Grid Edge Policy

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# Real Options Assessment – Energy network investment decisions under uncertainty

Working Paper

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**Grid Edge Policy**

# Real Options Assessment – Network investment decisions under uncertainty

## *Overview*

The energy system is changing rapidly in response to the challenge of de-carbonisation and new technologies. The approach that government will adopt to de-carbonisation of heat creates an existential uncertainty for the gas networks which, together with uncertainty around the pace of take-up of electric vehicles and local generation, makes it hard for the electricity networks to plan forward. Faced with this highly unclear future, the gas and electricity network companies have to consider how best to manage investment in what are essentially long term assets.

One of the questions raised by Ofgem in relation to the RIIO[1] price control framework for these companies is around managing uncertainty, and specifically how to ensure consumers do not end up paying for investment that is ultimately not needed[2].

In response, this paper goes back to the wider literature around management of uncertainty, including real options theory, where valuation does not focus on simply discounting cash flows, but includes the value of having options when faced with uncertainty.

The key conclusion is that what is needed is a "toolkit" approach rather than relying on one particular methodology, and to draw on the insights that methods such as real options assessment provide even if the methodology itself might not be practical to employ.

Some of this thinking is beginning to be reflected in industry discussions, with frequent reference to no or low regret decisions and the value in keeping options open. However, the real options literature would also point to the importance of investment in learning, of retaining flexibility and of being ready to quit and cut one's losses if circumstances change (which can be difficult for politicians and regulators, but doesn't mean the original decision was "wrong").

Some of the tools that are used to underpin regulatory decisions such as the "Least Worst Regret" (LWR) method can appear analytically sound, but have known weaknesses which regulators need to be mindful of and communicate clearly.

In terms of structure, this paper looks first at Ofgem precedents around decision making under uncertainty, then looks at wider studies in the energy sector and finally looks at the broader literature on real options theory. It includes an Annex summarising work by National Grid in this space plus a worked example to demonstrate the LWR method, and one of the problems with it.

[1] Revenue = Incentives + Innovation + Outputs
[2] Q9: What options, within the price control, should be considered further to help protect consumers against having to pay for costly assets that may not be needed in the future due to changing demand or technology, while ensuring companies meet the reasonable demands for network capacity in a changing energy system?

### *Ofgem precedents on managing uncertainty*

***Interruptible Gas Contracts***

During RIIO GD1, Ofgem produced a paper entitled "Real Options and Investment Decision Making"[3] (2012). The paper briefly discusses the theory of real options, but then the technique that it actually advocates is a fairly standard decision tree approach (what is termed a "binomial model" approach to real options[4]). This brings out the point that, for example, by utilising operational solutions - in this case interruptible contracts - when demand is uncertain, you can deliver value for consumers by being able to avoid investing in reinforcement, in situations where the anticipated demand growth does not materialise.

This thinking translates quite readily across to the electricity distribution networks, and UKPN have already made a commitment to do such analysis before undertaking any reinforcement in ED2.

However, what can be seen from the examples in the Ofgem paper, but is not drawn out in the report is that:

- The short term costs of employing a flexible solution may actually be higher on an annual basis than the annuitised cost of a CAPEX solution, but still be in the consumer interest. It is not clear whether Ofgem's approach to benchmarking of company performance is capable of taking account of the additional "option value" created, or whether such decisions would simply look inefficient;
- The methodology is dependent on being able to put probabilities on different demand growth scenarios. Given where we are with the energy transition, it would be hard to come up with such probabilities (historic variability is not relevant to the modern market), which is one reason why National Grid in their NOA methodology, discussed in detail below, have not gone down that path. That said, it may be more manageable to do it when looking at particular schemes - as Electricity North West (ENWL) have demonstrated, again as discussed below. In any event, it would be quite possible to test sensitivities to different probability assumptions (which is where National Grid seem to be heading).

***National Grid NOA Methodology***

In developing its Network Options Assessment (NOA), National Grid as system operator has to take account of uncertainty, which it does through the development of its 'Future Energy Scenarios'(FES) and then using the LWR methodology to determine which of a number of strategic options (i.e. a package of network investments) it should pursue. The LWR methodology selects which

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[3] https://www.ofgem.gov.uk/ofgem-publications/48227/realoptionsinvestmentdecisionmakingpdf

[4] So called because there are two outcomes assigned probabilities – in contrast to Black and Scholes which assumes an underlying normal distribution for the outcomes

strategy to pursue based upon which is least likely to produce a badly sub-optimal outcome in any of the potential scenarios.

