# Decision Analysis and Scenario Thinking for Nuclear Sustainability

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**Abstract:** Deciding how much – if any – of its power generation portfolio, the UK should commit to nuclear generation is not an easy problem and providing analyses to support that decision is no less difficult. In this paper we explore how combining decision analytic and scenario planning perspectives might help in the process. In doing so we explore firstly what are the main characteristics of decision analysis and how it may be used to support deliberations between the many stakeholders to this complex problem. We emphasise that decision analysis seldom points unambiguously to a particular option. Rather it is a tool to structure and articulate debate. The complexity of the issue of 'nuclear sustainability' is so great that we do not believe that a single decision model will be able to support the exploration of the gross uncertainties that face the UK. Thus we discuss how a range of models conditional on a range of potential future worlds – scenarios – may allow a wider and more appropriate exploration of the issues. In doing so, we offer a way of merging of scenario analytic and decision analytic methodologies.

**Keywords**: decision analysis; nuclear sustainability; scenario analysis; stakeholder deliberations.

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## 1 Introduction and Purpose

Our aim in this paper is to discuss how combining decision and scenario analyses can help in the assessment of the sustainability of nuclear power generation in the UK and how the process can support deliberations on this between various stakeholders. Such deliberations are difficult for many reasons: e.g.

- Sustainability is not a simple concept. For instance, a system may be deemed sustainable even when some subsystems become inoperable as long as alternatives can be developed to replace their functionality before inoperability occurs. Thus a sustainable energy system might involve nuclear power in the short term but evolve to other forms of generation; or it might involve Uranium fuel cycles in the short term, but Thorium fuel cycles longer term.

- Energy policy impacts on society, the economy and the environment in many ways: some good, some bad. There are many objectives and many conflicts between these.

- The consequences of any power generation policy are highly uncertain, whether or not nuclear energy is included in the mix. As Pierre Wack [1] noted, most forecasting techniques only consider a future stretching out a few years, generally assuming: “Tomorrow’s world will be much like today’s”. But the planning of an energy policy needs a time horizon of several decades, particularly when nuclear plant with expected lifetimes of 50 to 60 years are considered. Over such time spans many changes may happen, some evolutionary and some due to technological breakthroughs, political events and environmental catastrophes.

- There is the problem of bounding the discussion of energy policy. We might wish to focus on whether nuclear power fits into a sustainable portfolio of electricity generation, but there are inevitable overlaps with other aspects of a broader energy policy. For instance, if a hydrogen economy evolves, if electrically powered transport grows substantially or if combined heat and power is used more, then power generation becomes part of much wider sustainability considerations.

- Not only do long time scales imply great uncertainty, but they also introduce complex issues relating to values. How does one compare the value of more secure electricity in 2030 with the effects of any consequent climate change in 2060? Expressing all in monetary terms and discounting to present day values, as in common methodologies of cost-benefit analysis, is no simple panacea because discounting over decades can reduce all values to effectively zero. Intergenerational issues only add to the complexity.

- Many stakeholders, experts and decision makers are involved, bringing into the debate many differing needs and cultural perspectives as well as varied knowledge and understanding of the science and engineering issues. Stakeholders bring their own values to the debate and these often conflict, sometimes in detail, sometimes fundamentally. How does one provide them with tools and support to help them deliberate constructively? And how do you set up a process that lets them understand and use it? In the case of energy policy there are inevitably international political and economic issues, because both the environment and the overall economy are driven by global imperatives. Moreover, there is disagreement on the underlying science and engineering, with experts offering conflicting advice on the inherent risks.

Addressing any one of these issues would be a major task in itself; taken together they imply an enormous one.

