are met throughout the course of the VECTOR project.

3. Project Governance Structure

The following organogram depicts the lines of accountability for the governance of the VECTOR project.



4. Role of Committee Members

The role of the individual members and standing invitees of the Committee is to:

- Ensure the requirements of stakeholders, in particular Ofgem Governance and Project Direction, are met for the duration of the Project
- Contribute to the balancing and resolution of conflicting priorities
- Provide guidance and direction to the Project Manager and project team within their area of expertise
- Challenge and review all documentation referred to the Committee.

Members of the Committee are encouraged to take a holistic approach to Committee debates with the aim of guiding the VECTOR project delivery team in the most appropriate manner within the remit of the Committee.

5. Membership

The Committee for the Initial Design Phase shall comprise of:

		Individual Members	Standing Invitees
Name / Title	**Affiliation**	*Voting Rights*	*No Voting Rights*
Steering Committee Chair	National Grid	**X**	
Project Manager	National Grid	**X**	
NIC Manager	National Grid	**X**	
Compressor Engineer	National Grid	**X**	
Delivery Engineer	National Grid	**X**	
Carbon Assessment Specialist	Carbon Trust		**X**
Tbc	Rolls Royce		**X**
Tbc	OEM 2		**X**

The Committee for the Detailed Design, Manufacturer and Install Phases shall comprise of:

		Individual Members	Standing Invitees
Name / Title	**Affiliation**	*Voting Rights*	*No Voting Rights*
Steering Committee Chair	National Grid	**X**	
Project Manager	National Grid	**X**	
NIC Manager	National Grid	**X**	
Compressor Engineer	National Grid	**X**	
Delivery Engineer	National Grid	**X**	
Carbon Assessment Specialist	Carbon Trust		**X**
Tbc	Successful OEM	**X**	

6. Convenor / Chair

Ordinarily, the Chair, shall convene the Committee meetings.

If the designated Chair is not available, then he will nominate an Acting Chair. The Acting Chair is responsible for informing the Chair as to the salient points / decisions raised and agreed to at the meeting.

7. Conflicts and Business Separation

Prior to the Committee meeting the Chair shall consider whether the Agenda will create any conflicts of interest or business separation issues. In the event that a conflict of interest or business separation issue is identified then this will be noted on the Agenda and Minutes. The Chair will consider the best way of conducting the meeting so no conflict of interest or business separation issue arises. This may include removing the item from the agenda or asking the relevant individuals to leave the meeting for the duration of the relevant agenda item(s). In such cases the agenda item in question shall be the subject of a separate Minute and shall not be circulated to the individual(s) who were asked to leave the meeting.

The Chair should seek advice from National Grid's Business Separation Compliance Officer, if necessary.

8. Frequency of Meetings

The Steering Committee will meet at least every 3 months or at any other time at the request of any of the Parties to the Project Manager specifying in reasonable detail the reason why the meeting is required. Meetings of the Steering Committee should be convened with at least twenty-one (21) days written notice in advance. That notice must include an agenda. Minutes of the meetings of the Steering Committee shall be prepared by the chair of the meeting and sent to each of the Parties within 14 days after each meeting.

The venue of each meeting will be agreed, and in default of agreement at National Grid House, Warwick.

9. Minimum Agenda Items

Each Committee meeting must consider, as a minimum, the following agenda items:

1. Project safety
2. Progress against plan
3. Progress against budget, including review of bank or other financial statement
4. Review of project risk profile
5. Evidence of progress towards completing each of the Successful Delivery Criteria
6. Achievement of learning outcomes and appropriateness of dissemination activities undertaken
7. Review of Intellectual Property issues arising
8. Feedback from Ofgem and other key stakeholders that could materially influence the remainder of the project

9. Review of plans for the coming six month period
10. Approval of project progress report/close down report
11. Vote on whether a recommendation be made for the project to be halted.

10. Meeting Attendance

Any member of the Steering Committee may participate in meetings of the Steering Committee by tele-conference, video-conference or any other technology that enables everyone participating in the meeting to communicate interactively and simultaneously with each other.

11. Proxies to Meetings

If a regular member is unable to act due to absence, illness or any other cause, the member may appoint deputy/alternate or to serve as a temporary, alternate member to act on his or her behalf as necessary. Any appointments of an alternate member for a period longer than two months in duration must be approved by the Committee Chair.

12. Quorum Requirements

In order for the Committee meeting to be recognised as an authorised meeting and for any recommendations, resolutions or approvals to be valid a quorum must be present. A quorum shall be defined as a minimum of 67% of Committee members with voting rights and must include the Chair, or his appointed nominee acting as Chair for the meeting. In case of a split vote, the Chair or Acting Chair shall have the casting vote.

Decisions shall be taken by a simple majority of a quorate meeting of the Committee.

Decisions concerning the following are subject to unanimous approval of all voting members of the Committee:

- amendment to the allocation of any funding or change to any contribution;
- the decision as to whether to reject personnel from being involved in the project or dismiss the personnel from the Project;
- whether a Party to the Project shall be permitted to audit another Party;
- amendment and updates to any anti-bribery and anti-corruption policies;
- whether a recommendation be made to National Grid & Ofgem that the Project should be terminated; and
- material changes to the Project and changes to the Results to be delivered;

For the avoidance of doubt, the Committee does not have the authority to make any amendments to the contractual arrangements between the Parties involved in the project; however, it can make recommendations to National Grid Gas to consider amendments where a simple majority of a quorate Committee are of the view that it is necessary for the successful completion of the Project.

13. Project Manager Responsibilities

The Project Manager shall:

- be responsible to the Steering Committee for the day-to-day management of the Project,
- be responsible for the financial administration of the Project as required by the Funding Conditions,
- be responsible for coordinating the implementation of decisions taken by the Steering Committee,
- be responsible for the preparation of six monthly progress reports for review and approval by the Committee, and
- monitor the progress of the Project.

14. Review Timetable

The Committee will review these Terms of Reference and the effectiveness of the Committee every twelve months as a minimum with the first review occurring July 2015.

Appendix 8
Extract of initial Feasibility Report:
“Research into Variable Envelope Compressors”

Project VECTOR

Project Code/Version No:
NGGTGN01_V2

Research into Variable Envelope Compressors

Final Report

FNC 42020/40071R Issue 1

Prepared for National Grid

SYSTEMS AND ENGINEERING TECHNOLOGY

DOCUMENT INFORMATION

Project :	Research into Variable Envelope Compressors
Report Title :	Final Report
Client :	National Grid
Client Ref. :	3200405253
Classification :	COMMERCIAL-IN-CONFIDENCE
Report No. :	FNC 42020/40071R
Issue No. :	1
Date :	23 July 2013
Compiled By :	Stephen Livermore
Verified By :	David Munn
Approved By :	Richard Underhill
Signed :	*Signed on Original*

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SUMMARY

This study has investigated the potential of a series of methods for increasing the flexibility of compressors in the National Grid transmission network. Currently, variable speed control is used to provide an envelope which offers some dynamic flexibility, whilst more long term changes are provided by re-wheeling the compressor impellers. National Grid is looking for methods of providing greater dynamic flexibility without serious detriment to operational efficiency.

