Modelling Systemic Risks to Inform a Repowering Decision

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ABSTRACT: Our motivation is to inform an industrial decision to replace a conventional power station in a context where there are risks and uncertainties associated with new energy technologies such as renewables and smart grids. We develop a modelling approach to support this strategic engineering decision. Our goal is to support managers who need to define solutions for engineering systems within a compressed time scale, when there are multiple stakeholders and inter-related uncertainties. The general modelling process is described and analysis for the industrial case is presented.

1 INTRODUCTION

1.1 *Motivating repowering decision*

The power station providing most of the energy for the Shetland Isles, at the northern end of Scotland, requires replacement due to age and changes in the emissions regulations. The design of a repowering solution is being informed by analysis of Shetland's energy requirements and the availability of other generation options, including renewables, to meet demand. Moreover as part of Scotland's wish to increase energy generated through renewables, as well as recognizing the rising cost of fuel, there is a desire to use renewables to meet a greater proportion of energy demand and reduce reliance on fossil fuels. However connection of renewables is constrained by the capacity of the existing electricity grid and lack of grid connection to the mainland.

Scottish Hydro Electric Power Distribution (SHEPD) have designed the Northern Isles New Energy Solutions (NINES) project to trial a range of smart grid innovations to reduce capacity constraints and increase exploitation of renewable energy resources, while maintaining energy security, what we refer to as "*keeping the lights on*". See, for example, http://www.ssepd.co.uk/News/NINES/. The outcomes of the NINES project provide insight and knowledge to inform the design and size of the repowering solution. As well as accounting for the immediate anticipate risks, it is also imperative to build longevity into the solution since the expected lifetime of the new plant is at least 25 years and so need to be robust against a range of future uncertainties.

1.2 *General problem domain*

More generally we consider a strategic decision about the type of complex engineering system solution required to deliver an effective and efficient service. The context might be one in which the solution will be a replacement for an existing system, say one nearing its end of life, or a need for a completely new system provision as part of capacity building. Possible future engineering solutions might embrace, for example, new technologies, design principles, operating regimes, human interfaces and participation within the system. Some degree of uncertainty might be anticipated from such innovations, especially in relation to their inter-dependencies. The wider decision context may include many different parties, such as a regulatory body, customer groupings, the public, politicians and so on, in addition to the engineers with primary responsibility for defining the solution. The decision is likely to have to be made under time constrained conditions and so it will never be feasible to obtain full or perfect information. Furthermore, there may be multiple and overlapping time constraints.

1.3 *Approach to risk-informed decision analysis*

Drawing upon the theory and principles of decision analysis (Clemen and Reilly, 2001, Jensen and Nielsen, 2007), we develop a decision modelling formalism to interpret the uncertainties and risks identified from the point of view of the client organization which has responsibility for making decisions about the repowering design and size options. In collaboration with the client, we examine the actions available to them in terms of decision choices, considering both the "*what*" can be decided and "*when*" it might be decided. The consequences of such actions effectively represent the criteria against which the engineering solution options can be evaluated. By developing a formal model it is not only possible to explore the trade-offs between possible solutions under different scenarios, but also to articulate the value, or costs, of information uncertainties due to, for example, delays in the decision-making processes of related stakeholders.

In section 2 we outline the modelling methodology. Section 3 describes the decision model and Section 4 provides insights into the analysis for our industry case. We conclude by reflecting on the strengths and limitations of our modelling approach and discuss the implications of the analysis for the motivating repowering problem.