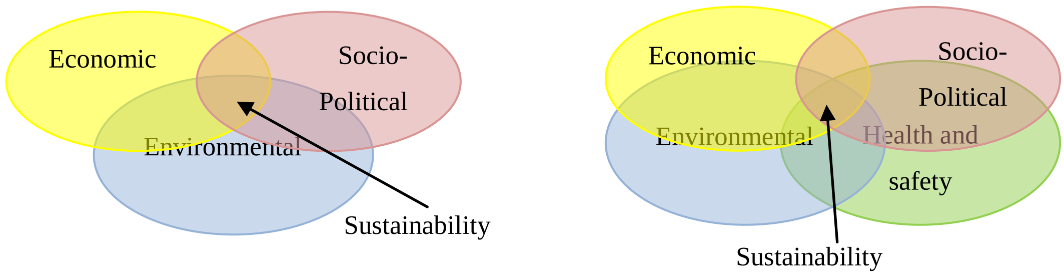
Our aim in this paper is to suggest how the combination of methodologies of decision analysis and scenario planning can help support and structure deliberations of these issues. We begin in the next section by discussing how the concept of sustainability might be operationalised in this context. What does it mean to say nuclear energy is sustainable in the context of the UK's power generation portfolio? Next, in Section 3 we briefly introduce the methodologies of decision and scenario analyses. In Section

4, we discuss the generation of scenarios to form the backdrop for deliberation on energy policy, emphasising that many scenarios developed to date are completely unsuitable for this purpose. We offer several illustrative scenarios in Section 5 and also describe a number of energy policies in terms of generation portfolios. In Section 6 we provide an illustrative analysis of the issues. We emphasise that the work presented in Sections 5 and 6 is illustrative since we have imputed values and uncertainty judgements on a range of stakeholders and experts. Finally in Section 7 we draw together the treads of our argument to provide a coherent overview of how decision and scenario analyses may support discussion of the sustainability of nuclear energy in the UK context.

This work grew out of our part in the EPSRC funded SPRIng Project *Sustainability Assessment of Nuclear Power: an Integrated Approach.*

## 2 Nuclear Sustainability

There are several distinct views on what sustainability is and how it should be assessed. A simplistic view would say that a system is sustainable if the resources needed to run it do not decrease over time: they must be continually replenished at least at the rate that they are used. But that approach focuses on the system *per se* rather than the functionality it provides; and, of course, nothing, not even sunlight, is unlimited in quantity and time. An more sophisticated definition promoted by the United Nations [2] is: "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs". For our purposes we would replace 'sustainable development' with 'sustainable system'. As noted above, this does not require that the needs of the future should be met by the *same* means as the needs of the present. A sustainable energy system for the UK might plan to use nuclear power generation for 60 years or so and then move to other technologies, e.g. fusion, which have been developed in the meantime. So the SPRIng project has *not* investigated whether nuclear energy is sustainable in its present form, but whether there is a sustainable energy policy which




**(a)** **(b)**

**Figure 1: Sustainability relates to economic, social-political and environmental issues (Figure 1(a)) and to health and safety issues (Figure 1(b))**

uses present forms of nuclear generation in its early years. Notwithstanding this more complex conceptualisation, we will use the term *nuclear sustainability* as shorthand.

Many discussions on sustainability begin from Figure 1(a), indicating that economic, socio-political and environmental issues should be balanced in any assessment of sustainability and the ability of society to meet the needs of the present and future generations. In the case of nuclear energy, health and safety issues have such a prominent position[2] in discussions that it makes sense to introduce them separately, leading to a fourth ellipse in Figure 1(b); we shall use this to structure our thinking.

Also in this context sustainability is of interest particularly because it may inform decisions on the UK's energy policy. This means that we shall be taking a decision analytic perspective throughout this paper, focusing on supporting policy evaluation.

## 3 Scenario Planning and Decision Analysis

Scenario planning and decision analysis are respectively qualitative and quantitative approaches to supporting policy evaluation. They are complementary and mutually supportive, if developed carefully [3-6]. Both seek to support deliberation on a

[2] Particularly in the light of the recent events in Japan surrounding the six Fukushima reactors.

*decision*: choosing a policy to achieve some desired goal, recognising that this desired goal may be one balances several conflicting objectives against a range of complex uncertainties.