National Grid has proposed four methods:

- Variable speed
- Suction throttling
- Variable inlet guide vanes (VIGV)
- Variable diffuser vanes

The study has shown that of the proposed methods, VIGVs are the most feasible method for extending the range of the compressors particularly when combined with variable speed control. However, the extent of the range extension will be dependent on the location of the VIGVs with close coupling (locating near the entrance of the impeller) more effective than loose coupling (locating further upstream).

VIGVs also offer a small potential for increased efficiency at certain operating conditions. Analytical modelling has shown that the maximum theoretical efficiency benefit is 5%. Drag losses caused by the VIGVs and their impact on the wider system performance will reduce this and in some circumstances will result in an overall reduction in efficiency. These losses are likely to be greater for the close coupled than the loose coupled option. There are also significant performance, operational and safety risks of using VIGVs which will be dependent on the location.

All the OEMs reported that other traditional options for increasing the flexibility of the compressors should be considered and compared with VIGVs. These include re-wheeling existing impellers and using multiple smaller compressors at designated design conditions rather than single compressors run across a large operating range.

Rolls-Royce and Dresser-Rand have expressed interest in a potential pilot study on VIGVs. Rolls-Royce has used VIGVs on a number of previous projects and is keen to directly pursue a solution incorporating this technology. Dresser-Rand would like the opportunity to propose a solution involving re-wheeling in preference to VIGVs. Engaging the OEMs to provide a variety of solutions besides VIGVs will provide further learning on the benefits of VIGVs (specific to a particular compressor station), quantify the difference between VIGV and re-wheeling, and also assist in the development of a potential pilot study.

This study has also highlighted that the prime-mover (usually a gas turbine) should be included in the efficiency analysis of a compressor system as this has the potential to significantly affect the overall efficiency. Furthermore, system level modelling should be undertaken on the network to understand how the interaction of the stations affects the overall network efficiency. VIGV and re-wheeling could then be included in this system level approach.

CONTENTS

7. CONCLUSION AND RECOMMENDATIONS

This study has investigated the potential of a number of methods for increasing the flexibility of compressors in the National Grid network. Currently variable speed control (typically using gas-turbines) provides an envelope of operation which affords some flexibility but National Grid is looking for other options to extend this.

The key conclusions from this work are as follows:

- As stand-alone methods of providing an operating envelope:

  - Suction throttling, though an effective means of compressor control is very inefficient and should generally be avoided.

  - Variable diffuser vanes offer reasonable range extension and small efficiency benefits but have significant risks as they are typically installed on the (larger) outlet side of the compressor where the pressure is greater and larger equipment is required.

  - VIGVs offer similar range extension and efficiency benefits to variable diffuser vanes. They also have significant risks but the OEMs generally considered these to be more manageable. There is a greater number of existing applications of VIGVs including Rolls-Royce and Dresser-Rand who have development experience of this technology.

- Of the proposed methods (suction throttling, variable diffuser vanes and VIGVs), VIGVs offer the greatest potential for extending the range of variable speed compressors.
- Analytical modelling has shown that VIGVs offer reasonable range extension, depending on the location of the VIGVs. Close coupled VIGVs (located close to the impeller entrance) are likely to be more effective than loose coupled VIGVs (located further upstream).
- Analytical modelling has shown that VIGVs offer a maximum potential improvement in efficiency of approximately 5%. In practice, the drag loss or wake caused by the VIGVs is likely to reduce this or even make VIGV detrimental to the overall compressor efficiency. Similar to range extension, the location of the VIGVs will also affect this. Overall, however, the impact of VIGV on the compressor efficiency is small compared with the operational variation in compressor efficiency and this will make any efficiency improvements more difficult to observe in practice.
- There are significant performance, operational and safety risks of using VIGVs. However, there is a reasonable body of previous experience (namely by Rolls-Royce and Dresser-Rand) which can be used to mitigate these risks.
- All of the OEMs interviewed expressed a preference for re-wheeling compressors and multiple trains for increasing the flexibility and efficiency of compressors.
- Rolls-Royce and Dresser-Rand have expressed interest in a potential pilot study on VIGVs. The other four of the six OEMs interviewed declined. Rolls-Royce has used VIGVs on a number of previous projects and is keen to directly pursue a solution incorporating this technology. Dresser-Rand would like the opportunity to propose a solution involving re-wheeling in preference to VIGVs.

The recommendations from this work are as follows:

- Engage further with OEMs on the use of VIGVs for range extension side-by-side with other traditional methods such as re-wheeling and use of multiple trains. This will most likely result in solutions involving both VIGVs and re-wheeling and will be extremely valuable for National Grid as it will i) provide further information on the benefits of VIGVs, ii) assist in the comparison of the different methods and iii) start communication lines with OEMs regarding a potential project.

- Consider the efficiency of the prime-mover (e.g. gas turbine) in conjunction with the compressor when determining the overall efficiency of a compressor system. The operational data collected from the Hatton station showed that the gas turbine has a lower nominal efficiency than the compressor and is also liable to significant variation based on the operational mode of the compressor.
- Consider multiple trains as an additional means of increasing the flexibility of improving compressor stations. Rather than one or two large compressors, a greater number of smaller compressors could be run either in series or parallel to provide flexibility of head and flow output. The individual compressors could then be run sequentially nearer their designated design point.
- Undertake system level modelling of the network. The present study has focussed on the analysis of methods for the range extension of individual compressors but it could be extended to consider the interaction of the methods which benefit the whole network. For example, this could include a sensitivity study on the use of VIGVs, re-wheeling and multiple trains at one station on the benefit to the wider network. It could also include a CAPEX vs OPEX analysis of the technologies.