Ofgem has to agree the NOA methodology, and in 2016 raised concerns[5] that inclusion of the FES Gone Green scenario was leading to "spurious investment" taking place. In response, National Grid carried out a full review of its NOA methodology, and the report[6] that it produced provides a comprehensive overview of the different techniques that exist for dealing with uncertainty, including real options assessment and probabilistic cost-benefit analysis (decision trees), as well as the Least Worst Regret (LWR) methodology it, resultantly, advocates. The attached Annex provides a summary of that document and some observations on it.

One of the options that has been raised by National Grid is to extend the NOA methodology to a whole-systems view, and, more specifically, to include distribution networks. This raises a number of potential issues:

- The use of scenarios is helpful in stimulating thinking about different possible futures. However, one still runs the risk of out-turns falling outside those ranges. For example, the rapid growth in solar PV was not anticipated.
- For the NOA, it is helpful to have a small number of quite detailed, internally consistent scenarios, given that ultimately National Grid are then trying to model the implications for the overall transmission system, reflecting geography, and taking account of different dispatch decisions under different scenarios to determine constraint costs. In contrast, typical distribution network reinforcement decisions are likely to be more discrete, and hence do not need such "rich" scenarios. That being said, if distribution network solutions are being presented as alternatives to transmission investment, then they probably will have to be assessed within the same framework.
- The primary advantage that National Grid cite for using LWR, rather than probability weighted assessment, is that LWR avoids the need to come up with probabilities for the different scenarios. This partly reflects the real difficulty in getting consensus around what is most likely to happen (and risk of abuse), but also the "political" difficulty in applying probabilities to questions of whether or not government will deliver on its policy goals.
- However, even though LWR formally avoids the need to come up with probabilities, it doesn't really avoid the issue. As the report makes clear the choice of scenarios will, in and of itself, determine the best option – so, including an option of the government delivering on its policies (Gone Green) drives investment to avoid significant regret in what might be viewed as a low probability scenario, and leads to what Ofgem terms "spurious investment". To address this, National Grid propose calculating implied probabilities that would be needed for the chosen option to be optimal – but methodologically they can only do this for two of the four scenarios at a time.

[5] https://www.ofgem.gov.uk/system/files/docs/2016/10/final_letter_on_noa_methodology_0.pdf

[6] https://www.nationalgrid.com/sites/default/files/documents/NOA%20Methodology%20Review%202017.pdf

- National Grid claim that there is a theoretical underpinning for LWR in "regret theory" which shows that individuals in taking decisions when faced with uncertainty are often most concerned to avoid taking decisions that turn out to be very wrong. However, this does not make it an appropriate basis for regulatory decisions – the aim there is to maximise consumer benefit, not the "utility" of the decision maker. One can see that this approach may have an appeal for politicians who may be most concerned about the public repercussions of getting something wrong (with hindsight)[7], but, in principle, Ofgem as an economic regulator should not be swayed by such concerns, and in other contexts happily relies on a rational economic approach, looking at expected returns.
- National Grid do also refer to Green Book advice on paying particular attention to risks where the investments are large compared to the size of the overall economy, and the uncertainty is correlated with general economic growth. While this may apply in relation to some major transmission investments, it would be less relevant to smaller scale distribution network investments.
- The flexibility built into the NOA approach (which involves an annual re-assessment) does allow for an incremental approach to decision making. In particular, the report highlights that this can lead to a proactive investment approach in the early years (when capital investment is low but is allowing options to be kept open), but a more cautious approach in later stages (where capital investment is more intense and "delay" can therefore come out as an attractive option where there is continuing uncertainty).
- As such, and as the report acknowledges, this is providing some similar insights to that which real options theory would provide (but draws on project management practice and thinking rather than that theory per se). The particular way that National Grid uses LWR (i.e. choosing between a set of predefined pathways rather than incremental options) limits the benefits, and this is an area that National Grid conclude they wish to do more thinking on, drawing on real options assessment ideas.
- Moreover, because the NOA model at this level is quite complex, it is not clear that the rationale for any individual decisions can be readily explained. A simpler approach may benefit from greater transparency, and allowing more debate around the assumptions relating to a particular investment. Using the insights of real options may also provide a way of explaining the benefits of different strategic options.