Scenario analysis [1, 7-9] at its simplest is a very straightforward technique. A range of scenarios, maybe 5 or 6, which represent different possible futures are developed and the relative merits of different possible policies are discussed against the backdrop of each scenario in turn. If the scenarios are chosen in ways that capture the key concerns of the decision makers, then the deliberations allow them to see which policies are robust to different futures. Choosing the scenarios is not easy: see Section 4; but experience has shown that with care scenario planning is a very constructive, catalytic and valuable process for supporting decision making. The deliberations within scenario planning are not supported by any quantitative analysis and there is no attempt to weigh together the scenarios in some formal way.

Decision analysis [10-14] is truly analytic: it breaks down a set of issues into more manageable chunks, explores each and then helps the decision makers synthesise them into a coherent whole that helps them take a balanced overview. The models and processes help decision makers explore not only their perception of the external world, but also their internal beliefs, i.e. the depth of their uncertainties about the world, and their preferences, i.e. their objectives in selecting an option. Decision analysis models the decision makers' uncertainties through subjective probabilities, their preferences through utilities and balances these by seeking to maximise expected utility. The quantitative modelling used is presented in varying levels of detail in the references cited above; and it should be noted that extensive sensitivity analysis is always part of the process, lest some spurious quantification dominates the solution process [15].

Neither scenario planning nor decision analysis dictate choice; they inform choice and support deliberation [12, 16, 17]. They form part of a general decision support process which proceeds from issue formulation through analysis, discussion and deliberation to decision and implementation, usually with many cycles though the earlier steps as the discussion indicates that more detail need be considered or that some factors had been forgotten.

What we shall do in the following is quite simple: we shall construct several scenarios as in scenario analysis, but we shall support deliberations about policy against each scenario by constructing a quantitative decision analysis specifically for the assumptions within that scenario.

## 4 Scenarios for Energy Planning

Over the past half century, many uses of scenarios to inform and structure deliberations on complex issues and policy have been developed. Generally, a *scenario* has been understood as a possible sequence of events that it would be useful in some sense to consider in deliberating on a decision or policy choice; but its precise meaning has differed across a range of uses. Below we give three of the several meanings found in the literature on energy policy and the environment [see also 18].

> **Scenario Planning**. As we have noted, the emphasis is on constructing a coherent story of the future context against which the consequences of policies or strategies will be worked out [8, 19]. Scenarios here form a backdrop to *strategic conversations* on the pros and cons of decision options. Each scenario relates to a set of external events against which options may be compared and evaluated. In this use of scenarios, it is important that policy options being considered *are not* part of the scenario; it must be possible to discuss *each* policy option in the context of *each* scenario. There is no pretence that the set of scenarios fully span the future; rather the intention is that the scenarios capture events, trends, possibilities and contingencies that are thought to be important to consider. Moreover, there is no intention to predict the future, simply to explore possibilities.

**Prediction Studies**. Another use of scenarios is to explore plausible futures without explicit consideration of any specific policy [20, 21]. The idea is to extrapolate several plausible futures by considering known current factors and behaviours and judging how they may interact. An example of such studies is provided by the Intergovernmental Panel on Climate Change Report on Emissions Scenarios [22]. This sought to provide general forecasts of future greenhouse gas emission levels, which could be used in turn as input to global climate models. The drivers of the emission scenarios were population, economy, technology, energy consumption, land use, agriculture.

**Advocacy** or **Political Argument**. This approach is closely allied to the previous, but policy decisions or directions which are either being advocated or opposed are now explicitly included in the scenario, in order to emphasize plausible consequences of the policy directions. The purpose in producing the scenario is to create a story which highlights either the benefits or dangers of following one or another policy. Such uses of scenarios have been very common in debates on climate change in which the consequences of current or future fossil fuel energy policies are worked through under somewhat extreme assumptions to show what might happen if we do not change the policy now [20, 23]. An example is provided by Meadow *et al*. [24].