Appendix 9
Future Gas Network Resilience

Project VECTOR

Project Code/Version No:
NGGTGN01_V2

VECTOR Appendix 9 – Future Network Resilience Issues

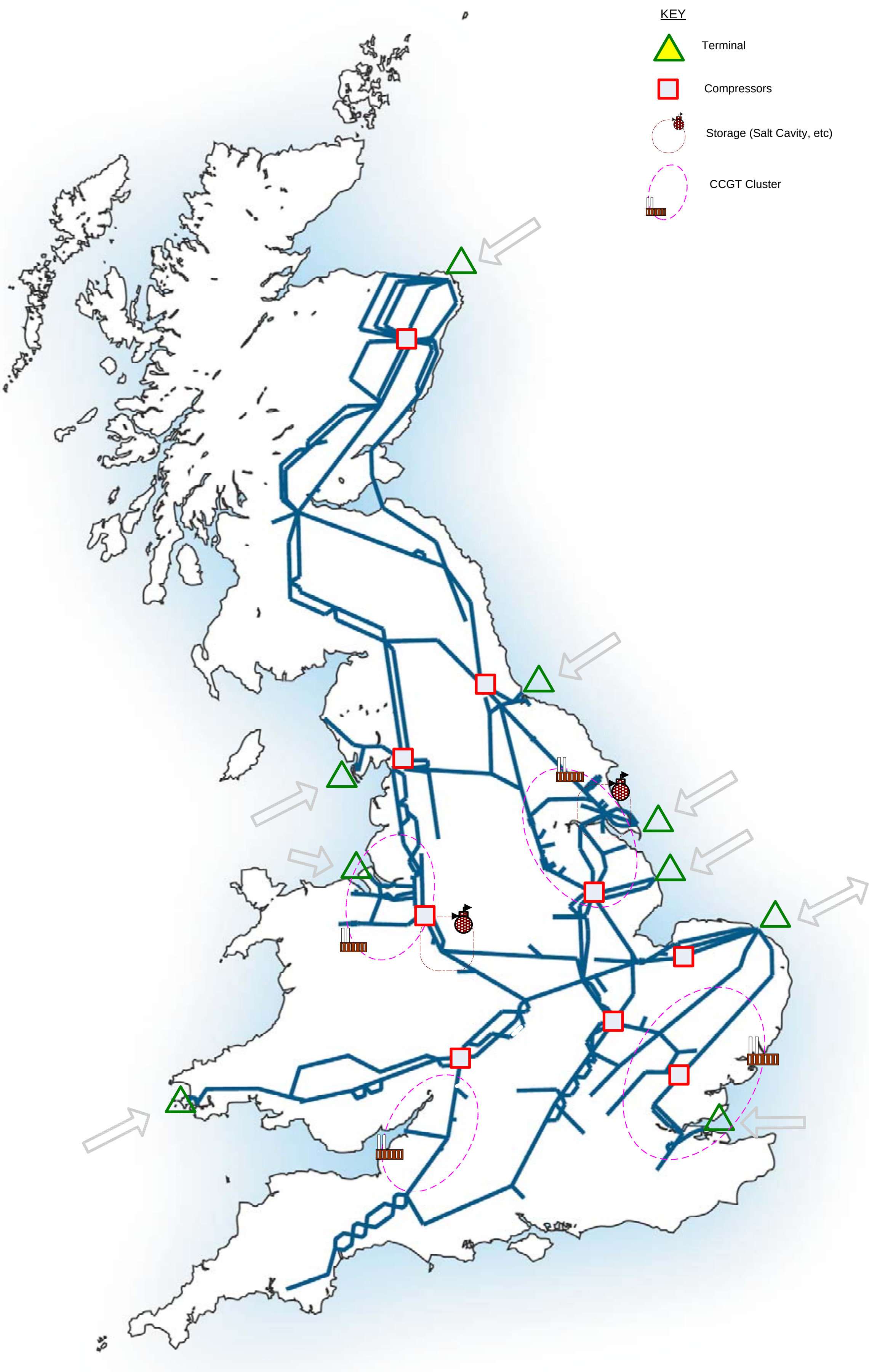


Figure 1: Chart Showing Compressor Likely to be affected by Increasing Volatility in Network Supply and Demand due to CCGT and Storage Clusters as well as Network Supplies.

Constraints and Assumptions

CCGTs may be the preferred choice against other options for balancing the electricity supply system as renewables take an increasingly larger share in supplying electricity to the network;

- Demand levels from CCGTs is expected to become increasingly variable and unpredictable as their role in providing balancing generation to cover the increasingly intermittent renewable generation on the electricity system increases;
- CCGT clusters can currently be seen in the North East, North West, South East and South West of the NTS (figure 1);
- CCGTs will provide the fast response required to accommodate highly variable renewable energy (largely wind) required to de-carbonise the UK energy sector.
- There are market indications of CCGT growth in these areas into the future; the rate of growth will depend on the dominant UK energy scenario (Slow Progression, Gone Green or Accelerated Growth; see National Grid 10-year Statement);
- New CCGTs are increasingly requesting ramp up and ramp down rates higher than the default of 50MW/min. Higher ramp rates will allow CCGTs provide balancing generation particularly to make up shortfall in renewable generation;
- There is a "time-of-flight" issue in terms of how quickly a large change in demand can be met with increased input at supply points without adversely affecting Distribution Network assured pressures; short duration cover is usually provided by local linepack.

  There will be instances when the timing and quantity of supply and demand profiles requested by customers cannot be accommodated from a system pressure or linepack perspective, but may remain acceptable from an end-of-day national balance perspective. When this situation occurs, National Grid may need to take time-bound and locational actions to resolve it (for example, to meet pressure requirements and ensure capacity rights can be delivered to users).
- Clusters or onshore gas storage in close proximity to CCGT clusters may further compound the variability of gas flows since they may cyclically fill and empty in response to market signals (figure 1).

Figure 3.3B:
Generation capacity for CCGTs and wind including likely load factor[34]
Source: National Grid

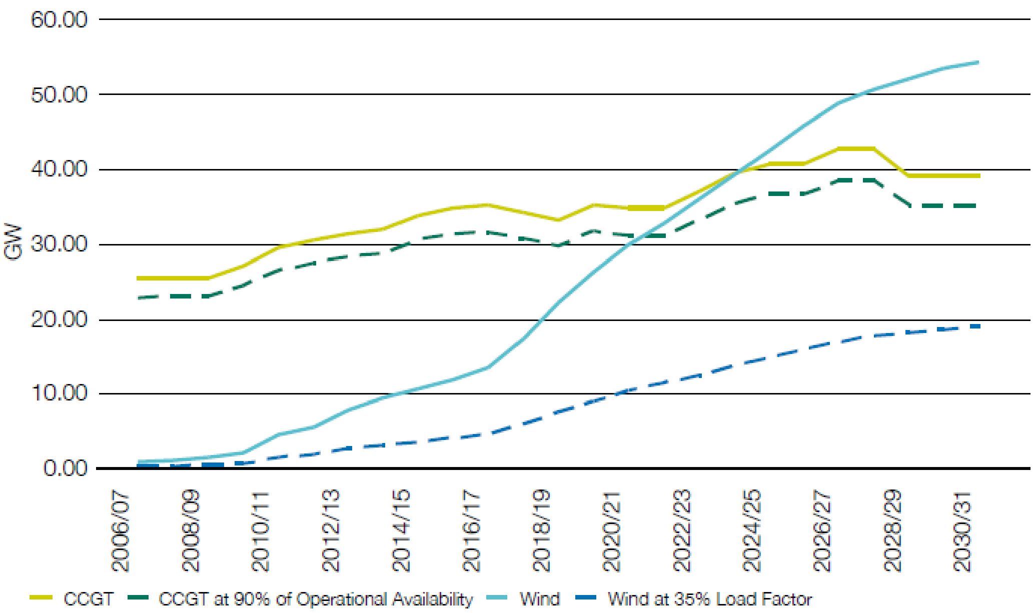


Figure 2: Based on Gone Green Scenario (National Grid 10-Year Statement), the above chart shows the likely shortfall in wind likely to be provided by CCGTs.