The flaws in the LWR methodology mentioned above were highlighted in a presentation by NERA at an EPRG event[8]. As they put it, LWR is independent of the probabilities of the included outcomes, but highly dependent on whether the probability is high enough to warrant consideration. They argued some way needed to be found to estimate probabilities.

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[7] And who are in some sense accountable to those who elected them. This last point is made in a paper on least regrets in transport planning http://oa.upm.es/31155/1/INVE_MEM_2014_176257.pdf

[8] https://www.eprg.group.cam.ac.uk/wp-content/uploads/2016/12/V.-Kvekvetsia-web.pdf

The appendix provides a worked example to show how LWR is calculated and how the inclusion of a particular option in the assessment can influence the end decision even if that option is not the preferred one.

## *Other GB Energy work*

### *Imperial College*

Work undertaken at Imperial College on behalf of the Department of Business, Energy and Industrial Strategy, looking at the value of flexibility[9], used the LWR approach in reaching its conclusion that:

"greater flexibility in the electricity system provides option value: small investments in flexibility enable room to delay decision making until there is better information, reducing the need to make potentially high regret decisions".

It also concludes that "a strategy of balanced deployment avoids maximum regret scenarios which can arise when one technology is favoured and it turns out to be the wrong choice".

However, as can be seen from these quotes the focus was less on a mechanistic use of the methodology but on using it as a way of exploring risks and options. In particular it looked closely at "high regret" situations as a way to prompt thinking about the steps that might be taken to avoid maximum regrets.

### *ENWL Real Options NIA Project*

ENWL have looked at the scope for applying real options thinking to decisions about the use of 'demand side response' (DSR) as an alternative to reinforcement and have built a decision support tool to facilitate this.

The paper describing their work[10] makes the point that Ofgem's CBA approach for ED1 used a standard CBA approach to the justification of investment, with no account taken of uncertainty.

The paper talks about the use of "tipping points" to define investment strategies (i.e. we will invest once demand hits a certain level) and, although it considers the future energy scenarios (FES), it focuses on the level of peak demand as the critical factor for their purposes and identifies a number of scenarios against which it assigns probabilities based on expert judgment. It then uses Monte Carlo simulation to model short term variability caused by factors such as weather, on top of the core scenarios.

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[9] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/568982/An_analysis_of_electricity_flexibility_for_Great_Britain.pdf

[10] https://www.enwl.co.uk/globalassets/innovation/enwl001-demand-scenarios--atlas/enwl001-real-options/journal-paper---flexible-investment-under-uncertainty-in-dno-networks-2016.pdf

The use of tipping points would seem a helpful way of articulating an investment strategy that needs Ofgem scrutiny but avoids being tied in to a particular profile of investment.

Their analysis shows that flexible solutions like DSR can have significantly greater value than if judged on a simple NPV basis. However, the paper also highlights some issues where the consumer view of the value would not align with that of the distribution network operator (DNO), and hence some regulatory changes may be needed. This includes electrical losses which are reduced by investment in the network but not by using DSR. The fact that losses are not properly taken account of in the regulatory framework at present could result in distorted decisions when comparing the two options.

ENWL claim[11] this model is now being used to support BAU decisions on managed connections.

### *Real Options Assessment – the wider literature*

The idea of real options assessment draws on the theory behind valuation of financial (put and call) options, and in particular the fact that options have more value the greater the market volatility and the longer the duration of the option[12]. The idea of applying this to real projects has been around for some time, but in practice has not taken off, particularly in regulated sectors involving infrastructure investment, where one might have expected it to have significant benefit.

Clearly there are practical problems with getting the data to perform a formal real options assessment (where the aim is to quantify the additional value created by having an option and requires a view of the distribution of the uncertainty, for example). However, what the literature suggests is that, even if you do not carry out a formal assessment, there can be value in bringing the insights from real options analysis into the way that one thinks about investing under uncertainty. In particular:

- The first and fundamental point is that there is value in having an option which is greater when there is more uncertainty;
- Specifically, the idea is that if you are able to stay flexible and avoid investing until it is clear whether the NPV is actually positive (and only investing where it is) then that improves the overall CBA;
- As you go through time you can then have a range of choices – to abandon, delay, invest to learn or expand.