Figure 2 offers an interpretation of the differences between these scenario concepts. The table in Figure 2(a) illustrates (very simplified!) circumstances in which one is considering how much nuclear power the UK should include in its generation portfolio. The four rows in the table correspond to no, low, medium and high penetration of nuclear into the portfolio. Deliberations on these policies would need to take into account the different levels of commitment to climate change mitigation both in the UK and the rest of the world. The three columns of the table correspond to low, medium and high commitment. Note, however, ‘commitment to climate change mitigation’ needs to be interpreted carefully. It excludes any decisions on the power generation portfolio, because those are the policies that are being discussed.

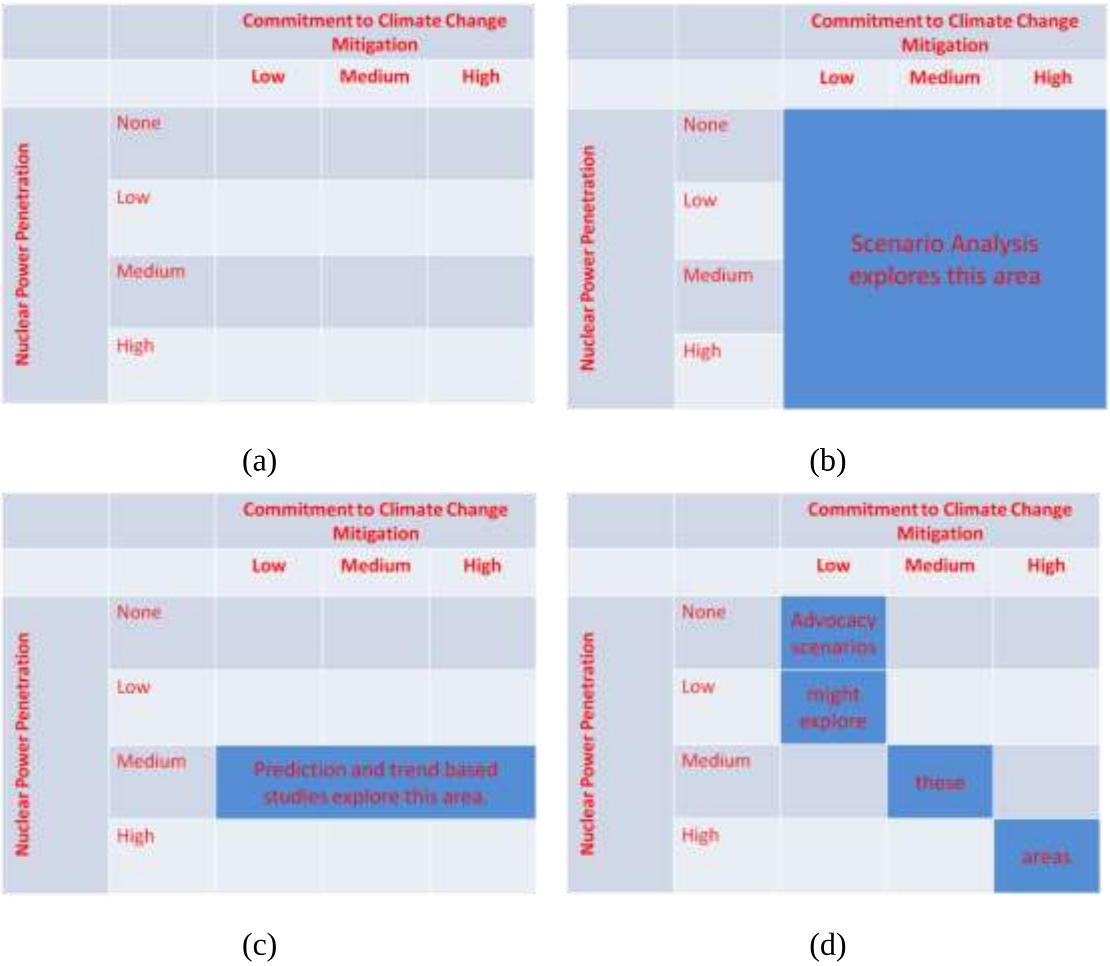



**Figure 2:** **An illustration of the different scenario concepts**

In this example scenario analysis would identify scenarios with three different levels of commitment to climate change mitigation, i.e. the columns of the table. Deliberations between the four options of nuclear penetration into the generation portfolio, i.e. the rows in the table, would be conducted against the backdrop of each of the scenarios. Thus scenario analysis opens the entire table up for discussion as shown in Figure 2(b).