2 MODELLING PROCESS

2.1 *Roles*

Five distinct roles exist within our decision context; namely the client with some decision-making responsibilities, the stakeholder, the engineering expert, the analyst and the facilitator. These roles need not be mutually exclusive. For example, the client may be someone who also has substantive domain knowledge and hence be technically qualified to provide expertise for model building. In this context, we reserve the term expert to represent someone who possesses relevant domain knowledge upon which a probability assessment might be made to assess the likelihood of the uncertainties from the point of view of the decision-making organization. An engineering expert can be considered a sub-set of the stakeholder set since both experts and wider stakeholders will hold knowledge about the system. However experts will possess overarching understanding of the technologies and be able to interpret any engineering solutions within a wider socio-economic environment. In contrast, stakeholders will be actors within the socio-economic environment within which that engineering solution will need to exist. Hence stakeholders will be required only to share their perceptions and preferences based on their perspective of the need for the system so that uncertainties can be surfaced, shared and unpacked to articulate the line of reasoning. We distinguish between the acts of analysis and facilitation, even though it is possible that one person assumes an analyst-facilitator role. An analyst is expected to possess knowledge and skills of the decision modelling theory as well as methods and tools in order to build and analyze the decision model. By contrast, the facilitation role is concerned with effectively managing, for example, stakeholder groups to support problem structuring and qualitative model building, or leading probability elicitation sessions with individual experts.

In the repowering decision problem the main client was the chair of the repowering group, as he possesses the responsibility of forming and recommending a decision to senior management and the regulator. The stakeholders include organizational staff (such as roles in engineering, operational and service functions), technology specialists (including researchers leading work on smart grids, demand side management, energy storage), domestic and commercial customers, politicians and local authority managers. Engineering experts, including those with a decision-making capacity, were involved in building and instantiating the decision model. The authors all assumed roles as analyst-facilitators, as well as research observers, at various points in the model building process as commensurate with their knowledge and skills. This is important, as different elements of the modelling process require distinct skills in facilitation and analysis to be fully effective.

2.2 *Staged modelling*

After establishing "*what*" is the nature of the decision problem and "*who*" might be involved in building a model to support that decision, we can consider "*how*" the process might be planned. Figure 1 illustrates the key stages of the process with reference to the key roles. This diagram captures the salient scientific steps although in practice we might expect less clarity and greater iteration between stages since model-building is a craft. Core to our process is the concept of a divergent-convergent dialogue between problem domain and the model formalism. Let us explain what we mean by this concept by describing the key activities within the model building process.

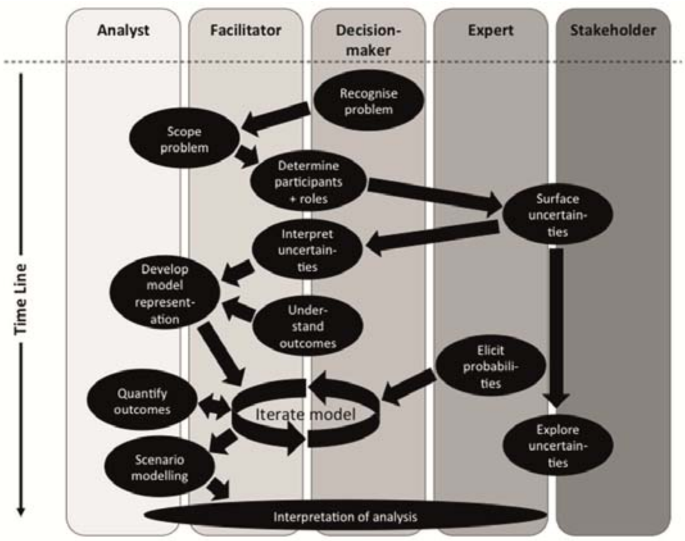

Figure 1. Modelling process by stakeholder role and timeline

2.3 *Stakeholder group workshops for divergence*

At the outset of modelling it is important to gather a sense of the scale and types of uncertainties as perceived by all relevant stakeholder groups because this allows us to explore the decision space and to surface important risks. To gather such insights both effectively and efficiently, a workshop format is designed drawing upon an existing body of work which focuses on the use of group support systems to help with the management of messy problems (Ackermann, 2012). Multiple workshops might need to be conducted to provide appropriate coverage. Including different stakeholder groups at the same workshop can be useful if the synergies are such that information will emerge from the discussion between different perspectives.