For networks, thinking about the options they have in this way – and in particular about the next steps rather than the whole path – can prompt the development of more creative solutions. For example, in the debate around investment-ahead-of-need the question that needs to be answered is what the network actually needs to

[11] https://www.enwl.co.uk/innovation/smaller-projects/network-innovation-allowance-projects/enwl001---demand-scenarios/real-options-model/

[12] http://people.stern.nyu.edu/adamodar/pdfiles/papers/realopt.pdf

do in advance to allow them to respond quickly to requests for new connections; this could simply be the acquisition of land, for example, which takes time but ultimately is not necessarily wasted investment if it can be resold. In some ways this is akin to project management techniques that build in checkpoints throughout the project life and focus on the critical path activities.

Reviewing the wider literature, one relevant paper looks explicitly at the use of real options assessment in regulatory decisions in telecommunications. This argues that one problem is that regulators (or public policy makers more generally) find some of the ideas in a real options approach uncomfortable[13]: This is understandable. Abandoning a project can look like an admission that you got it wrong; similarly, delaying a decision while you learn/wait for more clarity can look like indecision or a failure to deliver.

One example of this in energy would be on innovation projects where there is anecdotal evidence of a network company seeking to abandon a project part way through as it became clear it was not delivering value but Ofgem refused.

## *Conclusions*

The question of how to assess network investments in the face of uncertainty is an important one that needs significant further work.

The key conclusion is that what is needed is a "toolkit" approach rather than relying on one particular methodology, and to draw on the insights that methods such as real options assessment provide even if the methodology itself might not be practical to employ.

Reflecting on the known challenges around energy networks then points to some more specific conclusions:

- One issue that needs exploring is to ensure that the approaches taken by National Grid in developing its 'Network Options Assessment' (NOA) - using the 'Least Worst Regrets' (LWR) method - are fit for purpose when looking at whole-system issues, especially if it were to be extended to cover the distribution network.
- For distribution networks, one of the benefits of flexibility solutions such as DSR is – as Ofgem indicate – the option value of being able to avoid reinforcement that may not ultimately be needed.
- However, this may, on occasions, involve employing solutions that would be costlier in the short-term, but would still be in consumers' interests in the long-term. It is therefore important that Ofgem's approach to benchmarking recognises the additional "option value" that is being created, and does not penalise companies for pursuing such higher-cost solutions.

13 https://www.colorado.edu/engineering/alleman/img/Modelling_Regulatory_Distortions_with_Real_Options.pdf

- Moreover, Ofgem needs to recognise that taking account of uncertainty in decision-making may also on occasions lead to *additional* capital expenditure being undertaken. This could be preparatory work to keep an option open (what Ofgem might think of as "investment ahead of need"), or to build-in additional capacity (over-sizing), to cope with potential future growth, if subsequent expansion would be very costly[14].

More generally, while Ofgem may be encouraging the companies to think about decision making under uncertainty there is probably also a message back to Ofgem about how they can evolve their own processes for approving projects or the way that they judge companies' performance to support a more flexible/agile approach and to take account of the value created in real options.

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[14] Normally real options analysis is associated with advocating incremental investment but it will depend on the cost structure. A worked example would be helpful to make this point.

## Annex: National Grid NOA Methodology Review (2016)

National Grid produces an annual Network Options Assessment aimed at identifying where major reinforcement is needed on the transmission network. This draws on the future energy scenarios that they are responsible for producing, which are then reflected in a Ten-Year Network Development Plan. The NOA is used to identify potential projects, that can then be scrutinised in more depth through the Strategic Wider Works process (through which Ofgem agrees the case for investment).

Prompted by concerns from Ofgem that the NOA methodology in combination with the Gone Green scenarios was leading to spurious investment (i.e. investment that was not needed), National Grid carried out a major review that looked in some detail at the different approaches for managing investment under uncertainty.

National Grid manage constraints on the network through operational arrangements involving bids/offers to address the constraints. For low levels of congestion, this is likely to be efficient but for higher levels of congestion an enduring solution involving reinforcement is more likely to be justified. The NOA modelling process compares the constraint costs against investment costs under different scenarios.

