Network Options Assessment Methodology Review

EXECUTIVE SUMMARY

CONTEXT

As the System Operator (SO) we are committed to challenging ourselves and ensuring we are utilising the best approach for the Network Options Assessment (NOA). We also consistently seek to improve and enhance the NOA methodology as new tools and techniques become available and continuously review our approach with each NOA. In September 2016 Ofgem requested the SO to further analyse the NOA methodology and provide its views on the best way forward. Ofgem acknowledged that the SO had made good progress on introducing several new developments; however it was considered that the NOA 2 methodology had not gone far enough to address other issues highlighted last year.

Ofgem's concerns centre on the potential for the Gone Green scenario to lead to *false-positives* when paired with Least Worst Regret (LWR), a decision making tool that makes recommendations based on which options/strategy produce the least 'regret' across all of the scenarios analysed. By *false-positives* we mean *spurious investment recommendations* could be made which are ultimately inefficient, either in terms of the timing of investment (i.e. too early) or in terms of an entire network development option (i.e. under-utilised asset). We recognise these concerns.

As a result of our analysis and engagement with external experts this report:

- **Evaluates the approaches the NOA could utilise and provides a constructive demonstration of why we believe the current methodology, with improvements to address concerns, is fit for purpose**
- **Provide suggestions for future developments to the NOA methodology**

QUESTIONS

- Is the current process of scenarios and Single Year Least Worst Regret the best approach for undertaking the NOA in light of the alternatives available to us?
- What more can be done to provide additional insight into the drivers behind investment recommendations and minimise the risk of spurious investment recommendations?
- What improvements can we make to structurally address concerns and make the NOA methodology as robust as possible?

CONCLUSIONS

Is the current process, scenarios and Single Year Least Worst Regret the best approach for undertaking the NOA in light of the alternatives available to us?

We examined a number of decision making tools and methods for quantifying uncertainty including traditional decision making (expected net present value maximisation), Least Worst Regret, central forecasts, scenario analysis, and Monte Carlo. With regard to decision making tools we find Least Worst Regret the most pragmatic option since it is not reliant on subjectively weighting views of the future. However, LWR is not without its limitations. Specifically results are determined by the balance between the least and most onerous case for development, which can lead to spurious investment recommendations. The main alternative, traditional decision making, is reliant on potentially miss-specified and subjective weights for making investment recommendations. These are potentially open to abuse. As a result we believe LWR should be the main decision tool for the NOA. With regard to methods that quantify uncertainty we find that alternatives to scenarios pose a risk of making over-simplifying assumptions about the future, thus risking the robustness of recommendations. Scenarios are pragmatic for balancing both the need for a wide range of views over an uncertain future and the requirement for detailed analysis of the transmission network.

Scenario analysis and LWR sit within the Single Year Least Worst Regret process, which is a form of receding horizon optimisation whereby optimal networks are configured for each of the scenarios and a decision is made (using LWR) over whether to implement or not the options proposed. This is reviewed each year. The advantage of our current method is that it identifies a broad range of issues on the network which can be examined in more detail through Strategic Wider Works submissions, for example. However, this type of receding horizon optimisation can be proactive in the early years of an option's development when capital expenditure is relatively low and reticent to build later in the construction process when next year capital costs can be high. In addition, substitute network options can be developed in tandem using the current process.

These properties suit the current framework of annual NOA and Strategic Wider Works submissions since it keeps the best competing options 'alive' by not choosing between them too early and they can then be assessed in more detail. These properties are independent of the decision making tools and methods for quantifying uncertainty used. This form of receding horizon optimisation is the most pragmatic method currently available. This report explores alternative forms that could be used.

Following evaluation of the various methods available to undertake the NOA, set out in the report below, we have concluded that at the present time the current process of scenarios and Single Year Least Worst Regret is the most pragmatic and robust approach for evaluating future uncertainty and formulating investment recommendations. However, we recognise there are limitations to Single Year Least Worst Regret. We are therefore proposing two improvements to the methodology to minimise the potential for spurious investment recommendations. In order to reach this conclusion we have performed our own evaluation and drawn upon external industry experts from within academia and the energy industry.

What more can be done to provide additional insight into the drivers behind investment recommendations and minimise the risk of spurious investment recommendations?

Given the idiosyncrasies of the Single Year Least Worst Regret process, which can be proactive and reticent at different points in time and is open to the limitations of LWR, we feel it prudent to provide additional insight and further transparent oversight of the Single Year Least Worst Regret recommendations. We will be implementing two additional steps into the NOA methodology. With these additional measures in place we feel there is minimal risk of spurious investment recommendations being made. These steps are:

- **Introduction of a NOA committee** – an SO committee, chaired by the director of SO Operations, to make decisions on reinforcement recommendations from the Single Year Least Worst Regret, which are not clear cut (with Ofgem observers invited to witness). The NOA committee would scrutinise the results and utilise the latest market intelligence to help shape their decisions. This would enable scrutiny to be applied in a transparent, robust, and accountable way.
- **Implied scenario weights** – an additional insight designed to identify spurious investment recommendations by calculating the probability on each scenario we would have to believe in order to recommend (or not) investment.

What improvements can we make to structurally address concerns and make the NOA methodology as robust as possible?

Our recommendations for improvement of the NOA methodology, detailed above, minimise the possibility and impact of spurious investment recommendations. However there are still areas of improvement we would like to explore in order to structurally address concerns and further improve the NOA. We therefore set out our suggestions for the future development of the NOA methodology. These include:

- **Real Options** – how we could improve the real options element of the NOA so that we fully value the flexibility the NOA process affords.
- **Probabilistic Approach –** how we could incorporate a probabilistic approach into the NOA and the options this opens with regard to decision making tools.
- **Receding Horizon Optimisation –** a discussion on the merits of alternative forms of receding horizon optimisation. We find that alternative processes are less likely to recommend substitute options in tandem and can make recommendations more consistent. There are limitations to alternative methods however, which need to be considered in greater detail.

We are also establishing a NOA roadmap with the aim of providing an ongoing plan for continual improvement of our network development methodology. Part of the roadmap will reflect outputs from the Network Competition workstream of our Future Role of the System Operator programme. Here we have proposed several directions we plan to extend the NOA in:

- **Competition –** support identification of projects suitable for onshore transmission competition.
- **Whole-system –** in response to distribution networks becoming more active and the increasing decentralisation of energy sources we plan to extend the NOA to non-transmission options that could provide the best technical and economic solutions.

NOA REPORT

INTRODUCTION

As the System Operator (SO) we are committed to ensuring we are utilising the best approach for the Network Options Assessment (NOA). We consistently seek to improve and enhance the NOA methodology as new tools and techniques become available and continuously review our approach with each NOA. In September 2016 Ofgem requested the System Operator (SO) to further analyse the NOA methodology and provide its views on the best way forward. Ofgem acknowledged that the SO had made good progress on introducing several new developments; however it was considered that the NOA 2 methodology had not gone far enough to address some issues highlighted last year.

Ofgem's concerns centre on the potential for the Gone Green scenario to lead to *false-positives* when paired with Least Worst Regret (LWR), a decision making tool that makes recommendations based on which options/investment strategy produce the least 'regret' across all of the scenarios analysed. By *false-positives* we mean *spurious investment recommendations* could be made which are ultimately inefficient, either in terms of the timing of investment (i.e. too early) or in terms of an under-utilised network development option (i.e. under-utilised asset).

We recognise Ofgem's concerns. The aim of this report is therefore to evaluate the approaches the NOA could utilise and provide a constructive demonstration of why we believe the current methodology, with improvements to address concerns, is fit for purpose. We are committed to improving and enhancing the NOA methodology as new tools and techniques become available and therefore make several suggestions for the future direction of the NOA methodology.

Following the evaluation of these methods, set out in the report below, we have concluded that the current process of scenarios and Single Year Least Worst Regret analysis is, at the moment, the most pragmatic and robust approach for evaluating the uncertainty we face over the future and turning this into investment recommendations.

The report comprises the following four sections: **(1)** principles of transmission design; **(2)** decision making processes under uncertainty; **(3)** cost benefit analysis within the NOA; and **(4)** future directions – *'always finding a better way'*.

Section 1 provides insight into what we are trying to achieve when making investment recommendations and the NOA 'mission statement'. The purpose of **section 2** is to describe the constituent elements of a decision making process (i.e. tools for quantifying uncertainty, tools for decision making, and the process in which these tools sit that provides investment flexibility through time), and the individual methods currently available. We evaluate the merits of each of these and assess their applicability and practicality for use in the NOA process. **Section 3** describes our current NOA process in more detail and provides insight into its underlying character, as well as describing the FES at a high level and evaluating their adequacy for the NOA. We make near term recommendations for the next NOA cycle, NOA3, which seek to address the concerns borne out by Ofgem and our own evaluations. **Section 4** proposes several directions of travel the NOA methodology could take in order to structurally address ours and Ofgem's concerns, and make the NOA as good as it can be.

1. PRINCIPLES OF TRANSMISSION DESIGN

The Network Options Assessment (NOA) is the System Operator's (SO's) principle process for identifying and recommending development on the wider transmission system. It sits at the end of a process which begins by identifying credible futures through our future energy scenarios (FES). We then assess the future needs of the transmission system in the Electricity Ten Year Statement (ETYS). Finally the NOA takes network development proposals, assesses these relative to the future system requirements illustrated by the FES, and makes investment recommendations. This is illustrated in Figure 1, below.

At its most basic level the NOA makes investment recommendations based upon cost-benefit analysis. We use discounted-cash-flow (DCF) to compare the forecasted monetised benefits and capital costs of reinforcement over a project's life.

Monetised benefits take the form of forecasted reductions in operational costs, which are largely made up of constraint costs, as a result of network development which would otherwise be paid for by consumers. In order to solve a binding flow constraint within the transmission network in operational timescales, the SO take a series of bid/offer actions to rebalance the network to ensure demand and supply are equal and none of the flow constraints on the system are violated[1]. When a development to the network is commissioned, which increases boundary capability on a previously binding constraint, fewer bid/offer actions are required thus reducing operational costs.

For the purpose of investment recommendation we forecast bid/offer actions (and costs) using Bid-3, a market modelling tool developed by Pöyry Management Consultancy. The modelling of an investment's benefit is performed under different scenarios, which propose different demand/supply configurations across the networks, and so different levels of benefit. By modelling an option's benefit across a broad envelope of credible scenarios we acquire a range of expected benefits.

Developing the transmission network is an iterative and cyclical process by nature since the drivers for investment evolve over time and are influenced by a variety of external factors. The scale, type, and location of generation and demand, as well as the extent and location of new interconnection to other systems, are heavily influenced by government energy policy, the growth of new technologies, and the evolution of new business models. The lead-time for reinforcement of the wider transmission network is often greater than the lead-time for the development of new generation projects. Operational measures however, such as constraint management, provide us with the flexibility to be able to manage transmission congestion in the absence of network developments. This provides us with flexibility, and can be cheaper than adding capacity to the network for low levels of congestion, but is typically more expensive at higher levels of congestion.

[1] Rather than use load flow based tools to model flows on the network we use a system of boundaries which each split the network in half. Boundaries are chosen to represent weak points in the system and so provide a good approximation of the network without the need to over-engineer our constraint modelling tool, Bid-3. The maximum possible flow between the two sides of a boundary, whilst respecting N-D SQSS standards, is then calculated using AC load flow tools. This maximum flow provides the constraint that must be respected.

Prospective investments are often imperfect substitutes or complements to each other and existing assets on the network. Given the substitutability and complementarity inherent in combinations of options it is preferable that development options are analysed in concert with each other.

The fundamental dilemma in facilitating the development of an efficient, coordinated, and economical system of electricity transmission is the need to balance the risk of over-investment or too-early investment against the risk of under-investment or belated-investment in the transmission network. We aim to resolve this dilemma by considering a manifold of credible futures highlighting different possible needs for investment. Moreover, we must account for industry agreed criteria, such as the Grid Code, and the methodology for the planning and operation of the transmission system, the Security and Quality of Supply Standards (SQSS).

In our role as System Operator we must ensure we develop a system which is secure and reliable. The design of transmission developments is about design which addresses short-falls in system capability whilst ensuring the system has sufficient security of supply, and is reliable. By designing reinforcements in adherence to the SQSS we ensure that these fundamental standards of security of supply and reliability are met. The process of selecting which reinforcements are the most economic and efficient in meeting these standards is achieved through the NOA.

The NOA provides investment recommendations based on the Single Year Least Worst Regret (SYLWR) decision making process. The output from this process is a list of recommended wider works projects to proceed with or delay in the next year. A secondary output of the NOA is an indicative list of the reinforcements that would be proposed at present if each of the scenarios studied in the NOA were to occur.