All our workshops follow a common core design, namely generation of uncertainties and risks, consideration of the relationship between uncertainties (i.e. risk systemicity) and investigation of priorities. To ensure that a wide range of uncertainties and their relationship could be captured in a relatively short time period (e.g. we might expect each workshop to last 4-5 hours in duration) a particular group support system (GSS) named Group Explorer is used. This system provides participants with consoles through which they can enter risk statements, links between risks, priorities, as well as a main public screen where the collation of all views can be displayed and which facilitates continual amendment and development of the emerging landscape of uncertainties. In addition, the facilitator also has access to a third module – the chauffeur – which displays the participant activity allowing the facilitator to see which participants are actively contributing, what is being contributed, whether there is universal agreement or a disparity in views. In this way, the facilitator can effectively manage discussion by prompting, clarifying and indeed clustering uncertainties deemed to be related according to the participants. Within a workshop the initial stages are aimed to allow the divergence of views to be surfaced although as a workshop progresses a sense of shared understanding can be developed between participants.

Partly for reasons of geography, partly for reasons of size, we have conducted three sets of workshops with overlapping stakeholder groups at the outset of modelling. The views expressed have been collated into an overarching risk map that synthesizes the uncertainties and their inter-dependencies between these risks as perceived by all stakeholder groups. In this respect the risk map summarizes the divergence in the multi-dimensional landscape of uncertainties around the decision problem. Hence it provides a basis upon which to build a decision model formalism that is grounded in an understanding of uncertainties. Insights can be generated about project risks that go beyond those recorded in, for example, conventional risk registers where the potency of systemic risks cannot be easily captured (Ackermann et al, 2007).

The construction of the decision model is explained in Section 2.4. Here it is also worth mentioning the role of the group workshops in later stages of modelling because it will be useful to both revisit perceptions of uncertainties at regular intervals since the political, social and economic environment in which the engineering decision is to be made is dynamic. Hence the risk landscape can change. Also, workshops with stakeholders held even after a provisional decision model has been built provide a means of challenging the model assumptions, the exposition of variables and the meaningfulness of measurement of uncertainties. This can be achieved if an analyst acts as an observer and listener during the workshops to seed questions around variables as expressed in the decision model so that they might be unpacked to explore meaning and as a mechanism for comparing perceptions surfaced through the more usual divergent workshop process.

2.4 *Converging on a decision model structure*

An analyst must support the decision-maker to articulate the decision problem as a formal model by framing the uncertainties surfaced in the workshops and the problem needs in terms of actions (i.e. decision or design options under the control of the decision-maker or decision-making organization), outcomes (i.e. how the consequences of any decisions will be valued financially or otherwise) and uncertainties (i.e. risks to which the decision-maker is exposed and will not be able to directly control but might be able to manage).

In our case, an analyst scoped an initial decision model based on the insight to the problem gained by listening, for example, during the workshops, in project meetings with the client organization and in conversations with fellow researchers and engineers. Developing a simple model of the problem was effective in this context because it provided a focal point for both explaining the conceptual approach and engaging in a conversation about the decision problem that was grounded and bounded to a degree.

Our model can equally well be presented as a decision tree or an influence diagram (Clemen and Reilly, 2001). During face-to-face engagements with the decision-maker and engineering experts, we prefer the influence diagram. In part this is because, the translation from the risk maps from the workshops to the influence diagram presentation is more transparent, hence giving confidence that we are building upon the views of the key players in this problem. Also, the influence diagram can be built in stages to avoid cognitive overload that might be experienced on viewing the full model. For example, initially we focus upon the actions and uncertainties since these capture the workshop insights, hence allowing for a more natural conversation to translate the emergent issues as expressed in natural language into the formalism of an influence diagram; for example, by defining meaningful variables and states. Only once the uncertainties are explored, do we discuss the ways in which outcomes can be measured beyond the inevitable whole life cost. For example, in our context the level of carbon emissions is important and leads to discussion about how it might be measured.

Several iterations of the preliminary model can be required to arrive at a stable version for which assumptions are stated and understood in relation to boundaries, time horizons and so on. Even during this structuring phase we find it valuable to ask questions in relation to the quantification of uncertainties. This is because by asking for conditional probabilities, based on the dependencies between uncertainties, we can flag where logic represented in the model is not entirely consistent with the underlying reasoning of the expert. Hence iteration between qualitative structuring and quantification is usual and can help build a stronger and more defensible model.