Supplies are increasingly variable as follows:

- Fast response LNG facilities which are heavily influenced by price signals dominate the South NTS;

- The UK Interconnector at Bacton can swing within day from net export mode to net import depending on gas price volatility. With energy interdependence with the Continent increasing, the magnitude and frequency of such swings is expected to increase;
- There is a comparable but different "time-of-flight" issue with terminals supplying gas to transporting from supply to point of network demand without creating entry constraints (e.g. high pressures close to the terminals).

Some NTS compressors are located in close proximity (in transmission network behaviour terms) to the supplies and/or CCGT clusters (figure 1); these will most likely be the target for Variable Envelope technology which will increase their ability to respond to transient within-day fluctuations.

An example of the sort of machine resilience which may be required can be seen in the case below involving a real NTS power station ramp rate request.

The case below presents a graphical representation of the operation of a compressor located on the NTS South East which provides support to three power stations ramping at a rate of 200MW/min, 64MW/min and 50MW/min respectively.

The figure below shows the flows seen during the day by the compressor with the ramp up period highlighted:

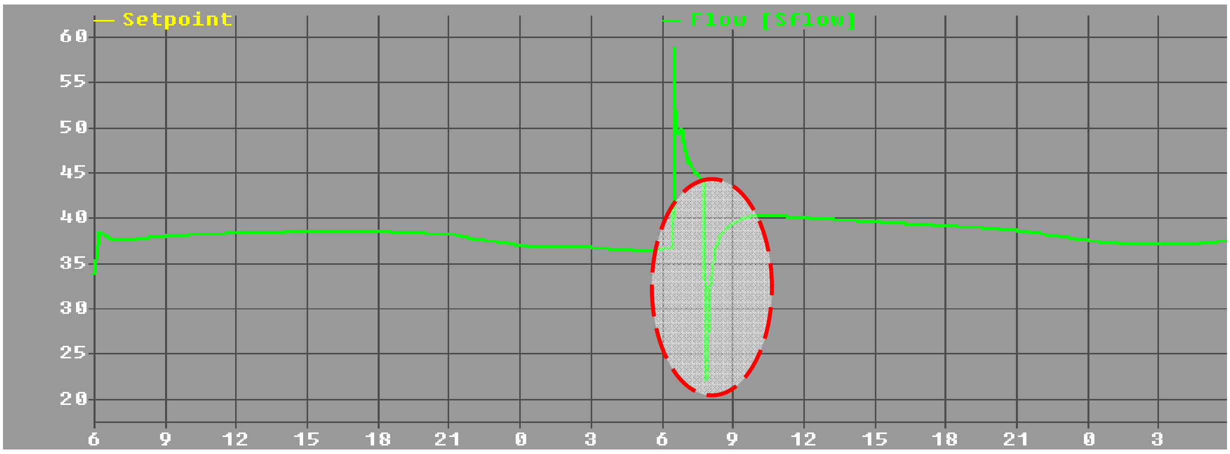
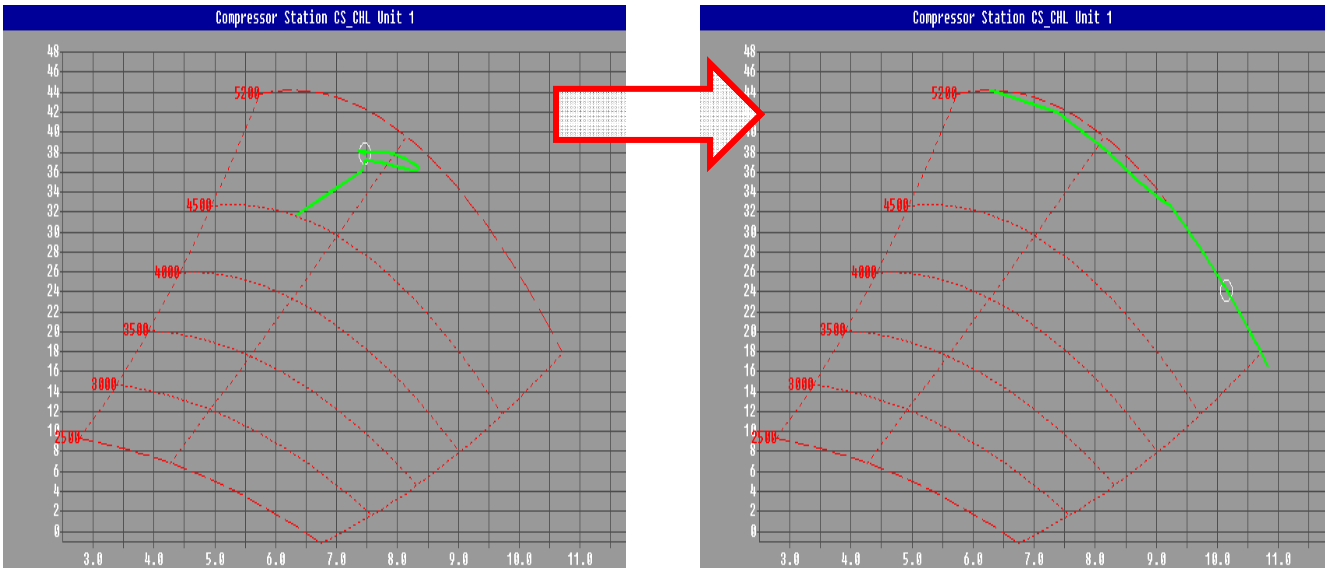


Figure 3: Flow through Compressor over Time Before, During and After CCGT Ramp-up (With Ramp-up at ~ 06:00hrs)

A: 06:00 hrs to Prior to Ramp-Up

B: Effect of Ramp-Up



It can be observed that the compressor initially operates stably within its envelope responding stably to local demand variations until the ramp-up begins downstream, after which it goes into surge for about two hours due to very rapid depletion in the downstream linepack.

