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Using Game Theory to Address Modern Resource Management Problems

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The headlines

- Global tensions over the provision of water, food and energy are growing in response to demographic change and rapid economic development.
- Whilst water-food-energy challenges are becoming increasingly interconnected by complex ecological, socio-economic and socio-political factors, this complexity is not adequately reflected in assessments of these challenges, or in problem solving.
- There is a need to integrate multi-actor, multi-objective frameworks for interlinked water-food-energy challenges across scales and between scales, whilst accommodating uncertainty.
- There are multiple decision making tools available but their ability to replicate the capacity for compromise amongst stakeholders and objectives in real-world decision making processes is limited.
- Game theory can offer an alternative decision making approach by generating a set of near-optimal, feasible and 'stable' results, allowing the analysis of the various trade-offs involved, and of potential fallback positions. The outputs from such an approach can be practical in real-world situations when compared to the 'optimal', but often impracticable options, given by conventional multi-objective optimisation methods.

The resources required for human and planetary wellbeing are under increasing strain from over-use. This strain is a consequence of a number of interlinked factors, including population growth, affluence, poverty and climate change. The resource nexus agenda has developed to provide a better understanding of the complex interrelationships between resources and the stresses involved. In the water-food-energy nexus, for example, the production of food on increasingly marginal land requires greater volumes of water and energy-intensive processes and inputs such as fertilisers to increase yields in order to match rising demand. Whilst a 'predict and provide' approach still pervades in resource planning, there is also a recognition of economic, social and environmental constraints and even limits. Decision making in this context is complex: it is multi-sectorial, often with a limited understanding of interdependencies; it is multi-objective i.e. attempting to balance competing factors; and has multiple stakeholders, each with their own objectives.

High levels of uncertainty about the interlinked water-food-energy nexus and about the future mean that traditionally preferred 'optimal' approaches to resource allocation may not provide flexibility or robustness, and this problem is particularly acute in the multi-stakeholder context. Game theory, the mathematical study of competition and cooperation, is able to offer insights for planning in such circumstances, supporting other recognised methods such as scenario analysis, robust decision making and integrated assessment modelling.

Key management challenges of the water-food-energy nexus

The rapid growth of the global middle class from 1.1 to 1.8 billion between 1980 and 2009 has already resulted in rapid increases in demand for water, food and energy, as manifested by commodity price spikes and persistent volatility across all strategic commodities. The middle class is anticipated to grow by a further 3 to 4.8 billion by 2030: an increase unprecedented in human history. It has been suggested that by 2030, demand for energy will have increased by 40%, food by 50% and water by 25%. Not only is the extent of growth significant but so are the speed and scale at which economies are growing. China and India are doubling their per capita incomes at 10 times the rate that the UK did during the industrial revolution, and at 100 times the scale.

Superimposed on this growing demand is an increasing connectivity and complexity in the water-food-energy nexus. Some of the reasons for the increasing connectivity in the modern resource system are:

- New technologies and markets;
- Coupling of commodity markets; and
- Higher levels of raw material resource trade, which globally increased six fold between 2000 and 2010.

This increased interconnectivity has not triggered a corresponding shift in the approach to resource analysis. Indeed, the capacity to accommodate multiple subsystems, multiple agents, their interaction and dynamics in multi-participant multi-objective agendas has been limited[1]. Studies still seek optimisation along one, or several parameters, rather than stability. However, practical problem solving requires solutions that are stable (feasible)[2]. While stable solutions are not necessarily 'optimal' from the system's (central planner's) point of view, they are reachable in the presence of multiple actors with conflicting objectives and can improve the status quo. The failure to deliver stable solutions to resource issues and integrate increasing complexity in the natural resource system has a number of associated risks, which include:

- Exacerbating the risks of temporary and/or regional source shortages;
- Increasing the likelihood of potentially negative knock-on and cascade effects, and;
- Increasing the likelihood of passing critical tipping points or triggering feedback-loops within environmental systems.

In the UK these challenges are manifested in the energy-water sector where long-term decision making is a function of:

- A multi-billion dollar infrastructure legacy which is capital intensive, highly variable in the capital required at any point in time and requires long-term investment. In the energy sector for example, £275 billion is in the pipeline to 2030 and in the water sector the Asset Management Programme 6 (2015-2020) is worth over £40 billion;
- Very long asset life of over 40 years;
- Significant long-term uncertainties in supply and demand resulting from e.g. population; efficiency savings; changes in demand; regulation; climate change; and
- Interdependencies between different sectors which can result in cascade failure where failure of one system results in knock-on failures on often multiple other systems.

Regulatory frameworks need to encourage the right incentives for competitiveness, investment and innovation for a specific set of policy goals. For the cautious, uncertainty – a manifestation of these complexities and interconnections – can limit action. This lack of action can have a detrimental effect on long-term investments in energy and water infrastructure needed for the effective transition to a resilient water and low-carbon energy system. Therefore, in decision making for long-term climate change, energy and environmental policy, the designing of policy mechanisms to establish long-term stability for investments is an important and significant challenge.