2.5 *Eliciting probabilities of uncertainties*

The elicitation of probabilities to quantify the uncertainties represented in the model is informed by the recognized process of structured expert judgement as reported in, for example, Cooke (1991) and Quigley et al (2008) and drawing on our experiences as reported in Hodge et al (2001). The questions are determined by the dependencies captured in the influence diagram. For example, child nodes without parents require assessment of probabilities of particular events in isolation, while conditional probabilities will be required for those uncertainties represented by nodes that have parents. Hence we seek to answer questions of the form "If event μ occurs and the value of β is Υ, what is the probability of α occurring?"A spreadsheet data collection form is designed to express all questions in terms of the meaning of the states of the variables and their dependencies and to capture the probabilities expressed.

Probability elicitation is conducted by a facilitator and an analyst with each individual engineering expert. Experts are selected because they have a deep understanding of the technology options for the repowering design as well as the management context. While the facilitator leads questioning and manages the elicitation script, the analyst listens, records reasoning, clarifies and challenges as needed. For example, to explain how subjective probability might be expressed in the form of a bet, to clarify how states are defined and to revisit these definitions if required, to prompt if there appears to be an inconsistency of reasoning or to explore challenges to the model boundaries.

2.6 *Quantifying the outcomes*

The measurement of outcomes will be problem dependent. For our repowering decision, two major outcomes, levelized annual cost and carbon emissions, are quantified using a method developed by the analysts, but verified and populated by the client organization. In summary, the lifetime costs require us to establish the peak and average loads, annual consumption and annual production in specified time horizons, then to calculate the annual operating and emission costs, combine this with any capital and upgrade costs, to generate the lifetime and annualized cost. These calculations are nontrivial given the variation for different system design options under different uncertainty scenarios.

2.7 *Analysis using the decision model*

Once the decision model is fully instantiated, specialized software tools, can support standard analysis of options, their sensitivity to changes in input settings and to estimate the value of information that would reduce or "buy down" key uncertainties. We used the DPL software tool to support visualization of the model and run preliminary standard analysis, including assessment of sensitivities. To explore, for example, trade-offs between design options against multiple criteria we developed customized analysis in Matlab.

3 REPOWERING DECISION MODEL

3.1 *Decision Context*

Although the current power station is aging, the deadline for construction of a replacement is defined by a deadline imposed by the Scottish Environmental Protection Agency (SEPA) to ensure compliance with European Commission emissions directives by 2016. With the existing plant this will only be feasible to meet standards if it runs in stand-by mode. Since the detailed design and construction of a new plant is around 3 years, a repowering decision is required in 2013.

Planning approval has been granted recently for the construction of a 370MW capacity wind farm on Shetland which would necessitate a DC interconnector to the Scottish mainland. Currently Shetland Isles are not connected to the National Grid, but an interconnector, should it be built, could be used to supply Shetland as well as take supply from Shetland to the mainland. A number of hurdles remain and a decision to proceed with the new wind farm is still to be taken owing to uncertainties over, e.g. future incentives. Any decision on the interconnector will require regulatory approval and it is anticipated that any go-ahead decision will not be taken until at least 2014. Given lead times for manufacture and installation, this implies a commissioning date beyond 2017.

In future, a major industry complex that currently supplies energy to the island may actually take power from the energy utility. The major industry complex might require the utility to either meet all its energy needs or provide a back-up supply.

Hence there are several decisions to be taken over the next few years by other stakeholders which will influence the repowering decision but that are beyond the control of the energy utility, the decision-making body in our context.

3.2 *Repowering design attributes*

There are five major design attributes that are part of the repowering decision.

3.2.1 *Location*

The two principal proposed locations: Location A is adjacent to a significant population centre; and Location B is close to a major industry complex.

3.2.2 *Pipeline*

A natural gas pipeline might be planned and subsequently installed to connect the power station to Location B. This variable has dichotomous states: planned and not planned.