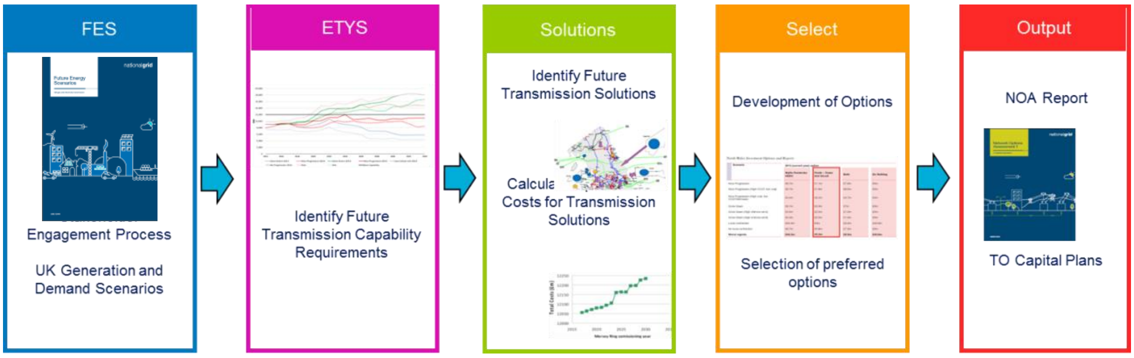

Figure 1: High level transmission design process

1.1. MISSION STATEMENT

The purpose of the NOA is to facilitate the development of an ***efficient***, ***coordinated***, and ***economic*** system of electricity transmission. Whilst cost benefit analysis (CBA) is the best practice way to achieve an economic and efficient transmission system, there are multiple ways in which it can be applied. How should we quantify future uncertainty? What decision tools should we use? How should we develop the network over time?

Whatever the chosen method, the approach must be optimal across key selection criteria:

1. The approach must be **transparent** – *we must be able to easily explain what we are doing and for it to be open to challenge.*

2. The approach must be **robust** – *we must be able to show that the decisions we make today and in the future are right over their lifetime.*

3. The approach must be **repeatable** – *we must recognise that the approach works across GB, for different types of network development, driven by different types of generation and demand.*

4. The approach must be **deliverable** – *undertaking cost benefit analysis, for all developments across GB on an annual basis, is computationally and resource intensive. A balance must be struck between the detail of analysis and repeatability through time.*

2. DECISION MAKING PROCESSES UNDER UNCERTAINTY

This section evaluates the methods we could utilise to make investment recommendations. Essentially we must quantify uncertainty over the future, turn this into robust decisions, and do this repeatedly over time. Generally the methods we could employ fall into three categories: **(1)** methods seeking to quantify the uncertainty we face; **(2)** methods that synthesise uncertainty into a decision; and **(3)** methods which seek to make the decision process flexible over time.

Bringing these together forms an overall decision making process. The characteristics of each component can potentially interact to such a degree to form properties unique to the specific combination. Section 2 proceeds by taking each of the three components of decision making processes in turn and evaluating the various alternatives that could be employed.

The following table provides a summary evaluation of the methods available to us with regard to quantifying uncertainty and decision making, which are analysed in greater detail below:

Table 1: Summary evaluation of alternative methods the NOA could employ

Methods to Quantify Uncertainty

- **Central forecast**
  A 'best view' of how we believe the future energy landscape will evolve
  - **Advantage**: Allows for extensive detail in a single view
  - **Disadvantage**: Ignores future uncertainty; what is 'central' and is it easily identified?

- **Monte Carlo**
  A probabilistic approach used to create many scenarios (in the order of thousands) from random sampling of an underlying distribution describing the future energy landscape
  - **Advantage**: Understands risk involved better; the estimate of each option's benefit could be more accurate
    Disadvantage: Too time intensive to deliver on an annual basis; easy to miss-specify underlying distributions of variables
- **Scenarios**
  Involves constructing consistent energy landscapes which describe how the future may unfold
  - **Advantage**: Provides a range of 'futures'; pragmatic balance between range of futures and detail of analysis

- **Disadvantage**: Can seem arbitrary in their construction (although have a central rationale); limited number of futures

- **Real Options Analysis (Black-Scholes & Binomial Options Pricing)**
  Real options analysis seeks to value flexibility in investment opportunities – both the flexibility offered once the investment is undertaken, and the flexibility of delaying the investment
  - **Advantage**: Acknowledges future uncertainty; values flexibility
  - **Disadvantage**: Some simplifying assumptions are too strong; difficult to model all the flexibility in transmission planning

Decision Making Tools

- **Traditional Decision Making Tools**
  Traditional decision making using scenario weights seeks to maximise expected returns and make the best decision on the balance of probabilities
  - **Advantage**: Very flexible; intuitive (best strategy on average); attractive theoretical properties (perfect rationality)
  - **Disadvantage**: Relies on potentially miss-specified weights; single variable decides CBA result (open to abuse); inappropriate to specify probabilities on contentious inputs
- **Least Worst Regret**
  LWR chooses the option which minimises the worst error or 'regret' across all the scenarios being considered
  - **Advantage**: Attractive theoretical properties (risk-neutral in nature, regret minimisation is a sensible, conservative approach to take, based on 'regret theory'); pragmatic; not reliant on subjective scenario weights
  - **Disadvantage**: Risk appetite decided by scenarios; result are determined by balance of regrets in least & most onerous case for reinforcement (could lead to 'false positives'); not independent of 'irrelevant alternatives', i.e. results are sensitive to the options included even if they are not among the leading contenders
- **Minimax**
  Minimax is more pessimistic than LWR since it seeks to minimise the maximum cost scenario rather than the regret
  - **Advantage**: Independent of 'irrelevant alternatives'; not reliant on subjective scenario weights
  - **Disadvantage**: Overly risk-averse (based on worst-case scenario) & degree determined by scenarios
- **Minimin**
  Minimin involves selecting the option that minimises the minimum cost scenario. In transmission terms minimin would choose the option that minimises costs in the minimum network cost scenario
  - **Advantage**: Independent of 'irrelevant alternatives'; not reliant on subjective scenario weights
  - **Disadvantage**: Overly risk-seeking (based on best-case scenario) & degree determined by scenarios

2.1. QUANTIFYING UNCERTAINTY

The following sections evaluate the various methods available to **quantify the uncertainty** we face over the need for transmission development. We find scenarios **pragmatic** at balancing the wish for a broad range of views over the future and the need for **detailed analysis** of the transmission network. However, there is a need for all those scenarios included in the decision making process to be **credible**. The degree to which this is significant depends on the decision making tool with which they are paired.

With regard to the alternatives we believe **central forecasts** offer too limited a view of the future, which could **ignore** the extent of **future uncertainty**, and would be difficult to construct objectively in practice. **Monte Carlo** based analysis is desirable in theory given the broad range of futures it examines and opens up the ability to better **understand the risk taken** with investments; however **sacrifices** would need to be made to the **accuracy** of constraint cost estimation. In addition, we do not believe the underlying uncertainty around transmission usage drivers can be adequately enough modelled for Monte Carlo to be desirable.

Standard Real Options techniques, such as **Black-Scholes** and **Binomial options pricing**, which seek to take into account the uncertainty we face, by placing an estimate on the underlying volatility of constraint costs, are in practice too **inflexible** to adequately model the different 'options' at our disposal. Furthermore, we believe several **simplifying assumptions** behind these standard options pricing formulas are **too strong** for our applications.

We proceed by describing and evaluating each of these techniques in turn.

2.1.1. CENTRAL FORECAST

Central forecasts provide a *'best view'* of how we believe the future energy landscape will evolve. If a central forecast was employed we would seek to minimise total operational and development expenditure for that central forecast, into the future. The estimated value of a network development would be calculated using DCF under the central forecast only given the absence of competing views over the future.

Essentially, the uncertainty over the future energy landscape, and consequently the need for network development, is taken into consideration at the start of the process when creating the scenario. If the scenario generating process was consistent[2] and represented the underlying uncertainty we face then the resulting scenario would represent the most likely, or what we could call 'modal' outcome.

The advantage of using a central forecast is that constraining ourselves to one, central, scenario might allow us to perform more detailed, accurate analysis into operational cost forecasting. In addition, by concentrating on what we feel is the most likely outcome we would remove the risk of planning the network for events which are unlikely.

However, limiting ourselves to a *'best view'* would likely give us, and the industry, an inflated sense of certainty over how the future energy landscape is going to evolve. By allowing ourselves only one scenario we would be ignoring the uncertainty we currently face over the need for network development. We believe there is a substantial amount of uncertainty, as demonstrated by the Electricity Ten Year Statement (ETYS), and by ignoring this we would design a network that is ideal in the most likely energy landscape, but could be very wrong when the future unfolds. By planning to a central forecast we would be ignoring the risk we, and ultimately consumers, face.

[2] *By consistent we mean that a central forecast would truly represent underlying uncertainty, without bias.*

Whilst this could be ideal ex-post[3], the chances are high that the *'best view'* energy scenario will not exactly come to fruition and consumers could be left with a bad deal.

Central forecasts are particularly susceptible to structural changes such as paradigm shifts and policy shocks since these are implicitly ignored and so forecasts flowing from them are also prone to error. Furthermore, since central forecasts have already distilled uncertainty into one, central view we would be unable to analyse what developments to the network would be ideal in high or low need energy landscapes and so potentially be unprepared in the case of either occurring.

We have so far assumed that a central forecast would be consistent in representing the uncertainty we face. It is entirely possible that the scenario created would not in fact represent the modal outcome for various reasons, including cognitive biases of the individuals creating the scenario, and the stakeholders they engage with. Further to this, it is not obvious that the 'best view', or a most likely, central forecast would lead to the most likely[4] operational cost on the system given that specific operational costs can be generated a number of different ways. It could therefore be that we under- or over-estimate modal operational costs by relying on a central forecast. Finally, the construction of a consistent central forecast is itself difficult since some of the uncertainty in the future energy landscape is 'Knightian'[5] in nature and so immeasurable; we have no previous data to draw on. In this way we risk our central forecast not being 'central' at all and being subjectively determined instead.

Finally, since we would be providing our opinion on what we feel is most likely to happen, central forecasts can be particularly contentious and controversial.

2.1.2. MONTE CARLO

Monte Carlo methods are a class of computational algorithms that obtain results by repeated random sampling. In a network development setting the process would be as follows: underlying distributions are specified which describe how each variable of the future energy landscape will evolve, random sampling then draws from them to create a large number of 'scenarios' (in the order of thousands) and operational costs are calculated based on these 'scenarios'.

The intuition behind using Monte Carlo would be that we believe there is a large amount of uncertainty over the future energy landscape, and consequently the operational costs we may witness. Therefore, if we can specify, even approximately, the values variables of the energy landscape may take and their likelihood, (i.e. a distribution) then we can draw many random samples from these distributions and so arrive at many 'scenarios' which should then describe the distribution of the potential energy landscape, as we currently see it. Whilst we will only observe

[3] Ex-post refers to 'after the event', whereas ex-ante refers to 'before the event'. These terms are widely used in relation to uncertainty.

[4] Given that operational costs are the product of many individual elements of an energy landscape it is likely that operational costs would follow a lognormal distribution where the modal value is less than the median, which is less than the mean.

[5] Also known as Deep uncertainty in other disciplines, and refers to uncertainty over which we do not know, and may not be able to learn, the underlying probability distributions.

one out-turned energy landscape we can think of there currently being many potential landscapes, and each ultimately have their own likelihood as specified by the underlying distributions for each element of the energy landscape. The 'scenarios' can be used to estimate operational costs and ultimately the distribution of potential operational costs.

In practice that means that we would be assuming the data generating process underlying the future development of individual elements of the energy landscape (such as generator open/closure decisions, electricity demand, and the penetration of low carbon technology) can be modelled by a distribution of our choosing. This may not be possible for uncertainty which is 'Knightian', as we do not know what distribution this uncertainty is being drawn from, if one at all.

Done well Monte Carlo would allow us to estimate the distribution that network development NPVs may take. This would not only provide what could be called a *'micro-founded*[6] estimate of the expected NPV (eNPV) of a network development, but also the distribution the NPV might take. This would enable us to quantify the risk we are taking with an investment, for example by using Value at Risk (VaR), which would estimate how much risk we are taking with a set of network recommendations, given what we know now.

Monte Carlo analysis of this kind, if done well, could be an excellent method of operational cost valuation. However, we have two broad concerns around using Monte Carlo.

Firstly, is it possible that the analysis can be *'done well'*, by which we mean will the analysis accurately represent the underlying elements of the energy landscape? The risk here is that the underlying distributions can easily be miss-specified if there is not previous data to draw upon. Further to this, there is the risk of systematically miss-specifying the covariance between the elements of the energy landscape. For example if there is a general increase in green ambition we may see an increase in heat-pumps and so transmission demand. But, we may also witness an increase in distributed low-carbon generation as a result of higher levels of green ambition, and so lower transmission demand. Without taking into account the covariance between these elements we would risk over-simplifying the energy landscape. This could systematically bias our estimates of operational costs.