Some commonly used analytical tools which accommodate uncertainty, multi-actor objectives and trade-offs

There are a number of methods which seek to address uncertainty to varying degrees – see table, below.

Method	Applicability and Applications
Agent Based Modelling	This computational modelling technique simulates the actions and interactions of autonomous agents – individual or collective entities – with a view to assessing their effects on the system as a whole[3].
Multi-Criteria/ Objective Decision Analysis	Multi-Criteria Decision Analysis seeks to provide an overall ordering of options, from the most preferred to the least preferred option. The options may differ in the extent to which they achieve several objectives, and no one option will be obviously best in achieving all objectives. Often some conflict or trade-off takes place between objectives, some of which might be quantified, and others less tangible[4,5].
Scenario Analysis	Scenario Analysis is used to explore how the future might evolve either in an open-ended manner (exploratory) or to meet a given goal (normative) e.g. ways in which to achieve an 80% reduction in greenhouse gas emissions in the energy sector (DECC's UK 2050 calculator, UKERC's The UK Energy System in 2050 or National Grid's UK Future Energy Scenarios). Scenario analysis allows the development of strategies, or tests existing ones. Optimisation tools can be used to identify the optimal plan, for example what demand side measures in the water sector could deliver higher water savings compared with their costs[6].
Robust Decision Making (RDM)	This technique explores how a set of options might evolve under future uncertainty e.g. water resource planning under climate uncertainty in London. Adaptation pathways use RDM by developing different plausible ways in which long-term uncertainties can be managed. From this it is then possible to assess how these pathways meet multiple objectives relating to cost, sustainability etc.[7]
Integrated Assessment Modelling (IAM)	This technique combines knowledge from multiple disciplines to understand systemic interlinkages[8] to develop pathways that meet multiple objectives relating to cost, sustainability or other targets e.g. UK MARKAL, CLEW, LEAP, FUND.

While these methods provide useful analysis of decision making problems, they fail to fully consider the socio-political dimension of policy making (i.e. those that involve buy-in from the public and the consequential political implications) and the strategic behaviour of local and regional stakeholders. This omission is considerable, considering the fact that long-term management for the water, food and energy systems does not rely on the strategy of a single, fully cooperative entity, but rather on multiple actors who strategically interact to achieve their self-optimising, often divergent objectives.

Questions that need to be addressed and which are often missed by these conventional tools are:

(1) How will an individual organisation's strategy fare in relation to the strategies of other stakeholders?

(2) How can multiple long-term aims of different organisations be reconciled?

(3) What are the most robust strategies across stakeholders e.g. for a particular region?

(4) What outcomes might result from different configurations for each of the stakeholders?

Game theory

Game theory can deliver valuable insights into the strategic behaviour of stakeholders in complex water-food-energy domains where the interactions of the stakeholders normally result in outcomes that are sub-optimal from a system's (central) perspective. Game theory can be applied in any field where more than one actor is involved in the decision making process and the final outcome depends on the participants' strategic behaviour, their willingness to cooperate, risk attitude, access to information, uncertainty exposure and other behavioural factors[9]. This technique reveals how the preferences of actors, their possible moves and counter-moves play out in strategic interactions delivering a range of outcomes.

Game theory can be used to predict or describe how people behave and fulfil their own interests during the interactive decision making process. Games are defined as mathematical frameworks, consisting of a set of players, a set of strategies available to them (preferences or moves), and players' payoffs (utilities) for each combination of possible outcomes of the 'game'. The main driver of each player's decision is their potential gain. In a typical game, the players try to outsmart one another by anticipating each other's decisions. The game is resolved as a consequence of the players' decisions.

Unlike other conventional system optimisation methods, game theory considers a close-to-reality interest-based behaviour of the individuals rather than taking an overarching system perspective. As a result, game theory assesses the attainability of a system's optimal outcomes starting from the current situation and with due attention to individual self-optimising behaviours. These behaviours can differ in geographic scope e.g. supranational, national, regional and local and in objective, e.g. profit creation, preservation of environmental quality, decarbonisation, etc. Solutions found using game theory for multi-criteria multi-decision maker problems[10] are normally different from those found through conventional decision or behaviour simulation methods such as multi-criteria decision analysis[11] or even agent-based modelling.

Game theory can be applied to decision making in bargaining, voting and negotiation situations when the dynamics of sequential interactions are not fully understood, such as in international climate change negotiations[17]. It can also apply to the architecture of governance structures on water and environmental systems,[13, 14, 15] and the process of making group decisions over developing a new energy supply source for a city[16] (Box 1), or better understanding the dynamics of military and geopolitical issues[17].