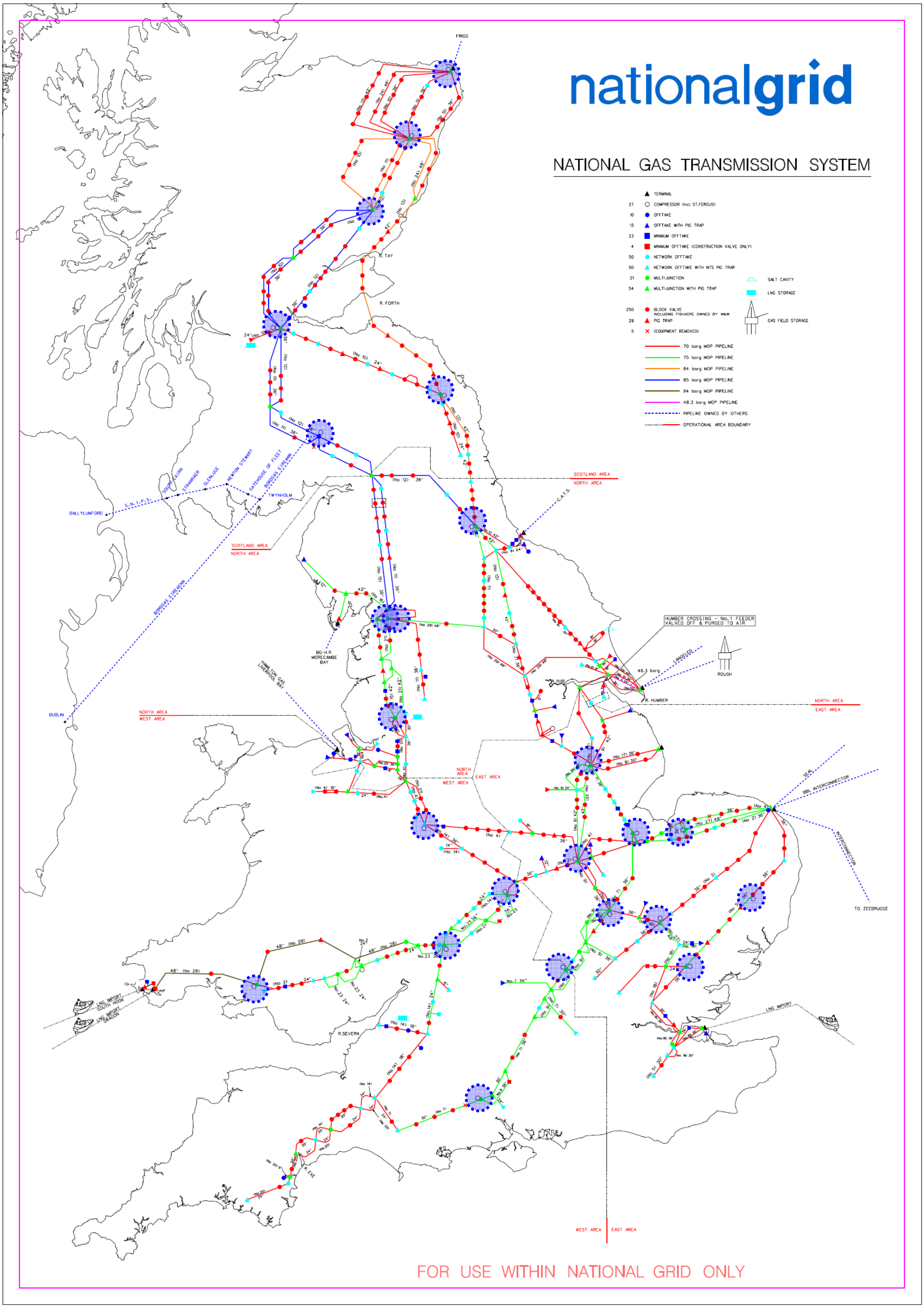
After the power stations achieve maximum stable flows the system gradually recovers and thereafter the compressor is driven into choke as it tries to make up the shortfall downstream and recover system pressures.

Appendix 10
Maps & Network Diagrams

Project VECTOR

Project Code/Version No:
NGGTGN01_V2

Appendix 10: The UK Gas Transmission System Showing Location of Installed Gas Pipeline Compressor Installations (blue circles)



Appendix 11
Glossary

Project VECTOR

Project Code/Version No:
NGGTGN01_V2

VECTOR Appendix 11 - GLOSSARY

Bar	The unit of pressure that is approximately equal to atmospheric pressure (0.987 standard atmospheres). Where bar is suffixed with the letter g, such as bar(g) or mbar(g), the pressure being referred to is a gauge pressure, i.e. relative to atmospheric pressure
BAT	**Best Available Technique.** Best available techniques are required to be considered in order to avoid or reduce emissions resulting from certain installations and to reduce the impact on the environment as a whole. They take account of the balance between costs and environmental benefits.
CCGT	**Combined Cycle Gas Turbine.** A unit whereby electricity is generated by a gas powered turbine and also a second turbine. The hot exhaust gases expelled from the first turbine are fed into the heat exchanger to generate steam, which powers the second turbine.
Compression Actual Flow	This is the volume flow of gas measured against the gas density at the inlet to the compressor
Compression Head	Compression Head is a measure of the amount of energy that is put into each kilogram of gas as it passes through the compressor
Compressor Choke line	The line on a compressor performance map beyond which the efficiency of a compressor rapidly decreases
Compressor Maximum Speed	The highest rotational speed (revolutions per min. [rpm]) at which the machine, as-built and tested, is capable of continuous operation. It is set by the original equipment manufacturer
Compressor Minimum Speed	The lowest speed (in rpm) at which the manufacturer's design will permit continuous operation to do useful work on the gas
Compressor Station	An installation that uses gas turbine or electricity driven compressors to boost pressures in the pipeline system; it is used to move gas through the network. A compressor station on the Gas Transmission System may have two or more compressors.
Compressor Surge line	The line on a compressor performance map to the left of compressor envelope beyond which the compressor can not physically operate; it marks the onset of destructive vibration known as surge
Compressor unit	A device that pumps gas by converts the motive power from the drive unit into higher gas pressure and/or higher gas flow rates in the gas pipelines. A compressor unit comprises a **prime mover** and a **process gas compressor.**
Drive unit	The device that provides motive power to the compressor - either a gas turbine or an electric motor
DSEAR	**Dangerous Substance and Explosive Atmosphere Regulations**. Requires employers to control the risks to safety from fire and explosions
Entry Point	Locations where gas is injected into the NTS, such as LNG terminals, interconnectors and connections to north sea gas fields
Exit Point	Locations where regional distribution networks or directly connected customers such as power stations and large industrial sites remove gas from the NTS.
GNCC	The **Gas National Control Centre** responsible for operating the UK gas transmission system.
Linepack	The extra gas that is held in the Gas Transmission Pipelines to provide an operational "buffer" above the minimum acceptable pressures.
NTS	The **National Transmission System (or Gas Transmission System)** is a high pressure gas network consisting of Terminals, Compressor Stations, pipeline systems and Offtakes. Operated and maintained by National Grid. NTS pipelines transport gas from terminals to NTS offtakes.
OEM	Original Equipment Manufacturer of major component e.g. process gas compressor or gas turbine
Offtake	An installation defining the boundary between NTS and LTS or a very large consumer. The offtake installation includes equipment for metering and pressure regulation, for example.
Process Gas Compressor	The component of the compressor unit responsible for adding energy to the process gas, increasing or reducing the head and flow rate
TBE	**Transporting Britain's Energy.** National Grid's annual industry-wide consultation process encompassing the Ten Year Statement, targeted questionnaires, individual company and industry meetings, feedback on responses and investment scenarios
TRL	**Technology Readiness Level.** Phase of development and technical maturity a project is in. Indicates how close a technology is to becoming both technically and commercially viable

Appendix 12
Project Partners Support Statements

Project VECTOR

Project Code/Version No:
NGGTGN01_V2

CARBON TRUST

David Oram
Network Innovation Competition Manager
National Grid
National Grid House
Warwick Technology Park
Warwick, CV34 6DA

3rd July 2013

Dear David,

Re: Network Innovation Competition 2013

Carbon Trust is fully supportive of the projects submitted by National Grid as part of the Network Innovation Competition. We have already provided support to National Grid during the Initial Screening Process for 3 of the projects (MEdiCi, MSB and VECTOR).