Secondly, operational cost forecasts, using our current NOA setup, take roughly 50 minutes per simulation, which is orders of magnitude too long for Monte Carlo analysis since Monte Carlo relies on many, perhaps thousands of, 'scenarios' to estimate properly. There has already been a lot of development to minimise run time[7], and so there is little scope to increase speed without sacrificing accuracy of both the market dispatch (across Europe), and the re-dispatch which simulates the post-gate-closure actions the SO takes to manage congestion on the network. The result of this is that the NOA CBA would take too long to complete using current methods of operational cost forecasting.

[6] Micro-founded implies that operational costs are built up from first principles, i.e. a description of how likely each element of the energy landscape is. This is approximated by the use of distributions of individual elements of the energy landscape, which seek to describe the future, and how likely each element is.
[7] This has included extensive collaboration with Pöyry, shift pattern work to fully utilise simulation time, and investment in considerable computing hardware to optimise run time.

It is our belief that it is not currently possible to specify the underlying distributions and their respective covariance with enough accuracy to be comfortable with this style of analysis. Furthermore, there are concerns over whether operational cost forecasting can be done accurately enough with enough speed to make Monte Carlo methods practicable within the timeframe allowed for the NOA CBA.

Finally, a more general point of concern about Monte Carlo based modelling is that the assumptions being made about the energy landscape and how the Monte Carlo process works could become something of a *'black box'* since underlying distributions for variables are specified which are not easily interpretable. This could harm the transparency of the NOA unless managed carefully.

2.1.3. SCENARIOS

Scenario based analysis involves constructing *'internally consistent'*[8] energy landscapes that describe how the future may unfold. The purpose of this is to provide insight into the range of demands the possible futures may place on the transmission network; in our context congestion and related operational costs. In this regard scenarios are similar to Monte Carlo simulations/'scenarios' in that they can be used to quantify the uncertainty we face. Scenarios therefore sit between a central forecast and Monte Carlo in their ability to describe what the future may hold and demonstrate the uncertainty we face. As such they provide a pragmatic way of evaluating future uncertainty.

Scenarios do have their own distinct value however. The property of internal consistency is very important since it makes each individual scenario a credible future landscape. As such, estimates (of operational costs) that derive from scenarios can be much more accurate than under other methods since the composition of the whole energy landscape is consistent. The underlying 'core values' of a scenario may be up for discussion but the fact that the composition of a scenario is internally consistent, and so the estimates of operational costs are more credible as a result is of great value.

In addition, by limiting ourselves to a limited number of future scenarios (rather than a multitude of simulations under Monte Carlo) we allow ourselves to analyse the capability of the transmission system and proposed network developments in greater detail through detailed 'boundary studies' of network transfer capability. This also extends to our own economic modelling where we can use more sophisticated market dispatch and re-dispatch simulations where balancing mechanism actions and the related operational costs are calculated.

Scenarios have three further features that make them an insightful tool for understanding uncertainty and developing strategy accordingly.

1. **Scenarios expand our thinking** – simply looking to the immediate past is often not good enough when considering the future.

[8] By internally consistent we mean that the core values of the scenario drive a variety of observations within the scenario which are consistent with each other. For example, a high green ambition scenario may drive renewable investment and electric car adoption but not extensive thermal generator build.

2. **Scenarios uncover inevitable or near-inevitable futures** – in a transmission context this means we can identify those demands on the network which are very likely, and are represented across all scenarios.
3. **Scenarios protect against 'groupthink'**– scenarios allow for a range of opinions to be incorporated in a controlled way so that current thinking can be challenged. Furthermore, by setting out a broad range of scenarios we reduce the risk that we are 'caught out' by network conditions that were not perceived as likely but still came to pass.

There are, however, potential pitfalls to scenarios, particularly in the way they are incorporated into decision making tools. These are discussed in greater detail below.

2.1.4. REAL OPTIONS – USING STANDARD REAL OPTIONS VALUATION TECHNIQUES

Real Options analysis is slightly different to the above methods of quantifying uncertainty. It seeks to take into account the uncertainty faced over the future benefit of investment, but does so by augmenting the NPV rather than providing NPVs for each 'scenario' considered.

In general terms a real option is the right, but not the obligation, to undertake an initiative, such as deferring, abandoning, expanding, or staging capital development projects. In a transmission network context this means we can recommend investment, but do not have to, and so can be flexible around when and what is recommended. For example, we can delay recommendations until more is known about the future need for development.

The basic insight from Real Options Analysis (ROA) is that traditional discounted-cash-flow analysis undervalues the flexibility inherent in organisations, processes, and investment opportunities. As such organisations tend to underestimate the benefits of waiting, or incorporating into their strategies the flexibility to expand or contract developments.

In general ROA leverages the similarity between 'real' options (i.e. physical investments) and financial options to apply financial options methods to capital investment, such as Black-Scholes, and Binomial Options Pricing. In our setting these standard techniques would be used to model what is known as the 'call option', i.e. the right to defer an investment until we believe it is optimal to invest. The call value is equivalent to the NPV of an investment, but one which takes into account the fact that by deferring an investment we have the option to revisit the decision in a year's time when more is known about the value of the investment and we may discover that the NPV of the option is in fact negative and so we would not recommend to invest.

Rather than basing our decision making on the NPV from a central forecast, as described above, ROA explicitly acknowledges the fact that there is uncertainty over the need for development. The central premise behind ROA valuation techniques is that we do not have an obligation to invest, and so acknowledges we will not invest in a project in the future if it turns out to have a negative NPV. Therefore, if we are uncertain now it may be valuable to wait to discover with more certainty whether the project has a positive or negative NPV. Therefore, if we imagine a distribution of the need for network development, with the modal NPV for the distribution being taken from the central forecast, ROA valuation assumes that we will not invest if the NPV is negative when uncertainty is resolved, and so truncates the NPV distribution at 0. This leads to a 'call-value' that is greater than the NPV. This acknowledges that we can be flexible in what and when we invest.

The advantage of this valuation technique is that we explicitly take into consideration the uncertainty we face and, what's more, augment the NPV of a development to take into account the fact that we have flexibility in our development recommendations.

In order to calculate ROA valuations using standard techniques we would need estimates of two key variables: the mean, or modal[9] NPV of a development; and the variance of potential operational cost savings. Whilst the mean NPV may be available from analysing a central forecast, an estimate of the underlying variance of operational cost savings would prove more difficult. However, a generic estimate of the variance can be used by making assumptions like 'transmission demand may double or half in the next 50 years' and calculating the variance that this statement implies. A reliable estimate of the variance is important however, as this directly affects the value flexibility brings.

It is worth noting that the estimated variance of operational cost savings is the explicit quantification of the uncertainty around the need for network development. It says how volatile we believe the investment is and therefore does the job of quantifying the range of values the development may take.

There are, however some important drawbacks to the use of traditional ROA valuation techniques. Techniques such as Black-Scholes assume that at 'exercise' of the option, i.e. when a development is commissioned, there is no remaining uncertainty. This is far from the case with transmission developments which typically have long lead times and see benefits accruing over 40 or more years. Therefore, the decision to defer network development by one year is not directly comparable to the valuation of a one year financial option using the Black-Scholes formula.

In addition there are other assumptions inherent in the Black-Scholes formulation, and by extension models like Binomial Options Pricing, which are not readily applicable to transmission development to one extent or another. For example the assumption that the underlying asset (operational cost) is traded in a complete market, and that the underlying asset's value follows a Geometric Brownian Motion, i.e. the evolution of operational costs essentially follows a random walk and is the product of many random variables impacting operational costs.

In the context of network development standard ROA would rely on generic and subjective assumptions about the variance of operational costs to evaluate the uncertainty we face. Whilst traditional ROA valuation techniques are commendable for taking uncertainty into account, and valuing the flexibility that waiting provides us, there are perhaps more accurate and insightful ways of evaluating uncertainty.

2.2. DECISION MAKING TOOLS

The following sections describe the **decision making tools** available. These **synthesise** the information provided by methods quantifying uncertainty into a **single decision**. We find that **Least Worst Regret (LWR)** provides the most **pragmatic** approach at this time. LWR has **attractive theoretical properties**, such as regret minimisation and being generally *risk-neutral* in nature, and is **not subject** to potentially **miss-specified scenario weights**. However, care must

[9] ROA valuation techniques assume the benefits of investment are normally distributed and so the mean and mode are equivalent.

be taken since LWR is not independent of *'irrelevant alternatives'* and the risk appetite of LWR is ultimately decided by the scenarios themselves. Results are determined by the balance between the least and most onerous case for development, which can lead to ***'false-positives'*** or ***'false-negatives'***; what could be termed ***'spurious investment recommendations'***. Therefore care must be taken over the makeup of scenarios used, and the results of LWR should be **scrutinised** to prevent 'spurious investment recommendations' from having harmful consequences on consumers.

With regard to the alternative forms of decision making, we feel that **minimax** and **minimin** are too **risk-averse** and **risk-seeking**, respectively, to be of practical use in transmission development. **Traditional decision making**, based on a 'rational agent' who seeks to maximise expected payoffs, is a very flexible form of decision making, which is both **intuitive**, and **theoretically attractive**. However, our main concern is that in conjunction with scenario analysis traditional decision making relies on **potentially miss-specified weights**, which are both **pivotal** for investment recommendation and potentially open to **abuse**. Furthermore, there are a variety of contentious inputs to scenarios over which it would be inappropriate to place probabilities. It is because of these reasons that we do not feel comfortable with traditional decision making being the main decision tool for the NOA. However, we are open to using traditional decision making tools as an additional insight into investment recommendations.

We proceed by describing and evaluating each of these techniques in turn.

2.2.1. TRADITIONAL DECISION MAKING TOOLS

Traditional decision making theory is founded in perfect rationality, as defined by individuals seeking to maximise their expected return on investment. In theory this is defined as an expected utility maximising individual[10] as propounded by von Neumann and Morgenstern (1947)[11], and Savage (1954)[12]. The intuition behind traditional decision making is that the decision maker wishes to be correct on average, and as such maximise ex-ante return on investment. This theory is embodied by expected or risk adjusted NPV (eNPV/rNVP).

In practical terms the way traditional decision making is employed depends upon which method of quantifying uncertainty is used. With a central forecast traditional decision making would maximise NPV of investment. With standard ROA it would choose the network developments which maximise 'call value'. With Monte Carlo it would choose the developments which maximise the eNPV across all 'scenarios' generated through randomisation. Under scenario analysis it would be used in a similar fashion but with fewer scenarios. The important point about scenarios is that in order to use traditional decision making scenario weights must be specified by the decision maker.

The most intuitive way of viewing probability weights on scenarios is a *Bayesian* interpretation of probability. Under this interpretation probabilities become *reasonable expectations* representing the state of knowledge as it currently is. For example, an informed sports fan may be able to

[10] Also known as economic man or Homo Economicus, and more generally relates to the idea of perfect rationality.
[11] Von Neumann & Morgenstern (1947): Theory of Games and Economic Behaviour
[12] Savage (1954): The Foundations of Statistics

provide a probability with which they believe a team will win the Premier League. This probability would be known as a *prior*, based on expertise and previous experience. As the season progresses and more is learnt about the teams in the league the sports fan could learn from what they observe and update their probability into what would be known as a *posterior* belief.

The two predominant methods for evaluating probability weights are 'informed priors', which are constructed using relevant expertise or previous data, and 'objective priors', which are used when constructing priors in one-parameter problems i.e. where there is one source of uncertainty. Using informed priors, like in our sports fan example, is therefore the method most relevant to evaluating the future energy landscape.

The future energy landscape is defined over a large number of variables meaning that there is significant uncertainty. This uncertainty increases the further ahead a scenario looks. Given the potential paradigm shift that energy sectors may experience, it is unlikely that historical data alone will be an adequate indicator of plausible futures.

The deficiency of data from which to derive probability weights for scenarios means that additional information based on expertise must be collected. Any qualitatively determined weighting would be subject to the judgement of the individual (or set of individuals) assessing the probability, and therefore would be a product of the judgement bias of that individual (or set of individuals) at the time the judgement was taken.

If members of the energy industry were polled for their opinion, for example, a gas shipper would likely ascribe a lower probability to a low carbon scenario than an offshore wind developer, even if they are not being strategic when deciding their weighting. Drawing an assessment from a larger set of industry participants would not necessarily remove the judgement bias present in a small sample; if the polling sample includes more offshore wind developers than gas shippers the offshore wind developer judgement bias will prevail. If the polling sample is appropriately balanced then the ascribed probabilities will be equally balanced.

The natural question is then, what is an appropriately balanced polling sample? Without quantifying the bias it is impossible to say, although the cumulative bias should disappear as sample size increases, as long as bias was not systematic across the sample, for example as a result of 'group think'. If we believed that the risk of bias is small we might be tempted to assign probabilities to scenarios using this kind of qualitative determinism.