3.2.3 *Connection*

The connection of the power station to the distribution network will be either through the utility's existing distribution network (D-network) or a future transmission spine (T-network).

3.2.4 *Units*

The number of units is defined by the anticipated peak load and level of redundancy. The latter will be "N+2" where N is the number of units required to meet demand (i.e. peak load/unit size). The peak load can be derived as:

Peak load = Current Peak Load + Oil Terminal Peak Load (if demanded) + Peak Load Growth (underlying + new loads) – Peak Load Reduction (1)

Note that peak load reduction may result from load shifting, e.g. domestic demand side management systems (DDSM)[1] and flexible demand through the community heating scheme (SHEAP), storage batteries or reliable wind power (if spatial/technology diversity is sufficient to ensure some minimum renewable generation will be available at peak time) under an Active Network Management (ANM)[2] scheme.

The type of unit will depend on the duty cycle it must perform, which in turn will depend on whether the mainland interconnector is in place or what derogation to emissions regulations is allowed by SEPA. Four duty cycles states are defined to cover all possible scenarios, namely: full duty gas (units are gas fuelled and fully fitted with heat recovery and emissions abatement equipment); full duty minus (as Full Duty Gas less any balance of plant required for gas running); standby plus (as Standby the addition of some unit-specific balance of plant); standby (minimum plant specification for standby running).

3.2.5 *Infrastructure*

The initial extent of the infrastructure required to house the units can be chosen to fit the initial design or to accommodate this design plus possible future expansion. Three states are defined: full 8 (accommodate maximum of 8 units); part 12 (accommodate maximum of 12 units although initially house 8 units); full 12 (accommodate maximum 12 units).

3.3 *Uncertainties*

Given the temporal aspects of the decision, we consider two time horizons. Time horizon 1 (TH1) refers to the short term up to 5 years from the time the new plant is in service; Time horizon 2 (TH2) refers to beyond 5 years. Including time effects in the model allows us to distinguish between short and longer term uncertainties associated with events (e.g. household take-up of DDSM heaters) as well as to specify time horizons for cost computations.

In total there are ten uncertainty variables, although some relate to the same event but measured over more than one time frame or relating to two enquiry points (EP1 and EP2) as defined by key gates of the repowering project; EP1 is the point *before* the initial unit type is decided whereas EP2 is the point *after* the initial unit type has been decided.

Table 1 provides a summary of the uncertainties. For example, the quantity of renewable energy will impact fuel costs and emissions at the power plant. DDSM will influence the utilization of renewable energy generation capacity and the capacity to impact peak load through time shifting. Two elements of peak load are considered. One reflects the underlying growth in demand associated with economic activity and degree of penetration of consumption devices. The other reflects step changes in load possible in the longer terms such as the opening of a new fish factory. We distinguish between the service requirements of the major industry complex as currently known and as might be known in due course after decisions have been made about the number of units. Since the interconnector is conditional upon the wind farm being progressed this represents our final source of uncertainty.

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[1] Under the NINES scheme domestic demand can the managed through the centralised control of domestic storage heaters in homes; these can be "charged" during periods of high wind or low demand to smooth out supply/demand imbalances

[2] The active network management scheme seeks to optimise utilisation of wind generation given electricity demand and network constraints

Table 1. Uncertainty variables

Uncertainty Variable	Number of States
Amount of renewable generation by end of TH1	3
Amount of renewable generation by end of TH2	3
Number of homes with DDSM added during TH1	4
Number of homes with DDSM added during TH2	4
Peak load growth in TH2 only	3
Industry complex service requirement in EP1	5
Industry complex service requirement in EP2	5
Wind farm progress status at EP1	3
Wind farm progress status at EP2	3
Wind farm completion status by plant operational	2