Prediction studies do not look at potential policies; but consider how the world may evolve if the current strategies continue under different plausible futures. To be specific, suppose this current policy corresponds with medium penetration in the table. The different plausible futures in this example would correspond again with the columns. Thus discussion would range over the row shown in Figure 2(c). Note that here the scenarios are the same as for scenario planning, i.e. the differing levels of commitment to climate change mitigation, the columns in the table.

Advocacy scenarios differ substantially. The imperatives driving their selection are *not* to produce a balanced argument, but to raise important issues for further consideration. This is not to impute a completely biased or prejudiced position to these, but to recognise that their purpose is to raise concerns to encourage more balanced deliberations to take place subsequently. In Figure 2(d) we illustrate this by selecting several elements of the table as advocacy scenarios. Note that while scenario analysis and prediction studies all identify scenarios with *columns* in the table, advocacy scenarios correspond with *elements* in the table.

The above should make clear that there is considerable potential for confusion if one talks about scenarios without clarity on their purpose and context. In this paper we interpret scenarios from the perspective of scenario planning. Many of the scenarios previously developed within in the context of energy and environmental debates have been prediction or advocacy scenarios and are thus, as they stand, unsuitable for deliberating on the relative merits of different policies. This has meant that we cannot simply adopt existing scenarios, such as those developed by the UK Energy Research Centre (http://www.ukerc.ac.uk).

With those points made, we now turn to the development of scenarios for our purpose. Firstly, remember that scenarios reflect 'interesting' backdrops to deliberation: There is no necessity to 'span' the future in any sense. We offer two complementary ways that this might be done.

**Exploration of Gross Uncertainties**. This use is not too dissimilar to that within prediction studies. The scenarios are selected to capture interesting combinations of key events or trends: perhaps the development of a hydrogen economy within the UK transport system by 2020 or steady economic growth above those of our European competitors.  This is not to predict that such events *will* happen but only to allow discussion of how different policy would play out *if they did*.

**Exploration of Ideal Societies**.  Societies are defined by, among other things, their values and behaviour.  The idea here is to allow stakeholders to consider what society would 'look like' if their personal values dominated in the decisions and behaviours that shape the future.  Douglas [25] suggested a gross categorisation of society into four cultural groups:

- *Individualist/Entrepreneurs* who see risks as presenting opportunities, save those that threaten freedom of choice and action within free markets;
- *Hierarchists* who fear threats to social order and believe technological and environmental risks can be managed within set limits;
- *Egalitarians* who fear risks to the environment, the collective good and future generations;
- *Fatalists* who do not knowingly accept risks but accept what is in store for them.

Each cultural group would prefer a very different ideal future world, corresponding to their general values and behaviours.  We suggest developing scenarios for each cultural group representing the world as it would evolve if their values and behaviours dominate.  Deliberations against such scenarios would enable each group to see not only how the options might perform against their ideal world, but also how they might perform against other cultural groups' ideal worlds.

We do not claim that developing and using scenarios in order to explore gross uncertainties and stakeholder ideals will be easy.  It may involve tens of scenarios, because the effect of each gross uncertainty needs to be explored in the context of each set of stakeholder ideals if fair debate is to be supported; and a decision analytic model will need to be built for each.  Nonetheless, we do not believe it to be impossible.  For an issue as significant as nuclear sustainability, building and exploring a decision model for each of 20 or 30 futures seems justifiable, particularly as the structure of the model may be common across many scenarios.

## 5 Building Scenarios and Alternative Energy Policies

In this section we illustrate how scenarios might be built. We emphasise that this is an illustration, because to build appropriate scenarios that capture various stakeholders concerns we would need to interact with them at some length.