However, if probabilities were to be ascribed by an individual, or a polling set, for use in eNPV/rNPV style decision making, it would become much easier to manipulate the results of CBAs. Changing one variable, the probability weighting, could change the recommendation from one development to another. Given the subjective nature of the probability it would be difficult to discover where there had been abuse. Furthermore, by placing probabilities explicitly on scenarios we would be implicitly stating how likely we believe individual elements of the scenarios are to occur, including elements it may be inappropriate to place probabilities on, for example the results of government policy which are currently undecided.

The above considerations mean that we do not advocate the use of subjective probabilities derived by qualitative determinism, and so decision methods based on traditional expected utility maximisation like eNPV/rNPV.

It is worth noting that traditional decision making techniques can be specified as risk-averse, risk-neutral, or risk-seeking by specifying a 'utility function' through which total network costs are passed through to arrive at a risk-adjusted value. The exact degree of risk-aversion can be specified by the user of traditional decision making tools and so what is being assumed can be made transparent. This is independent of the treatment of scenario weights. However, most often the risk-neutral form of decision making is used.

2.2.2. LEAST WORST REGRET (LWR) / MINIMAX REGRET

The premise of LWR, alternatively known as minimax regret, is that when faced with uncertainty over the future rather than wishing to be correct on average, as decisions tools such as expected NPV (eNPV) would, LWR wishes to never be very wrong. The task of LWR is therefore to choose the option which minimises the worst error or 'regret' across all the scenarios considered. It is worth noting that LWR can be used in combination with scenarios and Monte Carlo.

In a transmission setting, the use of LWR means choosing developments that exposes customers to the least amount of error when a scenario is revealed. Essentially LWR is a tool for someone who does not wish make the wrong decision regardless of which 'scenario' occurs in the future.

LWR combines two distinct elements into one decision tool: minimax decision making; and regret theory, where 'regret' is defined as the difference between the payoffs of the best strategy and the strategy under consideration.

Minimax decision making is discussed in greater detail below but essentially refers to the wish to choose the option which minimises the worst occurrence that could happen. Minimax and minimax regret differ in their measure of 'the worst occurrence': minimax deals with the 'payoff' itself, i.e. total network costs; and minimax regret deals with the regret between the option which is best for a scenario and the option under consideration. Regret theory can be applied to decision making in two ways: LWR; and expected regret. Here we focus on LWR, however expected regret would work in an identical way to eNPV, except regret would be the metric weighted by the probabilities rather than total cost.

It has been shown through experimental evidence that individuals can systematically violate the axioms of expected NPV analysis, i.e. perfect rationality[13]. Aside from cognitive biases and systematic errors of judgement which make individuals decision making under uncertainty diverge from perfect rationality, individuals can also have objectives other than expected value maximisation, such as regret minimisation. Regret theory itself, and related decision tools, have their foundations in experimental evidence of choice behaviour under uncertainty which show that decision makers are often concerned about the potential 'regret' they may face as a result of a decision[14]. Loomes & Sugden (1982) show regret theory to be a rational form of decision making when taking these alternative objectives into account. As such LWR has attractive theoretical foundations.

[13] *For example see Kahneman and Taversky (1979): Prospect Theory: An Analysis of Decision under Risk.*
[14] *See Loomes & Sugden (1982): Regret Theory: An Alternative Theory of Rational Choice Under Uncertainty, and Bell (1982): Regret in Decision Making Under Uncertainty.*

In the absence of probabilities LWR provides a conservative approach to balancing the potential for under/over investment and therefore taking into consideration uncertainty. However, LWR has a variety of idiosyncrasies that should be taken into consideration when applying it.

The most onerous of these is that decisions are determined by the two scenarios at the opposite end of the need for network development[15]. As a result, recommendations are particularly sensitive to the assumptions behind these two scenarios[16]. In particular, when these two scenarios are well separated the LWR result can be primarily determined by the most pessimistic scenario (i.e. with highest levels of congestion on the system) since the potential regret is unbounded and most likely convex with respect to network congestion. That is to say congestion management costs increase with congestion and likely at an increasing rate since more expensive forms of congestion management must be found to manage constraints. Whereas optimistic scenario (with the lowest levels of congestion) regrets are bounded by the capital expenditure outlay if the investment is ultimately not needed in that scenario.

There is an attempt with LWR to balance the risk of over- and under-investment, rather than minimise the outcome from the highest cost scenario. LWR does not explicitly care about how high the overall network costs of a ‘scenario’ are but instead cares about minimising any potential mistake. As such LWR is more *‘risk-neutral’* in nature than minimax and minimin, discussed below, which are *‘risk-averse’* and *‘risk-seeking’*, respectively, due to their construction.

Although LWR is ‘risk-neutral’ in character, the exact risk-profile LWR takes is decided by the scenarios used in the analysis and not by the tool itself. The risk appetite of LWR is therefore not specified entirely in the tool itself like eNPV (although ‘utility functions’ can still be specified as with eNPV). This is since LWR seeks to minimise the potential future regret, irrespective of the probability of that scenario coming to pass and so the scenarios shape LWR’s risk-appetite. It is therefore important to ensure scenarios are reasonable for use in investment decision making, or that there are at least safeguards in place to prevent spurious investment recommendations leading to over- or under-investment.

LWR is also not ‘independent of irrelevant alternatives’, i.e. by removing a ‘poor’ option from the decision set which is not among the leading contenders the LWR result can change. This can happen if the option being removed is the best under at least one scenario. In which case its removal changes the associated regrets for all of the options and can change the overall LWR option if this changes the maximum regret for at least one option. The inclusion of an additional option can have the same effect.

Whilst this may seem counter-intuitive the concept of regret theory relies on there being a reduction in ‘utility’ that comes about from knowing you have made the wrong decision. Therefore the fact that the removal/inclusion of an option can change the result, even if it is not among the leading contenders, is not particularly surprising. The ‘irrelevant’ alternative is necessarily not irrelevant in a regret context if it is the best option under at least one scenario. What is comforting,

[15] See Zachary (2016): Least Worst Regret Analysis for Decision Making Under Uncertainty, with Applications to Future Energy Scenarios, for a full description of how this occurs under LWR.
[16] Whilst the FES are at their core based on the 2-dimensional manifold of green ambition and prosperity, reinforcement recommendation reduces these 2 dimensions to 1: constraint costs. Therefore for our purposes scenarios can be sorted on a 1 dimensional axis from lowest to highest need for reinforcement.

however, is that the removal/inclusion of an option which is completely 'irrelevant', i.e. not among the leading contenders and is not best in at least one scenario, does not change the result of LWR.

As a result of this idiosyncrasy, there must be great care to include only those options which are realistic. By realistic we mean options which are deliverable. If an unrealistic option were included that was best in at least one of the scenarios, for example because it provided a great deal of capability, or was particularly low cost, then its inclusion could affect the result of the CBA[17].

As a general point on the conservative nature of LWR, we believe conservative decision making like LWR, where we do not wish be very wrong whichever scenario plays out, is a sensible course of action when there is a great deal uncertainty over the future. Green Book Government Guidelines suggest that risks which are systematically correlated with Gross Domestic Product (GDP), or other variables such as government policy (for example on CfDs), or are large relative to the size of the nation should be taken account of. The risks we must consider in making reinforcement recommendations, including future constraint costs and potential asset underutilisation, are large even when compared to the size of the economy, and are correlated with GDP and government policy, therefore do not wash out on average with other risks to the economy.

LWR provides a pragmatic method of decision making whilst utilising the advantages of scenario style analysis. As such LWR allows us to use scenarios in a generally 'risk-neutral' setting without relying on potentially miss-specified probability weights. However, we must be mindful of the potential pitfalls, documented above, that the combination of LWR and scenario analysis can bring.

One method to potentially ameliorate the outcome of LWR being determined by scenarios at the opposite ends of the need for transmission capability would be to down-weight these scenarios. Down-weighting a single optimistic or pessimistic scenario does reduce its influence on LWR. However, if the two extreme sensitivities are down-weighted by a similar amount the result of LWR would remain unchanged. If they are both down-weighted by a larger amount they would drop out of the analysis and alternative scenarios would replace them. This kind of weighting procedure is ad-hoc in nature and therefore not ideal for our purposes.

The following example shows how LWR works in practice. The first table shows the NPVs of several strategies against each of the FES. These are converted into regrets by taking the difference between the maximum NPV in each scenario and the strategy under consideration. LWR then chooses the option with the lowest maximum regret; strategy 3 here. It is important to note that since the method works in terms of regrets it is unconcerned with the overall cost of a scenario.

Table 2: NPVs

NPV	**GG**	**CP**	**SP**	**NP**
Strategy 1	17	22	20	20
Strategy 2	18	27	30	13
Strategy 3	15	32	25	18

[17] *There is less concern over the absence of an alternative option which would otherwise be best under one of the scenarios since there is already sufficient guidance as to how broad options should be.*

Strategy 4	10	15	16	20
Maximum	**18**	**32**	**30**	**20**

Table 3: Regrets

Regret	GG	CP	SP	NP	Maximum Regret
Strategy 1	1	10	10	0	10
Strategy 2	0	5	0	7	7
Strategy 3	3	0	5	2	**5**
Strategy 4	8	17	14	0	17

2.2.3. STANDARD MINIMAX

Standard minimax is more pessimistic than LWR since it seeks to minimise the maximum cost rather than the regret. In a transmission context minimax would seek to minimise the maximum cost of the network (both transmission development and operational costs). It would therefore seek to build the network to accommodate the highest cost scenario without consideration of any other scenarios.

How pessimistic minimax is in practice depends on the scenarios used for decision making. However, since minimax does not include the concept of regret there is no concern around recommendations being dependent on ‘irrelevant alternatives’.

Minimax has the same advantage as LWR, i.e. it is independent of potentially miss-specified probabilities, however we deem it to be too pessimistic a decision making tool for network development and risks ‘gold-plating’ the network against particularly onerous scenarios.

Using the example below we can show how minimax would work in practice. The table below shows the total cost (both operational and capital) of each of the strategies in each of the scenarios. Minimax minimises the worst case scenario. Here that is GG; in this example it is the highest cost scenario, and so strategy 2 would be chosen.

Table 4: Overall cost (Operational + CAPEX)

NPV	GG	CP	SP	NP
Strategy 1	200	140	110	80
Strategy 2	150	135	105	85
Strategy 3	175	125	120	95
Strategy 4	180	130	115	90

2.2.4. MINIMIN

Minimin involves selecting the option that minimises the minimum cost scenario. In transmission terms minimin would choose the option that minimises costs in the minimum network cost scenario. Intuitively a decision maker who used minimin would be risk-seeking by trying to achieve the best possible outcome if the least onerous case were to happen.

In terms of network development that would be the scenario with the minimum demands on the transmission network and so choose the option which was best for that scenario only. However, as with minimax and minimax regret, how risk-seeking the decision maker is in practice is determined by the scenarios themselves.

Minimin is independent of ‘irrelevant alternatives’ since it does not involve regrets, and independent of potentially miss-specified probabilities and so may seem attractive. However, we believe minimin to be too ‘risk-seeking’ and as a result not prudent enough to be used for network development.

Using the example below, minimin would choose strategy 1 since this minimises the total cost in the lowest cost scenario.

Table 5: Overall cost (Operational + CAPEX)

NPV	**GG**	**CP**	**SP**	**NP**
Strategy 1	200	140	110	80
Strategy 2	175	135	105	85
Strategy 3	150	125	120	95
Strategy 4	180	130	115	90

2.3. DECISION MAKING FLEXIBILITY

So far we have discussed the methods of quantifying the uncertainty we face and how we bring that together to form a decision. The third element of a good decision making process is the ability to *navigate ourselves through uncertainty over time*. **What we describe below is the overall process that the above methods sit within**.

We can consider that at one extreme we could complete the NOA once every ten years, choose what to develop, when to build it, and then not revisit the decision. The next NOA would, in a decade’s time, analyse the network developments for the proceeding ten years. The advantage of this is that the analysis underpinning the recommendations could go into a great deal of detail and potentially use very sophisticated techniques.

However, network developments that take place later in the decade could not take advantage of improvements in knowledge around future events. Therefore the suitability of developments would likely decrease over the optimisation horizon. If development decisions were made like this there would be a great deal of scope for errors. Reducing the time step between decisions reduces the time-lag of information, and so instead of every ten years the optimisation could be done every year, say. In this way the recommendations coming out of NOA would use the most up to date information, as well as not locking in ultimately undesirable recommendations.

It is also desirable that past recommendations are reviewed on a continuous basis so that the long build-time inherent in some developments does not lead to them being unable to take advantage of up-to-date information. Projects can also be cancelled if they are no deemed no longer necessary.

A good method for making recommendations under uncertainty through time is an iterative, 'receding horizon control' (RHC), process. This type of decision making is based on 'model predictive control' in the engineering literature and is used in a variety of industries. The intuition behind RHC is that uncertainty will resolve itself over time and so whilst we may need to take decisions now, there is a case to be made for reconsidering decisions at intervals so as to take advantage of more up to date, and hopefully accurate, information about how the future will progress.