3.4 *Simplified decision model*

Figure 2 shows a simplified version of the model in the form of an influence diagram. This is a graph where the nodes represent the variables and the arcs the dependencies. For example, for both renewable generation capacity and DDSM, there is a link between the states in the two time horizons, TH1 and TH2. While growth in both periods is not cumulative, growth in the short term may be associated with growth in the longer term, say due to incentives in a bid to meet targets. There will be links between sequential enquiry points. For example, if the wind farm is given a proceed decision at EP1 then it is unlikely to be reversed, but if there is no decision at EP1 then there are multiple states open at EP2. The decision on the interconnector (contingent on the wind farm decision) will influence the plant duty cycle since if the interconnector is available then a standby plant will be required, but if the interconnector does not exist then the plant will be required to perform full duty. It is believed that the decision on what service is required by the major industry complex will be influenced by the plant location.

The uncertainties were expressed as probabilities following the process of structured expert judgement described in Section 2.5 and operationalized by designing a customized spreadsheet based data collection form.

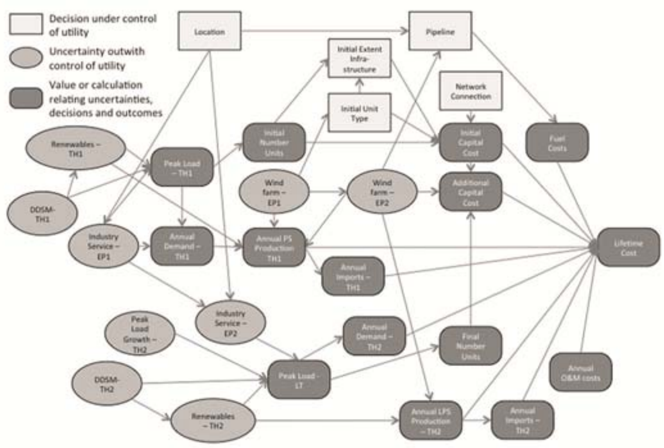


Figure 2. Simplified influence diagram of repowering decision

3.5 *Computation of cost and emission outcomes*

Figure 3 shows the elements of the calculations for the lifetime and emissions costs. This algorithm was used together with financial values provided by the utility to obtain costs for each pathway through the decision model.

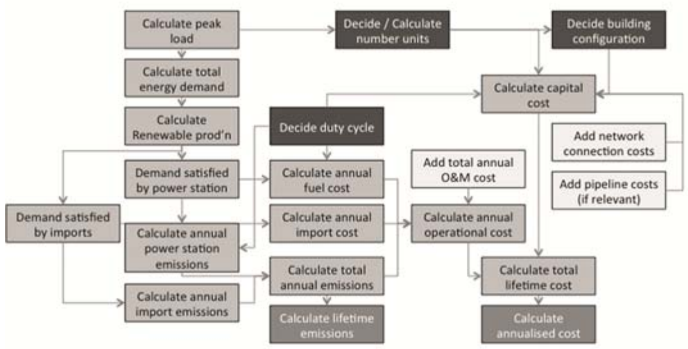


Figure 3. Logic for lifetime and emission cost calculations

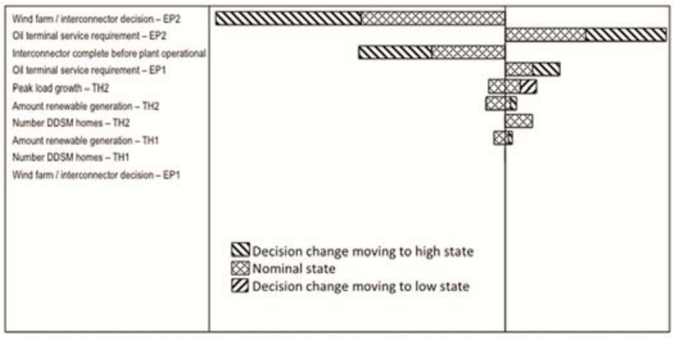
4 ANALYSIS

We present a selection of analysis from the perspectives of lifetime costs then emissions each independently, before exploring the trade-offs between repowering options assuming the goal is to minimize both lifetime and emissions costs.