If these projects are successful during the full submission, we look forward to on-going support of these projects, particularly in the areas of CO2 impact of each of the projects and dissemination of the outputs of the project to a variety of audiences via a range of methods, including but not limited to site visits, conferences, trade PR, website content and end-consumer factsheets.

If you require further information please do not hesitate to contact me on [redacted]

Yours sincerely,

Al-Karim Govindji

Al-Karim Govindji
Manager, Innovation
For and on behalf of
THE CARBON TRUST

From: Lewis, Peter
Sent: 01 July 2013 11:15
To: Feenan, Dominic
Cc: Creed, Stephen; Oram, David; Ariyo, Owen; Beddoes, James; Bapat, CP (RR Energy Systems)
Subject: VECTOR

Dominic,

Many thanks to you and the rest of the team for Wednesday's overview of the VECTOR project.

Based on our discussions last week we would be very happy to move forward with NG on this project and James Beddoes will provide the information (outline plan, budget and estimated improvement on compressor map) by 12th July as agreed.

Please note this will, however, be contingent on us being able to agree mutually acceptable terms for the engagement including the subject of IP ownership. I received the document from David last week and will have that reviewed internally (but that won't happen quick enough for your first submission deadline so I feel we should proceed on the basis that both parties will ultimately find agreement, which I am confident we will). I hope this is acceptable for NG.

Look forward to working with you.

Best regards,

Peter

Appendix 13
Additional Info

Project VECTOR

Project Code/Version No:
NGGTGN01_V2

VECTOR Appendix 13 – Functional Difference to Other International Equipment, IPR and GB Roll-out Potential, Further Benefit Quantification and Regulatory Requirements for Best Available Technique.

As the VECTOR project has progressed through the Expert Panel assessment process it, became apparent that a number of points of clarification are required to the original VECTOR submission. This appendix has been compiled to document the points raised and the clarification provided.

Functional Differences between VECTOR and other Related Technology

The functionality of the VIGV control project installed in Canada is described in the Fraser Nash feasibility study report.

The following information on the basic design and operating principles was provided in September 2013 by EUSTREAM, Slovakia who are installing a VIGV plus Variable Speed project on their gas transmission network.

"…The name of the project is Installation of Tandem Turbosets (ITT)…

The main scope of ITT is to install two 33MW Rolls Royce units at compressor station Veľké Zlievce.

Each unit consists of one gas turbine and two centrifugal compressors (independent casings) connected with shaft. Each compressor is equipped with variable inlet guide vanes (VIGV) which are utilized/designed for the parallel operating mode.

The two compressors on one shaft can by operated in both serial (high pressure ratio and low flow rate) and parallel (low pressure ratio and high flow rate) mode:

In the case of parallel mode it is possible to switch VIGV from Radial to Pre-swirl position. This possibility increases the flexibility of the performance map, because this switching moves the whole performance map from right to left.

Taking into account the operational modes:

- *Serial*
- *Parallel + VIGV Radial*
- *Parallel + VIGV Pre-swirl,*

we are able to cover the whole operational area of the compressor station with high flexibility of efficient operation. The whole concept including the optimization of the performance maps was developed by our specialists..."

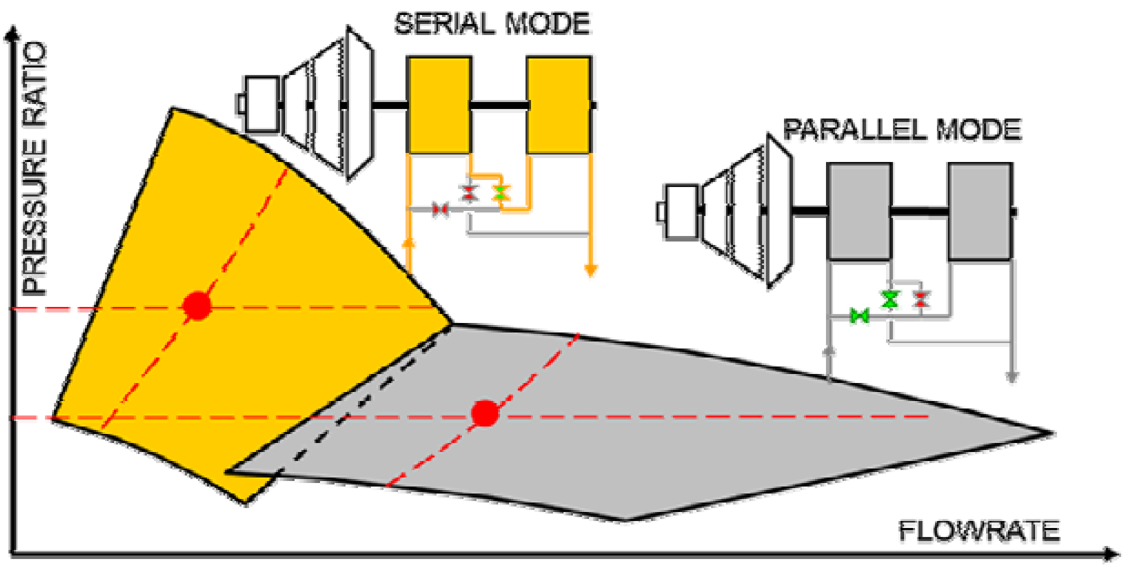


Figure 1: Schematic of the Slovakian Project Operating Concept

It can be seen that the Slovakian project feautres a manually actuated, two-position system used to increase the range of operation in combination with tandem operation of mutiple compressors by a single driver.

The table below summarises what additional knowledge the VECTOR project will generate beyond that of the Variable Inlet Guide Vane technology currently utilised in the Alberta and Slovakia applications.