In terms of its overall approach to dealing with uncertainty National Grid discusses separately:

(1) methods seeking to quantify the uncertainty they face;

(2) methods that synthesise uncertainty into a decision; and

(3) methods which seek to make the decision process flexible over time.

### *Quantifying uncertainty*

In terms of quantifying uncertainty, they consider four approaches - central forecast; Monte Carlo simulation; scenarios and real options theory (Black-Scholes / binomial).

Each has its strengths and weaknesses primarily around the difficulties in quantifying inputs for the more technical options (Monte Carlo and real options) and the balance between detail (in the central scenario) and the range of options (scenarios). They conclude that scenarios are a pragmatic way of balancing the wish for a broad range of views over the future and the need for detailed analysis of the transmission network.

Using central forecasts allows for very detailed pictures to be built up of that one forecast, but with no explicit account taken of the uncertainty involved.

Scenarios are based on the principle that they should be internally consistent which makes the subsequent analysis of operational options more meaningful. A smaller number of scenarios are generated than you would get with Monte Carlo simulation which makes the process more manageable given the significant effort involved in modelling the operational options (including, for example, dispatch of international generation). It is assumed that this is not such a concern for distribution reinforcement decisions that would typically be more self-contained.

Scenarios can expand thinking / avoid groupthink and also highlight which elements are near certain across scenarios (which than help identify 'low-regret' actions). Other models tend to use the past as evidence (e.g. of levels of uncertainty), whereas scenarios are more explicitly forward-looking.

Monte Carlo simulation has strong theoretical credentials but weaknesses include: risks in mis-specifying the model (e.g. where there is covariance between different parameters); heavy computational demands; and a "black box" feel.

Standard Real Options techniques, such as Black-Scholes and Binomial options pricing, would involve placing an estimate on the underlying volatility of constraint costs. Moreover, National Grid concludes that the methodology is in practice too inflexible to adequately model the different 'options' at their disposal. Furthermore, there are several simplifying assumptions behind these standard options pricing formulae which they believe are too strong for their applications.

Real Options Analysis (ROA) is acknowledged as being slightly different to the other methods of quantifying uncertainty mentioned above. It seeks to take into account the uncertainty faced over the future benefit of investment, but it 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 the context of transmission network development, standard ROA would rely on subjective assumptions about the variance in constraint costs as a measure of uncertainty. National Grid conclude that whilst traditional ROA valuation techniques are commendable for taking uncertainty into account, and valuing the flexibility that waiting provides, there are perhaps more accurate and insightful ways of evaluating uncertainty.

### *Decision-Making*

In terms of decision making, there are four main approaches: traditional decision-making, based on weighting the results according to the probabilities of different scenarios; the 'Least Worst Regrets' (LWR) approach, also known as Minimax Regret; Minimax; and Maximin.

Probabilities for weighting scenarios would need to be based on expert opinion which is inevitably still subject to biases and is open to potential abuse. Furthermore, by placing probabilities explicitly on scenarios National Grid are concerned they would be implicitly stating how likely they 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.

National Grid therefore argue strongly for using a technique that doesn't require probabilities. The Maximax approach is the optimistic approach, that assumes that whatever alternative is taken, the maximum profit will be the outcome, and leads to the decision being made based on which alternative therefore maximises profits. Minimax, the pessimistic approach, does the opposite, and minimises the maximum cost/loss across scenarios, selecting the alternative which produces the lowest loss in a worst case scenario.

LWR is seen as taking a middle course among those options that don't require an assessment of probabilities ("not reliant on subjective scenario weights") but is acknowledged as having a number of disadvantages:

- The best option can be affected by the inclusion of irrelevant alternative strategies (that may not be a contender but influence the regret);
- Results are determined by the balance between the least and most onerous case for development, which can lead to 'false-positives' or 'false negatives'; or 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.

These weaknesses are highlighted also in a paper presented at an EPRG seminar noted above.

The premise of LWR is that, when faced with uncertainty over the future, the decision on which path to take forward is based on what alternative will produce the least 'Regret', where 'Regret' is defined as opportunity loss, or the difference between the payoffs of the best strategy and the strategy under consideration. In this sense, the LWR approach focuses on never being very wrong, rather than wishing to be correct on average, as decisions tools such as expected NPV (eNPV) would.