The process works by, at each decision point (i.e. each NOA) the current state of knowledge about the present and future is sampled (i.e. future uncertainty is quantified), and an optimal strategy[18] is computed into the future (e.g. optimal 'paths' or 'chains' for each of the scenarios). For processes with only one 'scenario'[19] the first step of the optimal strategy is then implemented. At the next decision point we repeat the process. Through time the network should converge towards an optimal solution as the fog of uncertainty clears. Faced with uncertainty this is a very sensible approach to take since we allow ourselves to optimise at the current time-step, taking into consideration what we know at the moment, and the fact that knowledge will improve over time.

For processes that use multiple scenarios there are two options available to the decision maker over what to implement at this current time-step. One is to construct an optimal strategy across time (i.e. a 'chain' of developments) for each scenario and choose between the competing recommendations for this decision point (i.e. those developments which are 'critical') using a decision tool such LWR. In this case we are able to keep our options open, and keep recommendations earliest in service dates open if we choose to 'proceed'. This has the benefit that, in the case of divergent strategies ('chains') between scenarios we do not have to make decisions about which strategy we will follow in the future – we keep our options open. The implicit assumption behind this kind of decision is that we will end up in approximately one of the scenarios under consideration, and we will find out which one in the near future before too much expenditure has been spent on redundant options or on constraints before uncertainty has been resolved. The intuition behind such a decision method is the wish to have the best network for the energy landscape of the future and belief we will know which 'scenario' we are moving towards in time to develop the transmission network.

This method can be proactive in the early years of an option's development when capital expenditure is relatively low. For an option where some scenarios are advocating the option on its EISD and others do not need the option at all the cost of not meeting the EISD in the 'scenario' that needs the option on its EISD can be very onerous and so a small amount of capital expenditure can be readily justified by any of the decision making tools.

[18] We use the term strategy to mean a collection of options/developments which make up a 'chain' of developments for how the network may progress over time
[19] We can use any of the methods outlined above to quantify uncertainty here and so we refer to scenarios as a catch-all term to describe a unique future energy landscape, regardless of how this is arrived at.

However, towards the end of the construction process when next year capital costs can be very high, in the order of hundreds of millions of pounds, this type of RHC can be reticent to build. As long as there is one ‘scenario’ that does not need the option at all the potential mistake can be very large (the entire years capital spend), and so the decision making process can defer completion of the project until all scenarios agree the option is needed. Whilst this is can be a sensible, conservative, decision making process, it could result in the unnecessary (ex-post) delay of a project until there is complete agreement across the scenarios. Alternatively this type of conservatism could prevent ultimately unnecessary expenditure from being spent. In addition there is the potential for confusing signals to be sent to developers since early expenditure may be approved but later spend delayed or even cancelled.

The degree to which this is a problem depends in part on what the next years spend is on. If the costs are relatively small and largely incurred to scope out the option better, then the money could be viewed as being well spent, and further it keeps the EISD open. However, if physical assets were to be built which are ultimately not needed (and the NOA process reverses the decision in proceeding year) then this could be viewed as money poorly spent as the spend on building the asset would likely be expensive, and only keeps the option’s EISD open since we would not expect to learn much more about the project, in contrast to early developmental spend.

In addition to this there is further consideration around whether this type of decision making process is proactive or not in bringing forward capital expenditure when all scenarios agree an option is needed but the timing of delivery is not settled. Whether a ‘proceed’ or ‘delay’ decision is made is down to the balance between too early investment where financing costs could be delayed, versus too late investment where operational costs are inefficiently high. Again, this is largely dependent on how large capital costs are in the next year. For small early development works this type of RHC will be proactive (especially when paired with certain decision tools). However, when capital costs are larger and financing costs have the potential to be very inefficient the process will become more lethargic. It is worth noting that the degree to which this type of RHC is proactive or lethargic largely depends on how capital spend is structured. For example, if the time to build is extended and capital costs phased over a longer time period each year’s spend would be less and so the method would be more proactive in the early years and less lethargic towards the end.

The alternative method for deciding what to implement in the current decision point is to quantify the uncertainty we face over the future and construct a strategy (‘chain’) of option recommendations which is ‘best’ across all of the scenarios[20]. What ‘best’ is and how the decision maker decides which strategy is ‘best’ is down to the choice of decision making tool (eNPV, LWR, etc.) and its application[21]. RHC would then implement the first time-step of that strategy, in our case recommendations for that year. At the next time-step the process is repeated and the first step in the updated strategy[22] is implemented, and so on. The implicit belief behind this approach is that we face a great deal of uncertainty, which is not going to resolve itself very soon, at least not

[20] The choice would then be between entire strategies than between individual options.
[21] It is important to note that at this stage ROA can be implemented in the form of ‘trigger strategies’ which approximate what the NOA will do in the future should any one of the scenarios become real. This is discussed in greater detail in section 4.1.
[22] This is updated to take into consideration the evolution of information about the future. If much about the future has remained the same then the optimal strategy will remain broadly the same.

by the time network developments are built. Therefore, we should design a strategy that is 'best' across the scenarios.

The advantage of this type of receding horizon approach is that since only one strategy is advocated at each decision point the strategy is, what we could call, 'internally consistent'; all components of the strategy take into account the substitutability and complementarity between the options. This is not necessarily the case with the former technique where options within the same strategy will have considered this fully (in the creation of the optimal strategy for that scenario) but not between strategies (unless options appear in both strategies).

The latter method carries little risk of committing spend to multiple competing options that are substitutes to each other, in contrast to the first method. That is unless scenarios change wildly from one decision point to the next, in which case optimal options may change and spend may be sunk. However, there is the risk that options may be prematurely discounted and not developed fully through not recommending pre-engineering works to progress on promising but not currently optimal options

The main risk with the latter method is that we build a network that is optimal ex-ante across the scenarios, but which is not optimal ex-post since uncertainty has not cleared fast enough to build the optimal network for the scenario that has out turned. How much of a risk that is depends on the decision making tools used by the decision maker, e.g. how conservative the decision maker is about being wrong.

In contrast the former method risks building several different solutions simultaneously with the belief that we will soon discover which scenario we are headed towards and so stop developing substitute options. Furthermore, there is the belief that uncertainty will be lifted in time to build the optimal network for the end scenario and so uncertainty is effectively resolved by the time the network development is complete.

Both of these techniques have idiosyncrasies and risks that need ameliorating and so the recommendations arriving out of either of these techniques must be scrutinised to minimise those risks.

3. COST BENEFIT ANALYSIS WITHIN THE NOA

In this section our aim is threefold: **(1)** we **describe the NOA CBA process** as it stands and provide insight into the *character* of the decision making process as a whole; **(2)** go on to describe our **Future Energy Scenarios** and why we believe they are *fit for purpose* at making transmission development recommendations; **(3)** we make **recommendations** for **improving the NOA process in the near term** so as to guard against the potential for *spurious investment recommendations*.

3.1. CURRENT NOA CBA PROCESS

The premise behind the NOA is that there is an optimal set of reinforcements to meet future demands on the system and the NOA should iteratively discover them over time. At present the future energy landscape is unknown and uncertain, but the assumption of the CBA process is that the future need for reinforcement is contained within the manifold of scenarios considered.

Therefore the future optimal network is roughly described by the optimal set of reinforcements for one of the scenarios. What is uncertain at the moment is which scenario will transpire.

As a result of this assumption we first discover the optimal set of developments for each FES scenario and the optimal commissioning date. In order to do this we follow a process of iteratively building up a chain of options which confront each problem on the network as it arises through time, and retained if a positive NPV is observed. Since there are multiple configurations of reinforcement options, for example due to incompatibilities between reinforcements, we explore multiple avenues[23] across all the main paths development of the network could take. Once the range of option chains have been tested we optimally time the sets which show promise. The prospective chains of options are then ranked and the chain with the highest overall NPV is chosen as the optimal set for that scenario.

In order to keep the CBA process tractable whilst taking into consideration interactions between reinforcements the network is split into regions which can be thought of as being reasonably self-contained, i.e. South, West, East, and North. The option sets described above are then calculated for each region of the country. The optimal set of reinforcements may be different across scenarios and so the above process is repeated for each scenario.

Once the optimal set of options has been established for each scenario we must still make investment recommendations for the coming year. At this stage these generally fall into one of three categories: reinforcements which do not appear in any optimal set of reinforcements; reinforcements which do appear but are not critical[24] in any of the scenarios; and reinforcements which are critical in at least one scenario.

Where the recommendations across scenarios are divergent (at least in terms of whether an option is critical) we must make a decision over the trade-off between the possibilities of early/over-investment and belated/under-investment. In order to do this we use Single Year Least Worst Regret (SYLWR). There are two main components to SYLWR: the fact that investment recommendations are single year only; and that we use LWR as our decision tool.

At a high level: The SYLWR process calculates the total cost (CAPEX plus total constraint cost) of each possible combination of proceed/delay decisions (let's call this a strategy) for the critical reinforcements[25], across each of the scenarios. The potential regret is then calculated as how much worse each strategy is relative to the best strategy in each scenario. LWR then chooses the strategy that minimises the maximum regret that could materialise across the scenarios.

At a low level: When calculating the total cost of a strategy where an option is delayed it is assumed that reinforcement will commission at its next optimal date. For example, where an option is not needed in a scenario until its EISD+5[26] say, then the methodology puts the reinforcement in on EISD+5. Similarly if an option is needed on its EISD in a scenario but is delayed in a strategy

[23] If computational time was not an issue we could test every feasible combination of reinforcements. Since this is not practicable, given the large number of reinforcements, we follow the iterative process described above. We believe this does a competent job of discovering the optimal set of reinforcements per scenario.
[24] A critical reinforcement is one which is needed on its EISD in at least one scenario.
[25] This is done with the remaining optimal set of reinforcements which are not critical in the background, for each scenario respectively.
[26] Since it is 'critical' it is still needed on its EISD in another scenario.

then the worst we assume that could happen is a one year delay from EISD until commissioning. This is a lower bound, however, since delaying a project may push it back by more than a year if there is then, for example, an outage clash. The implicit assumption here is that uncertainty will be largely resolved in a year's time and we will know which scenario we are in. In the SYLWR we do not take into consideration that the potential regret could be higher. This is assumed away since the NOA is re-evaluated each year and we will review the decision in a year's time. This does not completely represent how the NOA process operates going into the future; it is instead an approximation of the NOA's receding horizon control optimisation.

The single year component of the decision making process makes explicit the fact the NOA is repeated annually, and each year we review our decisions. The NOA methodology is not explicitly 'real options' (ROA) based but the process of reviewing investment decisions each year and being able to defer investment if necessary in a receding horizon manner is grounded in a flexible investment rationale. By reviewing reinforcement recommendations annually the NOA is a very flexible process of network development.

The implicit assumption is that the future optimal network is at least approximately described by the optimal set of reinforcements in one of the scenarios. The single year component goes further by assuming that the uncertainty we currently face is going to be resolved in the next year. The regret associated with recommending an investment today is therefore at most only the capital expenditure over the next year.

The LWR component of SYLWR seeks to minimise the worst regret that could materialise across the scenarios. In the absence of probability weights on scenarios LWR provides a conservative way of balancing the potential for under/over-investment. LWR has a variety of advantages, disadvantages, and idiosyncrasies that should be taken into consideration when applying it. Furthermore, the particular RHC method employed in the NOA can be viewed as being relatively proactive in the early years of a capital project since capital costs are often low and the regret of not meeting an EISD can be high. Whereas it can be lethargic in the later years of a capital project if at least one scenario does not need the project.

3.2. FUTURE ENERGY SCENARIOS

In this subsection we aim to, at a high level, describe how the Future Energy Scenarios (FES) are constructed, and evaluate their applicability and efficacy at making transmission development recommendations. Scenario planning is the SO's preferred approach for identifying developments on the transmission network. They provide a consistent starting point for business and investment planning across gas and electricity and are the starting points for several National Grid processes.

Scenario planning in the energy industry is not a new phenomenon and is widely used across the energy industry and many other sectors. Table 6 highlights some of the organisations that use scenario planning.

Table 6: Examples of organisations which use scenario planning

	Examples of industry leaders using scenarios for planning and investment		
	Energy companies	Government bodies	Other industries
Used for planning	EirGrid Shell	Defra BEIS fossil fuel prices	Yorkshire Water Anglian Water

	Statoil		UK Climate Projections
Used for investment	Elia Gasunie Gassco Electricity NW UK Power Networks Western Power Northern Gas networks	Department for Transport NHS Brighton & Sussex	Heathrow

As there is a great deal of uncertainty in the energy industry we use the widely accepted approach of scenario development to explore plausible and credible futures. Additionally we consider possible futures which are more extreme than the four core FES, probable futures, and particular outcomes, such as meeting the 2050 decarbonisation target in Two Degrees (previously known as Gone Green). Figure 2, below shows a graphical representation of this.