The first thing that a scenario needs is a narrative, a description in qualitative terms of the general trends, events and behaviours that lead to its evolution. This narrative is needed for two reasons. First, it helps ensure coherence between the more quantitative parts of the scenario. Second, the decision makers and stakeholders need to understand the imperatives implicit in the scenario if they are to articulate their belief and preference judgements appropriately.

We constructed 6 scenarios[3]:

- Base Scenario, one that corresponds as closely as possible to current planning.
- Hierarchist Scenario, one that assumed stringent regulation, but faster planning cycles and lower probability of abandoning nuclear in event of accident, both because of a trust in UK regulation.

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[3] Note that this work was carried out largely before the Japanese Tsunami and the ongoing Fukushima incident and not allowances have been made for that. The UK government has indicated that current plans for nuclear new build will be delayed while a further safety assessment is undertaken, and clearly the uncertain economics of nuclear new will be changing on the presumption of the imposition of greater safety measures or, at least, longer and tougher examination of safety cases during planning cycles.

- Entrepreneurial Scenario, one with lower regulation, consequent faster planning cycles, but more likely to abandon nuclear in event of accident because of the response to financial risks.

- Egalitarian Scenario, one with stringent, slower regulation and planning, extremely likely to abandon nuclear in the event of an accident.

- UK Economic Decline, one in which the UK's economic position declines relative to the rest of the World, but all else as in the Base Scenario.

- UK Economic Growth, one in which the UK's economic position grows relative to the rest of the World, but all else as in the Base Scenario.

Note that if the Base Scenario is also interpreted as a Fatalist Scenario, then the first four scenarios represent futures that Douglas' four cultural groups might wish to consider. The first, fifth and sixth scenarios represent current plans allowing for different economic growth rates relative to the rest of the world.

To define each of these scenarios we made assumptions about various quantities such as the annual growth in demand for energy *vis a vis* the annual rate at which energy efficiency measures are adopted, the expected life times of different generation plant, the length of planning cycles, etc. Similarly we assumed different probabilities with which certain key events may occur: e.g., the availability of a proven, commercially viable carbon capture and storage (CCS) technology, the coming on line of a major interconnector to a European supergrid, or a nuclear catastrophe which would lead to demands to abandon nuclear power. All such assumptions were made to be compatible within the broad context of the scenarios.

Alongside the development of the scenarios, we developed four energy policies.

- Current plans (i.e. the status quo). This assumed an energy policy broadly in line with the stated wishes of the UK government, mindful that the government can only set a framework and then the market delivers the policy.

- Abandon New Nuclear Build. This policy assumes that there is no nuclear new build, that the old nuclear plant serves out its time, and that there is a corresponding increase in the short term in building gas and renewable generation capacity.

- Reduce reliance on gas. This policy reduced the number of gas generating plant to be built relative to current planning and increased nuclear new build and renewable capacity correspondingly.

- Go it alone. This policy abandoned any intention to build further interconnection with the European grid, increasing domestic generation accordingly.

Each of these policies is best understood by thinking of the UK energy generation portfolio, i.e. the different plant grouped into nuclear, coal, gas, oil, renewable and interconnector to the European grid. We know the present number of plant and their current expected lifetime before decommissioning. Thus a policy describes the number of each type of plant to be built over the coming years and at what construction rate. In our case, the policies are decided now, but we recognise that after a few years the policy must be contingent on events and changes in the world. For instance, if commercially viable CCS technologies are developed then these may enter the portfolio. Equally if a nuclear accident happens somewhere in the world, then public concerns may mean that further building of nuclear plant is abandoned and perhaps that all operating nuclear plant is decommissioned. Thus we define the policies so that building and commissioning of plant become dependent on contingencies in the different scenarios.