4.1 *Decisions to minimize lifetime costs*

Using standard analysis of the decision tree version of the influence diagram it is possible to identify the decision pathway that minimizes expected annuitized costs. For example, the plant should be at Location B, fueled by gas, dimensioned for the maximum number of units, the duty cycle will depend on the decision on the wind farm interconnector at EP1 and the plant should be D-connected irrespective of other considerations. The expected cost of Location B is around 10% less than for Location A. The relative savings range from around 6% to 20% as we explore the change in settings from high to low states, where we set low (high) values to be those states associated with lesser (greater) uncertainty.

Figure 4 shows the effects of systematic changes of uncertainty states from their low to nominal to high states in the form of a tornado diagram. The length of the bar indicates the impact of an uncertain variable on the outcome decision. The change in shading indicates when a transition from the nominal to either the high or the low state results in a change in policy. Figure 4 suggests that the uncertainties over the interconnector have the largest impact on cost. In particular, "Wind farm EP2" and "Wind farm complete before power station operational" as well as the "industry complex service requirement". However, even though there is a wide range in the expected annuitized costs over the range of possible outcomes, the actual changes in decision policy through this form of sensitivity analysis show relatively little effect on the expected cost values.



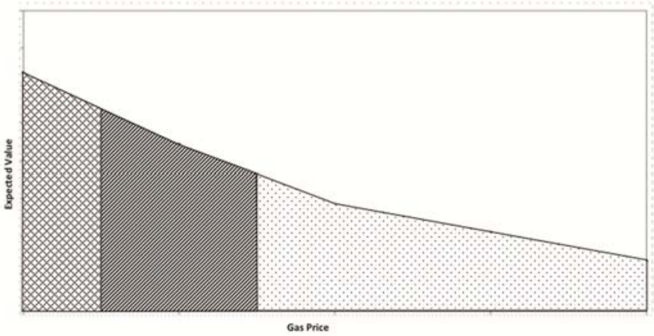


Figure 4. Diagram showing effect on decision outcomes of varying uncertainty states; longer bars indicate a greater effect

Figure 5. Effect of varying gas prices

Figure 5 shows the effect of varying the cost of “gas price”, as measured by the cost of producing 1 MWh of electricity using gas in a unit with heat recovery, between £0 to £200. The breakpoints between decision policies appear around £20/MWh, £85/MWh and £95/MWh. Using these breakpoints to define state settings we can examine the respective decision policies. For example, if gas price is very high then Location A is preferred over B, and full minus duty cycle over standby is preferred if the decision is to build an interconnector at EP1.

Although not shown we have examined the opportunity costs of over-specifying the plant in terms of its generating capacity and duty-cycle, when this may not be required. We have also derived the value to the utility of having perfect information about some of the key uncertainties. For example, if it is known that the major industry complex will require a service function from the utility then if the interconnector is implemented, a full minus duty cycle appears to be preferred over the standby option.

4.2 *Decisions to minimize emissions*

Similar analysis has been conducted for the emissions outcome. We find that the expected emissions, measured in kilotonnes p.a., is around 2.5% less for Location A than Location B. This reduction varies between around 1% to around 4% as the states are fixed at their low and high settings as in the analysis for lifetime costs.

From this perspective, Location A is preferred, gas is preferred over distillate and either full duty, or full duty minus, is the preferred cycle irrespective of the wind farm decision at EP1. Interestingly the option when the wind farm does not proceed appears to offer lower emission than the case when this wind farm does proceed. This might be explained in terms of, for example, the increase in total emissions attributed to the utility in the likelihood that major industrial facility takes power from them.

4.3 *Trade-offs between lifetime costs and emissions*

There is an inherent tension between the requirements to select a repowering option to minimize both lifetime costs and emissions. By plotting all the possible decision outcomes (i.e. relating to all combinations of states of decision variables) in the cost-emissions space, it is possible to generate a set of decisions which form an “efficient frontier” where both lifetime costs and emissions are at their respective minimal points in some combination. Figure 6 presents the results of this trade-off analysis. Seven, so-called Pareto optimal points corresponding to the seven most efficient repowering design options can be identified (given by black rectangles). These seven options dominate all others (shown in grey diamonds) because the seven repowering options on the efficient frontier represent those for which the combined lifetime costs and emissions are minimum, even though the values of the lifetime costs and emissions will different for each of the seven options. This analysis supports a trade-off between emissions and lifetime costs. Which of these repowering options might be preferred will depend on the relative importance given to the emissions and costs outcomes.