Box 1: A Multi- Participant Multi-Criteria Analysis of Energy Supply Sources in Alaska – Case Study

Figure 1: The location of the city of Fairbanks and the location of possible energy sources. (Image credit: Alaska Center for Energy and Power (ACEP))

Energy source selection can be modelled as a multi-criteria decision maker problem to provide support that combines technical, economic, environmental, and social-political factors with respect to the stakeholders' interests. In the following case study, multiple decision making methods were used, each accommodating differing levels of cooperation amongst stakeholders, to assess the most stable decision outcomes.

Decision making in this complex setting should also account for the uncertainty present in the input data. Therefore a stochastic (i.e. probability-based) decision analysis framework to evaluate different choices lay at the heart of the model. Stakeholders were asked to identify both quantitative (e.g. carbon footprint)

Alt	Description
A1	Large diameter pipeline Edmonton, Canada to Chicago, Illinois.
A2	Liquid natural gas export from North Slope to Valdez.
A3	Bullet line to Anchorage, spur to Fairbanks.
A4	Small diameter pipeline: North Slope to Fairbanks.
A5	Liquid Natural Gas (LNG) trucking project.
A6	Big Lake gas pipeline: Beluga to Fairbanks.
A7	High voltage direct current line from North Slope.
A8	Coal-to-liquids power plant in Fairbanks.
A9	Sustina Hydro-electric dam.

Table 1: The proposed alternatives for energy supply used in the modelling process which might be applied to Fairbanks, Alaska.

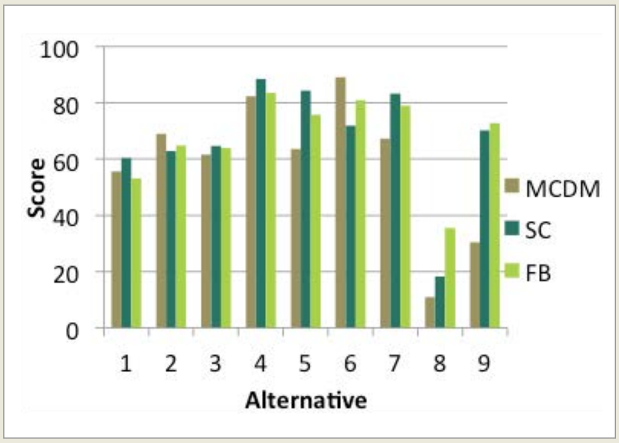

Figure 2: The value in using multiple analysis methods (MCDM: multi-criteria decision analysis | SC: Social Choice | FB: FallBack Bargaining Game Theory Framework)

and qualitative (e.g. political support) selection criteria and performance metrics, which carry uncertainties. The resulting framework was tested using a case study from Fairbanks, Alaska, where decision makers and residents must decide on a new source of energy for heating and electricity – Figure 1 and Table 1.

This problem was approached in five steps: (1) engaging experts (role players) to develop criteria of project performance; (2) collecting a range of quantitative and qualitative input information to determine the performance of each proposed solution according to the selected criteria; (3) performing a random selection (Monte-Carlo) analysis to capture uncertainties given in the inputs; (4) applying multi-criteria decision making, social choice (voting), and fallback bargaining or game theory methods to account for three different levels of cooperation among the stakeholders – high, medium and low for each respective technique; and (5) computing an aggregate performance index (API) score for each alternative based on its performance across criteria and cooperation levels.

The results in Figure 2, show that the aggregate performance indexes for the alternatives from Table 1 – based on the stakeholder-defined criteria across all decision analysis methods. As the level of cooperation in a negotiation is not known, these methods allow the accounting for a range of possible low, medium and high levels of co-operation. For example, in cases where the parties are not cooperative but willing to bargain, the fallback bargaining methods are more suited to solving the problem; on the other hand, if the decision makers are only concerned with the optimal solution and benefit from a high level of cooperation, then multi-criteria decision analysis (MCDM) methods can inform decisions. Social Choice methods indicate results that are achievable when parties are neither fully non-cooperative nor fully cooperative.

By including a range of decision analysis methods and accounting for uncertainty this methodology added robustness to the decision-making process. This robustness can be demonstrated in a challenging case such as this regional energy supply problem. The results of the different methods used in this study were very close to the sequence of decisions that were made in practice at the time of this analysis.

Increasing the use of game theory in the environmental resource management context

Game theory has the potential to identify and assist with the selection of solutions to challenging resource sharing and management problems that can be supported by a range of stakeholders, and that might not otherwise have been considered the ideal outcome. This method can also support negotiators and decision makers in navigating difficult political decisions and avoiding deadlock situations, by understanding better how the needs of different players may interact.

Policy makers should consider the power this decision analysis framework presents at a variety of levels:

- Facilitating internal decision making and cooperation about priorities within governments and civil service bodies and between institutions;
- Strengthening negotiation approaches and outcomes, e.g. at the international climate change negotiations, between all nations concerning a common good;
- Finding solutions to specific resource management questions at local scale, and also more broadly.

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