A practical example of how these three approaches would work is shown in the Appendix.

National Grid argue that 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.

Loomes & Sugden (1982) show regret theory to be a rational form of decision making when taking these alternative objectives into account. As such they argue LWR has attractive theoretical foundations. It is worth noting, however, that just because individuals make decisions this way does not make it a sound basis for public policy decision making. Individuals use heuristics and are generally a long way from the rational economist that one would expect public policy-makers to resemble. The concept of regret theory relies on there being a reduction in 'utility' that comes about from knowing you have made the wrong decision, but the challenge here is not to maximise the utility of the decision maker.

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. This concept is demonstrated in the Appendix.

As a general point on the conservative nature of LWR, National Grid believe conservative decision making like LWR, where they do not wish be very wrong whichever scenario plays out, is a sensible course of action when there is a great deal of 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, or are large relative to the size of the nation should be taken account of. They argue that the risks they must consider in making reinforcement recommendations, including future constraint costs and potential asset under-utilisation, are large even when compared to the size of the economy, and are correlated with GDP and government policy, and therefore do not wash out on average with other risks to the economy. It is worth noting that this does not extrapolate to distribution networks.

### *Flexible Decision Process*

The NOA is revisited annually which provides an opportunity to revisit assumptions. This is based on the concept of an iterative, 'receding horizon control' (RHC), process used in engineering. 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 specific form of LWR which National Grid uses is Single Year LWR where they only look at the implications over the coming year of the different options. This is intended to encourage flexibility. (In contrast the strategic wider works methodology uses whole life LWR for looking at the specific options around a particular investment).

National Grid identify two possible approaches for carrying out single year LWR. The first looks at the different elements of the competing strategies, and determines the ones that should be progressed using LWR. The second determines the optimal strategy across all scenarios and then implements the first year actions. The strategy is then updated the following year and again the first year is implemented. These two approaches have quite different implications. For example, in the former you are more likely to see competing projects started in parallel which may appear wasteful but means you can evolve a strategy that is better suited to the future that emerges. National Grid use the latter approach which implicitly assumes that at some point the uncertainty will be resolved. The NOA then provides a delay/proceed decision for all "critical" decisions (i.e. decisions where you need to proceed to meet the required by date under at least one scenario).

### *Proposed improvements to NOA*

Following this review National Grid identified two changes it planned to make to the NOA methodology:

- To calculate implied probabilities (i.e. what the probabilities of different scenarios would need to be for the chosen strategy to be optimal). This was intended to reduce the risk of undue weight being given to low probability scenarios;
- To introduce an (internal) NOA committee to scrutinise and test the decisions from the model.

These changes are reflected in the latest NOA methodology document.

National Grid also identified some areas that it said it wished to explore further (but there is no evidence in the latest NOA methodology of them having progressed these as yet):

- How to include real options analysis in the NOA, which links with the form of RHC used. The benefits of using real options analysis (ROA) with the alternative style of RHC discussed above is that it provides more flexibility to deal with the emerging landscape. One would be more likely to recommend developments now which are able to adapt to the future better. Furthermore, the benefits of waiting are only fully internalised through ROA. ROA also fully values the flexibility smaller, modular developments have in allowing more capacity to be added to the system over time, but without the risk of over-investing now. They see this linking with the idea of "trigger points" as used by ENWL.
- The use of probabilistic weights to address some of the problems noted above. They recognise that what matters for evaluation is the probability of different levels of constraint costs rather than the probability of different broad scenarios. This may be more practical and less contentious.

## Appendix: Worked examples of non-probabilistic decision tools

This Appendix illustrates how some of the decision tools referred to in the main paper (and the Annex) work in practice. The examples are based on considering the results of three alternative actions in the face of an uncertain future represented by three scenarios.

| | *Scenario A* | *Scenario B* | *Scenario C* |
|---|---|---|---|
| *Action 1* | **70** | 25 | -15 |
| *Action 2* | **15** | 40 | 25 |
| *Action 3* | 55 | -10 | 45 |

***Table 1 –*** *Decision table with payoff scores.*

Table 1 above presents a decision table with payoff scores, where high positive values reflect a positive 'payoff' (i.e. extremely beneficial to consumers, extremely lucrative, etc), and high negative values reflect a poor 'payoff' (i.e. consumers are left at a severe disadvantage, the scheme produces financial losses, etc).