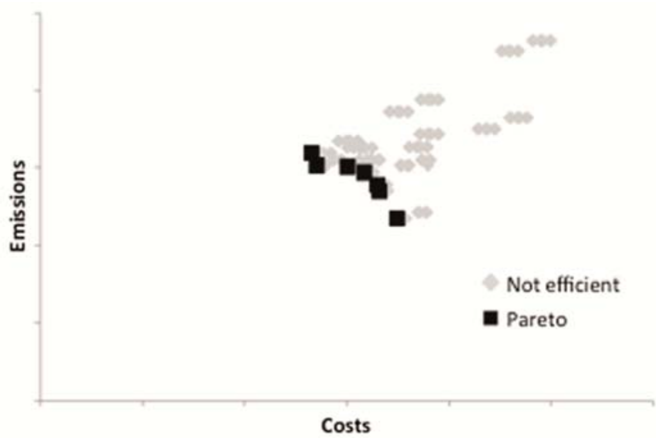


Figure 6. Pareto set of repowering design options that are most efficient in the emission-cost space

5 CONCLUSIONS AND FURTHER WORK

The decision analysis carried out and described in this article has led to a number of important conclusions being drawn about the repowering decision. The analysis is being developed and should inform the decision to be made by the utility later in 2013 since the model has been built collaboratively with SHEPD engineers and managers. A process grounded in scientific principles, but cognizant of the softer aspects of modelling, has underpinned our analysis to ensure that the model scope is relevant, the representation of decisions, uncertainties and outcomes are a representation of the reasoning and beliefs of those who understand the problem and the engineering solutions.

As analysts we have sought to make the modelling process transparent and to discuss a selection of analysis that will help inform decision-making. As with any decision modelling approach, the intention is not to prescribe a solution, but to logically present a summary of the possible solutions that will allow decision-makers to focus on a smaller set of options and the trade-offs between them. For example, we have managed to reduce the set of possible decision options from over 200 to 7 that are equally efficient in terms of minimizing both emissions and lifetime costs. Thus providing more focus to support management discussions about possible engineering solutions.

The analysis presented is based on assumptions about, for example, the representation of number/descriptions of states and the means by which costs have been computed. However sensitivity analysis allows us to challenge facets of the model such as exploring the impact of variation in parameter values. We emphasize the role of the model in supporting, but not making, decisions. The power of such a model is that it provides a representation that can be revised and extended to reflect understanding of, for example, important criteria, types or states of uncertainty, or different decision time horizons.

The integration of the workshops to surface risks and uncertainties to usefully feed into the formalism of a decision model has been a distinctive element of our approach. The sharing and understanding of risks achieved through the workshop process has been fundamental to the development of the decision model. Building a divergent-convergent dialogue between the problem structuring the workshops has been important in understand the risk landscape and allowing us to translate the systemic uncertainties surfaced from multiple stakeholders into the those that a within the direct control, or not, of the decision-making organization. That is, to define decision actions that can be taken by the client and to recognize the uncertainties that need to be managed. The valuation of risks can be better understood and so suitable criteria against which decision outcomes are to be assessed can be defined. The workshops make an important contribution to conditioning experts prior to the elicitation of subjective probabilities.

We have used the term systemic risk as a global expression for the inter-dependencies between risks. We need to acknowledge that both acyclic and cyclic dependencies emerge in the risk mapping workshops and yet there is a translation to an acyclic influence diagram to represent the decision model. This was achievable because the decision model effectively represents the steady-state behaviour of any feedback loops observed from the risk maps. Hence we use the information about the inputs and outputs from such loops within as parameters within the decision model and the insight into the temporal aspects of cycles to inform the time slices that might be important in decision-making.

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