Summary Description of Functional Differences

KNOWLEDGE AREA	**ALBERTA (VIGV + Fixed Speed Project)**	**SLOVAKIA (VIGV + Variable Speed Project)**	**VECTOR *(VIGV + Variable Speed Project)***
Manual VIGV Actuation on Gas Compressor	YES	YES	-
Manual VIGV Actuation + Variable Speed on Gas Compressor	NO	YES *(not yet Operational)*	-
Automatic (remotely operable) VIGV + Variable Speed Control on Gas Compressor	NO *(manual Operation only)*	NO *(manual Operation only)*	YES
Multi-Position / Modulated VIGV Control	NO *(2 Position System Only)*	NO *(2 Position System Only)*	YES
Two-Plane VIGV + Speed Control *(+/- of 0^0)*	NO *(0^0 and $+30^0$ only)*	NO *(0^0 and $+30^0$ only)*	YES *(e.g. $+45^0$ to -15^0 to exploit maximum range)*

IPR and Strategy for roll out to other Original Equipment Manufacturers (OEMs)

We have reached an outline agreement with Rolls Royce which will result in Rolls Royce funding their own design costs. Therefore the IPR developed by this project will relate to the installation and performance of the VECTOR technology which we will disseminate in line with default IPR arrangements.

Frazer Nash’s enquiries show that most OEMs have explored to varying degrees, aspects of the application of inlet guide vanes to gas pipeline compressors in the past and have the capability to develop the ‘know-how’ without needing access to Rolls Royce IP (see table 4 of Fraser Nash report). One of the OEMs apparently, has not, but it is not credible to consider that they could not develop this technology if they had a business driver. Based on the above, all OEMs appear to have the ability to develop VECTOR technology.

VECTOR project involves the following stages of knowledge generation:

STAGE 1: → Design – including software modelling & prototyping

STAGE 2: → On-site Installation

STAGE 3: → Commissioning

STAGE 4: → Performance Trials & Development of Operating Philosophy

Rolls Royce’s IP concerns Stage 1 only – design. The other areas of knowledge generation would not be limited by Rolls Royce’s IP. The OEMs could independently develop a safe and effective design which achieves VECTOR functionality for their equipment utilising the learning from this project. The result of the VECTOR project would enable NGGT to specify the following in its specification documents:

- Functionality;
- Performance requirement and performance guarantees;

- Acceptable installation criteria;
- Acceptable operational criteria e.g. Mean Time Between Failures, Mean Time To Repair;
- Safety Requirement.

Therefore consumers will be funding the demonstration of this technology and proving its value in the transition to the low carbon economy which will stimulate the demand for other manufacturers to offer this technology to the UK market in response to NGGT including it in our future specifications.

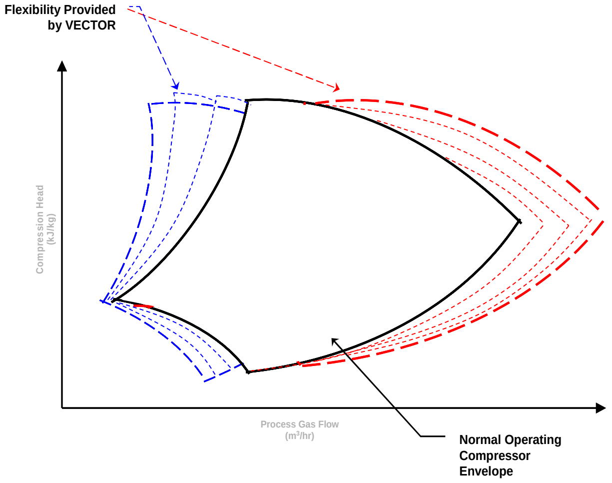
Quantification of Further Benefits

To summarise the concept, VECTOR provides a level of flexibility that is currently not achievable by a re-wheel but falls short of new machine installation.

Previously National Grid has focussed on supply pattern changes we have seen which have required a relatively fixed movement in the operating envelope of a compressor. Therefore in the submission and subsequent presentation we have evaluated the VECTOR technology against rewheels.

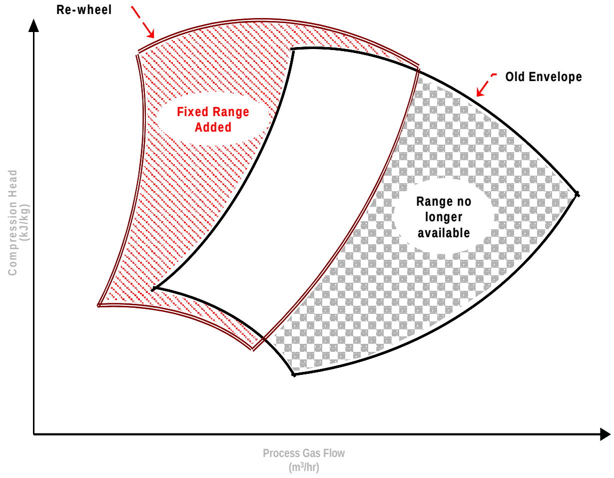
A – Increased Range Flexibility

Provided by VECTOR (modulated)



B – Increased Range Flexibility

Provided by a Rewheel



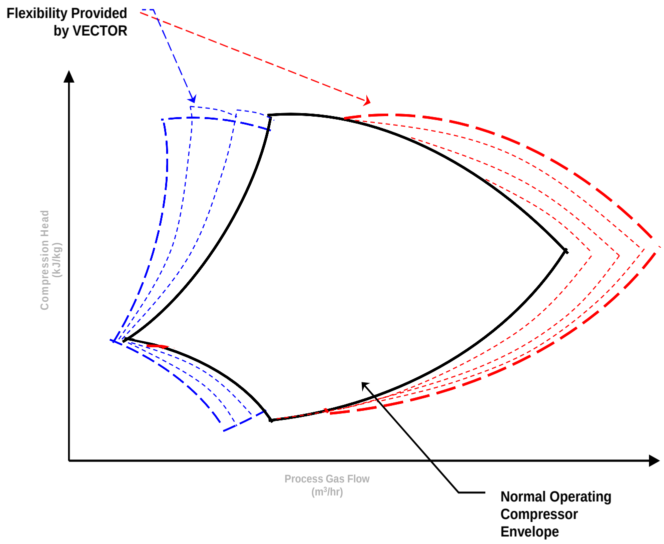
However to give a better indication of the future full potential of this technology we have below, set out a demand side scenario, where the requirement is it to respond to changes "within day" and therefore the appropriate cost comparison is against the installation of a new small compressor unit.