## 6 Decision Analytic Modelling

We have developed an outline decision analytic model [26] to implement and explore the outline of a scenario based decision analysis sketched here. It has two components: an Excel spreadsheet model and a decision tree model, built using DPL (www.syncopation.com). The spreadsheet model builds a deterministic time series

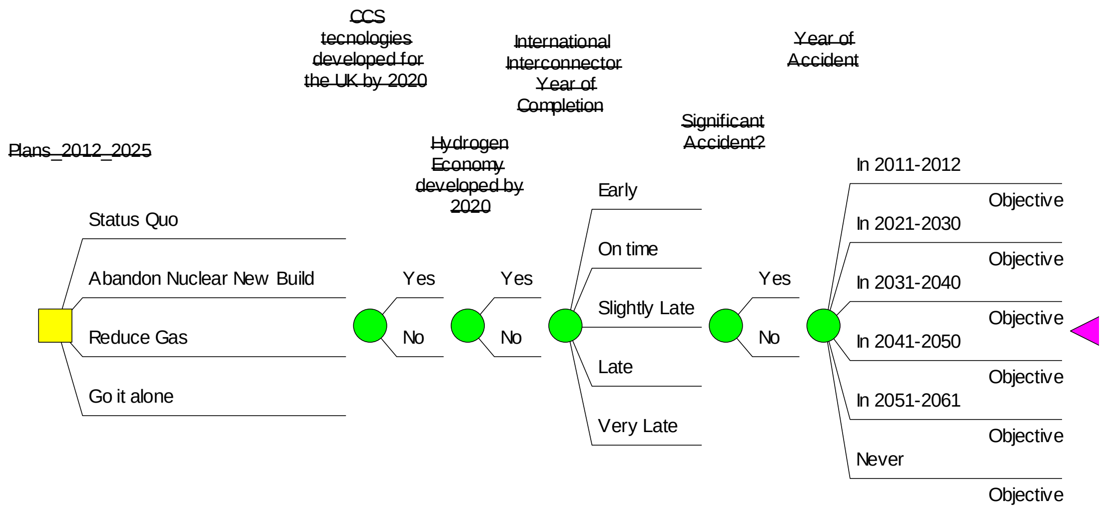


**Figure 3: The decision tree model**

for the years 2010 – 2060 of the costs, carbon emissions, supply deficit and similar quantitative consequence descriptors given a complete specification of the build and decommissioning programme of generating plant, domestic demand, economic growth, development of CCS, existence of a hydrogen economy, etc. The decision tree model is shown in Figure 3. For each of the four possible policies it explores four key uncertainties: whether viable CCS technologies are developed by 2020, whether a significant hydrogen economy is developed by 2020, whether any planned interconnector with the European grid is completed on time, and whether there is a significant nuclear accident and if so when. As this is an outline model to explore the methodology, we have taken a rather gross partition of the possibilities, e.g. only considering the date of a future accident to within a decade. The decision tree model seeks to minimise an objective which represents the overall loss of a pathway through the tree. In our current model the objective is an additive loss function [27] calculated from the deterministic times series produced by the spreadsheet model.

To run the decision tree and spreadsheet model pair, we take a scenario which fixes the parameters and probabilities needed by the models. We also need to set some weights in the additive loss function. We envisage that each stakeholder group which