At its core the FES are built upon the energy trilemma; that is, the balance between energy security, energy costs, and carbon emissions. Security of supply standards are kept constant to protect consumers from energy landscapes which do not provide the necessary level of security of supply. Prosperity and green ambition are then flexed to generate four internally consistent scenarios. Given the challenges the energy industry faces now and in the future we believe deconstructing these challenges using the energy trilemma is a fundamentally sensible approach to take since these are the fundamental directions over which the energy landscape could develop.

The analysis behind scenario construction builds on stakeholder feedback from the energy industry and data we capture each year through bilateral meetings, seminars, webinars, Government statistics, capacity market and low carbon capacity auction results, and metered data etc. We take a rigorous, bottom-up, holistic approach to scenario creation by analysing the different sectors and factors that impact electricity and gas demand and supply (e.g. heat, power and transport, global commodity markets, technology, build rates, generator economics, and supply chains etc.). The wide range of sources FES draw upon allows for the quantification of unprecedented changes to the energy industry to take place, for example the electrification of heat, within the scope of what the industry thinks is practical, if not probable, and to analyse the changes that would need to happen to allow it.

In order to analyse these we have a number of models for the different sectors which we use to develop trends for each of the individual elements. The output of these sector models is then applied to the scenario framework to construct internally consistent scenarios. However, a number of assumptions are applied uniformly across the scenarios, such as population growth, exchange rates, oil prices, and existing legislation.

Our scenario construction framework can then be decomposed into four layers: ‘scenario world’ where the core themes of the scenarios on the energy trilemma are captured and fixed within scenarios; ‘PEST’ which looks at the scenario themes of politics, economics, society, and technology in more detail; ‘assumptions’ which describes how each of the modelling input elements, such as EV rollout, are flexed, i.e. high, medium, and low; and finally levers which are detailed data points to be flexed and are underpinned by the scenario assumptions. These layers ultimately allow the scenarios to be internally consistent with the core assumptions behind them.

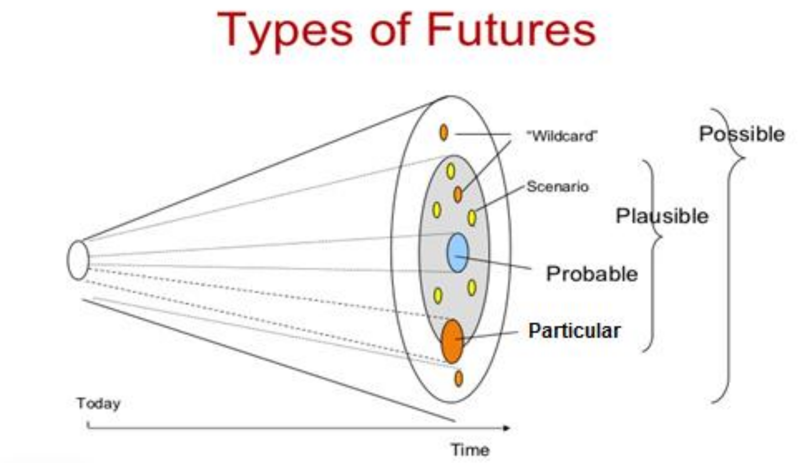

Figure 2: Illustration of futures for scenario creation

Aside from the depth and breadth of analysis which goes into the FES, the main advantage of this type of approach is that each scenario is internally consistent, and so provides credible future energy landscapes. As a result network analysis and operational cost estimates deriving from them are more accurate and credible than under other methods since the composition of the whole system we are modelling is consistent.

A further benefit of the FES is that since they are based on prosperity and green ambition they are capable of providing broad, unbiased views of the where the energy landscape may evolve. For example they are not transmission centric; there are two distribution focussed scenarios in FES17.

The FES outputs are also benchmarked against other externally published scenarios and forecasts to ensure they are broadly consistent with industry wide views. Furthermore, they are widely used and respected within the industry; for example they are regularly quoted in industry reports and presentations.

Another advantage of FES over other industry projections is that they provide the precise geographical location and scale of future generation and demand. As such they are unique in allowing us to forecast network congestion and so operational costs into the future. As such the FES allows us to model in great detail potential future energy systems (and their respective operational costs). In addition the FES allow us as to model a broad range of scenarios based on core assumptions around the energy trilemma, which give rise to a broad range of credible operational cost forecasts.

There has been concern around whether the inclusion of Gone Green (GG) in the NOA is justified, given what we know about LWR and the RHC method we employ. Fundamentally we consider GG (or Two Degrees as it is now known) as being a credible scenario. Our reasoning is that GG is the only scenario which meets the 2050 decarbonisation target. We are aware of the impact a scenario like this can have on our investment recommendations and this is why we are proposing improvements to the methodology in the near term, and also future directions the methodology could take to structurally address these concerns.

In summary, the rigoour, breadth, and depth of analysis that goes into the construction of the FES, the justified structure of the FES based on the energy trilemma, the internally consistent nature of the scenarios, and the geographical detail FES afford us to analyse future energy systems means that we believe the FES are the most suitable vehicle to use for making transmission development recommendations.

More detail on the FES and its construction is given in the Appendix at the end of this report.

3.3. SUGGESTED IMPROVEMENTS TO THE NOA FOR INCLUSION IN NOA3

In the following section we set out our **recommendations** for improving the NOA process in the **near term**, i.e. for NOA3. Given the **idiosyncrasies of the SYLWR process** we feel it is prudent to provide **additional insight** and further **transparent oversight** of the SYLWR recommendations. The reasoning behind these proposals is to guard against the potential for spurious investment decisions to come out of the NOA CBA process.

The section proceeds by describing each of these improvements in turn; **implied scenario weights**, and the creation of a **NOA Committee**.

3.3.1. IMPLIED PROBABILITIES

Bearing in mind the nuances and potential pitfalls of LWR in conjunction with scenarios we acknowledge that we must guard ourselves against the possibility of making spurious investment recommendations. We are therefore proposing to provide additional insight into the investment recommendations arriving out of the NOA.

Although ascribing scenario weights may be difficult or inappropriate using qualitative determinism, it is however insightful to understand the range of probabilities that would be compatible with the decisions made using LWR under an eNPV maximisation. We are proposing to calculate these implied probabilities to provide a useful indication and metric as to whether we believe an investment recommendation is reasonable. If the SYLWR recommendation was proposing spend in order to appease the regret in a single scenario we could calculate the implied probability weight on that scenario. If we believe this to be unreasonably high, i.e. we would have to be reasonably certain the scenario in question was going to occur, then we may feel that next year's spend is too risky despite the LWR recommendation. Furthermore, these implied probabilities can also be used to flag any potential concerns which can then be analysed in more depth, for example are there specific generation mixes which are driving the need for investment? What is the latest information on whether this generation mix will arrive?

The way that we will calculate these implied probabilities is by using traditional decision making theory, described above. Under traditional decision making, if we assume we are a risk-neutral decision maker, in order for the LWR chosen strategy to be preferred it must be that the weighted NPV of the chosen strategy must be greater than for any other strategy. We can therefore compare each competing strategy against the LWR chosen outcome and compute the probabilities which would make us indifferent between the two.

For any number of scenarios greater than two it is not possible to find unique probability weights which would lead to the LWR outcome. There are multiple weightings which could give us the same answer as the LWR outcome.

To keep the computation and interpretation of the implied probabilities tractable and accessible we are proposing to restrict attention to the two scenarios which decide the result of LWR for each strategy. For some strategies it may be a high potential regret of under-investment under two degrees (TD), or slow progression (SP), or consumer power (CP) that LWR is trying to guard against. Steady state (SS) is generally the scenario with the lowest requirement for reinforcement and so the scenario with the most potential for over-investment. Therefore we can calculate the implied probability between the high and low need scenarios, which decide the result under LWR.

As an example, take Table 7, below. Here we have two scenarios and two options. The LWR outcome is option 2 since it has the lowest regret across the scenarios (1 vs. 4). However, we can calculate what the implied probability between the two options must at least be in order to come to the same conclusion using traditional decision making tools.

In order for option 2 to be chosen over option 1 the following must be true:

$5p + 3(1-p) \geq 2p + 4(1-p)$, where p is the probability of scenario A materialising, and $1-p$ is the probability of scenario B materialising.

That is to say, the average NPV of option 2 must be higher than the average NPV of option 1 for eNPV analysis to have chosen option 2. Solving for p we find that the probability of scenario A must be greater than or equal to ¼ for option 2 to be chosen. This is because there is a large regret in scenario A for option 1, and so if we believe it is ¼ or more likely we should implement option 2. Conversely, if we thought scenario A was less than ¼ likely there would be the possibility of a spurious investment recommendation being made, and we may be inclined to challenge the LWR decision.

Table 7: Implied probability example

NPVs:			Regrets:		
Options:	A	B	Options:	A	B
1	2	4	1	3	0
2	5	3	2	0	1

3.3.2. NOA COMMITTEE

In order to make our investment recommendation process more transparent, and demonstrate its rigour we are proposing to establish a NOA Committee to scrutinise the SYLWR recommendations. We have documented the potential drawbacks of the SYLWR decision making process and how this may lead to spurious investment recommendations, and so to guard against this in a transparent, rigorous, and accountable way, we are proposing the introduction of a committee of SO representatives, with a wealth of industry expertise, to scrutinise the SYLWR recommendations. To further enhance the transparency of the investment recommendation process we recommend that an Ofgem representative is present as a non-voting member to enable regulatory scrutiny. The objective of this committee would be to ensure that investment recommendations for the next year are justified and not being driven by unlikely events we would not wish to guard against.

As well as their own industry expertise, the committee would utilise additional insights, including the one described above, and potentially the single year recommendation that would result from using different decision making tools. Furthermore, where it is possible to identify the leading drivers behind reinforcement, for example new generation connections, the committee will be able to utilise the latest market information, supplied by the Energy Insights team, to gauge whether investment is justified. The Transmission Owners (TOs) could also provide additional information about their options as they saw fit.

Synthesising these insights into reinforcement recommendations would be done by majority voting; the results of which could be published. In this the NOA Committee could be seen as being similar in design to the Monetary Policy Committee (MPC) of the Bank of England. There is precedence for this style of committee at some of the independent system operators (ISOs) in the US, particularly PJM and CAISO. In their context they use decision by committee to decide the capacity margin for the year ahead.

The NOA Committee would meet after the NOA CBA is complete and decide the NOA investment recommendation for the marginal options based on this analysis. A transcript of proceedings could be made available to the TOs to increase transparency further; however it is not clear at this point whether this would be possible given the confidential nature of some of the material being discussed.

The guiding principle behind the NOA committee would be that, on the marginal decisions the committee reviews, the members should advise the investment recommendation they believe is most prudent. This means that they believe, on the balance of probabilities, the recommendation (to proceed or not) is the best course of action for the GB consumer. This will take into consideration the many facets of the decision including, but not limited to: forecasted constraints in the scenario(s) advocating the option; the drivers behind the investment recommendation (e.g. specific generation build-up) and the latest market information on those drivers; what the regret is across the other scenarios; what next year's expenditure is acquiring and what it will achieve (e.g. will the expenditure allow the TO to learn more about the option?); what effect a delay decision will have on the earliest in service date (e.g. more than one year postponement in the earliest in service date); what the implied scenario weight of the decision is (i.e. what probability would have to be placed on the driving scenario to make the same decision under expected net present value maximisation); and wider system operability considerations including the availability of commercial solutions to congestion issues. The committee members would seek to have an approximately risk-neutral outlook in their deliberations.

After deliberation committee members could vote on the marginal options, or at least a consensus would need to be reached. In the event of a vote the result could follow a majority rule whereby the decision of the committee would be the proposal for the option (to proceed or not) with the most votes. A written account of the rationale for the decision could also be provided. This could be made available to Ofgem and the TOs along with the voting record. The voting record could then be made publically available in the NOA report along with the RSPI redacted rationale for decisions on marginal options.

4. FUTURE DIRECTIONS – "ALWAYS FINDING A BETTER WAY"

Whilst the recommendations we are making for the near term, i.e. inclusion in NOA3, go a long way to reduce the possibility and impact of spurious investment recommendations, there are still areas of improvement we would like to explore in order to structurally address ours and Ofgem's concerns and make the NOA *as good as it can be*.

In this section we set out our **suggestions for the future development of the NOA process**. We sketch out how we may improve the **real options** element of the NOA so that we fully value the flexibility the NOA process affords; how we may be able to incorporate a **probabilistic approach** into the NOA and the options this opens with regard to decision making tools; and finally a discussion on **receding horizon control** and the merits of moving the NOA to the alternative form of RHC.

4.1. REAL OPTIONS ANALYSIS IN THE NETWORK OPTIONS ASSESSMENT

In section 2.1.4 we illustrated why we believed ROA, using conventional financial options pricing equations, was not to be recommended in a transmission context. However, the insights from ROA are extremely useful when a great deal of uncertainty is faced, and that uncertainty is not going to be resolved for some time.