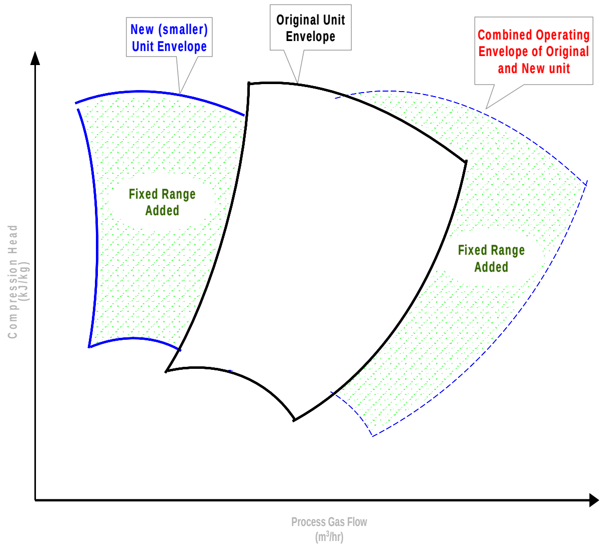
A – Increased Range Flexibility

Provided by VECTOR (modulated)

C – Increased Range Flexibility

Provided by Installing New Units





In this scenario a new gas fired power station requests a connection to the gas transmission system. As part of the request the customer requires to increase the power output of the power station, corresponding to a ramp up rate of 200MW/min. National Grid currently offers a default rate of 50MW/min which may not be sufficient for the new power station to provide services to the electricity grid. These services may be required to manage intermittent operation of renewable sources and hence facilitate the move to the low carbon economy. The problem encountered with offering the 200MW/min ramp rate with the current compressor technology and number of available units leads to an upstream compressor going successively into choke and surge over a 2 hour window in an effort to manage the resulting rapid changes in local linepack, pressures and flow generated by the ramp up.

At present the main physical solution to deal with this situation is to build a new compressor unit. To build a new compressor unit to provide this flexibility could take up to 7 years. Therefore to provide a service that our customers require in a timely manner we need to develop new solutions.

As stated in the submission VECTOR appears a promising and cost efficient technology. At the moment we are unable to quantify the benefit to our customers of providing the operational flexibility and ramp rates they require.

Below we have set out the financial benefits from a National Grid perspective, which ultimately flows through to customers. We have done a cost benefit analysis to compare the cost of fitting VECTOR technology to eight units to installing small new compressors at the four stations. This assumption is based on potential demand side requirements at the four CCGT clusters highlighted in appendix 9.

Row #	Assessment Criteria	VECTOR	New Unit
A	Range Flexibility	~ 30%	~30 - 100% (depends on size of prime mover)
B	Speed of response to Transient Network Changes	Seconds / Minutes (time required to adjust envelope)	Minutes / Hours (time required to bring additional unit online)
C	Operating Cost Savings	No efficiency difference has been assumed	
D	Capital Cost	[redacted]	[redacted] (8MW Unit)

E	Number of Units (from 2020 to 2040)	8 (2 units per CCGT cluster)	4 (1 unit per CCGT cluster)
F	Time Required to implement	12 - 18 months	Up to 7 years
G	Annualised cost of flexibility over the 20 year period (DxE/20)	[redacted]/yr	[redacted]/yr

NOTES:

Row A – This is the increased range flexibility possible with the use of each method discussed.

Row B – The speed of response of each method when applied to manage transient constraints on the network.

Row C – This is the operating cost over the life of the solution.

Row D – The cost of installing the solution.

Row E – The number of units to support demand side network requirements

Row F – The time required to bring the solution to service when a new network change occurs (this assumes VECTOR technology is built into the unit on purchase).

Row G – The cost - benefit of applying the solution calculated on an annual basis.

In summary, the transition to low carbon energy supplies using CCGTs as the carbon plan indicates, will require the flexibility provided by either installing VECTOR or multiple units.

Regulatory Requirements for Adoption of Best Available Technique

National Grid's fleet operation is subject to EU Integrated Pollution Prevention and Control Directive which sets out the main principles for the permitting and control of installations based on an integrated approach and the application of best available techniques (BAT). National Grid is mandated to employ Best Available Technique (BAT) in the selection of technologies installed on the gas transmission system. This ensures that gas can be transported safely, reliably and efficiently while achieving a high level of environmental protection.

BAT is defined in Article 11 of the European Union Council Directive 96/61/EC – Integrated Pollution Prevention and Control as well as Section 5 of the Environment Protection Act as follows:

> '**best available technique'** shall mean the most effective and advanced stage in the development of activities and their methods of operation which indicate the practical suitability of particular techniques for providing in principle the basis for emission limit values designed to prevent and, where that is not practicable, generally to reduce emissions and the impact on the environment as a whole:
>
> - '**techniques'** shall include both the technology used and the way in which the installation is designed, built, maintained, operated and decommissioned,
>
> - '**available'** techniques shall mean those developed on a scale which allows implementation in the relevant industrial sector, under economically and technically viable conditions, taking into consideration the costs and advantages, whether or not the techniques are used or produced inside the Member State in question, as long as they are reasonably accessible to the operator,
>
> - '**best'** shall mean most effective in achieving a high general level of protection of the environment as a whole.

An "available" technique is either:

1. A technique that has been tried and tested in similar application environments to such a level as to provide sufficient information of its design, operation, failure modes, maintenance,

reliability (e.g. mean time between failure and mean time to repair), environmental impact and overall energy efficiency. A single dissimilar prototype installed on a different network would not be admissible as BAT. To allow new technology to be introduced on the UK gas transmission system and fulfil BAT requirement National Grid require the OEMs to demonstrate a minimum that a minimum of 5 of the same design of equipment should have been installed and operational in similar applications anywhere the world;

Or

2. A technique that whilst nascent in application can be built and thoroughly tested and assessed on National Grid's gas transmission system as a demonstration project. This would provide a similar level of confidence for admission as BAT in new builds of future retrofits.

VECTOR technology could not be admitted as BAT on the gas transmission fleet under business as usual conditions since the technology required is not yet "available" – there is no known operational design from which sufficient design, operating, maintenance, etc information could be obtained.

However, a VECTOR demonstration project on the gas transmission system would prove the technology and make it "available" in the shortest possible timescales.

Appendix 14
Addendum

Project VECTOR

Project Code/Version No:
NGGTGN01_V2

Section (s)	Change
1, 4.5 and cost spreadsheet	VECTOR design and development costs and associated contingencies will be funded by Rolls Royce as OEM 1
4.5 (OEM commercial arrangements), 5 IPR arrangements and Appendix 4 risk item number 2	Updated position on Intellectual Property Rights and basis of appointment of Rolls Royce.
10 List of Appendices	Updated to reflect the inclusion of appendix 13 and addendum
Appendix 2 Full Submission Spreadsheet Worksheet “Front Sheet” Cell D17	Submission date updated
Appendix 2 Full Submission Spreadsheet Worksheet “2014-15” Cells: R 12 and 13 S 12 and 13 W 12 and 13 and resultant calculated cells	Design costs to be covered by OEMs
Appendix 2 Full Submission Spreadsheet Worksheet “2015-16” Cells: R 19 S 19 W19 and resultant calculated cells	Development costs to be funded by OEM
Appendix 2 Full Submission Spreadsheet Worksheet “Whole Project” Cells: R 12, 13 and 19 S 12, 13 and 19 W 12, 13 and 19 and resultant calculated cells	Updated to reflect changes above
New Appendix 13	Clarification of important functional differences between VECTOR and the projects underway in Alberta and Slovakia and the reasons why this can’t simply be adopted on the GB network