Using a **Maximax** approach, in effect taking an optimistic view, we can see that Action 1 is the chosen action as it has the potential to produce the greatest payoff value across all scenarios of 70 (in green), despite the fact that Action 1 also has the potential to produce the worst payoff value of -15.

Using a **Minimax** approach, in effect taking a pessimistic view, we can see that Action 2 is the chosen action, as in a worst case scenario it produces a payoff value of 15 (in orange), which is higher than the two alternative worst case values of -10 and -15 (in red).

Rather than taking an overtly optimistic or pessimistic view, more sophisticated approaches involve looking at the "regret" or opportunity loss involved in particular decisions under different scenarios, if a decision is taken which turns out to be sub-optimal in the scenario that ultimately unfolds. To obtain a value for 'regret', we have to first find the highest payoff value in each scenario, which is 70 in Scenario A; 40 in Scenario B; and 45 in Scenario C. We then subtract the payoff value from each action from this highest payoff value in each scenario to obtain all 9 values for 'regret' as shown in Table 2 below. For the optimal action in each scenario the regret is zero.

| | *Scenario A* | *Scenario B* | *Scenario C* |
|---|---|---|---|
| *Action 1* | 70 – 70 = 0 | 40 – 25 = 15 | **45 – (-15) = 60** |
| *Action 2* | **70 – 15 = 55** | 40 – 40 = 0 | 45 – 25 = 20 |
| *Action 3* | 70 – 55 = 15 | **40 – (-10) = 50** | 45 – 45 = 0 |

***Table 2 –*** *Regret table*

This regret table is then used to assess which action should be taken using **Minimax Regret**, or **Least Worst Regret** (LWR) method.

To do this you start by looking at the worst regret for each action. So if you undertake Action 1, for example, the highest value of regret occurs under scenario C (shown in bold) as there would be the biggest difference between your payoff having undertaken Action 1, versus if you had undertaken the optimal action in that scenario, Action 3.

With the Minimax Regret (LWR) approach, we look to minimise this "worst regret", in effect assuming a sod's law scenario where the worst scenario for the particular action is the one that materialises and looking for the action that delivers the least regret in that case.

We can see that the lowest of the "worst regret" values (shown in bold) is 50 (in green), therefore showing that using the LWR approach Action 3 is considered most suitable.

(It is worth noting that although, in this scenario, the three approaches to decision-making produce different suggested actions, this will not always be the case.)

One of the criticisms of LWR, as noted in the main paper, is that the results can change with the inclusion in the assessment of other actions even if they are not actually preferred actions. This is illustrated below.

Table 3 gives a payoff table, identical to Table 1, but with an additional fourth action that does not change the outcomes in either Maximax or Minimax approaches. Table 4 is then the updated regret table.

| | *Scenario A* | *Scenario B* | *Scenario C* |
|---|---|---|---|
| *Action 1* | **70** | 25 | -15 |
| *Action 2* | **15** | 40 | 25 |
| *Action 3* | 55 | -10 | 45 |
| *Action 4* | 20 | 50 | -20 |

***Table 3 –*** *Payoff table with additional fourth action*

| | *Scenario A* | *Scenario B* | *Scenario C* |
|---|---|---|---|
| *Action 1* | 70 – 70 = 0 | 50 – 25 = 25 | **45 – (-15) = 60** |
| *Action 2* | **70 – 15 = 55** | 50 – 40 = 10 | 45 – 25 = 20 |
| *Action 3* | 70 – 55 = 15 | **50 – (-10) = 60** | 45 – 45 = 0 |
| *Action 4* | 70 – 20 = 50 | 50 – 50 = 0 | **45 – (-20) = 65** |

***Table 4 –*** *New Regret table, with additional fourth action.*

What is notable is that Table 4 produces a different outcome from Table 2. Due to the higher best payoff in Scenario B, the "worst regret" value for Action 3 has increased to 60. As a result, Action 2 is now considered the most suitable using the Minimax Regret/LWR approach. We note that the inclusion of the fourth action, despite not being considered a suitable action using any of the three approaches, is affecting the final decision using this technique.