| | | **Base Scenario** (i.e. as close as possible to current planning) | | **Hierarchist Scenario** (i.e. Stringent regulation, but faster planning & low probability of abandoning nuclear in event of accident) | | **Entrepreneurial Scenario** (i.e. Lower regulation, faster planning cycles, more likely to abandon nuclear in event of accident) | | **Egalitarian Scenario** (Stringent and slower regulation and planning, extremely likely to abandon nuclear in the event of an accident) | | **UK Economic Decline** (relative to the rest of the World; rest as base scenario) | | **UK Economic Growth** (relative to the rest of the World; rest as base scenario) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Strategies** | | Industry | Consumer | Industry | Consumer | Industry | Consumer | Industry | Consumer | Industry | Consumer | Industry | Consumer |
| Status Quo | Rank | **3** | **3** | **3** | **4** | **2** | **2** | **4** | **4** | **4** | **4** | **2** | **3** |
| | Exp Loss | 1525.78 | 269.65 | 1419.44 | 208.53 | 2057.91 | 186.25 | 1426.53 | 241.12 | 1010.4 | 190.92 | 2308.88 | 245.29 |
| Abandon New Nuclear Build | Rank | **1** | **1** | **1** | **1** | **4** | **4** | **1** | **1** | **1** | **1** | **1** | **1** |
| | Exp Loss | 1445.41 | 255.72 | 1394.72 | 202.73 | 2146.66 | 195.14 | 1363.00 | 231.29 | 947.59 | 178.91 | 2269.14 | 239.68 |
| Reduce Gas | Rank | **4** | **4** | **4** | **2** | **3** | **3** | **2** | **2** | **2** | **2** | **3** | **4** |
| | Exp Loss | 1571.86 | 270.94 | 1430.54 | 207.78 | 2140.76 | 192.26 | 1377.83 | 234.87 | 981.68 | 185.49 | 2326.31 | 246.06 |
| Go it alone | Rank | **2** | **2** | **2** | **3** | **1** | **1** | **3** | **3** | **3** | **3** | **4** | **2** |
| | Exp Loss | 1523.83 | 269.26 | 1416.01 | 208.02 | 2054.08 | 185.87 | 1406.75 | 239.44 | 1005.71 | 190.03 | 2278.66 | 242.83 |

**Table 1:** **Illustration of the results from the sketch analysis. The ranks reflect the ordering implied by the expected losses from lowest to highest. Note that it is the rankings that are meaningful. Comparisons of the numerical values of the expected losses between the different scenarios are meaningless because of the differing assumptions within the scenarios. Similarly comparisons between industry's and consumers' expected losses are meaningless.**

is party to the deliberations will need their own set of weights to reflect their preferences. In our exploration of this sketch model we have considered just two stakeholder groups: industry and consumers. We imputed their preferences for weights over some of the outputs of the time series. We then ran the model pair for each of the six scenarios and for each stakeholder group.

Table 1 indicates our results. We emphasise that these are illustrative of the scenario based decision analytic methodology. We make no claim that they represent the evaluations of strategies that any stakeholder group might make. Before we could make such a claim, interaction with stakeholders and subject matter experts would be necessary to finalise an appropriate set of scenarios, to structure the decision models, and to obtain the judgements of uncertainty and values and weights upon which the analyses are built. Indeed, we are not sure that the scenarios and parameters that we have built reflect the consistency that would come from interaction with experts.

We believe that results such as those indicated in Table 1 would inform deliberations between different stakeholder groups. Agreements and disagreements within scenarios are clearly visible. Similarly the robustness of different policies to the different scenarios is also apparent.

## 7 Conclusions

We have sketched how a scenario based decision analytic model might be constructed to inform deliberations on the sustainability of different energy policies for the UK, particularly in so far as these might involve nuclear plant. Sketched is perhaps an optimistic euphemism! There are lots of omissions in the current model. For instance,

- The objective represented the additive loss function includes only a few economic and environmental attributes. We need to add further ones to capture socio-political and health and safety issues, as well as further economic and environmental ones (Figure 1). However, many of these will be subjective rather than quantitative attributes that can be calculated by the spreadsheet model. To introduce these we need to work with stakeholders to model their values directly [12, 13].

- The scenarios may not be the most appropriate and are certainly sketched quickly rather discussed with stakeholders to capture a range of their concerns and anticipated futures.

- We have only included a limited number of key events and we have done so in a very gross fashion. We need build a more complex decision tree than that in Figure 3, although we recognise that there will be a need to address computational issues as the model becomes more complex.

Furthermore, we need explore whether and how results such as those illustrated in Table 1 can support deliberations between stakeholders. We have implicitly suggested that this would happen through discussion without further analytic support, but there are methods which might be used to 'weigh together' the different scenarios in some sense [3].

However, none of these points may be addressed without substantial interactions with stakeholders and decision makers.

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