Our thinking on how ROA can be implemented fully into the NOA CBA process is still at an early stage, however we have identified that there are some processes that would need to be amended to allow ROA to be integrated into the NOA. The RHC method we currently use provides little or no scope for implementing ROA. Since each chain of options is designed to be the best it can be for each of the scenarios there is no scope for building in flexibility there. Furthermore, when critical options from competing chains are compared in the SYLWR the current method of RHC cannot take into account flexibility in transmission design, or the benefit of waiting a year to discover more about the future. The implicit assumption behind it is that we will end up approximately on one of the scenarios and so the transmission network will be optimal for the scenario that plays out. Any ultimately suboptimal investment recommendations that are made now will be rectified when we know which scenario we are on, and so we do not need to hedge our bets by building flexible transmission infrastructure. We would therefore need to implement the alternative RHC method to be able to incorporate ROA into the NOA.

Practically ROA could be implemented by taking into account flexibility when valuing the chain of options itself. For example, a set of developments that meet the needs of a high-cost scenario does not have to be fully implemented in a low-cost scenario. The later reinforcements either will or won't be recommended depending on how the energy landscape progresses. So in a high-cost scenario we may implement all of the options in the set, whereas in the low-cost scenario we may only implement a handful. In this way it internalises the fact we have the right but not the obligation to recommend transmission reinforcements.

In practice we can approximate the actions of the NOA by implementing what we could call 'trigger strategies'. What these would be based on is still not decided but the premise of a trigger strategy here is to approximate the decision the NOA will make in the future in a specific scenario by basing the later recommend or not decision on something we can observe, for example forecasted constraint volumes per year.

The benefits of ROA with the alternative style of RHC is that when a chain of developments is chosen the flexibility the chain allows us in the future to deal with the emerging energy landscape is fully internalised. We are therefore more likely to recommend developments now which work better with future recommendations and allow us to adapt to the future better, thereby reducing the risk that today's developments will be unsuitable for the challenges of the future. Furthermore, the benefits of waiting (e.g. discovering we do not need to recommend an option) are only fully internalised through ROA. ROA also fully values the flexibility smaller, modular developments have in allowing us to add more capacity to the system over time, but without the risk of over-investing now.

Our thinking on how ROA can be implemented into the NOA is at an early stage and we still need to clarify whether adequate enough 'trigger strategies' can be specified for ROA to be insightful. Also, it is not completely clear whether ROA can be meaningfully implemented in the timeframe allowed for the NOA CBA process, especially since it would rely on a change in the form of RHC. Our ideas for how ROA can be embedded within the NOA are based on the Electricity North West (ENWL) ROA model and as such there is a precedent for this type of model being implemented in an electricity network context. However, as mentioned, there are still question marks over whether it is implementable in the NOA. We therefore plan to explore these issues in more detail before deciding whether to implement ROA within the NOA.

4.2. PROBABILISTIC DECISION MAKING

In this report we have illustrated why we feel the use of subjective, qualitatively determined scenario weights are not advisable for the NOA. As such we have advocated the continued use of LWR as the NOA's main decision tool in concert with scenario style analysis[27] and RHC.

However, traditional decision making tools, such as eNPV, do have attractive qualities and are flexible in their application. Consistent, robust, and transparent scenario weights and the application of eNPV analysis would also reduce the risk of spurious investment recommendations. Tools such as VaR could also potentially be used.

In terms of NOA recommendations we are ultimately interested in future congestion on the transmission network, the resulting operational costs, and how likely we believe these are to occur. Whilst scenarios provide a great level of detail and insight into how exactly constraints occur, and allow us to model the system in as accurate a way as possible, we are reasonably apathetic around how exactly constraints arise in areas of the network and so the specific scenario which materialises.

When making transmission infrastructure investment recommendations we are concerned with the potential distribution of operational costs on boundaries, and therefore the NPVs and regrets that could materialise from investment strategies, as well as their likelihood. It is this that we are ultimately trying to approximate through our use of the 2-dimensional manifold of FES and the forecasted spread of constraint costs.

[27] We have also made clear we do not advocate the use of a central forecast since this ignores the level of uncertainty we face over the future.

The question we are concerned with is therefore where do the scenarios sit within this distribution? By comparing constraint costs between scenarios we learn about where the scenarios lie in relation to each other. However we are interested is how likely these constraint costs are.

By calculating a minimum constraint scenario, and a maximum constraint scenario, we could have a better understanding of where other scenarios are on the potential constraint cost distribution, specifically where a scenario is in relation to the extremes. What this would not inform us of however is the shape of the constraint cost distribution.

Fundamentally we will never know what the data generating process of congestion cost progression looks like. We will only observe the out turned flows on the network and the operational costs they produce. However, we can make an informed judgement on the likely form of the underlying distribution the data generating process draws on. Since constraints are the product of cumulative, what we could call, 'multiplicative' shocks as additional generation or demand incrementally builds up in areas it is sensible to suggest that the underlying distribution is lognormal[28]. The lognormal distribution is also very flexible and can used to draw a range of distributional shapes, and as such is very useful empirically.

What we would still not know is the mean and variance of this distribution. We can however think of this as similar to the discussion of Bayesian probabilities, above. Whilst not making subjective judgements on the probabilities of scenarios themselves we could make subjective judgements on the mean and variance of the lognormal distribution from which we believe constraint costs are generated. Whilst subjective these judgements would be based on the current state of knowledge on constraint costs, including the minimum and maximum forecasted constraints. Furthermore, the position of the FES on this scale and our bottom-up beliefs around their likelihood could further inform our choice of mean and variance of the distribution. Finally, considerations such as risk-aversion could be incorporated as appropriate by choosing a distribution with fatter tails if we really did not wish to be caught out by a high or low constraint scenario.

The result of this would be a distribution of potential operational costs which would provide insight into where our scenarios lie and what we feel are their likelihoods. Whilst the specification of a distribution of potential constraints may be subjective, it would be based upon the current best state of knowledge about future minimum and maximum constraints, and a sensible choice of distribution which reflects the fact that constraints are the result of many random variables[29].

The advantage over qualitative determination, described above, is that we are narrowing the set of variables over which a decision must be made (i.e. over the mean and variance of a distribution, rather than over a complex set of industry conditions), and so the choice of these variables should hopefully be more accurate and less prone to the behavioural biases documented above. Furthermore, the choice of distribution shape is more transparent than the qualitative determinism of scenario weights described above since it could be arrived at through open consideration of where existing scenarios would sit, how risk-averse we are, and expert judgement based on

[28] A lognormal process is the statistical realization of the multiplicative product of many independent random variables, each of which is positive. This is justified by considering the central limit theorem in the log domain.
[29] Not all of these would, however be independent.

historical projections of constraint costs. Furthermore, we are focussing on the variable we are concerned about; constraint costs.

The scenarios location on that distribution would go on to inform their scenario weight[30]. These would be derived from what moment of the distribution we wished to approximate, for example the mode, median or the mean.

Decisions on network developments could then be made using a variety of decision tools by synthesising the results of them, and thereby incorporate the viewpoints each of them provide. For example, a decision on network reinforcements could take into consideration what we believe is the best strategy on average (i.e. eNPV), what is never very wrong and the implied probability weights of this recommendation (i.e. LWR), what risks we are taking by recommending this course of action (i.e. VaR), among others. The suggestion is that a NOA Committee would then be in a position to synthesise these metrics and make a decision based them all. The committee would also be able to provide their expertise and insight as an additional layer of rigour.

Our thoughts on this are in their infancy but we would like to explore the possibilities. We do acknowledge that the choice of scenario weights must be transparent and well justified or they risk having the same limitations and concerns expressed around qualitatively determined weights. However, we hope that by focussing the conversation on how likely operational costs are, rather than how likely a specific scenario specification is, it will allow us to be rigorous and transparent in our choice of scenario weights and so open up a number of attractive decision tools.

4.3. RECEDING HORIZON CONTROL

In section 2.3, above, we evaluated two distinct RHC methods that can be employed. The method we currently employ is a sensible approach, and is computationally pragmatic in terms of our current use and understanding of operational/constraint cost modelling, and poses little risk when paired with transparent oversight from a NOA committee. However, it does rely to some extent on the assumption that we will resolve the present uncertainty and know on which trajectory we are headed, and so which optimal chain of options we should be recommending.

The other method of RHC implicitly acknowledges that uncertainty will take a long time to recede and so we should develop a network that works together regardless of which scenario occurs and takes into consideration the substitutability/complementarity that individual options possess because the uncertainty we face will not have been resolved completely by the time we commit to network development (especially given the long lead times of some options). Furthermore, this style of RHC is more conducive to the type of real options analysis described above as it takes into consideration the flexibility inherent in the whole chain of options and how we can stitch them together to either meet a low need scenario or a high need scenario depending on which way the energy landscape moves. In that way we can make investment decisions now which take into account that the developments we recommend now must be able to work in a low or high need case, whichever occur.

[30] Weights need not equal one, and in fact on need to be specified relative to each other. This would explicitly acknowledge the fact that the scenarios we use in our analysis do not span the full distribution of potential constraint costs.

Our thinking on the merits of switching to the alternative method of RHC is still in its infancy and a more detailed appraisal must be made. Further, the method we currently employ fits very well with our current methods and is deliverable within the timescale allowed in the annual NOA process. It is uncertain how exactly the alternative method would be employed in practice and whether this could be achieved in the time allowed for the NOA CBA. Furthermore, there is concern around whether the alternative RHC method is not proactive enough in the early years to discover more about projects through pre-engineering works, and so prematurely reducing flexibility and discounting options. Therefore, there may need to be an alternative method for building and appraising business cases for early development work.

5. CONCLUSION

As a result of detailed evaluation of the NOA methodology we find that the current process of scenarios and Single Year Least Worst Regret is, at the moment, the most pragmatic and robust approach for evaluating future uncertainty, and formulating this into investment recommendations. However, we recognise there are limitations to Single Year Least Worst Regret and so are proposing two improvements to the methodology to minimise the potential for spurious investment recommendations. In order to reach this conclusion we have performed our own evaluation and sought input from external experts from within academia and the energy industry.

We find that scenarios are pragmatic at balancing the wish for a wide range of views over an uncertain future and the need for detailed analysis of the transmission network. However, we agree with Ofgem that there is a need for all those scenarios included in the decision making process to be credible. The degree to which this is significant depends on the decision making tool they are paired with.

With regard to alternative ways of quantifying uncertainty we believe central forecasts offer too limited a view of the future, which could ignore the extent of future uncertainty. Furthermore, there are questions over whether a central forecast could be reliably constructed. In theory Monte Carlo based analysis may be desirable given the broad range of futures it examines. However sacrifices would need to be made to the accuracy of constraint cost estimation to enable the thousands of simulations Monte Carlo needs. It may also not be possible to accurately enough model the underlying uncertainty around transmission usage drivers for Monte Carlo to be desirable.

Standard Real Options techniques, such as Black-Scholes and Binomial options pricing, which seek to take into account the uncertainty we face by placing an estimate on the underlying volatility of constraint costs, are in practice too inflexible to adequately model the different ‘options’ at our disposal. Furthermore, several simplifying assumptions behind these standard options pricing formulas are too strong for our application.

We find that LWR provides the most pragmatic decision making tool at this time. LWR has attractive theoretical properties, and is not subject to potentially miss-specified scenario weights. However, we acknowledge that care must be taken since LWR is not independent of ‘irrelevant alternatives’ (i.e. results are sensitive to the options included even if they are not among the leading contenders) and the risk appetite of LWR is ultimately decided by the scenarios themselves. Results are determined by the balance between the least and most onerous case for development, which can lead to ‘false-positives’. Care is therefore required over the makeup of scenarios used for investment recommendation, and the results of LWR require scrutiny to prevent ‘spurious investment recommendations’.

Traditional decision making, based on a ‘rational agent’, who seeks to maximise expected returns, is a very flexible form of decision making, which is both intuitive and theoretically attractive. However, if used in conjunction with scenario analysis traditional decision making relies on potentially miss-specified, subjectively determined, ad-hoc weights, which are both pivotal for investment recommendation and potentially open to abuse. Furthermore, there are a variety of contentious inputs to scenarios over which it would be inappropriate to place probabilities. We therefore do not believe that traditional decision making should be the main decision tool for the NOA. However, we are open to using traditional decision making tools as an additional insight into investment recommendations.

Scenario analysis and LWR sit within the Single Year Least Worst Regret process. This is a form of receding horizon control whereby optimal networks are configured for each of the FES and a decision is made (using LWR) over whether to implement or not the options proposed. This is then reviewed each year in a receding horizon manner. The advantages of our current receding horizon control are that it identifies a broad range of issues on the network which we go on to examine in more detail, through Strategic Wider Works submissions for example. It also implicitly assumes we are going to iterate towards the optimal network solution as uncertainty clears.

The current RHC method can be proactive in the early years of an option's development when capital expenditure is relatively low. For example, regarding an option where some scenarios advocate building an option now, and others do not need the option at all, the cost of not building in the scenario that needs the option can be very onerous. In this case a small amount of capital expenditure can be justified by any of the decision making tools. However, later in the construction process, when next year capital costs can be very high, this type of RHC can be very reticent to build. Further, substitute options can be developed in tandem using the current RHC.

Given the idiosyncrasies of the Single Year Least Worst Regret process and LWR itself we feel it prudent to provide additional insight and further transparent oversight of the single year least worst regret recommendations. The reasoning behind these proposals is to guard against the potential for spurious investment recommendations to come out of the NOA. These recommendations are: implied scenario weights, and the creation of a NOA Committee. With these additional measures in place we feel there is minimal risk of making spurious investment recommendations.

Our recommendations for near term improvements to the NOA methodology minimise the possibility and impact of spurious investment recommendations. However there are still areas of improvement we would like to explore in order to structurally address concerns and further improve the NOA. We therefore set out our suggestions for the future development of the NOA methodology. These include how we could improve the real options element so that we fully value the flexibility the NOA process affords; how we may be able to incorporate a probabilistic approach and the options this opens with regard to decision making tools; and finally a discussion on receding horizon control and the merits of moving to an alternative process less likely to recommend substitute options in tandem, and make recommendations more internally consistent. However, we note that the alternative method can limit options early on, and so an alternative process for recommending early development works on projects may be needed to keep options open, especially in the early years.

There has been concern around whether the inclusion of the Gone Green scenario in the NOA is justified, given the limitations listed above around LWR and the RHC method we employ. Fundamentally we consider Gone Green (or Two Degrees as it is now known) as being a credible scenario. Our reasoning is that Gone Green is the only scenario which meets the 2050 decarbonisation target. We are aware of the impact a scenario like this can have on our investment recommendations and this is why we are proposing a NOA committee and additional insight in the near term to prevent spurious recommendations. Future directions the methodology could take would seek to structurally address these concerns and further improve the methodology.

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APPENDIX: FUTURE ENERGY SCENARIOS

CONTEXT

This note is an overview of the Future Energy Scenarios: how they are created; and how they are used within National Grid, focusing on:

1. What are the Future Energy Scenarios?
2. How do we create the Future Energy Scenarios?
3. What do we use the Future Energy Scenarios for?

THE USE OF SCENARIOS IS THE ACCEPTED APPROACH WHEN DEALING WITH UNCERTAINTY AND OUR APPROACH HAS EVOLVED OVER TIME

Scenarios are a tried and tested approach for dealing with future uncertainty. They are used by major utilities, government bodies and other industries for planning and investment. Whilst most organisations use them for testing business strategy some also use them to plan investment, see examples in appendix A.

The scenarios provide a consistent starting point for NG business and investment planning across gas and electricity. Additional analysis is done depending on the need. They are the starting point for ETYS, SOF, NOA GTYS, GFOP, EMR and Charging. How they are used and what further analysis is done on them is covered in appendix B.

National Grid's Future Energy Scenarios (FES) were first produced in 2011 and have evolved over the last six years, being revised annually. This approach has led to the current four holistic (by considering the whole energy system) and discrete (each scenario is created independently of the others) scenarios. To ensure they are credible and plausible scenarios they are reviewed each year with the approach and detail tested with stakeholders.

In 2014 the current 2x2 matrix approach was introduced:

This approach reflects the energy trilemma, where we take security of supply to be met (Capacity Market assumed to deliver for electricity) and flex the other two elements of prosperity and economic growth (economic ability to change) and green ambition (government and societal ambition to prioritise climate action). Stakeholder feedback has consistently supported the use of this approach.

HOW WE CREATE THE SCENARIOS - SUMMARY:

The 2x2 matrix creates the four scenario worlds which we build a narrative around, based on prosperity and green ambition and further detailed on the PEST model. Scenarios are built up from a number of sub sector models that produce high, medium and low projections based on economic or market modelling. We then use the scenario framework and the narrative of the scenario world to determine whether the high, medium or low level of that component is required for that scenario and use these as building blocks to create the scenario.

For example, Consumer Power has high electric vehicle (EV) take up due to high prosperity (axes) and a consumer technology focus (narrative). Therefore the high case projection from the EV model is used in that scenario compared to Steady State which has low prosperity (axes) and a lower innovation focus (narrative) and consequently has the low EV projection.

The sub sector models are a mixture of top down and bottom up economic models on the demand side, or wider economic market models on the supply side. Where the sectors include large physical assets such as generation, we incorporate market data on known and speculated projects.

Gone Green and, for FES 2017, Two Degrees are developed differently to the other scenarios. There is an additional rule that it must meet the 2050 carbon reduction target. In order to do this we set a trajectory using the RESOM whole system optimisation model which produces a least cost route to 2050. We then utilise the market intelligence and subsector models to move to that pathway over the life of the scenario.

This has the effect of delivering a scenario that meets the target but is tempered by current trajectories. In practice this means that the scenario is constrained in the near term by slower technology deployment and more of the politically challenging decarbonisation options, such as carbon capture and storage (CCS), significant new nuclear build and heat pumps, do not appear until later in the scenario than would be cost optimal.

USING STAKEHOLDER ENGAGEMENT

Stakeholder engagement and market information are used throughout the development of the scenarios. We engage annually with 350+ organisations across the energy sector, NGOs, think tanks, customer groups and government. There are principally five main ways we use and collect the information from stakeholders as shown below.

Type of engagement	How used	How collected
Consensus	Test framework, no. of scenarios, 2x2 axes, pick out key themes to focus on e.g. electricity storage	FES conference, workshops, webinars
Project specific	To feed into specific site profiles e.g. EDF decommissioning plan	121s, confidential and non-confidential information
SME/Industry Bodies	Sub sector projections: Understand technology and sectorial potential e.g. LED developments by lighting manufactures, boiler developments by heating industry.	121 dedicated workshops e.g. 2050
Published and Purchased Industry data/ expertise	Economic and price forecasts to feed into modelling, wider market information e.g. LNG developments, Solar projects	Published and purchased from recognised providers e.g. DUKES, Experian, Oxford Economics, Wood Mac etc.
Consultancy reports	Pick out key themes, benchmark our projections	121s, published reports, subscriptions, commissioned projects e.g. Aurora storage study, Delta heatpumps, RegenSW

In addition to the external stakeholder feedback we review and challenge with our internal business customers and take learning from the downstream activities. For example NOA interconnector analysis and SOF outcomes feed into the following years FES analysis.

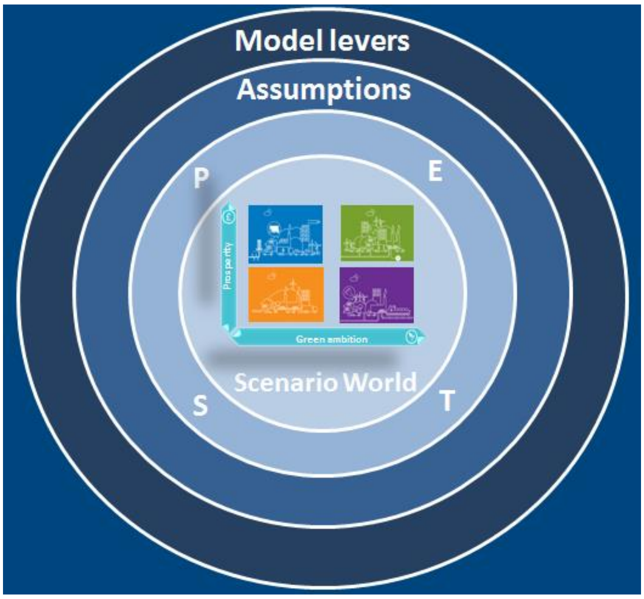
DETAIL ON THE SCENRIO FRAMEWORK

We use a framework approach to create the FES. This framework has three layers:

- **Scenario World** -The scenario world captures the core elements which are fixed across the scenarios. Any rules which cannot be flexed across the scenarios are held here, e.g. Security of Supply.
- **Assumptions -** For every sectorial model there is a high level assumption that is flexed. Assumptions are set to High, Medium or Low

- **Model Levers -** Model levers are the most granular level of detail required for the sectorial models and cover all data inputs to the models The assumptions guide how multiple model levers are determined

The framework's PEST layer looks at the scenario themes: Political, Economic, Social and Technological. This provides structure to the narrative and categories for the assumptions:



The use of the framework has the following benefits when creating the scenarios:

- **Modelling Consistency** - This approach drives consistency across our analysis as each analysis area is underpinned by a common scenario framework. Right up to the point of defining and applying model levers the scenario creation process is consistent across the analysis areas of Power Demand, Power Supply, Gas Demand and Gas Supply.
- **Structured Approach** - Allows us to clearly define the inputs and assumptions for all of our scenarios in one central location. Provides a single reference document to group all inputs and assumptions
- **Flexibility -** This approach is easily adapted to incorporate more layers or assumptions if desired. The framework allows any changes to be considered in a holistic way.
- **Stakeholder Engagement -** This scenario framework is a simple approach and allows us to easily explain to stakeholders how our scenarios are created

Each layer of the framework is created in different ways, involves different stakeholders and employs different process to create.

DETAIL ON THE SCENARIO WORLD

The Process:

Form the launch of FES, an intensive period of stakeholder engagement begins and culminates in a series of workshops (this year held in Edinburgh, Cardiff, Warwick and London) in the autumn.

This engagement is consensus focused looking to test frameworks credibly and pick up key themes to focus on. The topics discussed in this engagement are:

- Is the scenario world complete or missing anything? Is the method of using the scenario world still relevant?
- How will the scenarios be related? This is currently the matrix 2x2 approach.
- How many scenarios should there be? The number of scenarios is dictated by stakeholder feedback. Over the last 5 years the FES has contained different numbers of scenarios. Current stakeholder feedback from the industry is that four is a suitable number.
- What will the scenarios be called? The scenario names must be appropriate and reflect a particular set of underlying assumptions.
- Are there any fixed rules relevant to all scenarios? The only rule that currently underpins all of the scenarios consistently is security of supply. This is fixed across all four scenarios.
- Are we flexing the matrix in the right way? The matrix is currently flexed by prosperity and green ambition as these relate to the energy trilemma.

This feedback is assesses alongside internal engagement and creates the Scenario Worlds. The following updates to the Scenario Worlds for FES 2017 have been published in our Stakeholder Feedback document in February:

- Retiring of the scenario name **Gone Green** and changing to **Two Degrees** – This better reflects how the scenario has been moving away from a focus on renewable generation towards longer term decarbonisation
- Retiring of the scenario name **No Progression** and changing to **Steady State** – This better reflects how the scenario has some progression towards longer term carbon targets, driven by the current policy framework only
- Rebalancing the scenarios to reflect the increase in distributed generation by making **Slow Progression** a high distributed scenario alongside **Consumer Power**
- Consider a wider range of economic scenarios to reflect the uncertainty around the UK's decision to leave the European Union

Theses updates to the scenario worlds are balanced with stakeholder calls for year on year consistency within the FES. As such the following remain unchanged from FES 2016:

- Maintain the four scenarios and the 2 x 2 matrix against prosperity and green ambition
- Maintain the use of the scenario framework
- Keeping security of supply as a fixed rule across all the scenarios

The scenario worlds do not contain quantitative detail, but they provide the narrative to what the world is like from an energy perspective

DETAIL ON THE ASSUMPTIONS

Process:

After the Scenario Worlds are agreed they form a guide for creating the Scenario Framework assumptions. The PEST process allows for easy categorisation of all the assumptions under the framework. The Energy Insights team creates the assumptions based on the requirements for their sectorial modelling; broadly each sectorial model has at least one assumption. Every modelling assumption is set to High, Medium or Low. The framework is published alongside the FES publication for stakeholder feedback.

DETAIL ON THE LEVERS

Process:

The scenario framework assumptions allow for the detailed modelling levers to be determined. These levers are the quantitative inputs to the various analytical models. The framework ensures that each area of detailed modelling is consistent with the scenario world and with other areas of analysis, thus creating our holistic scenarios. Additionally this allows the scenarios to be created without the need to create one particular scenario first, thus creating discrete scenarios.

The detailed modelling combines the team's expertise with data and intelligence captured each year through from project specific engagement, SME/Industry Bodies, published and purchased Industry data/ expertise and consultancy reports.

We also consider any feedback from our internal processes from either SOF or NOA, where network constraints are taken into consideration.

As we consider the different variables that impact supply and demand across the gas and electricity sectors, we require a number of different models. These models are used to analyse heat, power and transport, plus global commodity markets, technology build rates, generator economics supply chain etc. Our key models are described below:

Each of these models are used develop scenarios for the individual elements of supply and demand across the gas and electricity sectors. We combine all these elements to build a holistic energy future for each scenario. As the scenarios are holistic in their design the input to one part of the detailed modelling is often the output from another, this process ensures consistency but does increase the time required to produce each scenario, as parallel modelling can be limited.